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ABSTRACT

Although nuclear power plants are being built in South and East Asia, they have not been ordered in the U.S. since the accident at Three Mile Island in 1978. For many reasons, including the Kyoto Protocol, new attention is being given to light water reactors. Currently operating nuclear power plants in the U.S. were built under rate-of-return regulation. Now they are competing in wholesale power markets. This paper models the profitability of building an Advanced Boiling Water Reactor in Texas using a "Real Options" approach. It finds that a cost of about $1,200 per kilowatt-electric for advanced light water nuclear power plants could trigger new orders. On the other hand, investors might be willing to pay higher prices if methods for mitigating price, cost, and output (capacity factor) risk through contracts or real assets can be found.

Keywords: nuclear power economics, investment under uncertainty, Monte Carlo simulation

JEL classification numbers: C53, D81, L94

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1. Ordering New Power Plants

Electricity generation deregulation has opened U.S. wholesale electricity markets to unregulated power producers. In this uncertain environment, how should a generating company evaluate the risk of investing in new capacity under competitive deregulation?[1] This paper addresses (1) how investors might evaluate new power plant capacity and (2) what construction cost per kilowatt-electric might trigger orders for new nuclear power plants.

1.1. The Net Present Value of Power Plants

Under standard investment criteria, the investor-generator should invest in new power capacity if the Net Present Value (NPV) of the project were positive. **Net Present Value equals** the discounted value of (1) the power plant's **net revenues** (R) per year (in millions of dollars) **minus** (2) total **construction cost** (I) including financing costs (e.g., Interest During Construction):

$$\text{NPV} = R / \delta - I > 0 \quad \Rightarrow \quad R > \delta \cdot I , \tag{1}$$

where δ is the capital recovery factor.[2] Under NPV investment criteria, *the generator invests if net revenues are greater than the levelized cost of construction*: $R > \delta \cdot I$. Let R^* be the "net revenue trigger value," such that if expected present value of net revenues is greater than R^*, the investor would order new power capacity. Under NPV analysis, $R^* = \delta \cdot I$. If net revenue is less than R^*, the investor-generator waits (does not invest).

What are net revenues? Appendix 1 shows that net revenues are

$$R = (P \cdot CF - \underline{C}) \cdot MWYEAR, \tag{2}$$

where (1) P is the market price of electricity in dollars per MWh (megawatt-hours),

(2) CF is the capacity factor equal to total electricity generated per year divided by the maximum dependable capacity per year,

(3) $\underline{C}$ is average production cost **at full capacity** (i.e., total production cost divided by maximum output), and

(4) *MWYEAR* is the maximum dependable capacity (in megawatt-hours) per year.

For example, if P = $40 per MWh, CF = 90%, $\underline{C}$ = $16/MWh, and *MWYEAR* = 22M (million) MWh/year, then R_t = [($40 · 90%) – $16] · 22M = $440M/year. With a **real** cost of capital of 7% (the nominal cost is closer to 10%), the capital recovery factor (δ) is 0.0772 over a 40-year life, and the NPV of annual net revenues (R/δ) is $5,700M (ignoring taxes).[3]

Discounted net revenues can be calculated, but each of the three variables (P, CF, and $\underline{C}$) is uncertain, because future electricity prices, generation output, and operating costs are unknown. Therefore, net revenues are uncertain and the NPV is uncertain. The traditional NPV analysis does not have a consensus method for evaluating NPV probability distributions.[4]

1.2. A Real Options Analysis of Investing in New Power Plants

Traditional NPV analysis assumes that *all uncertainty* is reflected in the risk premium associated with the cost of capital. How is this risk premium determined? The “real options” approach provides one answer, based on an evaluation of the probability distribution of net revenues.

Two assumptions must be made to evaluate this probability distribution with the real options approach. First, assume that percentage changes in net revenue follow a proportional Brownian motion with a normal distribution. See Dixit and Pindyck (1994, p. 65). Second, assume that uncertain net revenues are perfectly correlated with a portfolio of tradable assets (both real and financial). See Dixit and Pindyck (1994, p. 148).

Dixit (1992, p. 113) shows under these assumptions the net revenue trigger value, R^*, is

$$R^* = (1/\phi) \cdot \delta \cdot I^*. \qquad (3)$$

where ϕ represents an investor's discount of the NPV of uncertain net revenues; see Appendix 2.[5] From Equation (3), the trigger value for total construction cost, I^*, can be found:

$$I^* \quad = \quad (\phi / \delta) \cdot R^* . \tag{4}$$

Finally, let K^* be the construction cost per kilowatt at I^*. For a plant of W kilowatts-electric, $K^* = I^* / W$. To summarize,

$$\begin{aligned} K^* &= (\phi / \delta) \cdot (P \cdot CF - \underline{C}) \cdot (MWYEAR / W) \\ &= (\phi / \delta) \cdot (P \cdot CF - \underline{C}) \cdot 8.760 , \end{aligned} \tag{5}$$

where the final term is equal to the number of hours in a year divided by 1000, the number of kilowatts in a megawatt. What is the value of K^* (the total construction cost per kWe) that might trigger new power plant orders? In the example above (assuming $\phi = 1$, i.e., no net revenue risk), if K* < $2270/kWe, investors should be willing to order new plants.

1.3. Application: Building a Dual-Unit ABWR in Texas

To calculate K^* for new nuclear power capacity, consider the option of building an Advanced Boiling Water Reactor (ABWR) in Texas coming into commercial operation in 2010.[6] (On purchasing existing nuclear power plants, see Rothwell 2001.) Section 2 provides a technique for estimating the mean and variance of net revenues from the power plant. Section 3 calculates the variance of net revenues and determines a K^* that might trigger new orders for the current generation of nuclear power plants. Section 4 discusses how to mitigate net revenue uncertainties in the form of controlling Price Risk, Output Risk, and Cost Risk.

2. ABWR Construction Investment, Price, Output, and Cost

Public data is available to estimate construction cost, electricity prices, megawatt-hours generated, and operating costs. First, consider total construction cost for a dual-unit ABWR.

Table 1 presents the average capital cost of a dual-unit ABWR built in the U.S. (see NEA, 2000, pp. 96-99). The following summarizes the reactor supplier's statement regarding Table 1:

> The ABWR plant can be constructed in just four years for US$1 600/kWe and suppliers are willing to undertake a project on a fixed price, fixed schedule basis. As a result, the ABWR nuclear plant has proven itself in Japan and Chinese Taipei to be economically competitive with other power generation options and estimates indicate that it can be economic in other countries as well. (p. 99)

Let the construction cost (*K*) of the ABWR be $1,600/kWe (including financing charges) for a dual-unit 2,800 MW (gross) capacity plant (with 2,700 MW net). The plant could generate 23.65 M MWh each year at full capacity. The total investment, *I*, would be about $4,500 million (M).

