Economics of Nuclear Power in Liberalized Power Markets[1]

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Carmine Difiglio, Ph.D.[2]
Brent Wanner[3]

Abstract

Projections of electricity markets such as the International Energy Agency's (IEA) *World Energy Outlook* (*WEO*) or the Energy Information Administration's (EIA) *Annual Energy Outlook* (*AEO*) rely on estimated levelized costs for nuclear power and other power generation technologies. These levelized cost estimates show nuclear to be a very competitive power generating technology in most regions of the world. This paper analyzes unpublished data from the *2011 WEO* to assess the competitiveness of nuclear power in liberalized and non-competitive power markets. We consider alternative estimates of nuclear capital costs (Risk Scenario) that might well be considered before investing in nuclear power in competitive markets without government guarantees. The Risk Scenario also assumes lower natural gas prices that could result from higher shale gas recovery in the United States and new shale gas development in Europe. The Risk Scenario causes the relative cost difference of nuclear power vs. natural gas to change by 5 cents/kWhr. Instead of nuclear power holding a competitive advantage over natural gas, in the Risk Scenario, natural gas gains a competitive advantage over nuclear power, even if a \$50/ton CO_2e charge is assessed.

The analysis suggests that nuclear power plants will not be built in liberalized power markets without government guarantees. If nuclear power plants built with government support or those built by state-owned power industries prove that nuclear power plants can be reliably built at a competitive cost, power plant economics will be a significant positive factor for the nuclear industry, especially taking into consideration national commitments to reduce greenhouse gas (GHG) emissions. If costs continue to increase over the estimates being used by the IEA and EIA, power-plant economics become a significant negative factor for the nuclear industry that may not be offset by pricing CO_2 emissions.

These findings do not apply to reactor projects in many Asian countries. Nuclear power is estimated to enjoy a more favorable cost advantage than in the United States, Europe or Japan. In addition, private financing is less important in many Asian countries and delays due to licensing problems are less likely.

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[2] Deputy Assistant Secretary for Policy Analysis, U.S. Department of Energy. The analysis and data included in this paper are those of the author and are not necessarily endorsed by the U.S. Department of Energy.
[3] International Energy Agency, Paris.

Given the high electricity demand growth expected in Asia, more competitive costs, and government support, it is not surprising that over 60% of currently-planned nuclear reactors are in Asia.

Introduction

Estimating the future mix of electric power generation technologies usually begins with a comparison of the costs of competing forms of electricity generation. Most major energy models employ a "bottom-up" methodology that takes into consideration estimated capital, fuel costs and operating costs of alternative power-generation technologies. These are usually expressed as a "levelized-cost." Levelized cost represents the wholesale cost to produce each kilowatt hour (kWhr) of electricity over the economic life of the power-plant investment. While energy models consider a variety of factors, including the dispatchability of power in relationship to daily and seasonal power demand, there is a tendency to estimate high future market shares for power technologies with the lowest levelized costs. Given the estimated levelized costs of nuclear power compared to natural gas, coal and renewables, one would expect the projected growth of nuclear power to be greater than most projections might imply. This is partly explained by different public policies among countries. Modelers must restrict model projections in countries that have national policies that are adverse to nuclear power development. However, there may be other reasons why current cost estimates may imply a stronger future for nuclear power than may reasonably be expected. This paper considers the factors that might explain an apparent mismatch between estimated costs and realistic expectations for nuclear power expansion, even in markets that price GHG emissions.

Liberalized Power Markets

For the purposes of this paper, power markets are divided into two general types: traditional and liberalized. Traditional power markets are uncompetitive arrangements that adhere to the concept of a natural monopoly. A natural monopoly is a condition in which a single firm can provide a product or service more efficiently than multiple firms. Since a power company must provide power-lines to their customers, it would be inefficient to have multiple power lines from different power providers. For this and other reasons, integrated power companies arose that encompassed all aspects of providing power to consumers, from generating electricity through distribution to consumers. These companies have traditionally been regarded as natural monopolies that should enjoy exclusive access to customers. These natural monopolies have usually been organized as a state-owned company or a private company with an exclusive right to serve that must seek approval from government regulators when making large investments or setting prices.

Utilities and regulators use estimates of levelized cost to acquire a "level-playing-field" comparison of alternative power plant investments that have substantially different combinations of capital cost, fuel cost, operating cost, and plant life. Levelized cost estimates the per-kilowatt hour (kWr) cost of a technology derived from the present value of building and operating a generating plant, assuming a particular duty cycle, amortized over its economic life. It was a tool that allowed State regulators to determine whether to approve investments in new power plants by private utilities. Levelized cost estimates allowed the regulatory authorities to evaluate whether new power plant investments would be prudent and the likely effect they would have on consumer costs over long periods of time. If approved, the utility could proceed with the power plant investment and the utility's banks and shareholders would be confident that the power plant would generate revenues sufficient to pay the loans and provide expected dividends.

The U.S. utility industry was initially unregulated. Thomas Edison's first power plant began operation in 1882 (New York City). By the beginning of the 20th century there were about 3,000 unregulated U.S. electric firms in addition to almost 1,000 municipal systems. State regulation of power plants began in 1907 in New York and Wisconsin. The private providers actively sought State regulation as the competition among power providers was counterproductive and the private companies needed some protection against the municipal providers. Under state regulation, there were fewer power companies as the investor-owned utilities became much larger. A collapse of utility stocks during the Great Depression led to the Public Utility Holding Company Act (PUHCA) that gave significant powers to the Securities and Exchange Commission (SEC) to control the structure of investor-owned utilities. In 1935, the Federal Power Commission was created to oversee Interstate transmission of electricity, including rates.

