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Power Systems Life Cycle Analysis Tool (Power L-CAT)

Thomas E. Drennen and Joel Andruski

Prepared by
Sandia National Laboratories
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Abstract

The Power Systems L-CAT is a high-level dynamic model that calculates levelized production costs and tracks environmental performance for a range of electricity generation technologies: natural gas combined cycle (using either imported (LNGCC) or domestic natural gas (NGCC)), integrated gasification combined cycle (IGCC), supercritical pulverized coal (SCPC), existing pulverized coal (EXPC), nuclear, and wind. All of the fossil fuel technologies also include an option for including carbon capture and sequestration technologies (CCS). The model allows for quick sensitivity analysis on key technical and financial assumptions, such as: capital, O&M, and fuel costs; interest rates; construction time; heat rates; taxes; depreciation; and capacity factors. The fossil fuel options are based on detailed life cycle analysis reports conducted by the National Energy Technology Laboratory (NETL). For each of these technologies, NETL's detailed LCAs include consideration of five stages associated with energy production: raw material acquisition (RMA), raw material transport (RMT), energy conversion facility (ECF), product transportation and distribution (PT&D), and end user electricity consumption. The goal of the NETL studies is to compare existing and future fossil fuel technology options using a cradle-to-grave analysis. The NETL reports consider constant dollar levelized cost of delivered electricity, total plant costs, greenhouse gas emissions, criteria air pollutants, mercury (Hg) and ammonia (NH_3) emissions, water withdrawal and consumption, and land use (acreage).

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Introduction and Overview

The Power Systems L-CAT is a high-level dynamic model that calculates production costs and tracks environmental performance for a range of electricity generation technologies. This report summarizes key assumptions and results for the first generation of L-CAT. As development of L-CAT is a work in progress, results or conclusions presented in this report are likely to change or evolve as the model is reviewed and improved. This report has three goals: to explain the basic methodology used to calculate production costs and to estimate environmental performance; to provide a general overview of the model operation and initial results; and to demonstrate that the methodology used for cost estimation is consistent with the estimates made by NETL using more detailed, but less transparent, methodologies.

Model Structure and Assumptions

The Power Systems L-CAT calculates projected levelized cost of energy (LCOE)[1] for six electricity generation technologies summarized in *Table 1:* natural gas combined cycle (using either imported (LNGCC) or domestic natural gas (NGCC)), integrated gasification combined cycle (IGCC), supercritical pulverized coal (SCPC), existing pulverized coal (EXPC), nuclear, and wind. All of the fossil fuel technologies include an option for including carbon capture and sequestration technologies (CCS).

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1 Sometimes referred to as busbar or production costs.

Table 1. Technologies Included in L-CAT

Technology Acronym	**Technology**	**Source**
Natural Gas		
NGCC	Natural Gas Combined Cycle	NETL (2010a)
NGCC w/CCS	Natural Gas Combined Cycle with carbon capture & sequestration	
LNGCC	Natural Gas Combined Cycle (using imported NG)	NETL (2010b)
LNGCC w/CCS	Natural Gas Combined Cycle with carbon capture & sequestration (using imported NG)	
Coal		
ExPC	Existing Pulverized Coal	NETL (2010c)
ExPC w/CCS	Existing Pulverized Coal withcarbon capture & sequestration	
SCPC	Supercritical Pulverized Coal	NETL (2010d)
SCPC w/CCS	Supercritical Pulverized Coal with carbon capture & sequestration	
IGCC	Integrated Gasifictation Combined Cycle	NETL (2010e)
IGCC w/CCS	Integrated Gasifictation Combined Cycle with carbon capture & sequestration	
Nuclear	Nuclear	Du and Parsons (2009)
Wind	Onshore Wind	EIA (2010)

The fossil fuel options are based on detailed life cycle analysis reports conducted by the National Energy Technology Laboratory (NETL). For each of these technologies, NETL's detailed LCAs include consideration of five stages associated with energy production: raw material acquisition (RMA), raw material transport (RMT), energy conversion facility (ECF), product transportation and distribution (PT&D), and end user electricity consumption. The goal of the NETL studies is to compare existing and future fossil fuel technology options using a cradle-to-grave analysis. The NETL reports consider constant dollar levelized cost of delivered electricity, total plant costs, greenhouse gas emissions, criteria air pollutants, mercury (Hg) and ammonia (NH_3) emissions, water withdrawal and consumption, and land use (acreage).

