Levelized Costs and Cost Risks of Electricity Generating Asset Portfolios

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Outline:

Objective: Develop a method for approximating the probability distribution of the levelized cost of electricity (*LC*) for each generating technology and portfolios of generating technologies (providing a generalization of D'haeseleer, 2012)

(1) Define levelized cost, its mean, and variance => Monte Carlo simulation
(2) Identify cost drivers, parameters, and variables
(3) Approximate the probability densities of influential variables with historic data
(4) Simulate probability distributions of LC for nuclear power, CCGT, and coal
(5) Simulate probability distributions for combinations of generating technologies
(6) Discuss implications for electricity policy
(7) Identify topics for further research

Long-Run Average Levelized Cost:

See OECD-NEA-IEA, *Projected Costs of Generating Electricity* (2010, 2015)

LC = [*CAPITAL*(*OC*, r, *lt*) + *FUEL* + *O&M*] / *E*

CAPITAL **is the product of Fixed Charge Rate and Total Capital Construction Costs, which depends on the Overnight costs, OC, cost of capital, r, and the lead time, lt**

FUEL **is the *annual* fuel payment and a function of the amount of fuel and price of fuel**

O&M **is the *annual* Operations and Maintenance expense and Capital Additions, CAPEX**

E **is *annual* energy output equal to MW · TT · *CF*, i.e., the size of the generator in megawatts, MW, the total number of hours in a year, TT, and the Capacity Factor, *CF***

What is the probability distribution of *LC* ?

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Mean and Variance of Levelized Cost:

$$LC = [CAPITAL(OC, r, lt) + FUEL + O\&M] / E$$

$$E\{ LC \} = E\{ [CAPTIAL(OC, r, lt) + FUEL + O\&M] / E \}$$

$$VAR\{ LC \} = E\{ LC - E(LC) \}^2$$

(1) Unfortunately, each element is likely to be a function of the size of the generator, MW

(2) Therefore, the expectation of LC cannot be a simple ratio of the expectation of cost and the expectation of output (the numerator and denominator are correlated)

(3) Further, calculating the variance is likely to be cumbersome given the underlying distributions

So, another strategy is used:

(1) simulate the probability density of each important variable (calculate elasticity),

(2) approximate the mean and variance with the moments of the probability distribution of the simulated value, and

(3) conduct sensitivity analysis for important parameters

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Cost Drivers: Variables, Parameters, and Constraints

Variables:

OC	**Construction Overnight Construction Cost**
lt	**Construction Lead Time**
FUEL	**is a function of quantities and prices of inputs (e.g., natural uranium, natural gas, coal)**
O&M	**is a function of quantities and prices of labor and materials, etc.**
CF	**Capacity Factor, is defined as *E* / MW · TT (actual output/potential maximum output)**

Parameters:

r	**is the Cost of Capital (assumed to be equal to real 5%, 7.5%, or 10%, as a function of the market)**
MW	**is the size of the generator in megawatts, assumed to be fixed as a function of technology**
TT	**is the total number of hours in a year, equal to 8,766 hours in an average year**

Constraints:

(1) **Simulated outcomes cannot be negative (hence, no symmetric input probability densities)**

(2) **Input probability densities should have closed-form distributions (for transparency)**

(3) **Output probability densities, when necessary for exposition, will be fitted to extreme value, exponential, normal, or lognormal (for comparability)**

Probability Density Functions in this Analysis:

Extreme Value density: **maxv**(**a**, **b**) = (1/**b**) · **ab** · exp{ (– **ab**) } ,

Extreme Value distribution: **MAXV**(**a**, **b**) = exp{ – **ab**} ,

where **ab** = exp { – [(x – **a**) /**b**] } and

a is the mode and the standard deviation is b *times* (π/√6) (≈ 1.28). The direction of the skewness in the extreme value distribution can be reversed, such that it has an extreme minimum value; this is designated here as minv(a, b) and MINV(a, b)

Exponential density: **expo**(**b**) = [exp(– x / **b**)] / **b**

Exponential distribution: **EXPO**(**b**) = 1 – exp(– x / **b**) ,

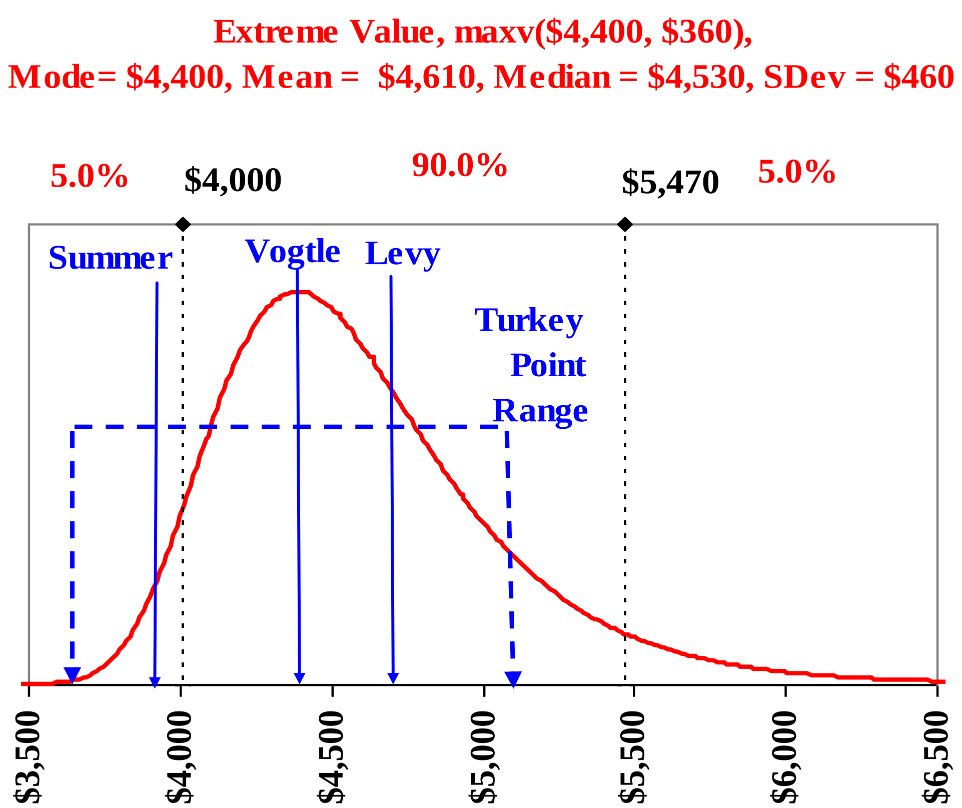
where *b* and *x* must be greater than 0 (thus avoiding negative outcomes in simulation), and *b* is equal to the mean and the standard deviation (can include a shift parameter)

Normal density **normal**(μ, σ^2) = $(2 \pi \sigma^2)^{-½} \cdot \exp\{ -(x - \mu)^2 / (2 \cdot \sigma^2) \}$ and

Lognormal density **lognormal**(μ, σ^2) = $x^{-1} (2 \pi \sigma^2)^{-½} \cdot \exp\{ -(\ln x - \mu)^2 / (2 \cdot \sigma^2) \}$,

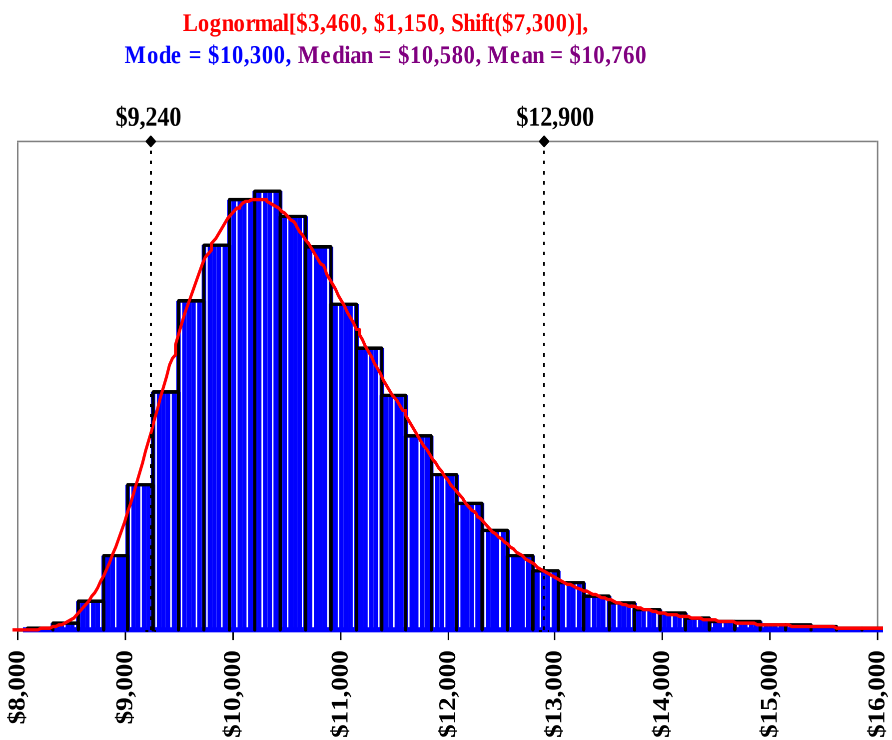
where the μ are the means and the σ^2 are the variances

Overnight Construction Costs (AP1000) fitted to a extreme value density (2013$):



Total Construction Investment Costs (twin AP1000s) fitted to a lognormal density (2013$, r = 7.5%):

(compare to announcement of Kozloduy's AP1000 at $5.3B, http://online.wsj/com/articles/bulgaria-signs-deal-with-westinghous-on-nulcear-plant-1406890323)



ALWR Fuel Costs:

$F\_MWh = [\, FC / (24 \cdot B \cdot \varepsilon) \,] / CF$, where

(1) FC is the cost of nuclear fuel in dollars per kg

(2) 24 is the number of thermal MWh in a thermal megawatt-day

(3) **B** is the burnup rate measured in thermal megawatt-days per kgU

(4) ε is the thermal efficiency of converting MW-thermal into MW-electric

(5) CF is the capacity factor, assumed to be constant for all periods.