Between 1935 and 1970 U.S. electricity consumption grew at an annual rate of 7.9% requiring predictable power plant additions. Under the U.S. regulatory regime, the investor-owned utilities would acquire permission from their State regulator to build the plants. They were assured that the cost to build, fuel and operate these additional plants would be considered when setting tariffs and they were assured that these investments would provide a normal rate of return to the utilities' investors. The cost of carrying excess generating capacity was also included in the rate base. Consequently, the investors' returns, within limits, did not depend on whether actual electricity demand fulfilled expectations when the power plant investments were planned.

Levelized cost calculations are also considered by state-owned power companies. In each type of market, investor-owned regulated utilities or state-owned utilities, the investment in a new power plant is substantially less risky than private sector investments without guarantees. Until the 1970s in the United States, there was little likelihood that a power-sector investment would adversely affect a privately-held utility. Regardless of less-than-expected electricity sales, capital cost overruns or increased fuel costs, retail electricity rates would be adjusted to make the investment whole.

These arrangements were taken for granted until the mid-1970s energy crisis. High oil costs required retail rate increases that led to a flattening of electricity demand ending decades of predictable electric power growth. This particularly affected the nuclear power industry as plans for 113 U.S. nuclear power plants were scrapped between 1972 and 1984. At the same time, many players in the U.S. power industry and non-governmental organizations (NGOs) began to propose new ways to organize the power industry recognizing that it consisted of three distinct services: generation; transmission; and local distribution. A dozen U.S. States implemented regulatory reforms that allowed competition for industrial and private consumers. The reforms also affected markets that remained regulated. While regulated utilities could still build power plants and have them admitted to the rate base, they often have to show that their plants would provide power at lower costs than contracting for power from independent power producers. Several regulated utilities also purchase power from unregulated private companies using competitive contracting procedures.

These reforms can be generally characterized as a "liberalized power market." Any party considering a power-plant investment in a liberalized power market realizes that it carries the risks of any business investment, substantially riskier than a corresponding investment by a non-competitive regulated utility. In addition, regulated utilities in States that have not implemented significant regulatory reform often evaluate power plant investments as if they were engaged in a competitive market since these utilities are less confident that State regulators will add the full cost of new power-plant investments in the rate base if there is excess generating capacity or if the cost of the added generation is higher than expected.

IEA's *2011 WEO* Estimates of Levelized Costs

Table 1 shows the estimated long-run marginal cost of four power-generation technologies in the United States, the European Union, China and Japan. These estimates underlie analysis used in the *2011 WEO's* World Energy Model. There is a wide range of estimated levelized costs for renewable energy since a variety of power-generating technologies are included in this group, from inexpensive wind power to more-costly solar power. The costs shown for natural gas only reflect combined-cycle base load plants. Peaking plants were not included since these would not be considered to be alternatives to nuclear power plants. The estimated costs for coal plants include a variety of coal power technologies with different operating efficiencies. The estimated nuclear costs reflect a Generation III+ pressurized-water or boiling water plant. Plants of this type include the Westinghouse AP1000, the General Electric Economic Simplified Boiling Water Reactor and similar designs from other manufacturers. IEA's *WEO* capital cost estimates were informed by *Projected Costs of Generating Electricity, 2010 Edition* published by the IEA in collaboration with the Nuclear Energy Agency (IEA/NEA 2010).

The levelized costs for nuclear power are estimated to be very similar in the United States, the European Union and Japan. However, the levelized cost for nuclear power is substantially lower in China (about one-half). The IEA/NEA estimates that the overnight cost of building a Generation III+ reactor in China is about one-third lower than in the United States ($2,302/kWe vs. $3,382/kWe).[4] After taking into account the differences in estimated construction times and financial risks, the IEA's estimated levelized cost is about half as much in China compared to the United States (4 cents/kWhr vs. 8 cents/kWhr). Construction times are estimated to be lower in China due to an entirely different structure of licensing and oversight than exist in the United States. Likewise, financial risk to the State-owned power industry is substantially lower in China than in the United States unless the power-plant investment has Federal loan guarantees and backing from a State Public Utility Commission.

[4] p. 59, IEA/NEA 2010.

Renewable energy technologies have a wide variation of estimated levelized costs. The lowest costs are for wind power with favorable wind energy environments. When the best wind resources are taken, the cost of wind power increases as less-productive wind sites are employed or if wind has to move offshore. Other renewable technologies such as solar or geothermal tend to be at the higher end of the estimated costs for renewable energy and, consequently, can be the most expensive sources of electricity. In addition, these estimated levelized renewable electricity costs do not include natural gas peaking plants or energy storage systems that are typically required as back-up for intermittent renewable energy production.