Second, to forecast electricity prices over the life of the plant, consider energy sold in the Texas electricity market. The Texas market is unique in the U.S. because of its separation from the rest of the country into its own reliability region, known as ERCOT, the Electric Reliability Council of Texas. (Although all of ERCOT is in Texas, not all of Texas is in ERCOT.) Figure 1 shows Texas monthly electricity prices (cents/kWh) and natural gas prices ($/M BTU) from 1990 to 2003.[7] Since the price spikes in 2000, the price of electricity (for example, "Type B Electric Energy" in ERCOT) has been higher and is likely to remain higher for the foreseeable future.

Figure 2 presents prices from 1990 to 2003 and simulated prices from 2004 to 2050. These simulated prices represent one of 1,000 Monte Carlo trials. In these trials, average price follows the parameters estimated in Appendix 3 given in Figure 2, but for each year there is a random draw from a normal distribution that adds variance to electricity prices. (The standard deviation of this normal distribution is $1.69.) In the particular simulation presented in Figure 2 the mean electricity price was $40.13 and the standard deviation was $1.62.

Third, during the 1980s and 1990s, capacity factors at U.S. nuclear power units improved dramatically. Figure 3 presents capacity factors from 1990 to 2002 at (1) dual-unit BWRs in the

U.S. that came into commercial operation after 1982 and (2) the Japanese ABWR that came into full commercial operation in 1997. The cycles in the figure could be interpreted as reflecting refueling outages that generally take place every 18 months.[8] Data for General Electric BWRs larger than 1,100 MW are used to simulate capacity factors at ABWRs operating in the U.S. Following Rothwell (2000a), Ordinary Least Squares parameters were estimated with this sample of capacity factors. The estimated trend line is identified in Figure 3. Assuming ABWRs follow the same trend, the expected **lifetime** capacity factor would be about 86%. Using estimated parameters, a Monte Carlo simulation of capacity factors for a dual-unit ABWR is presented in Figure 4. (This is the from same simulation as in Figure 2.)

Fourth, following the definition of average variable expenses in Rothwell (2000a), Figure 5 presents $\underline{C}$ (operating cost at full capacity) for dual-unit BWRs in commercial operation in the U.S. after 1982 for the years 1990 to 2000 (inflated to mid-2001 dollars). Assuming ABWRs follow the same trend, Figure 6 presents a Monte Carlo simulation of variable expenses. In this simulation, the mean $\underline{C}$ is \$16.38 with a standard deviation of \$1.58. To summarize, expected net revenues might be

$$R_t = ((\$40.13/\text{MWh} \cdot 86\%) - \$16.38/\text{MWh}) \cdot 23.65\text{M MWh/year} = \$430\text{M/year}.$$

3. The Value of a Dual-Unit ABWR in Texas

With a **real** discount rate of 7%, the capital recovery factor (δ) is 0.0772 for 40 years. The NPV in 2010 (assuming both units are completed in 2010) is

$$\begin{aligned} \text{NPV} &= R / \delta - I &&= (\$430\text{M} / 0.0772) - \$4{,}500\text{M} \\ &= \$5{,}600\text{M} - \$4{,}500\text{M} &&= \$1{,}100\text{ M}. \end{aligned} \quad (6)$$

The NPV is positive, so the investor-generator would build the ABWR under traditional investment criteria.

However, net revenues are uncertain. Simulations of the electricity prices, generation output, and input costs can be combined to determine the probability distribution of net revenues. Figure 7 presents a simulation of revenues for each year from 2010 to 2050, based on the particular simulation in Figures 2, 4, and 6. Figure 8 presents a histogram of 1,000 simulations of NPV. Average NPV is $740M with a standard deviation of $160M. Underlying this NPV are average net revenues of $430M per year. How might an investor-generator evaluate this probability distribution for NPV?

The variance of percentage changes in net revenues was 4.2% in the 1,000 simulations represented in Figure 8. With a variance of 4.2%, ϕ = 60%.[9] So,

$$I^* = (\phi / \delta)\, R^* = (60\% / 0.0772)\ \$430M = \$3{,}340M \tag{7}$$

and K^* = ($3,340M / 2,800MW) · (1,000 MW/kWe) = $1,200/kWe. Alternatively, the capital recovery factor could be adjusted to reflect the uncertainty in NPV, i.e., (δ / ϕ) = 0.1287, inferring a real discount rate of 12%, or a risk premium of 5%. (A 12% cost of capital yields a 12.87% capital recovery factor for a 40-year life.) This represents a decrease of about 25% from construction cost in Table 1. Therefore, if investors implicitly discount nuclear power because of these uncertainties, new nuclear power deployment requires lower construction cost.

4. Mitigating the Risks of Investing in New Nuclear Power Capacity

Section 1.2 assumed there is a portfolio of tradable assets that is perfectly correlated with the risks of the project. Three risks have been considered here: Price Risk, Output (capacity factor) Risk, and Cost Risk.[10] This section examines the sensitivity of the trigger K^* to mitigating each of these risks and what nuclear power plant owner-operators might be willing to pay for real and financial assets to mitigate each of these risks.

To examine the sensitivity of K^*, each risk can be suppressed in the Monte Carlo simulation. For example, if the owner-operator might be able to contract with a buyer to guarantee the price of all output at $40/MWh (real) for 40 years, the standard deviation of the price could be reduced to zero and the trigger price (*K**) would rise. Each of the three risks can be held to zero; two of the three can be held to zero; or all three can be held to zero.

As a benchmark, with the assumptions and simulations described in this paper, holding most revenue-related risk to zero, the nuclear power plant supplier could sell new nuclear power plants on a fixed-construction cost basis for about $2,000/kWe (including IDC). See Table 2. Controlling Output and Cost Risk, Price Risk alone reduces *K** by $200/kWe. Controlling Output and Price Risk, Cost Risk alone reduces *K** by $320/kWe. Controlling both Price and Cost Risk, Output Risk alone reduces *K** by $380/kWe.

Further, controlling Output Risk, Price plus Cost Risk together reduce *K** by $500/kWe. (Because of the slight correlation between Price Risk and Cost Risk in the simulations, there is an economy of risk reduction, compared to controlling Price and Cost Risk separately for the equivalent of $520/kWe.) The influence of each pair of risks on K* can be calculated. See Table 2. Finally, to trigger sales with no risk mitigation (Output, Price, or Cost Risk), *K** is about $780/kWe lower than the benchmark, i.e., $1,200/kWe (as found above).