$FC = RU \cdot P_{UF6} \cdot (1 + r)^{ltU} + SWU \cdot P_{SWU} \cdot (1 + r)^{ltS} + P_{FAB} \cdot (1 + r)^{ltF}$, where

(1) RU is the ratio of natural uranium input to enriched uranium output

(2) P_{UF6} is the price of natural uranium input plus its conversion to UF6

(3) SWU is the number of Separative Work Units required in enrichment

(4) P_{SWU} is the price of enriching uranium hexafluoride, UF6

(5) P_{FAB} is the price of fabricating UO2 fuel from enriched UF6

(6) lt_U, lt_F, and lt_S are carrying times, e.g., 2.0, 1.0, 0.5 years, respectively

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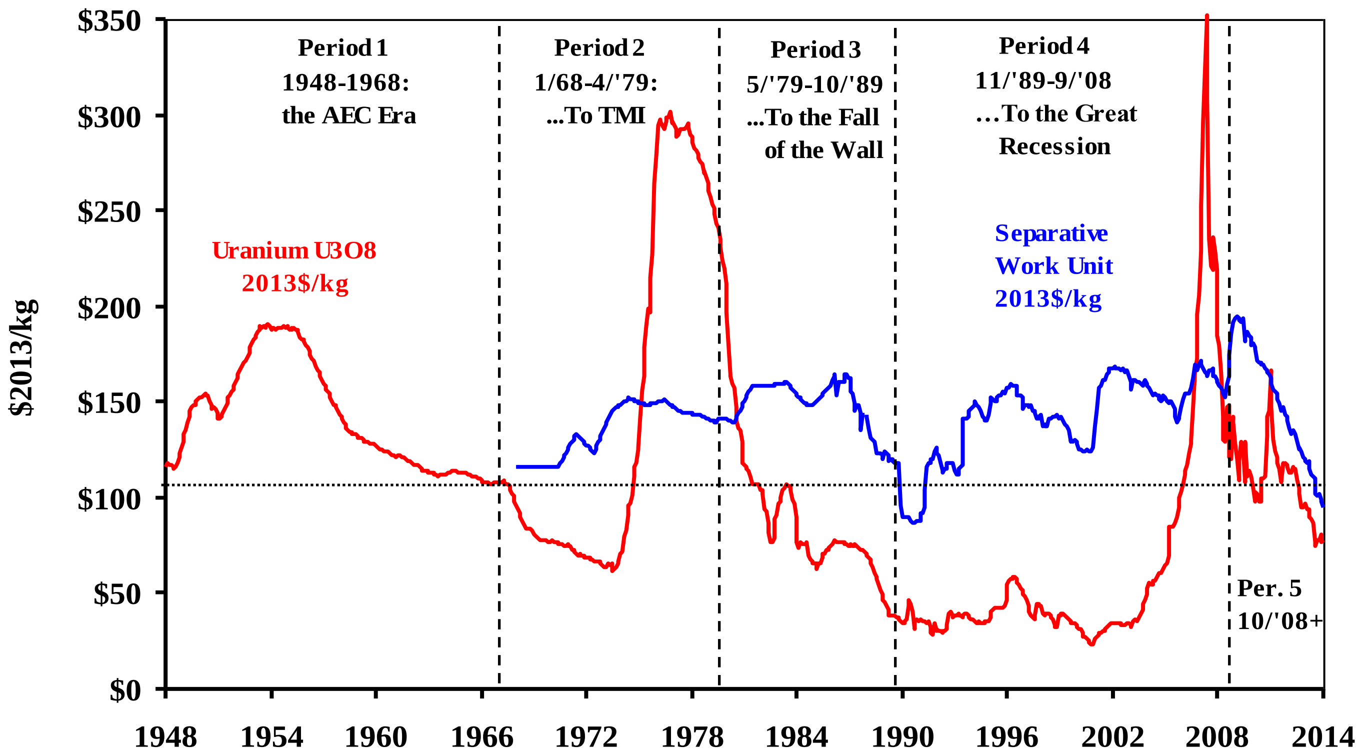
Fuel Costs Depend on Costs of Uranium and Uranium Enrichment:

***Sources*: Prices 1948-1972 from US DOE (1981), 1973-2006 from ABARES (2007), and 2006-2014 from UXC website http://www.uxc.com/review/UxCPrices.aspx**



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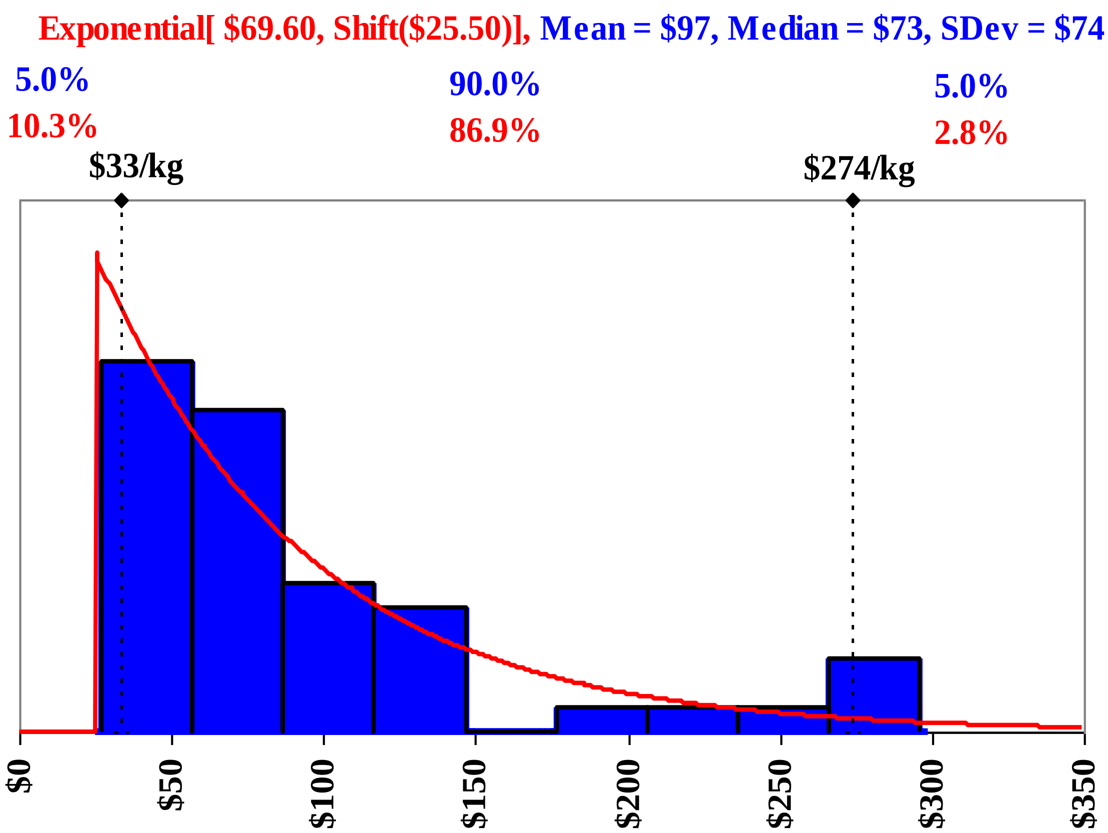
Uranium Price Distribution, fitted with an exponential density:



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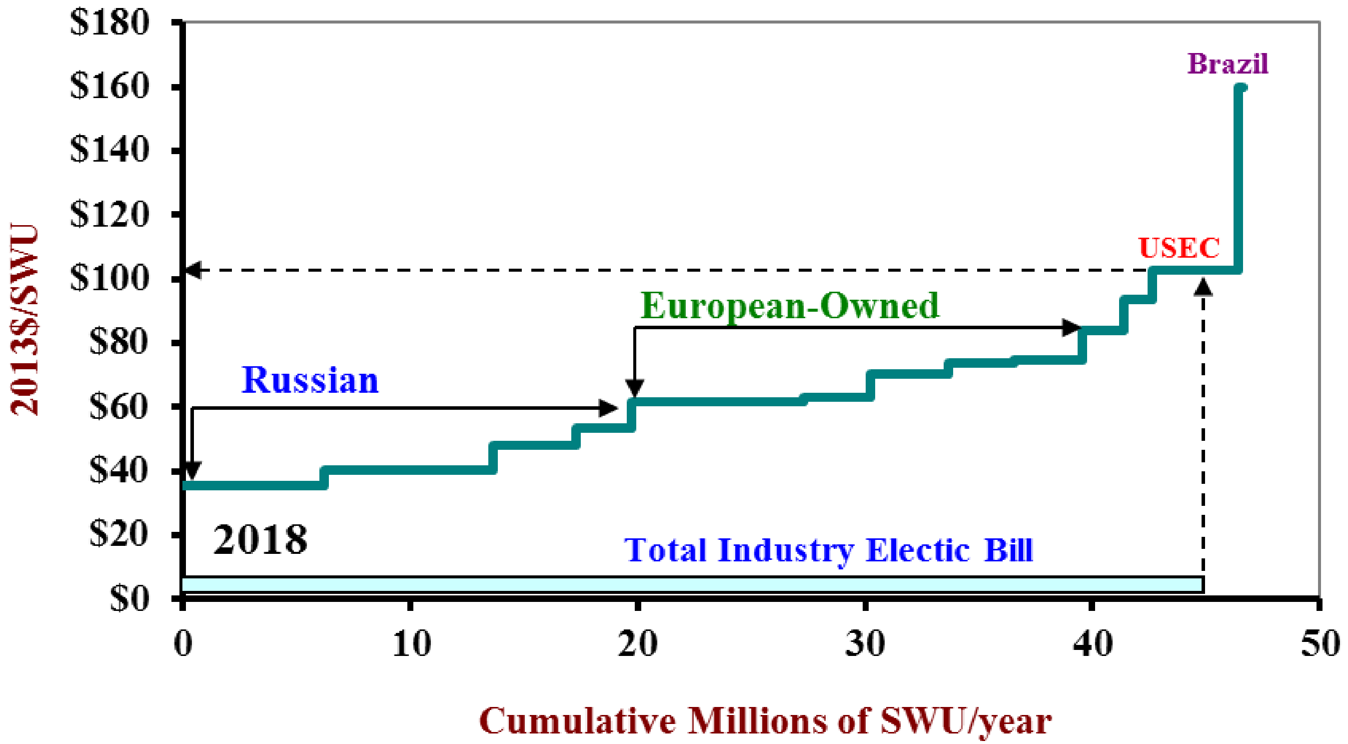
The Uranium Enrichment Market, measured in Separative Work Units, SWU:

Rothwell, G.S. 2009. "Market Power in Uranium Enrichment," *Science & Global Security* 17(2–3): 132–154. http://scienceandglobalsecurity.org/ru/archive/sgsr17rothwell.pdf



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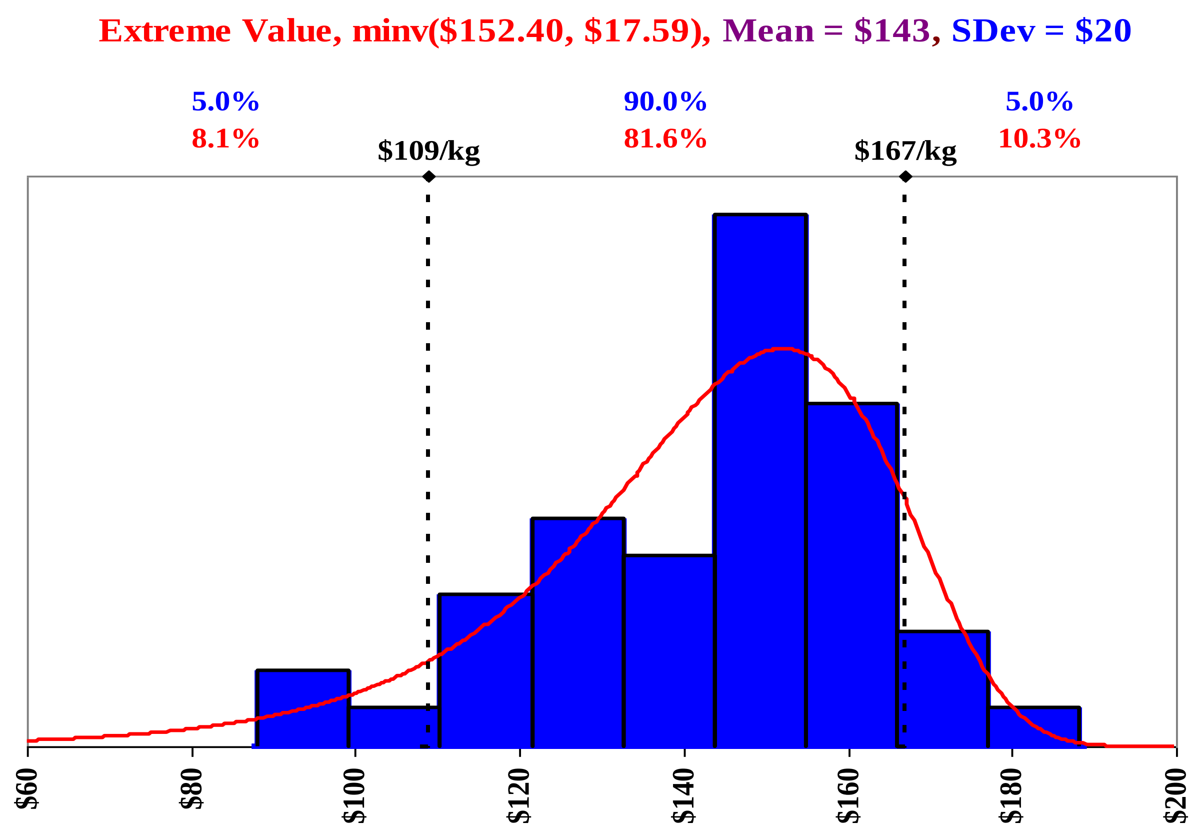
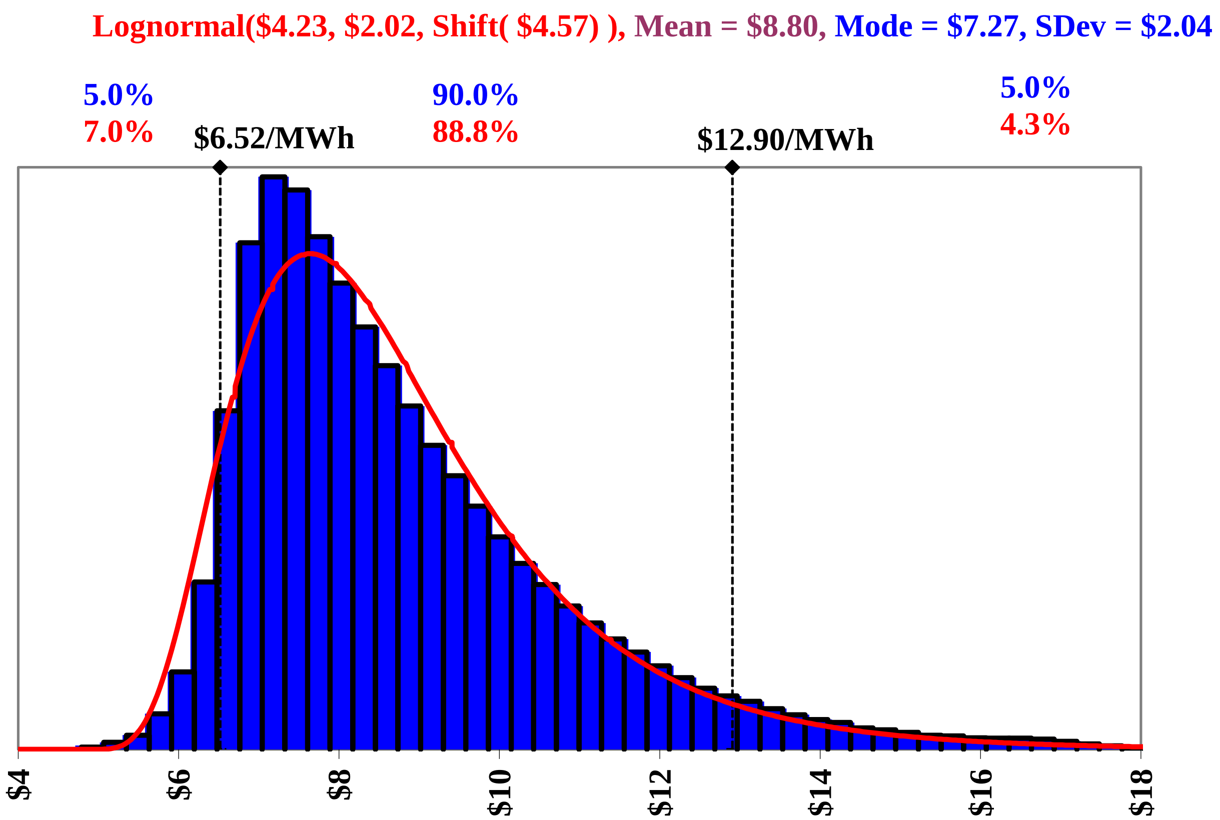
Separative Work Unit Price Distribution, fitted with a minimum extreme value density:



Calculated Nuclear Fuel Price Distribution, fitted to a lognormal density:



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ALWR O&M Costs:

$$O\&M = (p_L \cdot L) + M$$

$$O\&M = (1 + om)(p_L \cdot L)$$

(1) p_L is the average employee wages and benefits

(2) L is the number of plant employees

(3) M includes maintenance materials, capital additions, supplies, operating fees, property taxes, and insurance