Table 1: Long Run Levelised Cost (U.S. cents/kWhr)[5] in 2035

	Nuclear	Renewables	Natural Gas	Coal
United States	**7.5 – 7.8**	**7.7 – 12.8**	**8.5 – 8.8**	**8.1 – 8.7**
EU	**7.3 – 7.6**	**7.8 – 15.9**	**10.4 – 10.8**	**9.6 – 11.4**
China	**3.8 – 4.1**	**4.8 – 9.5**	**9.6 – 10.8**	**5.7 – 6.9**
Japan	**7.9 – 8.2**	**7.6 – 15.3**	**12.1 –12.9**	**10.3 – 11.6**

Nuclear power is estimated to have the lowest estimated levelized costs in the United States, European Union, China or Japan. If competitive levelized costs were the dominant factor determining future power investments, the share of nuclear power should increase in these countries and world-wide.[6] Competitive nuclear costs are not relevant in countries that have polices to restrict or prohibit new nuclear reactors. Opposition to nuclear power becomes stronger and more widespread with nuclear accidents. Fortunately, nuclear accidents are infrequent but, when they occur, they can reverse a country's policies on nuclear power. The Fukushima accidents have brought about a near-total loss of confidence in the Japanese nuclear power industry. As a result, a country that had been committed to increasing its fleet of nuclear power plants is now considering a phase out of its existing nuclear fleet. Nonetheless, nuclear power remains an acceptable power option in most countries. The cost estimates in Table 1 suggest that nuclear power should be an attractive power investment in these countries.

Nuclear power economics improve if there are GHG taxes or a GHG cap-and-trade system. Table 2 shows IEA levelized cost estimates with a \$50/ton CO_2 charge added to the cost of natural gas and coal power plants.

[5] Unpublished data from the World Energy Model used for the IEA *2011 WEO* (2008 U.S. cents).

[6] Based on IEA data, the relative levelized cost estimates presented for the United States, European Union, China and Japan are not significantly different than those estimated for India, Brazil and Russia.

Table 2: Long Run Levelised Cost (U.S. cents/kWhr)[7] with a \$50/tonne CO_2 Charge in 2035

	Nuclear	Renewables	Natural Gas[8]	Coal w CCS[9]	Coal w/o CCS
United States	**7.5 – 7.8**	**7.7 – 12.8**	**10.2 – 10.5**	**8.5 – 11.8**	**11.8 – 13.1**
EU	**7.3 – 7.6**	**7.8 – 15.9**	**12.1 – 12.5**	**10.2 – 13.3**	**13.3 – 16.1**
China	**3.8 – 4.1**	**4.8 – 9.5**	**11.4 – 12.6**	**6.3 – 9.4**	**9.4 – 11.6**
Japan	**7.9 – 8.2**	**7.6 – 15.3**	**13.7 –14.7**	**NA[10]**	**14.0 – 16.5**

We have estimated the carbon charge for natural gas plants assuming efficient base-load natural gas plant instead of a less-efficient peaking plant. A base load natural gas plant is the alternative to a nuclear reactor investment. Without the carbon charge, U.S. natural gas plants are estimated to produce electricity at 0.7 to 1.3 cents/kWhr higher cost than a nuclear plant. With the \$50 carbon fee, this increases to a much more significant advantage of 2.8 to 3.5 cents/kWhr (natural gas becomes 31% to 40% more expensive than nuclear power). The advantage of nuclear power over natural gas with a carbon charge is estimated to be higher in the European Union, China and Japan: a \$50/ton CO_2 charge increases the cost penalty of natural gas compared to nuclear to as high as 71% in the European Union, 232% in China and 86% in Japan.

Table 3: Cost Advantage of Nuclear Power Relative to Natural Gas with and without a \$50/tonne CO_2 Charge in 2035

	Cost Advantage of Nuclear over Natural Gas w/o Carbon Charge		Cost Advantage of Nuclear over Natural Gas with Carbon Charge	
	U.S. cents/kWhr	**% Cost Increase Over Nuclear**	**U.S. cents/kWhr**	**% Cost Increase Over Nuclear**
United States	**0.7 – 1.3**	**9 – 17**	**2.4 – 3.0**	**31 – 40**
EU	**2.8 – 3.5**	**37 – 48**	**4.5 – 5.2**	**59 – 71**
China	**5.5 – 7.0**	**134 – 184**	**7.3 – 8.8**	**178 – 232**
Japan	**3.9 – 5.0**	**48 – 63**	**5.5 – 6.8**	**67 – 86**

As shown in Table 2, we have estimated the effect of a carbon charge on two different types of coal plants: with and without carbon capture and storage (CCS). A \$50/ton CO_2 charge is sufficient to make CCS plants more competitive than coal plants without CCS. If CCS could be deployed at costs estimated for 2035 by the IEA, a \$50/ton CO_2 charge only adds about 0.4 cents/kWhr to the estimated levelized cost of a coal plant with CCS. Since this does not constitute a significant cost increase, we will not discuss how a carbon charge affects the competitiveness of coal plants with CCS. For the remainder of

[7] 2008 U.S. cents

[8] The carbon charge for natural gas (1.7 cents/kWh) is for a combined cycle gas turbine without CCS and is based on a plant efficiency of 59% and fuel carbon content of 2.3 tCO_2 per toe.

[9] The carbon charge for coal varies by technology, for an ultra supercritical coal plant without CCS it is 3.7 cents/kWh and is based on a plant efficiency of 47% and fuel carbon content of 4.0 tCO2 per toe. CCS plants are estimated to have the lowest costs with a CO_2 charge if favorable assumptions are made about CCS deployment.