These values for mitigating risk give an opportunity to consider bargaining among nuclear power industry participants to share risk and returns from new nuclear power plants. For example, the owner-operator might be willing to reduce the price of firm power below the expected spot market price to encourage very long-term contracts. According to the assumptions here, the owner-operator might be willing to pay up to the equivalent of $200/kWe to eliminate Price Risk. (This is a price per MWh difference of about 10%, holding all else equal.)

Under electric utility rate-of-return regulation, Price Risk was reduced by giving electric utilities price increases to cover increases in reasonable costs of operation and capital. In deregulated markets, Price Risk is shared between the owner-operator and the electricity consumer. Further research should determine the willingness-to-pay of Texas electricity consumers for firm power under very long-term contracts. (This would also provide a test of whether the method and simulations in this paper are reasonable.)

A related question concerns Output Risk (because risk-mitigating measures to control Price Risk require the delivery of firm power). The owner-operator must backup committed output with either (1) financial instruments, such as hedges and swaps, or contracts for purchases on the spot market, or (2) physical assets, such as natural gas peaking units. The owner-operator should be willing to pay up to $500/kWe to eliminate both Output and Price Risk. Future research should consider alternative real asset and financial portfolios to best mitigate these two forms of risk simultaneously for new nuclear power plants.

The remaining risk to the investor is Cost Risk, which could be eliminated through contracting. For example, nuclear fuel (which has an asset life of decades) could be leased at a fixed price for a finite period and returned to the lessor. Also, an operations management company could operate the plant under contract. But the transaction cost of monitoring an operating contract is likely to be prohibitive. Therefore, Cost Risk should be assigned to a party best able to mitigate Cost Risk on a day-to-day basis, i.e., the owner-operator. Future research should consider how much Cost Risk can be mitigated and how much equity in the project might be required of the owner-operator to create optimal incentives to deliver cheap, reliable, and safe electricity.

5. Conclusion

This paper has examined the risk in net revenues from operating a new nuclear power plant. It considered the possibility of building an ABWR in Texas (because of the availability of the ABWR and the unique electricity market in Texas-ERCOT). It identified three risks that influence annual net revenues (revenues before payments on construction expenditures): Price

Risk, Output Risk, and Cost Risk. It proposed measures of each of these risks and discussed how each risk might be mitigated.

Currently operating nuclear power plants were built under rate-of-return regulation. Future nuclear power plants will likely be built in deregulated environments. These environments put competitive pressure on nuclear power plant suppliers to lower new nuclear power plant construction cost and to develop a new business model for new plants. Future research should examine risk-mitigating components of this new business model. Until a new business model is created and implemented, it is unlikely that there will be new orders for nuclear power plants in Texas (or anywhere in the U.S.).

ENDNOTES:

1. On deregulated electricity markets, see Rothwell and Gomez (2003).

2. The capital recovery factor, δ, is equal to $[e^{rT} (e^r - 1)]/(e^{rT} - 1)$, where r is the generator's cost of capital and T is the economic life of the plant (ignoring tax effects, see below). This is a generalization of Dixit (1992) where $\delta \rightarrow r$ (the risk-free cost of capital) as $T \rightarrow \infty$. Here, with r equal to 0.07 and a 40-year life, δ equals 0.0772.

3. Neglecting income taxes is not likely to influence the primary conclusions of this paper under competitive market conditions, low corporate income tax rates, and the use of accelerated depreciation. However, the error will increase with increases in the cost of capital.

4. Consider Brealey and Myers (2000, p. 275): "Finally, it is very difficult to interpret a distribution of NPVs. Since the risk-free rate is not the opportunity cost of capital, there is no economic rationale for the discounting process. Because the whole edifice is arbitrary, managers can only be told to stare at the distribution until inspiration dawns. No one can tell them how to decide or what to do if inspiration never dawns." Hopefully, the analysis here provides some inspiration for identifying sources of risk and how to mitigate them. It also provides a method for calculating the risk premium. Interestingly, Brealey and Myers' discussion of "Misusing Simulation" (2000, p. 275) was dropped in Brealey and Myers (2003) and a new section, "Real Options and Decision Trees" (p. 268-278) was added.

5. Here, ϕ equals $[(\gamma - 1)/\gamma]$ where $\gamma = 1/2 \cdot \{1 + [1 + (8\ \delta / \sigma^2)]^{1/2}\}$, see Appendix 2. This formula for γ assumes that financial markets price risk consistently across assets, including assets in a portfolio that is perfectly correlated with ("spans") net revenues for new power plants. On "spanning," see Dixit and Pindyck (1994, p. 148). This approach must be extended to find the market's discount of assets with uncertainties equivalent to those facing the investor.

6. Two ABWRs have been operating in Japan since 1997 and four units are under construction in Japan and Chinese Taipei. On ABWRs and other currently available nuclear technology alternatives, see the Near Term Deployment Report (2001).

7. For daily electricity and natural gas prices in the year 2000, see Public Utility Commission of Texas, Market Oversight Division (2001).

8. The periodicity of nuclear power plant capacity factors depends on when each unit refuels and for how long. BWRs usually refuel every 18 months in the spring or the fall. With two units each operating on 18 month cycles (in equilibrium) during one year out of three, one unit will be refueling in the spring and the other unit will be refueling in the fall, yielding a low point in the annual (calendar year) capacity factor every three years.

9. Here, $\gamma = 1/2 \cdot \{1 + [1 + (8 \cdot 0.077 / 0.042)]^{1/2}\} = 2.5$ and $\phi = (\gamma - 1) / \gamma = 0.60$.

10. This paper does not address investment risk. The explicit assumption is that the nuclear power plant supplier assumes this risk with a fixed-price contract for the nuclear island and balance of plant; see Section 2. Future research will incorporate investment risk into the approach used here.

TABLES

Table 1. Average capital cost of a dual-unit ABWR built in the U.S.