(4) om is 0.65 (varies in simulation uniformly between 0.55 and 0.75)

$$\ln(L) = \underset{(0.181)}{5.547} + \underset{(0.099)}{0.870}\,(GW)$$

$R^2 = 96\%$

Standard Error = 12.43%

(1) ln(L) is the natural logarithm of the number of employees and

(2) GW is the size of the plant in gigawatt

$$p_L \cdot L = p_L \cdot e^{5.55} \cdot e^{(0.87)(1.2)} = \$80{,}000 \cdot 730 = \$58.4\text{ M}$$

$$O\&M = (1 + om)(p_L \cdot L) = 1.65 \cdot \$58.4\text{ M} = \$96.4\text{ M}$$

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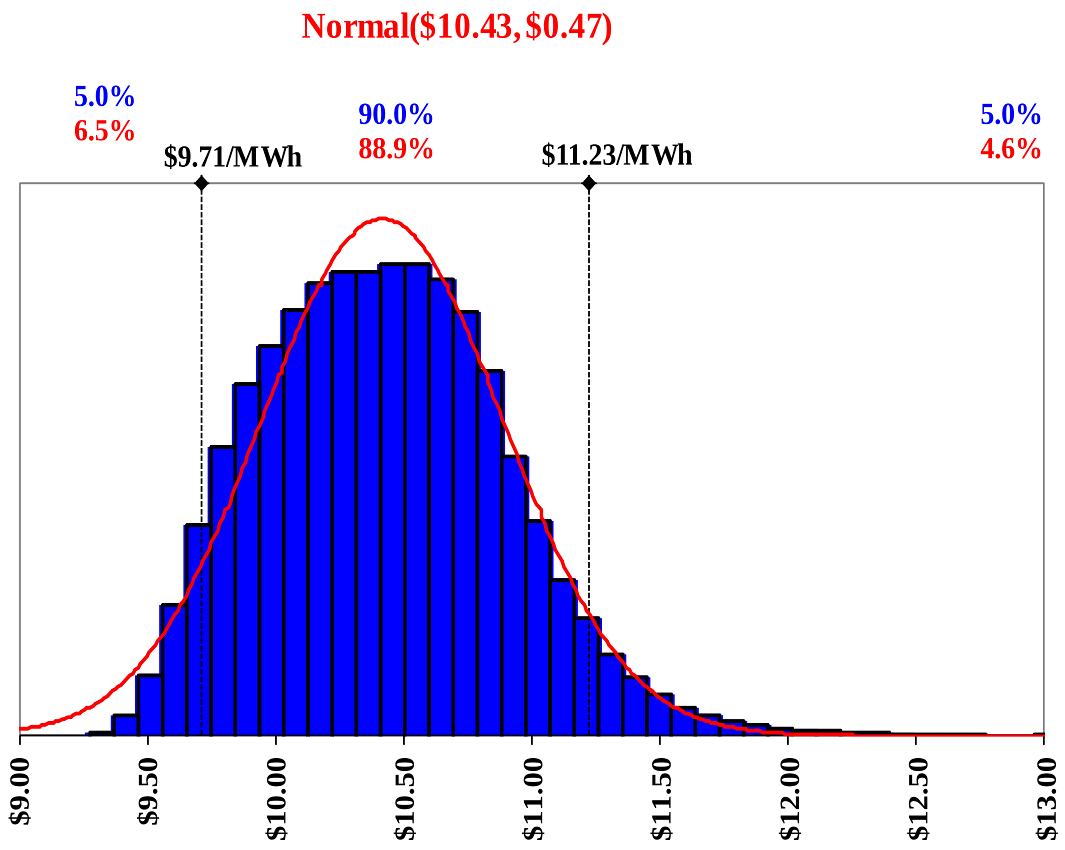
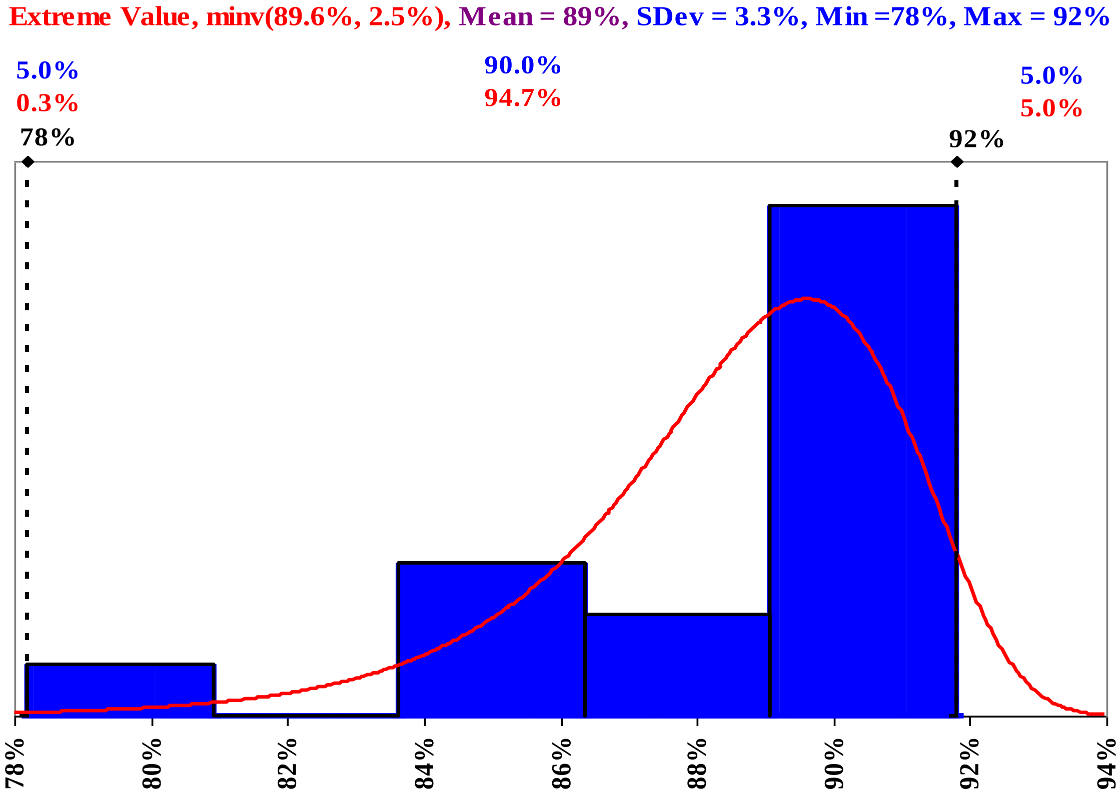
Calculated Operation and Maintenance Cost Distribution, fitted with a normal density:

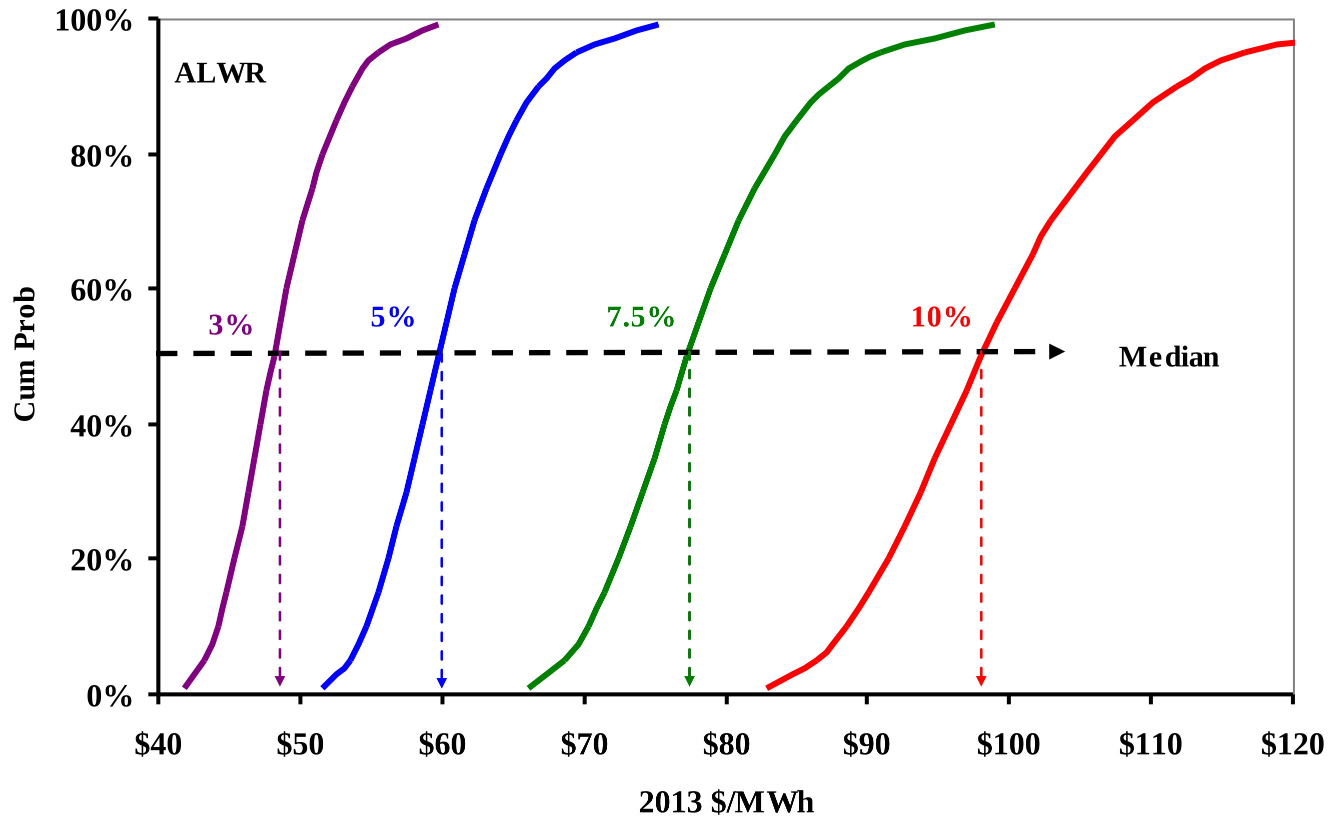


Nuclear Power Plant Capacity Factor Distribution, fitted with a minimum extreme value density:

Source: **http://www.eia.gov/totalenergy/data/monthly/pdf/sec8.pdf**



Cumulative Distributions for Levelized Costs of ALWRs:



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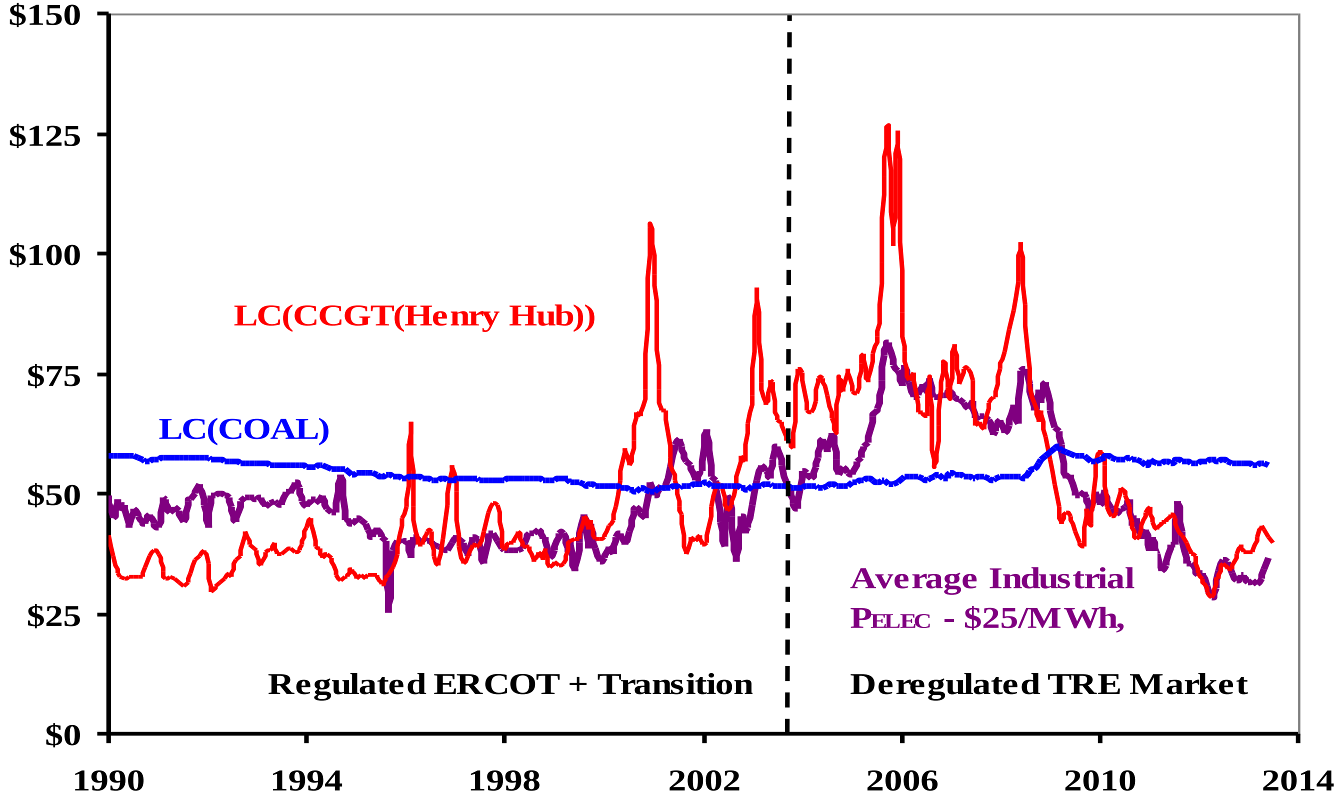
Electricity Prices and Levelized Costs

e.g., Electricity Prices in Texas ERCOT/TRE, 1990-2013,

mean was $74.18/MWh with a standard deviation of $11.83/MWh

Source: **http://www.eia.gov/electricity/data.cfm#sales**



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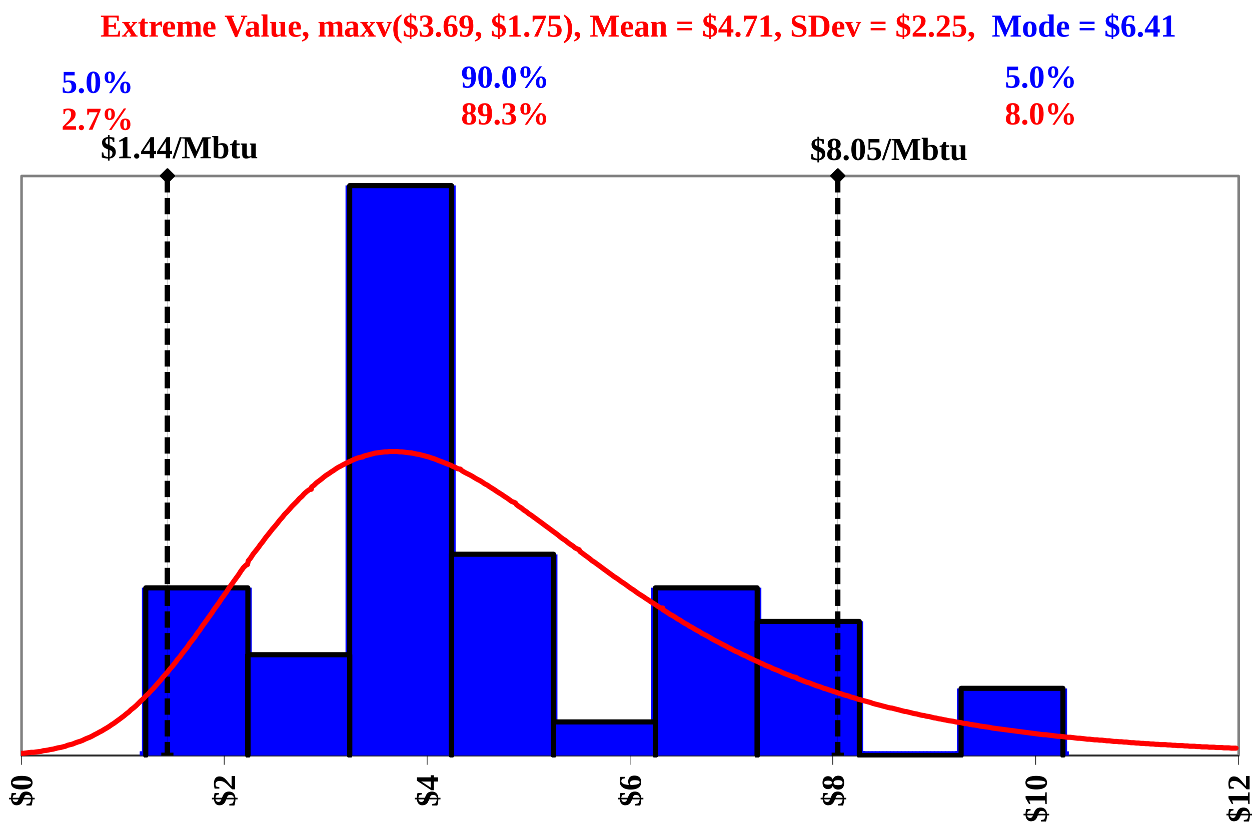
Natural Gas Prices, fitted with an extreme value density:

Source: http://www.eia.gov/state/seds/seds-data-fuel.cfm?sid=US



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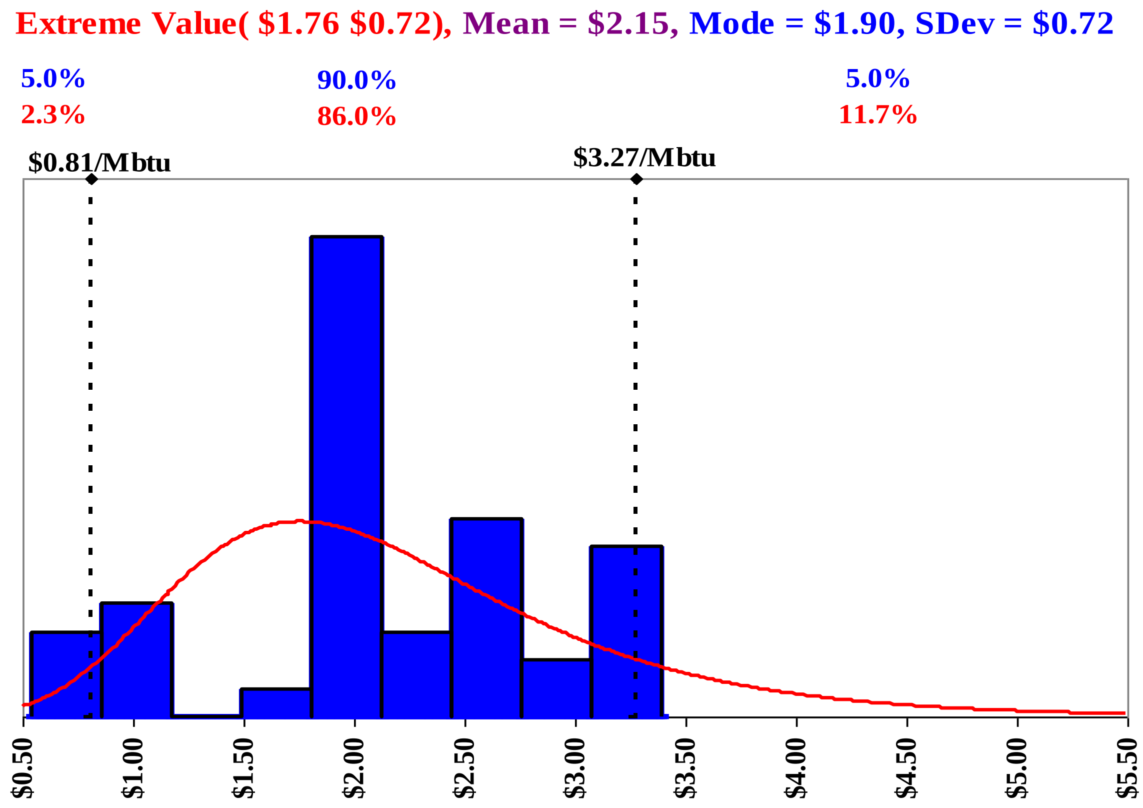
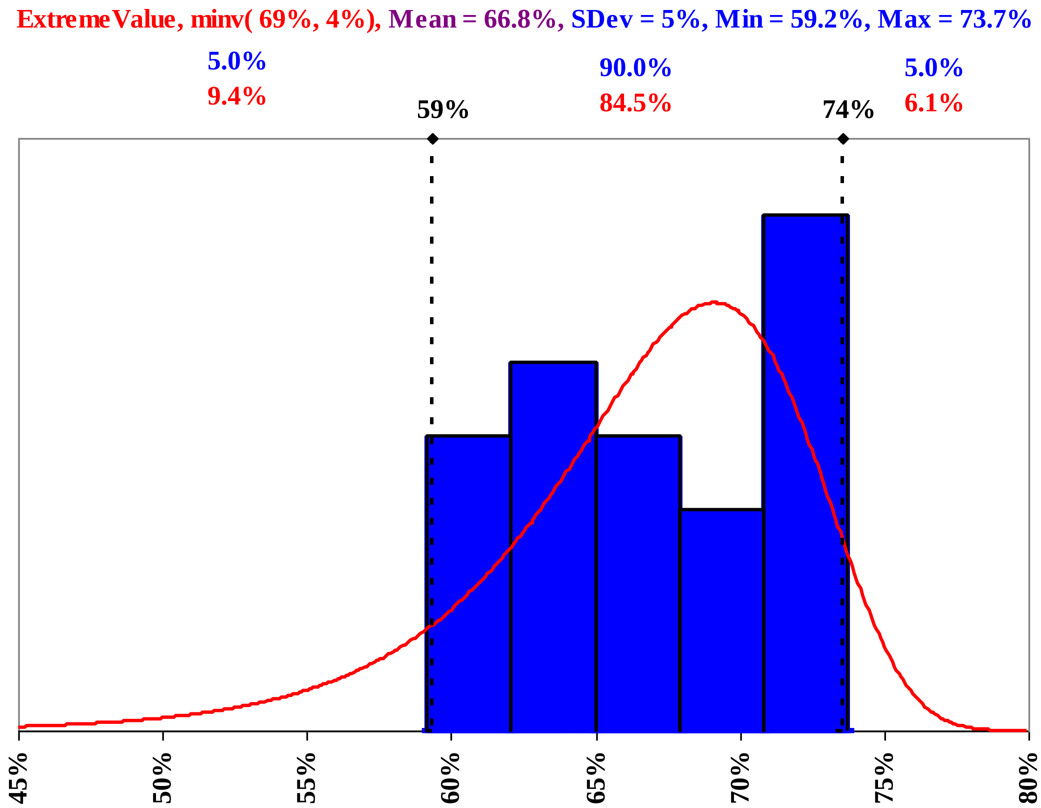
Texas Coal Prices, fitted with an extreme value density:

Source: http://www.eia.gov/state/seds/seds-data-fuel.cfm?sid=US



CCGT and Coal Plant Capacity Factors, fitted with a minimum extreme value density:

Source: **http://www.eia.gov/totalenergy/reports.cfm?t=182**



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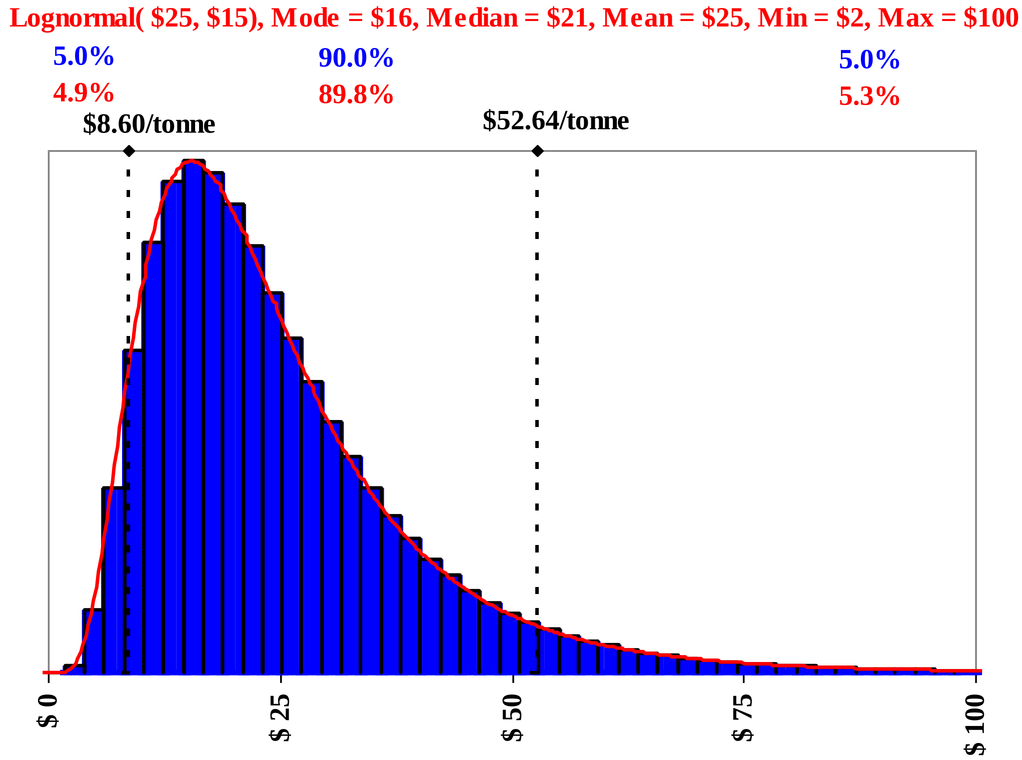
Proposed Carbon Dioxide Cost Distribution, modelled with a Log-Normal density:

***Sources*: $25 mean from MIT(2009) with SDev = $15, Nordhaus (2011) Figure 5**



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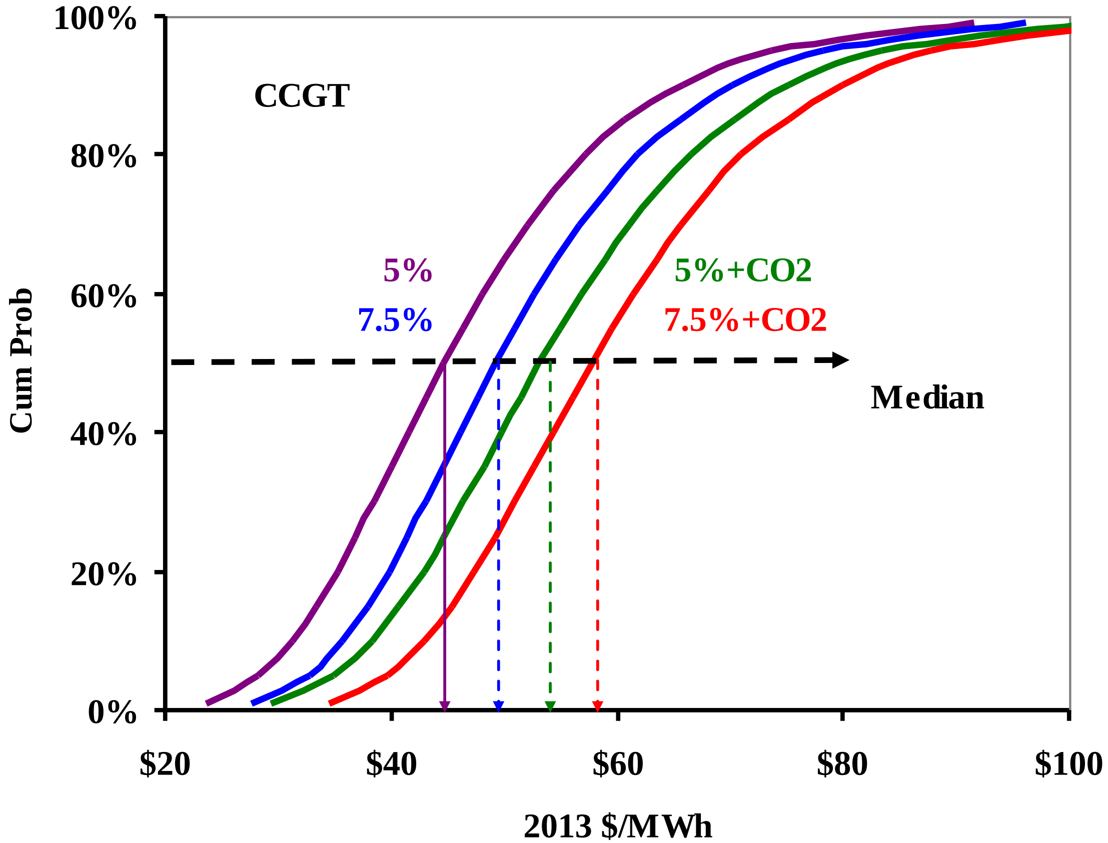
Cumulative Distributions for Levelized Costs of Combined Cycle (Natural) Gas Turbine:



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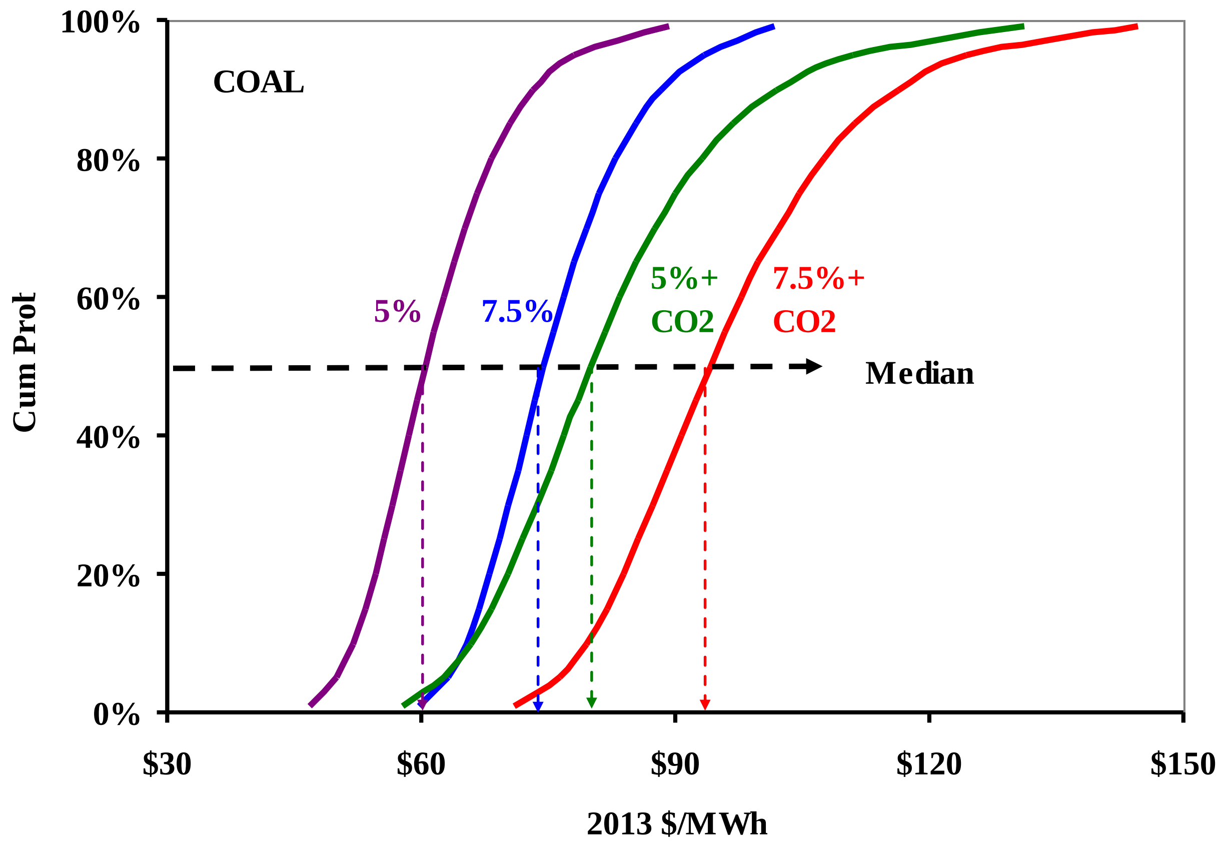
Cumulative Distributions for Levelized Costs of Coal with Advanced Pollution Controls:



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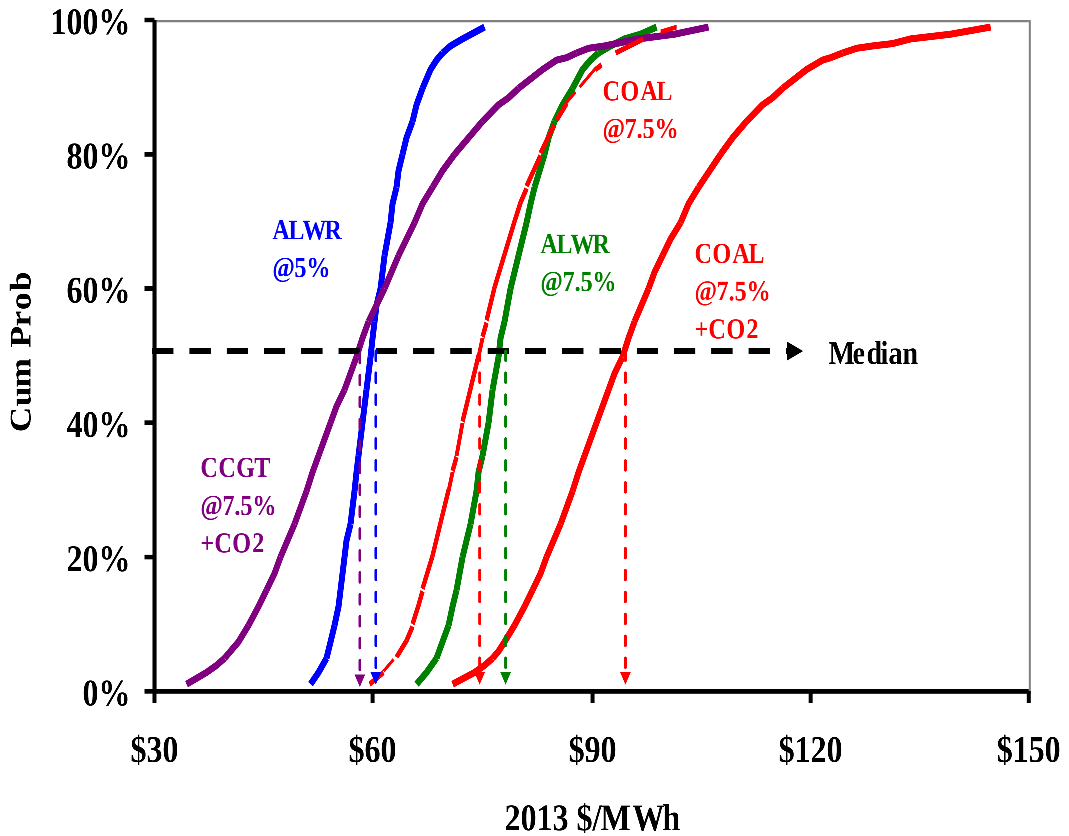
ALWR, CCGT, and Coal Levelized Costs: simulated cumulative distributions with and without CO_2 Fee



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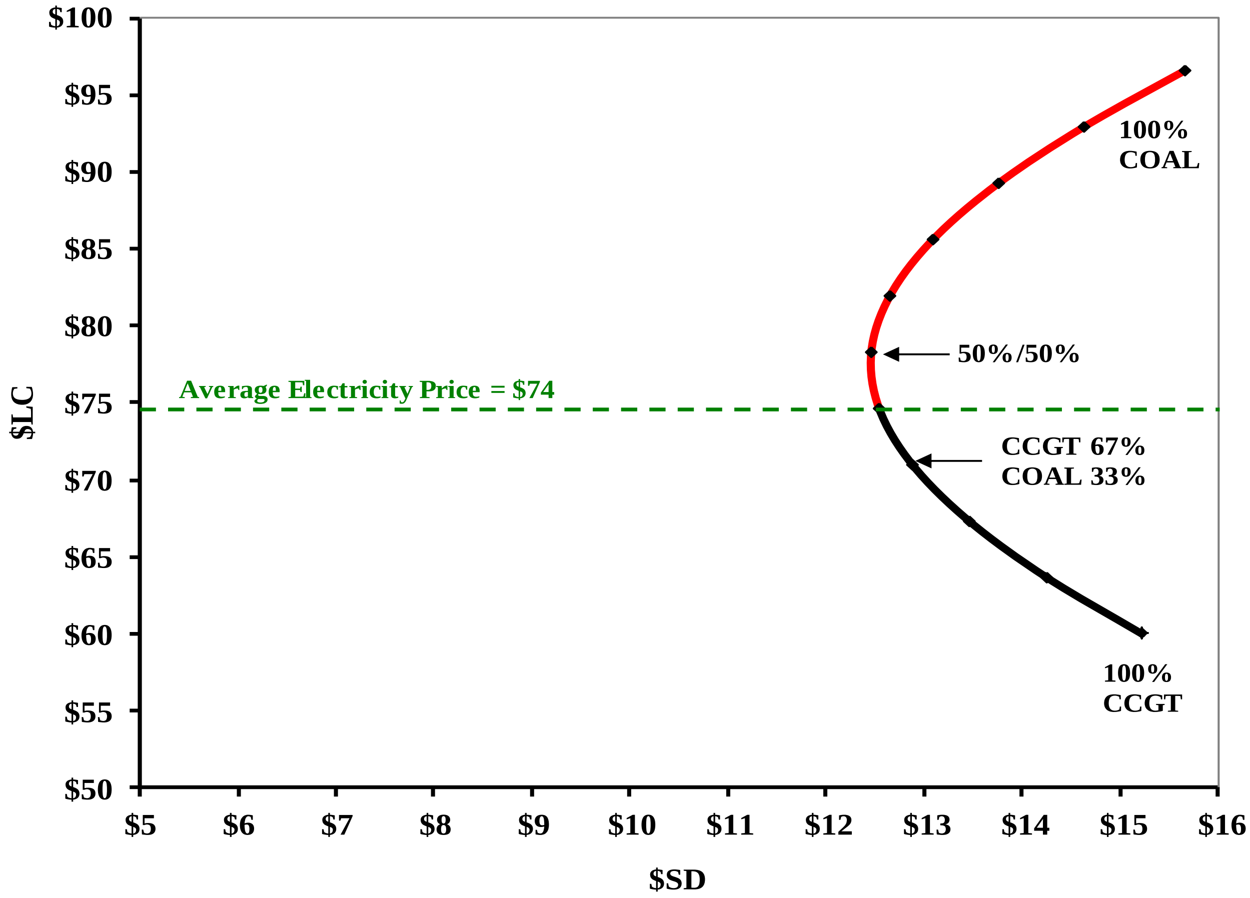
Levelized Cost and Risk with Portfolios of CCGT and Coal:



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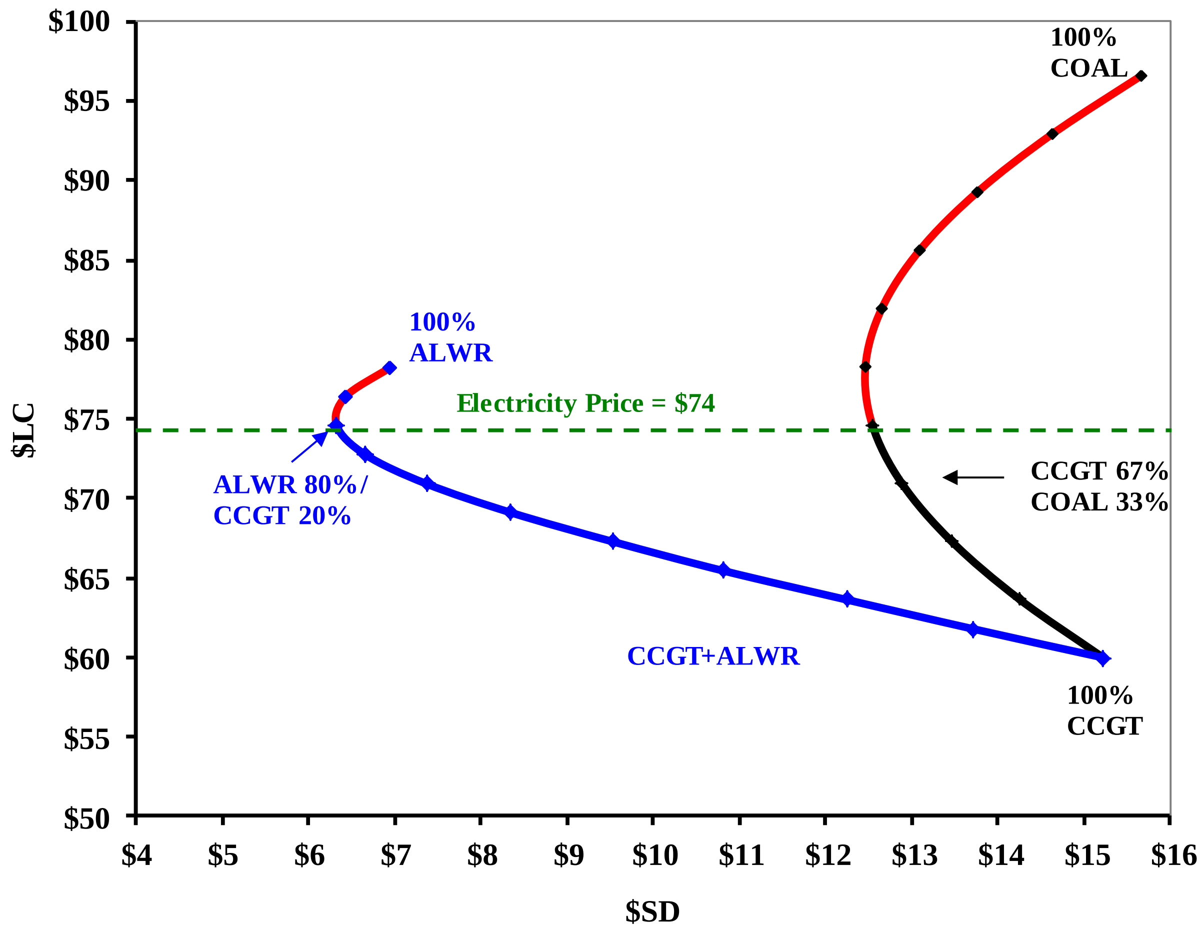
Levelized Cost and Risk with Portfolios of CCGT, Coal, and ALWRs (7.5%):



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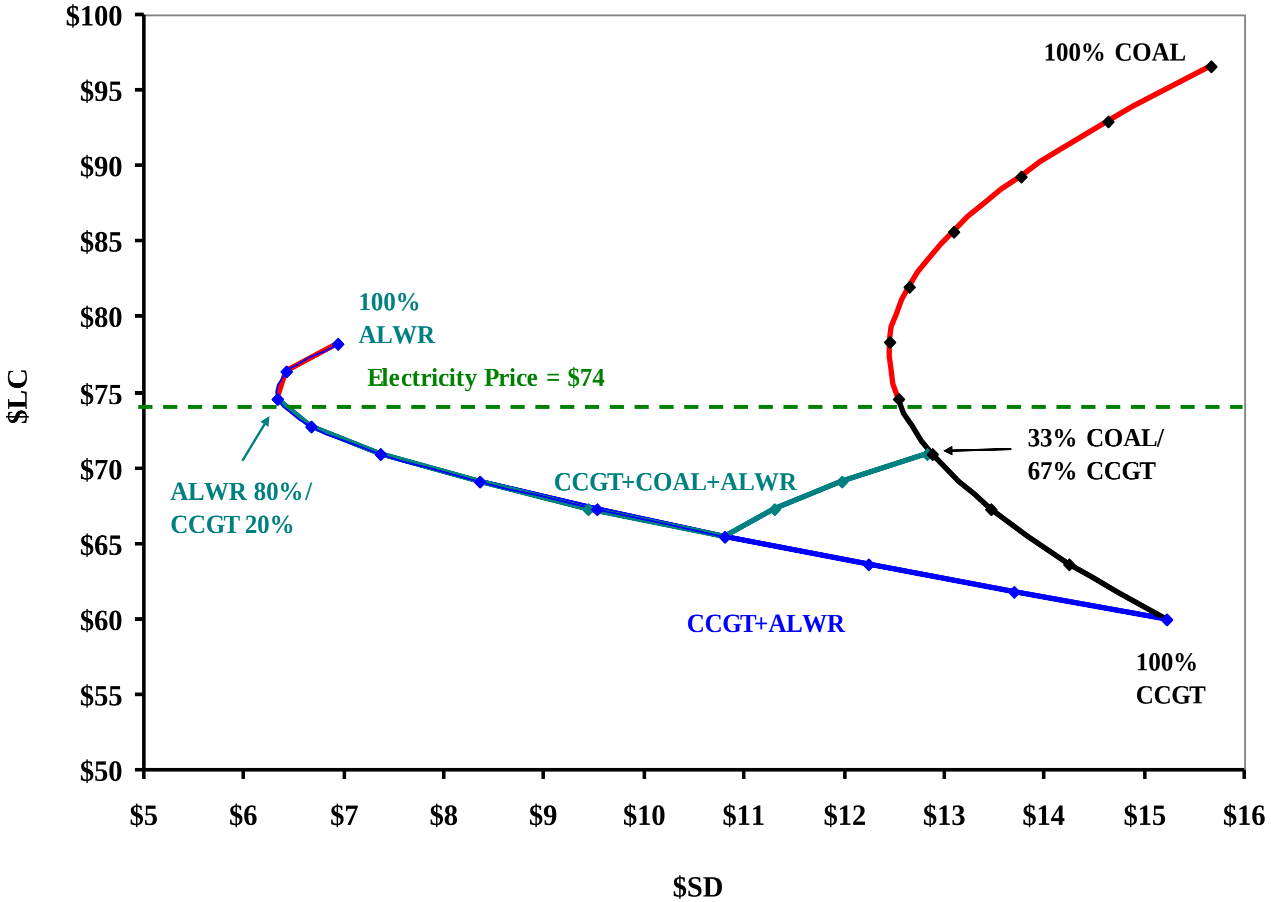
Levelized Cost and Risk with Portfolios of CCGT, Coal, and ALWRs (7.5%):



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U.S. Nuclear Power Costs: Blurred Bottom Lines

- **Natural gas prices are volatile and will rise (1) as U.S. petro-chemical industries shift from oil to gas and (2) as the U.S. exports Liquefied Natural Gas to Asia and Europe.**

- **With increases in gashouse gas costs (and prices) portfolios of electricity generating assets with nuclear power costs will lower the volatility of electricity costs making industry more competitive, energy supply more secure, and until electricity storage is developed, electricity systems more sustainable.**

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Further Research:

- Specify Correlations, e.g., between Construction Costs and Lead Time
- Add wind to portfolio analysis
- Add load duration & system effects
- Add competitive electricity markets
- Endogenize the Cost of Capital
- Others? Suggestions?

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Thank you for your attention, for more, see

Rothwell and Ganda, "Electricity Generating Portfolios with Small Modular Reactors" (June 2014), available at http://energy.gov/ne/downloads/electricity-generating-portfolios-small-modular-reactors

This paper provides a method for estimating the probability distributions of the levelized costs of electricity. These probability distributions can be used to find cost-risk minimizing portfolios of electricity generating assets including Combined-Cycle Gas Turbines (burning natural gas), coal-fired power plants with sulphur scrubbers, and Small Modular Reactors, SMRs. Probability densities are proposed for a dozen electricity generation cost drivers, including fuel prices and externalities costs. Given the long time horizons involved in the planning, construction, operation, refurbishment, and post-retirement management of generating assets, price data from the last half century are used to represent long-run price probabilities. This paper shows that SMRs can competitively replace coal units in a portfolio of coal and natural gas generating stations to reduce the levelized cost risk associated with the volatility of natural gas prices and unknown carbon costs.