[10] The geology in Japan does not favor carbon storage.

this paper, we will only compare the competitiveness of nuclear plants to coal plants without CCS.[11] As shown in Table 4, a \$50/ton CO_2 charge causes nuclear power to have cost advantages over coal at least as high as 51% (minimum U.S.) and as high as 205% (maximum China). Given this carbon charge (\$50), natural gas and coal cease to be competitive power technologies compared to nuclear in these four countries, and, barring special circumstances, world-wide.

Table 4: Cost Advantage of Nuclear Power Relative to Coal (no CCS) with and without a \$50/tonne CO_2 Charge in 2035

	Cost Advantage of Nuclear over Coal w/o Carbon Charge (no CCS)		**Cost Advantage of Nuclear over Coal with Carbon Charge (no CCS)**	
	U.S. cents/kWhr	**% Cost Increase Over Nuclear**	**U.S. cents/kWhr**	**% Cost Increase Over Nuclear**
United States	**0.3 – 1.2**	**4 - 16**	**4 – 5.6**	**51 – 75**
EU	**2.0 – 4.1**	**26 – 56**	**5.7 – 8.8**	**75 – 121**
China	**1.6 – 3.1**	**39 – 82**	**5.3 – 7.8**	**129 – 205**
Japan	**2.1 – 3.7**	**26 – 47**	**5.8 – 8.6**	**71 – 109**

Projected Power Generation in the *2011 WEO*

The *2011 WEO* provided three projection scenarios: 1) Current Policy Scenario - assumes no change to current national polices; 2) New Policy Scenario - assumes the adoption of policies that have been announced to address energy security and environmental goals; and 3) 450 Scenario – assumes policies sufficient to maintain world-wide atmospheric GHG concentrations at 450 parts per million CO_2e.

The New Policy Scenario assumes that, by 2035, the EU, Korea, Australia and New Zealand have adopted a \$45/ton CO_2 charge and China has adopted a \$30/ton CO_2 charge. The 450 Scenario assumes, by 2035, CO_2 charges of \$120/tonne or \$90/tonne have been adopted in the OECD, China, Russia, Brazil and South Africa. The 450 Scenario is a very ambitious end-state driven scenario that would require immediate uptake of strong climate policies in the twenty or so countries that are responsible for the bulk of world-wide CO_2 emissions. The types of changes to the world energy economy implied by the 450 Scenario appear less likely with each passing year (Difiglio, 2010). Consequently, for the purposes of this paper, we only consider the *2011 WEO* Current Policy and New Policy Scenarios.

Electric power generation is expected to grow from 20 thousand TWhr to 36 to 39 thousand TWhr (New to Current Policy Scenarios respectively). As might be expected, the *2011 WEO* projects substantial additions to coal, natural gas, renewables and nuclear power generation capacities through 2035. However, despite the favorable costs estimated for nuclear power, nuclear power is estimated to have a smaller share of world-wide electricity supplies than in 2009 in either the Current Policy or New Policy

[11] As with cost estimates for nuclear power, cost estimates for CCS are highly uncertain and CCS faces deployment obstacles that may be has great or greater than those for nuclear power.

Scenarios. The share of nuclear power is only expected to increase in the 450 Scenario with its very high carbon charge.

Table 5: IEA *2011 WEO* - World-Wide Projected Share of Electric Generation Technologies in 2035 (percent)

	Fossil Fuels	Nuclear	Hydro-Electric	Other Renewables
2009	**67.1**	**13.5**	**16.2**	**3.2**
Current Policy Scenario	**66.5**	**10.3**	**13.1**	**10.1**
New Policy Scenario	**56.5**	**12.8**	**15.2**	**15.4**

The projected share of nuclear power is also estimated to be smaller in OECD countries in the Current Policy Scenario and the New Policy Scenario as shown in Table 6.

Table 6: IEA 2011 WEO - OECD Projected Share of Electric Generation Technologies in 2035 (percent)

	Fossil Fuels	Nuclear	Hydro-Electric	Other Renewables
2009	**60.7**	**21.6**	**12.7**	**5.1**
Current Policy Scenario	**55.3**	**17.7**	**11.1**	**15.8**
New Policy Scenario	**46.3**	**20.9**	**12.0**	**20.8**

The *2011 WEO* lists several factors causing a cut back in nuclear plant builds. These include: government reviews of nuclear policy following the Fukushima accidents; early retirement of German nuclear plants by 2022; no lifetime extension of nuclear plants in Switzerland; delays in capacity additions in China; and difficulties in securing financing for nuclear power plants. The *2011 WEO* also cites an increase in expected construction costs, compared to the *2010 WEO*, of 5% to 10%.

Asia

As shown in Tables 3 and 4, the advantage of nuclear power over natural gas or coal is substantially higher in China than in the United States, the EU or Japan. This cost advantage is also shared by other Asian economies. In addition, the structure of the power markets in Asia, the importance of government investment instead of private investment, government policies favoring nuclear power, less likelihood of delays due to regulatory problems and a relative absence of political opposition all make it likely that nuclear power will expand in Asia. Consequently, of the currently planned nuclear reactors, 130 are in Asia, 54 are in Western and Eastern Europe, 8 are in the Middle East, 11 are in North America and 4 are in South America (World Nuclear Association 2012).