Direct costs (per 1400MW unit)		
Structures and improvements	$400	
Reactor plant	$500	
Turbine plant	$250	
Electrical plant	$150	
Miscellaneous plant (e.g., cooling)	$100	
Total direct costs (per unit)		$1,400
Total indirect costs (per unit)		$400
Base (Overnight) Construction Cost		$1,800
Contingency (per unit)		$165
IDC at 7% (4-year lead time per unit)		$275
Total Cost (per 1,400 MW unit)		**$2,240**
Total Cost (for two units, 2800MW) = *I*		**$4,480**
Plant Cost per kW(gross) = *K*		**$1,600**

(in millions of 2001 dollars)

Source: based on Nuclear Energy Agency (2000, p. 99)

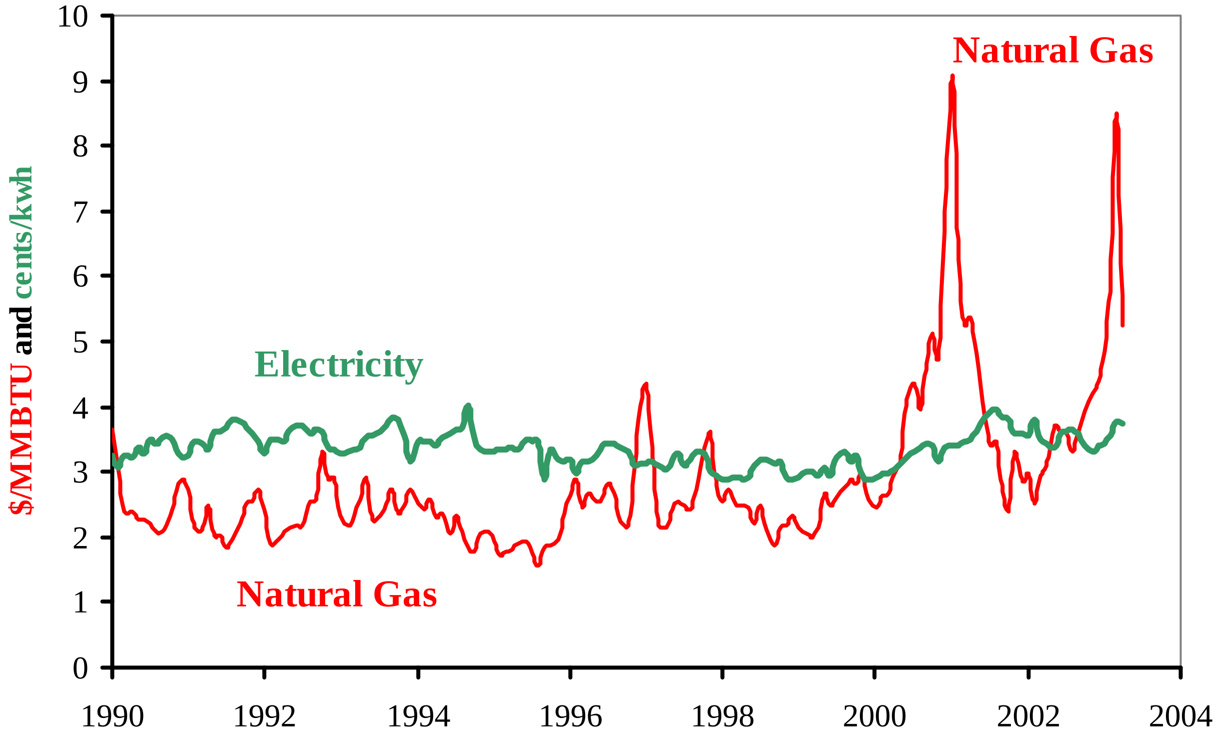
Table 2. Decomposition of Revenue Variance

Source of Variance	σ^2	I	"Price" of Control
Almost none	0.0001	$1,980/kW	$0
Price	0.009	$1,780/kW	$200/kW
Cost	0.014	$1,660/kW	$320/kW
Output	0.017	$1,600/kW	$380/kW
Price + Cost	0.024	$1,480/kW	$500/kW
Price + Output	0.026	$1,450/kW	$530/kW
Cost + Output	0.032	$1,360/kW	$620/kW
P + Cost + Output	0.042	$1,200/kW	$780/kW

Note: There are differences due to rounding.