Expanding Liberalized Electricity Markets Would Help Meet World-Wide Growing Electricity Demand

Electricity generation is estimated to increase by 81% to 96%[12] between 2009 and 2035 (IEA 2011). The estimated growth outside the OECD is much higher (138% to 164%). Large investments will be needed to finance this expansion of electric generating capacity. The IEA estimates that $9.8 trillion will be required to finance new power plants (New Policies Scenario). Of this, $5.5 trillion will be required outside of the OECD. It is not likely that these capital requirements can be met without a predominate role for the private sector. In many of the countries outside of the OECD, several challenges need to be overcome in order for the private sector to have an effective role. First of all, there has to be a likelihood of profits. Inefficient state-owned power systems make an attractive business model more difficult. When power is sold for less than it costs, an investor would then depend on government payments in addition to electricity sales. When you add uncertainty about government policies and regulations, it is unlikely that sufficient capital can be raised without power-sector reforms. Power-sector reform reduces government fiscal responsibilities, improves the reliability of electricity supplies to industry and households, and can improve electricity access to the poor (Difiglio, 2010b).

A successful pattern of power-sector reform involves separating the electric utility from the relevant ministry and obliging it to operate according to commercial principles. The second step involves developing economic regulation of the power market that is applied transparently by an autonomous regulator. Third, independent power producers can help the reform process by demonstrating the benefits of private investment and management. The forth step is unbundling or restructuring the electric power supply chain to enable the introduction of competition, Fifth, the unbundled electricity segments are privatized under dispersed ownership. Finally, the development of competition in the generation and supply segments follows from the development of power exchanges (World Bank, 1993).

Non-OECD countries may adopt this pattern of reform to achieve a more efficient and reliable power sector and to reduce federal fiscal liabilities. Such reforms may be required in order to raise the $5.5 trillion needed to build the power plants that will be needed outside of the OECD. If they are, the scope of liberalized power markets will grow and, with their growth, reduce the opportunities to secure State financing or guarantees for nuclear power plants.

Uncertain Nuclear Power Plant Costs

Cost estimates for Generation III+ power plants have been based on vendor estimates rather than actual experience (Kessides, 2010). These estimates might underestimate future nuclear power plant costs compared to estimates for other power technologies that are based on numerous actual projects and contracts. Generation III plant designs emerged in the 1990s. The cost estimates for these designs were typically in the neighborhood of $1,000 per kWe. As these designs have evolved, current U.S. or

[12] For the New Policy Scenario and Current Policy Scenario respectively. The additional efficiency investments in the New Policy Scenario reduce the need for additional electric generating capacity compared to the Current Policy Scenario.

European cost estimates have grown to be several times higher. Plant cost estimates in the United States currently range from \$2,500/kWe to \$10,000/kWe. If the outlier cost estimates are deleted, current U.S. cost estimates range from \$4,200/kWe to \$6,600/kWe (Thomas, 2010). Unfortunately, there is no assurance that cost escalation will not continue. Past experience in the U.S. nuclear power industry is not encouraging. For example, between 1974 and 1975, fourteen power plants were estimated by utilities to cost, on average, \$1,263/kWe. Actual costs averaged \$4,817 (281 percent overrun). While the cost overrun for these 1974-75 plant start ups were higher than earlier plants, the average cost overrun for all U.S. nuclear power plants was 207 percent (Schlissel, D., Biewald, B., 2008).

Technology Learning

Predictions of future energy technology costs usually employ the concept of technology learning. The general principal is: for each doubling of capacity of a new energy technology, cost goes down by a fixed percentage (IEA 2000). Since the nuclear industry is well established, additions to capacity would fall well short of any opportunity for further technology learning unless the Generation III and III+ designs were judged to be sufficiently different than Generation II reactors to be new technologies. Most estimates of future nuclear technology costs do not view them as such and do not anticipate cost reductions in Generation III reactors. For example, the cost estimates for a European Generation III+ in the *2011 WEO* remain constant at \$3,800/kWhr from 2015 through 2035.

An analysis of the cost trajectory of the French nuclear reactor fleet indicates that construction costs, in constant dollars, have increased over time (Grubler, A., 2010). While this is consistent with U.S. experience (described above), it may be surprising since the French reactor fleet is generally regarded as the most successful and well-managed nuclear power deployment, in part, by avoiding the U.S. experience of building many different designs each requiring individual regulatory assessments.

Going forward there may be reasons for nuclear reactor costs to systematically increase. About 60% of the cost of a nuclear reactor stem from on-site engineering as opposed to the major equipment items (reactor vessel, steam generators and turbines). Reactor cooling is also an important cost component that has increased. In particular, environmental regulations to protect fish and other species have made it more likely that cooling towers would be required when reactors are located on rivers.

With high Asian economic growth that is not expected to lessen, the demand-supply balance for construction materials is likely to produce higher prices. For example, metallurgical coal prices are now at record levels despite a weakening world economy. As with petroleum, the supply of mineral resources is not likely to keep up with high world demand growth at constant prices. [13] Likewise engineering and labor costs are likely to increase with high economic growth. Compared to the opportunities to reduce the costs of manufactured products, large nuclear power plants appear to face the likelihood of higher costs, not lower costs.

[13] While technological breakthroughs, such as hydraulic factoring, can significantly reduce the cost of mineral resource extraction, these are likely to be the exception rather than the rule.

Importance of Capital Cost Escalation and Other Risks in a Liberalized Power Market

Risks of cost over-runs are less likely to deter nuclear power plants investments in uncompetitive power markets or state-owned enterprises. A costly power plant in these markets will not necessarily have adverse consequences on investors as the higher cost can be averaged into the existing fleet of power plants. A private investor in an uncompetitive State-regulated power market would still receive the normal rate of return. A state-owned company likewise passes on the incremental costs to ratepayers or the government incurs higher electric subsidy costs.

A liberalized power market presents an entirely different picture to an investor. Delays and cost over-runs not only threaten to diminish their rate of return but put the investment itself at risk. This risk is compounded by five factors: 1) nuclear power has high capital costs per kilowatt of electrical generating capacity (kWe) compared to natural gas or coal power plants; 2) nuclear power has large economies of scale and require large investments for a unit of investment (1 gigawatt or more); 3) having high capital costs, nuclear power is more vulnerable to increases in material costs and construction delay; 4) construction delays are more likely due to uncertainties in the regulatory process, especially for new plant designs; and 5) because of potential public and NGO opposition to nuclear power, construction delays can also be caused by delays in issuing local permits, lawsuits and political pressure. Because of these risk factors, financing is not feasible without government guarantees. Equity financing is typically not an alternative to debt financing as it is difficult to ask shareholders to forgo dividends and accept risk that banks were unwilling to take.

Recognizing these barriers to nuclear power plant investments, the U.S. government established government subsidies and risk-sharing for nuclear power plants in the Energy Policy Act of 2005. These included production tax subsidies for the earliest new nuclear plants, guarantees against regulatory delays and a loan-guarantee program to attract private financing. While no new nuclear plants have been built take advantage of the production tax subsidies, the U.S. Department of Energy (DOE) has issued two loan guarantees for two 1.1 gigawatt Westinghouse AP1000 nuclear reactors at the Vogtle generating plant. Like all of the several loan-guarantee applications DOE received, these new plants would be built at an existing nuclear plant campus. The project sponsors include the Georgia Power Company. Notably, the Georgia Power Company does not operate in a liberalized power market. The Georgia Power Company is fully regulated by the Georgia Public Service Commission. Competition is limited to customers with manufacturing or commercial loads of at least 900 kW. The Vogtle plants received $8.33 billion of DOE loan guarantees, or approximately $3,800 per kWe capacity. The plants are estimated to cost $11.9 billion or $5,000 per capacity (Thomas, 2010). A project such as Vogtle should enjoy low interest rates. The project is guaranteed in two ways: first, the DOE loan guarantees ensure that the banks will receive 76% of the total estimated plant cost; and second, the Georgia Public Service Commission will likely guarantee any remaining exposure to the Georgia Power Company.

Because of the high cost to build a single nuclear power plant, along with the likelihood of delays and cost overruns, Moody's Investors Service has characterized a decision to build a nuclear power plant as a "bet-the-farm" risk. "From a credit perspective, companies that pursue new nuclear generation will take on higher business and operating risk profile, pressuring credit ratings over the intermediate- and long-term…Of the 48 issuers that we have evaluated during the last nuclear building cycle (1965-1995), two received ratings upgrades, six went unchanged and 40 had downgrades…the average downgrade fell four notches" (Moody's Global). It is notable that these credit downgrades affected utilities that were mostly operating in a state-regulated environment where regulators have effectively transferred the utilities' risks to ratepayers. Moody's concludes that utilities that pursue new nuclear power plants will experience credit downgrades and should: 1) rely on strategic partnerships; 2) increase reliance on equity financing; 3) moderate dividend policies to increase cash flow; and 4) adopt a "back-to-basics" focus on core electric utility operations. These recommendations are aimed at utilities that "can expect regulators to support the financial health of the utilities they regulate and will authorize recovery of investments and costs over a long time frame" (Moody's Global 2009). In a liberalized power market where power companies and investors would not enjoy such protections, the risk of credit downgrade would be much higher.

Levelized Costs and Modeling Future Nuclear Power

Considering the difference in risk between traditional and liberalized power markets, it may be necessary to reconsider how levelized cost estimates are used when modeling the uptake of power-generation technologies. Current levelized cost estimate that do not account for possible cost overruns may be perfectly appropriate when modeling the uptake of nuclear power in uncompetitive power markets. Governments or government regulators can consider their long-run need for additional power and be willing to accept problems that may be encountered with the first few nuclear plants. Governments may also be committed to nuclear power development as a matter of climate or energy security policies. If climate policies are a high priority, it is reasonable that governments would assume additional financial risk to increase the share of nuclear power as modeling studies show how difficult it would be to avoid high concentrations of greenhouse gases in the atmosphere without nuclear power (IEA 2010). Likewise, for countries that do not enjoy indigenous fossil fuel resources, avoiding reliance on energy imports can be an important policy consideration.

A private investor considering a nuclear power plant in a liberalized power market will carefully consider the risk of construction delays and cost over-runs. Current estimates of levelized cost may not be given much weight by such an investor. If contingencies for overruns and delays are built into the capital cost estimate, the estimated levelized cost for nuclear power could be significantly higher. If these estimates showed the power-plant to be uncompetitive, it is not likely that the investment would be made.

In order to develop a levelized cost estimate that would be appropriate in a liberalized power market we have developed a Risk Scenario and, as before, compare the Risk Scenario power sector levelized costs with and without a $50/ton CO_2 charge. This type of Risk Scenario would certainly be considered by utilities and investors before building nuclear power plants in competitive power markets.