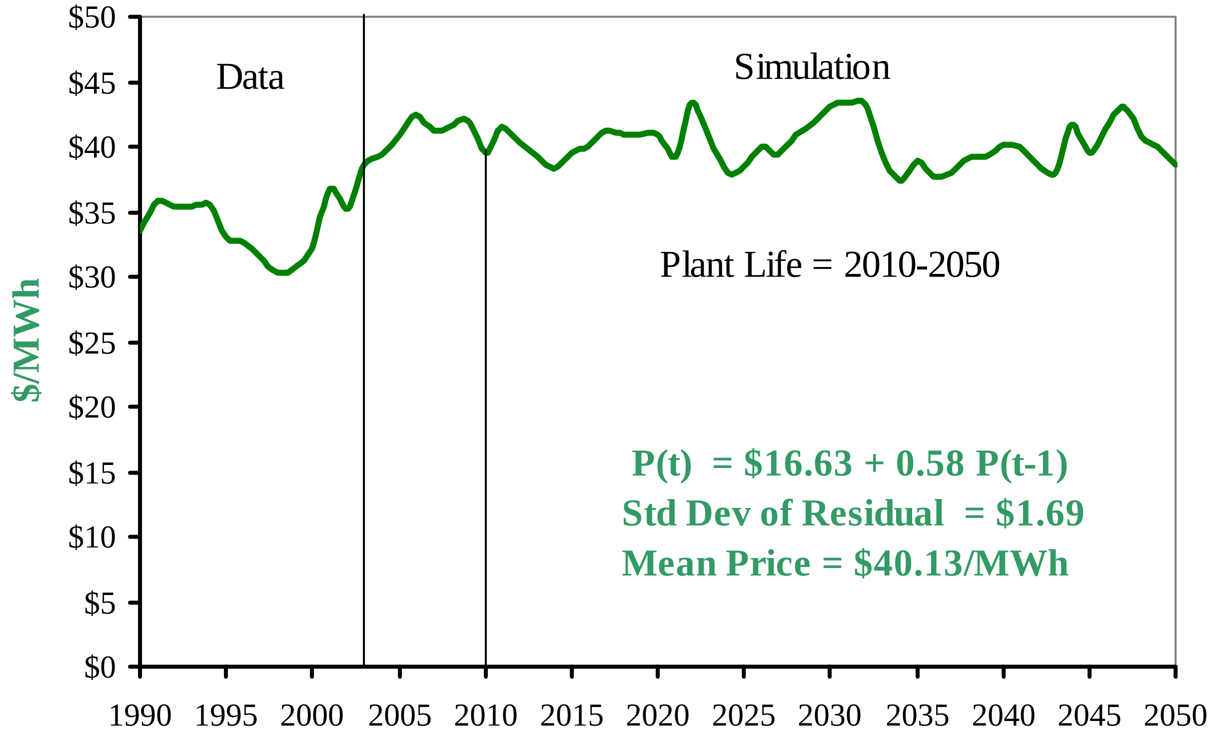
FIGURES

Figure 1: Monthly Texas Electricity and Natural Gas Prices, 1990-2003



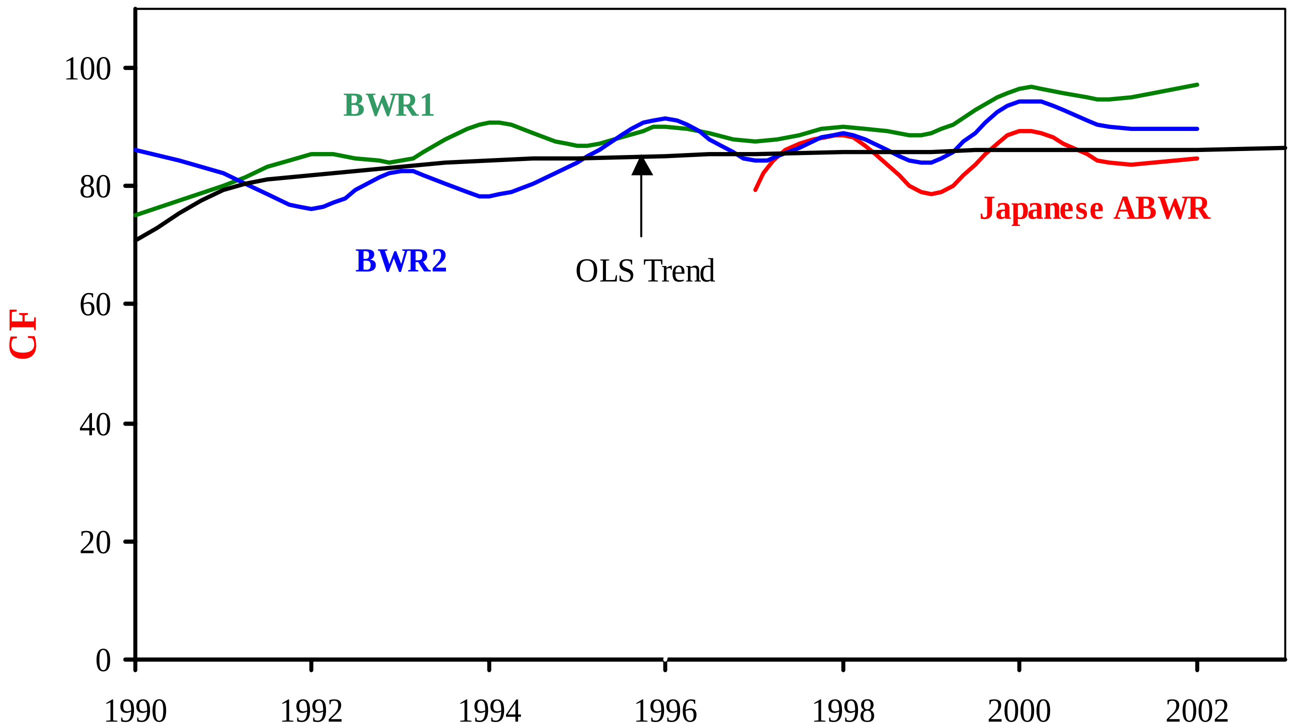
Source: www.eia.doe.gov/neic/historic/helectricity.htm and
www.eia.doe.gov/dnav/ng/ng_pri_sum_stx_m_d.htm,
deflated to 2001 with GDP implicit price deflator

Figure 2: A Simulation of Annual Competitive Market Prices in ERCOT (one of 1,000 Monte Carlo simulations)



Source: www.eia.doe.gov/neic/historic/helectricity.htm

Figure 3: Capacity Factors at Dual-Unit BWRs in US and ABWR in Japan



Source: International Atomic Energy Agency (2003).