Risk Scenario

Considering the history of cost overruns for the vast majority of nuclear power plants, it is reasonable to assume that there is a high likelihood that any particular nuclear power plant project might be more costly than planned. For example, Lew Hay, Chairman and CEO of Florida Power and Light said "although suppliers keep quoting overnight costs of $2500 to $3500 per kilowatt, I believe the all-in costs are likely to be much higher – possibly twice as much once you factor in the owners' costs such as land, cooling towers, etc., interest during construction and cost escalation due to inflation and cost overruns. And of course, we have to have a contingency as well."[14] Florida Power and Light has, in 2007, estimated that a nuclear plant would have overnight costs of $3,108/kWe to $4,540/kWe and total plant cost of $5,492/kWe to $8,081/kWe. Entergy Corporation Chief Executive J. Wayne Leonard has said regarding a decision to build a new nuclear power plant "Utilities do not want to take that risk…it's risk we don't control." Leonard added that to make the economics of nuclear work for Entergy, he would need to see "double-digit natural gas prices and carbon blow-out prices" starting at $25 per ton and escalating toward $50. He added, since nuclear vendors don't want to assume the risk of a cost overrun they have put construction costs too high for most companies.[15] These statements and available data for a number of nuclear plant bids show that vendors and utilities are assuming significantly higher capital costs for new Generation III+ reactors than the $3,800 to $4,000 per kWe being used as long-run capital costs for U.S. and EU nuclear plants by the IEA. That said, it does not mean that $4,000/kWe is not a reasonable cost estimate for what new power plants in these markets may eventually cost. Due to government guarantees and climate policies, some plants are likely to be built. These plants could establish a nuclear industry capable of building near-identical plants at predictable prices within an efficient regulatory process. Nonetheless, the predictable price could be considerably higher than the current estimates used in the IEA modeling studies.

A Risk Scenario should account for several factors. There is very limited experience constructing or operating any of the Generation III+ reactor designs and no experience for some of the proposed designs. The limited experience building new reactor designs is not encouraging as projects in Finland, Japan and elsewhere have experienced delays and cost overruns. It should be expected that reactor costs will increase further to meet stricter safety requirements especially with regard to on-site spent-fuel management in light of the Fukushima accidents. Based on various vendor offers (Thomas, 2010), past cost overruns, factors likely to increase future construction costs and the likelihood of construction delays (resulting from regulatory changes, etc.) nuclear capital costs could increase capital costs by 50% to 100% higher than the $3,800/kWe to $4,000/kWe estimated for the EU and U.S. by the IEA. Using the 50% figure, the capital cost for a Generation III+ nuclear plant in the United States and European Union is assumed to be $2,000/kWe higher in the Risk Scenario. This increases nuclear capital costs to $6,000/kWe in the United States and $5, 800/kWe in the EU.

[14] Biannual General Meeting of the World Association of Nuclear Operators, Chicago, September, 2007.
[15] Reuters Global Energy Summit, Houston, May, 2010.

Natural Gas Price Risk

The competitiveness of nuclear power would also be reduced if natural gas prices were significantly lower than assumed in the *2011 WEO*. Since 2005, the United States has greatly expanded its natural gas production by fracturing natural-gas bearing shales. There are uncertainties whether this technology will be as widely adopted in other countries with promising shale resources. There are "above-ground" and "below-ground" uncertainties whether European countries with shale resources (including Poland, France, Sweden, Austria, Germany and the Baltic States) will repeat the U.S. experience. There are also different estimates of the sustainability of U.S. production. Higher shale-gas production, along with lower natural gas prices, would make nuclear less competitive. Should U.S. shale productivity be at the high end of the plausible range, U.S. natural gas prices would be significantly lower than estimated in the *2011 WEO*. Likewise, European natural gas prices would be significantly lower if European shale plays turned out to be productive and a variety of "above-ground" constraints were overcome. Consequently, for the Risk Scenario, we have lowered the estimated 2035 natural gas price in the United States from $8.56/mmBTU to $5.99/mmBTU.[16] For the European Union we have lowered the 2035 natural gas prices from $12.08/mmBTU to $8.70/mmBTU.[17]

Risk Scenario Results (Higher Nuclear Cost & Lower Natural Gas Prices)

Tables 7 provides the revised levelized cost estimates for the Risk Scenario showing a higher estimated cost for nuclear and a lower cost for natural gas. Table 8 shows the estimated levelized costs with a $50/tonne CO_2 charge.

Table 7: Long Run Levelised Cost (U.S. cents/kWhr) (Higher Nuclear Cost & Lower Natural Gas Prices Scenario) (2035)

	Nuclear	Renewables	Natural Gas	Coal
United States	10.8 – 11.1	7.7 – 12.8	6.9 – 7.0	8.1 – 8.7
EU	10.6 – 10.9	7.8 – 15.9	8.4 – 8.5	9.6 – 11.4

Table 8: Long Run Levelised Cost (U.S. cents/kWhr) with a $50/tonne CO_2 Charge (Higher Nuclear Cost & Lower Natural Gas Prices Scenario) (2035)

	Nuclear	Renewables	Natural Gas	Coal w CCS	Coal w/o CCS
United States	10.8 – 11.1	7.7 – 12.8	8.6 – 8.7	8.5 – 11.8	11.8 – 13.1
EU	10.6 – 10.9	7.8 – 15.9	10.1 – 10.2	10.2 – 13.3	13.3 – 16.1

[16] $5.99/mmBTU is the EIA estimated 2035 price for natural gas from its *2012 Annual Energy Outlook*: High Estimated Ultimate Recovery case. See Figure 105.