**Figure 4: A Simulation of Capacity Factor for a Dual-Unit ABWR
(one of 1,000 Monte Carlo simulations)**

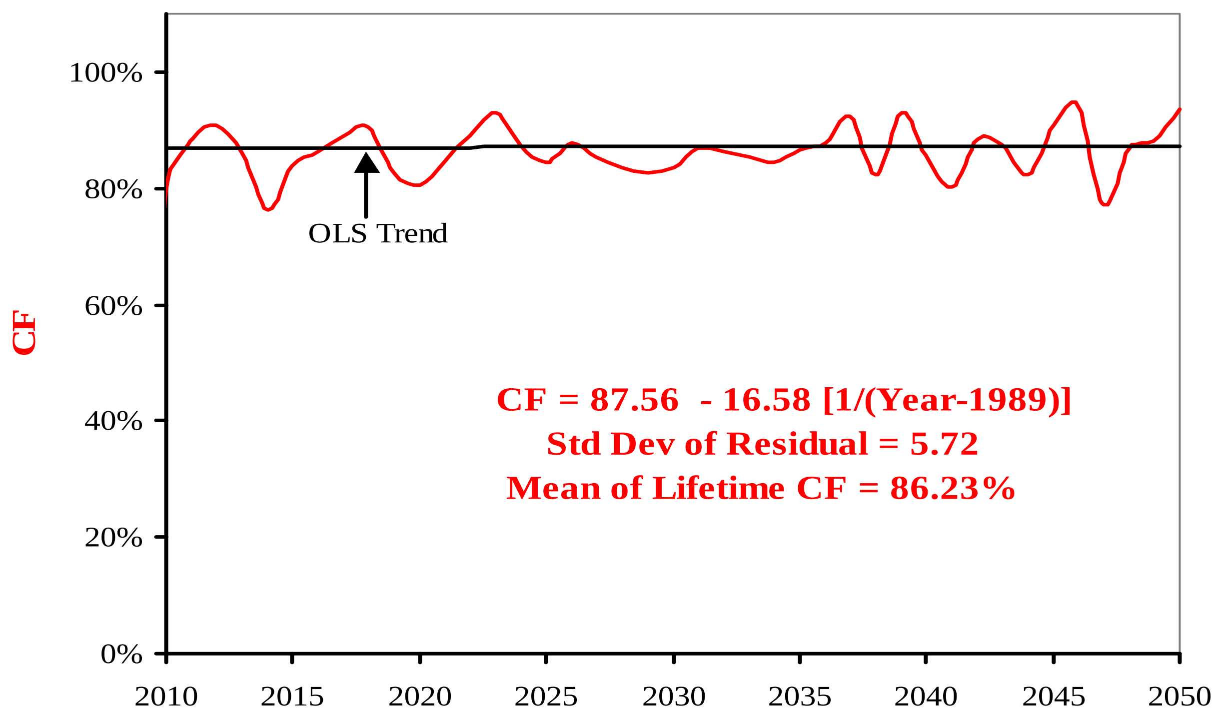


Figure 5: Annual Average Variable Expenses (<u>*C*</u>) at 100% Capacity Factor

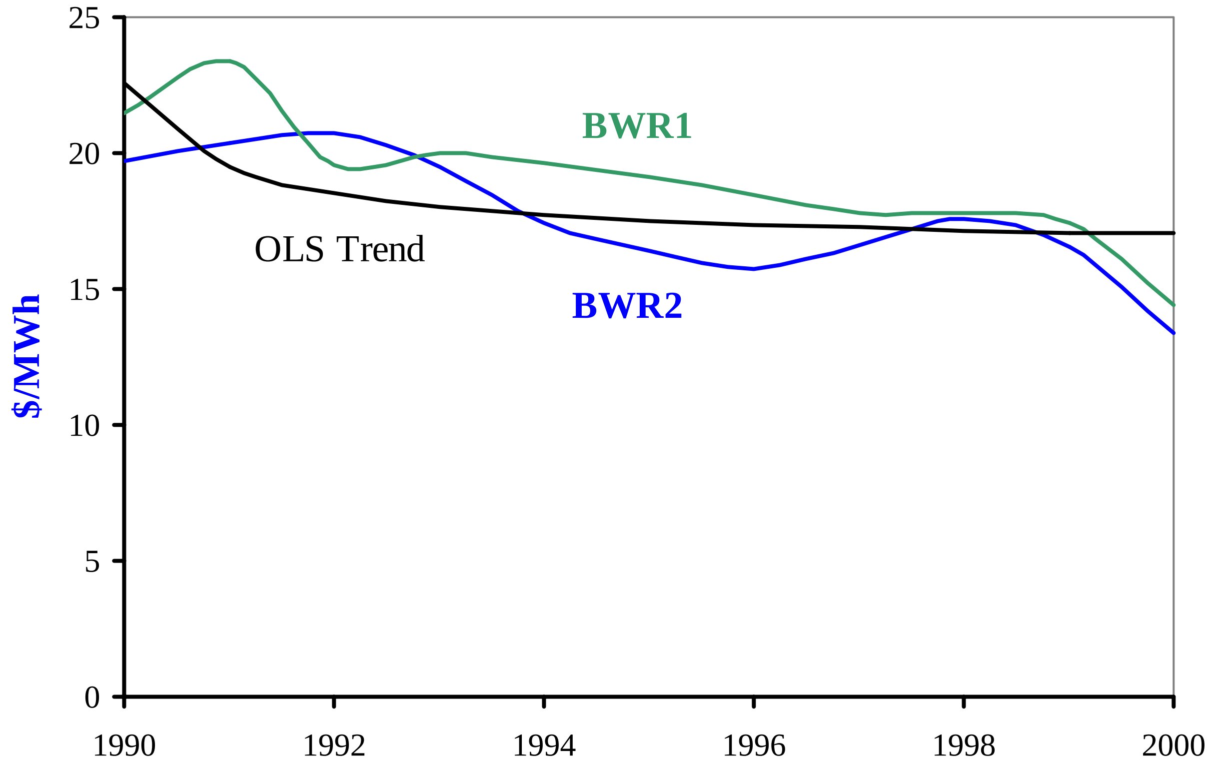


Figure 6: A Simulation of Annual Variable Production Cost (*C*)
(one of 1,000 Monte Carlo simulations)

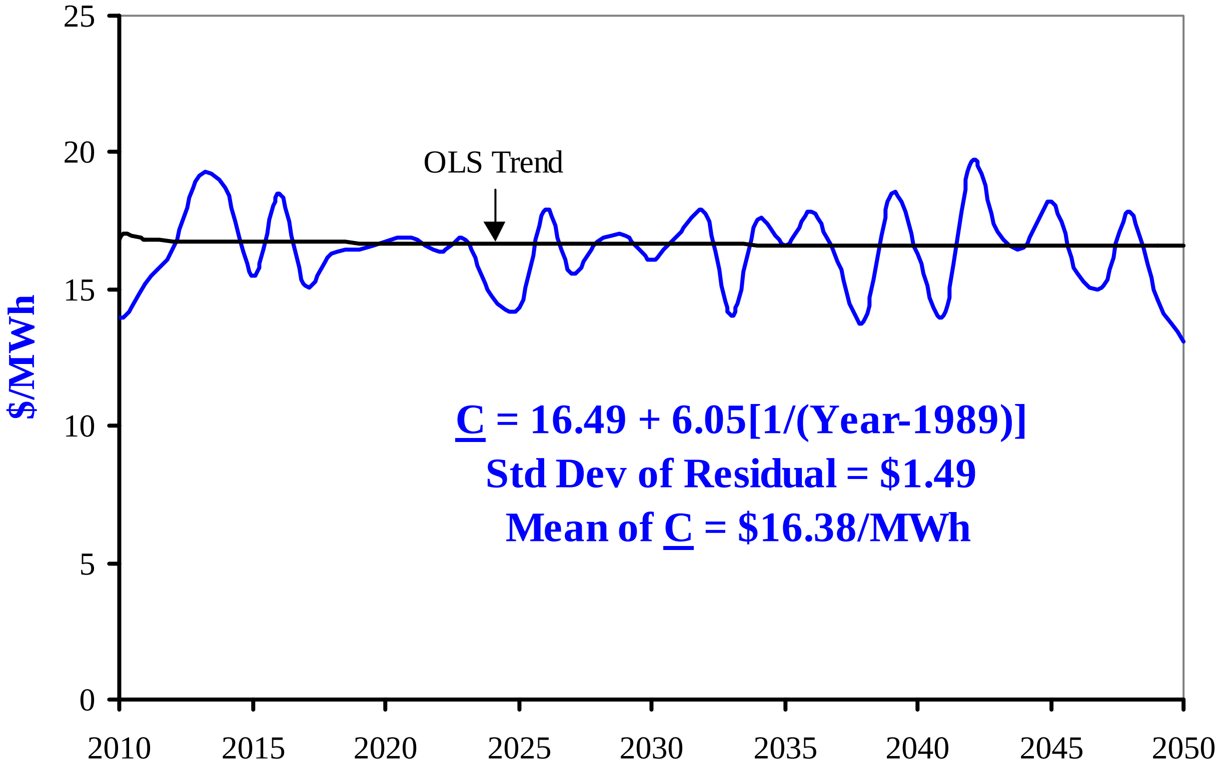


Figure 7: A Simulation of Annual Revenues, 2010 to 2050
(one of 1,000 Monte Carlo simulations)

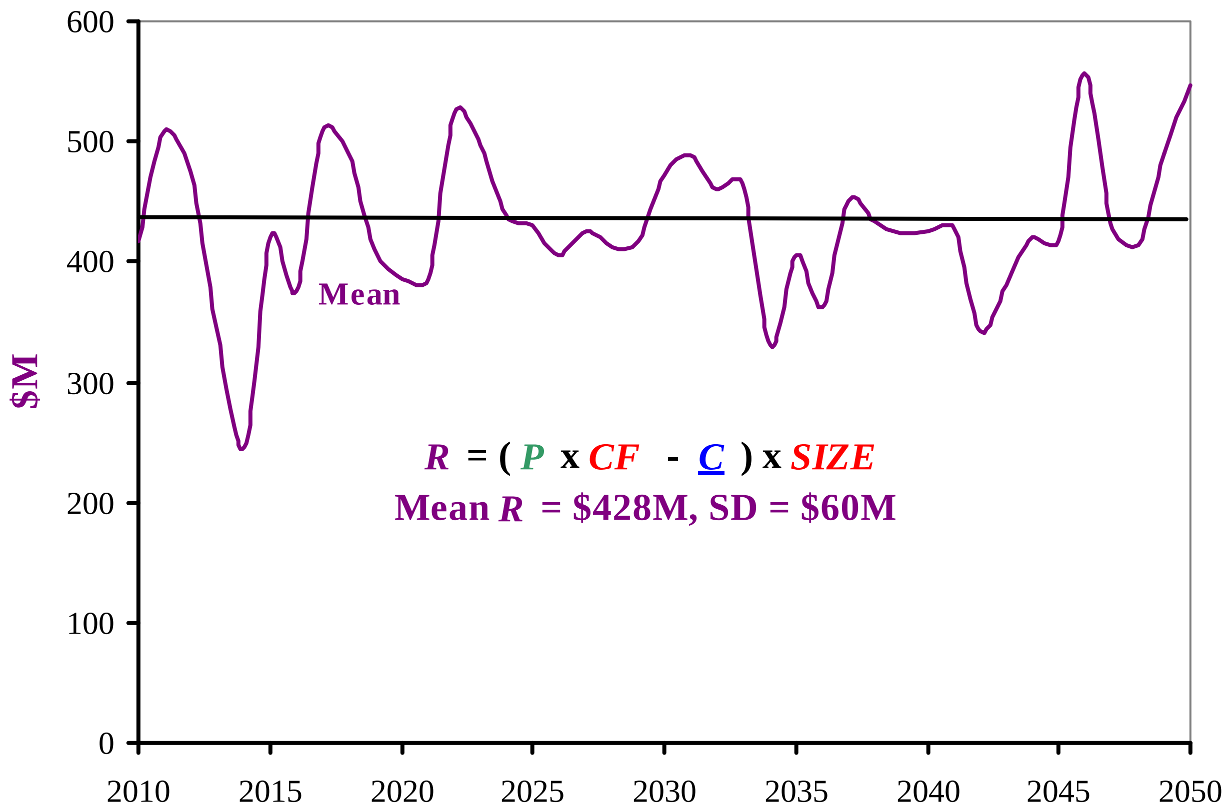
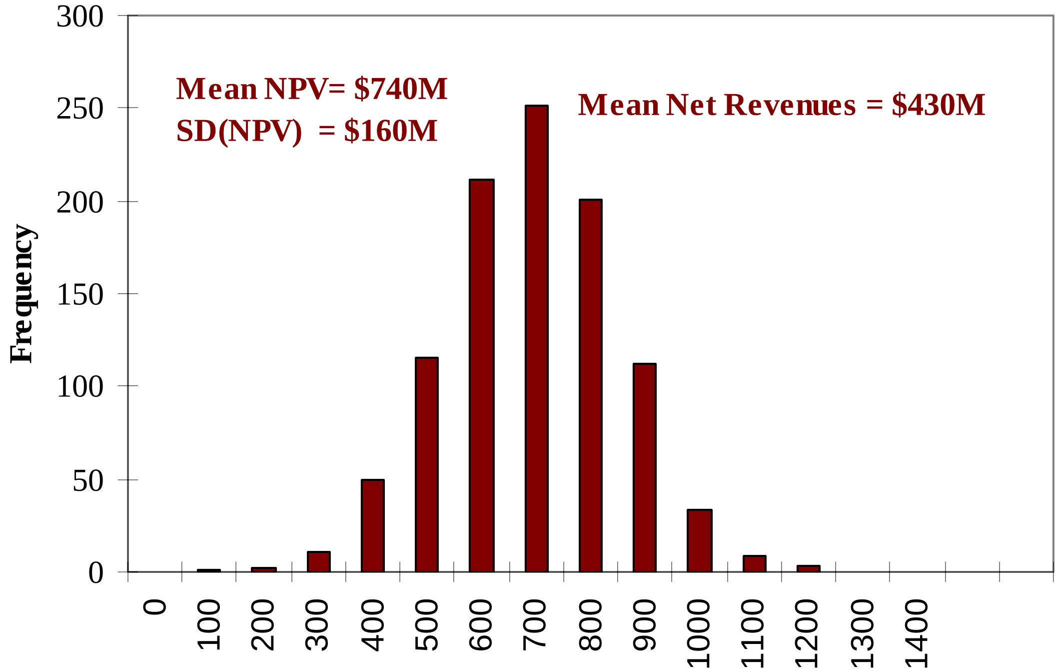


Figure 8: 1,000 Simulations of NPV of a dual-unit ABWR in Texas



APPENDIX 1: Derivation of Net Revenues

Net Revenues from an electricity generator are equal to

$$R_t \quad = \quad Q_t \cdot (P_t \; - \; AVC_t), \quad \text{where} \qquad (1A1)$$

- R_t is net revenue per year in millions of $,
- Q_t is the quantity of megawatt-hours (MWh) sold (i.e., net MWh produced) per year,
- P_t is the price of electricity in $/MWh, and
- AVC_t are the average variable (production) costs in $/MWh.

A few modifications to Equation (1A1) will aid the specification of net revenue uncertainty. First, the capacity factor (*CF*) is total output (*Q*) divided by the maximum dependable capacity (*MWYEAR*, in megawatt-hours per year):

$$CF_t \quad = \quad Q_t \; / \; MWYEAR \qquad \text{or} \qquad Q_t \; = \; CF_t \; \cdot \; MWYEAR \qquad (1A2)$$

(See Rothwell 2000b for a more extended discussion of capacity factors.)