[17] $8.70/mmBTU is the estimated European natural gas price in the Unconstrained Shale-Gas Scenario from a DOE study: World-Wide Unconventional Gas Potential: Energy Security and GHG Emissions. See Difiglio 2012a.

Table 9 provides the estimated cost advantage of natural gas over nuclear for the United States and the European Union. In the United States, instead of enjoying a 9% - 17% cost advantage over natural gas (or 31% - 40% with a \$50/tonne CO_2 charge), nuclear is now estimated to be more costly than natural gas by an average of 4 cents/kWhr (or 2.3 cents/kWhr with the carbon charge). Consequently, natural gas enjoys a cost advantage of 54% to 61%. Even with a \$50/tonne CO_2 charge, natural gas retains a substantial cost advantage (24%-29%).

Table 9: Risk Scenario - Cost Advantage of Natural Gas Relative to Nuclear with and without a \$50/tonne CO_2 Charge (2035)

	Cost Advantage of Natural Gas over Nuclear w/o Carbon Charge		Cost Advantage of Natural Gas over Nuclear with Carbon Charge	
	U.S. cents/kWhr	% Cost Increase Over Natural Gas	U.S. cents/kWhr	% Cost Increase Over Natural Gas
United States	**3.8 – 4.2**	**54 – 61**	**2.1 – 2.5**	**24 – 29**
EU	**2.1 – 2.5**	**25 – 30**	**0.4 – 0.8**	**4 – 8**

In the European Union, instead of enjoying a 37% - 48% cost advantage over natural gas (or 59% - 71% with a \$50/tonne CO_2 charge), nuclear is now estimated to be more costly than natural gas by an average of 2.3 cents/kWhr (or 0.6 cents/kWhr with the carbon charge). Consequently, natural gas enjoys a cost advantage of 25% to 30%. With a \$50/tonne CO_2 charge, natural gas retains a slight cost advantage (4% - 8%).

Considering that natural gas plants have significantly lower capital costs per kWe capacity, investors' rationale to build a nuclear plant pretty much disappears if a natural gas plant is estimated to undercut the nuclear plant by 4 cents/kWhr. With these cost estimates, and taking into account the various risks facing any specific nuclear plant project in a liberalized power market (licensing problems, public opposition, changing government policies, spent fuel disposal, etc.), the "bet-the-farm" risk becomes a "lose-the-farm" certainty. These costs constrain nuclear builds to governments that value energy security, have a high priority to reduce their greenhouse gas emissions or have other priorities that nuclear power would support.

The Risk Scenario also reverses the estimated competitiveness of coal and nuclear when there is no carbon charge. As shown in Table 4, nuclear had a 4%-16% cost advantage over coal in the United States and a 26% - 56% advantage in the European Union. As shown in Table 10, with the Risk Scenario, coal now has a 24% - 37% cost advantage over nuclear. In the European Union, the cost advantage of coal is minus 10% to plus 15% (a lower- efficiency coal plant would be less competitive than a nuclear plant, hence the minus 10% estimate). With the Risk Scenario, nuclear power plants are not only uncompetitive with natural gas plants but do poorly against coal plants.

Table 10: Risk Scenario - Cost Advantage of Coal Relative to Nuclear with and without a \$50/tonne CO_2 Charge (2035)

	Cost Advantage of Coal over Nuclear w/o Carbon Charge (no CCS)		Cost Advantage of Nuclear over Coal with Carbon Charge (no CCS)	
	U.S. cents/kWhr	**% Cost Increase Over Nuclear**	**U.S. cents/kWhr**	**% Cost Increase Over Nuclear**
United States	**2.1 – 3.0**	**24 - 37**	**0.7 – 2.3**	**6 – 21**
EU	**minus 0.8 to 1.3**	**minus 10 to 15**	**2.4 – 5.5**	**22 – 52**

Closing Comments

We do not intend to represent the Risk Scenario as a projection of what nuclear power plants will cost. It is intended to show the high economic uncertainty facing nuclear power in competitive power markets. Nonetheless, the Risk Scenario is as likely to be an accurate projection of future nuclear power costs as the costs assumed in the *2011 World Energy Outlook.* More significantly, from the standpoint of current investments in nuclear power, investors are unlikely to rely on cost estimates as low as \$4,000/kWe when evaluating nuclear power projects.

Very strong climate policies could support higher nuclear plant costs. These climate policies may be in the form of carbon charges, as considered in this paper, or regulations such as those that have recently been proposed by the U.S. Environmental Protection Agency that prohibit new coal power plants without CCS.

While the economic obstacles appear to be formidable in the United States, U.S. policies continue to support nuclear power development with production subsidies and guarantees. If U.S. plants built with government support establish stable or declining nuclear cost expectations, the future of nuclear power in the United States could be strong. However, until positive experience is achieved building nuclear plants in the U.S., investors are unlikely to build U.S. nuclear power plants without Federal guarantees.

The low nuclear costs estimated for China suggest that China, and other countries outside of the OECD, may succeed in building large nuclear plant fleets. State-supported construction in China and elsewhere could help demonstrate that nuclear plants can be built at competitive and predictable prices without delays or other problems.

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