Second, AVC_t includes all costs that vary with additional units of output. But nuclear power plants are continuous production facilities where costs vary little with the production of an additional MWh. To distinguish annual nuclear power plant costs from the traditional definition of AVC_t, Rothwell (2000a) refers to these costs as annual Average Variable Expenses (AVE_t):

$$AVE_t \quad = TVE_t \; / \; Q_t \, , \qquad (1A3)$$

where TVE_t is total variable expenses in year *t*. Variations in AVE_t are a function of (1) unanticipated cost, i.e., changes in TVE_t, and (2) variance in annual output (Q_t). To account for changes in annual output, substitute $Q_t = CF_t \cdot MWYEAR$ from Equation (1A2) into Equation (1A3):

$$AVE_t \quad = \quad [\, (TVE_t \, / \, (\, MWYEAR \cdot CF_t \,)] \quad = (\, \underline{C}_t \, / \, CF_t \,) \, , \qquad (1A4)$$

where $\underline{C}_t$ (= TVE_t / *MWYEAR*) are average variable expenses *at full capacity*, i.e., $\underline{C}_t$ are annual variable expenses divided over the maximum megawatt-hours that could be generated. For example, if *AVE* was \$20/MWh and *CF* was 86%, the input cost at full capacity (*CF* = 100%) would be $\underline{C}$ = \$17.18. This approach decomposes the variance in average variable expenses into (1) the variance of in annual output, *Q*, and (2) the variance in input costs, $\underline{C}_t$. Substituting for AVC_t and Q_t, Equation (1A1) becomes

$$R_t = (CF_t \cdot MWYEAR) \cdot [P_t - (\underline{C}_t / CF_t)]$$

$$R_t = [P_t \cdot CF_t - \underline{C}_t] \cdot MWYEAR \ , \qquad (1A5)$$

This is the same as Equation (2) in the text without the time subscripts.

APPENDIX 2: Derivation of γ and φ

Dixit (1992, p. 113) shows that the value of waiting, *W* (i.e., not investing now), can be represented as

$$W = B \cdot R^{\gamma}, \qquad (2A1)$$

where *B* is a positive constant and γ is a function of the standard deviation of net revenues and the capital recovery factor. See Takizawa et al. (2001) for a similar derivation.

First, what is *B*? When $R = R^*$, the firm is indifferent between investing and waiting. So, the value of investing, NPV, is equal to the value of waiting, *W*. Equating Equations (1) and (2A1) and substituting R^* for *R*,

$$(R^* / \delta) - I = B \cdot R^{*\gamma} . \qquad (2A2)$$

Solving for *B*,

$$B = [(R^* / \delta) - I] \ / R^{*\gamma}. \qquad (2A3)$$

Second, what is γ? Dixit shows γ is a solution to the differential equation that describes the Brownian motion of *R* through time. The solution involves a quadratic expression in γ:

$$\gamma^2 - \gamma - (2\delta/\sigma^2) = 0 \qquad (2A4)$$

where σ^2 is the variance of net revenues. Solving for the positive root of this expression,

$$\gamma \quad = \quad 1/2 \cdot \{ 1 + [1 + (8 \, \delta / \sigma^2)]^{1/2} \} . \tag{2A5}$$

What value of *R** would trigger investments in a new power plant? *The optimal value occurs where small changes in R are equal for investing and waiting at R = R**. Differentiating both sides of Equation (2A2) with respect to *R**:

$$1 / \delta \quad = \gamma \cdot B \cdot R^{*\,\gamma - 1} \tag{2A6}$$

Substituting for *B* in Equation (2A3) and solving for *R**:

$$R^* \quad = \quad [\gamma / (\gamma - 1)] \cdot \delta \cdot I . \tag{2A7}$$

Letting $\phi = [(\gamma - 1) / \gamma]$, Equation (2A7) is equal to Equation (3) in the text.

APPENDIX 3: Econometrics

The following model of electricity prices (P_t) was estimated using average electricity prices in Texas:

$$P_t \quad = \; 13.79 + 0.58 \, P_{t-1} \; + 2.84 \, AFTER2000 \, , \qquad \mathrm{SD}(E_{1t}) = 1.69 \, , \tag{3A1}$$

where t indexes the year, P_{t-1} is the price of electricity in the previous year, AFTER2000 is a dummy variable for observations after 2000, and SD(E_{1t}) is the standard deviation of the residual (or Root Mean Squared Error, MSE), see below. Monthly average revenue for all sectors from 1990-2003 was translated into annual average revenue (weighting by monthly sales to all sectors). This was deflated to 2001 with the GDP implicit price deflator and multiplied by 50% to account for average transmission and distribution expenses. The Ordinary Least Squares (OLS) results are

F Value	Prob>F	Root MSE	Dep Mean	R-Square
8.301	0.008	1.691	34.087	0.624

Variable	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob>|T|
CONSTANT	13.788	7.970	1.730	0.114
AFTER2000	2.838	1.159	2.449	0.034
PRICE(t-1)	0.583	0.238	2.448	0.034

Second, following Rothwell (2000a), data was collected for General Electric BWRs larger than 1,100 MW in commercial operation after 1982. OLS was performed on this sample of capacity factors, yielding the following estimates:

$$CF_t = 87.56 - 16.76\,(1/\,TIME_t\,) \qquad SD(E_{2t}) = 5.72\ , \qquad (3A2)$$

where $TIME_t$ are years since 1989. The OLS results are

F Value	Prob>F	Root MSE	Dep Mean	R-Square
18.175	0.001	5.721	82.619	0.355

Variable	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob>|T|
CONSTANT	87.558	1.509	58.023	0.001
(1/TIME)	-16.576	3.930	-4.263	0.001

Third, following the definition of average variable expenses in Appendix 1, data on $\underline{C}_t$ was collected for dual-unit BWRs in commercial operation in the U.S. after 1982 for the years 1990 to 2000 (inflated in mid-2001 dollars). Using these data, variable expenses were estimated with OLS:

$$\underline{C}_t = 16.49 + 6.05\,(1\,/\,TIME_t\,), \qquad SD(E_{3t}) = 1.49 \qquad (3A3)$$

where $TIME_t$ are years since 1989. The OLS results are

F Value	Prob>F	Root MSE	Dep Mean	R-Square
21.836	0.001	1.486	18.378	0.577

Variable	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob>|T|
CONSTANT	16.490	0.535	30.836	0.001
(1/TIME)	6.052	1.295	4.673	0.001

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