Table 2 summarizes the key assumptions for each technology, including capital costs, fixed and variable operating and maintenance (O&M), fuel costs, years to construct, plant size, plant capacity factor (% of time plant normally operates), heat rates (with exception of existing PC plants), and thermal efficiencies. All values are for new plants and are based on sources given in *Table 1*. While L-CAT defaults to these assumptions, the user can vary the assumptions and view the implications for LCOE. For example, the user can explore the effects of increased fuel costs or decreased heat rates or delays in construction time on projected economics.

Table 2. Base Case Assumptions for L-CAT

	Capital ($/kW)	Fixed O&M ($/kW)	Variable O&M ($/kWh)	Fuel ($/mmBtu)	Years to Construct	Plant Size (MW)	Plant Capacity Factor	Heat rate (Btu/kWh)	Efficiency (%)
Natural Gas									
NGCC	718	22.06	0.0013	6.55	3	555	85%	6798	49%
NGCC w/CCS	1497	42.10	0.0026	6.55	3	474	85%	7968	42%
LNGCC	718	22.06	0.0013	6.55	3	555	85%	6798	49%
LNGCC w/CCS	1497	42.10	0.0026	6.55	3	474	85%	7968	42%
Coal									
ExPC	0	7.94	0.0009	1.64	3	434	85%	9276	36%
ExPC w/CCS	1320	19.60	0.0091	1.64	3	303	85%	13724	24%
SCPC	2024	59.33	0.0050	1.64	3	550	85%	8686	38%
SCPC w/CCS	3570	96.72	0.0087	1.64	3	550	85%	12002	28%
IGCC	2447	79.01	0.0073	1.64	3	622	80%	8756	38%
IGCC w/CCS	3334	103.88	0.0093	1.64	3	543	80%	10458	32%
Nuclear	4000	56.00	0.0004	0.67	5	1000	85%	10400	32%
Wind	1966	30.98	0.0000	0	3	50	44%	0	

Plant heat rates are the measure of the plant's efficiency. Heat rates are given in terms of British thermal units per kWh (Btu/kWh). These can be used to derive the overall efficiency of the plants by noting the energy content of a kWh is 3412 Btu/kWh. Hence, the NGCC plant in Table 2 with a heat rate of 6798 Btu/kWh has an assumed efficiency of 48.7%.

Levelized Cost of Energy (LCOE) Calculation Methodology

Production costs are esimated using a levelized cost of energy (LCOE) approach.

LCOE calculations estimate the per unit ($/kWh) cost of production over the economic lifetime of the technology. Specifically, this calculation takes the capital costs, associated financing costs, O&M, fuel costs, and any externality costs (such as CO2) and calculates a per unit production cost. The LCOE is often used as an economic measure of energy costs as it allows for comparison of technologies with different capital and operating costs, construction times, and plant load factors.

The LCOE methodology used in L-CAT is sometimes referred to as a "first year cost of energy approach", as it assumes costs are constant over time (i.e., fuel costs do not change over time). As such the L-CAT LCOE results should be viewed as costs if you built the plant today. The NETL reports use a more complex methodology for calculating LCOE, which takes into account inflation, and requires an annualized consideration of revenue and costs, which are then discounted back to the present. The first year LCOE methodology employed here is often used when comparing and contrasting various technologies for purposes of decision making or education. Investors would likely use the more detailed approach. The simplified approach taken here allows user to easily explore the key sensitivities in a more transparent fashion. We demonstrate in the discussion section that the two methods provide comparable first year LCOE costs.

The LCOE calculation is given by:

$$LCOE = \frac{I * FCR}{Q} + \frac{O \& M}{Q} + \frac{E}{Q} \quad (1)$$

where: I = Total financed capital costs

FCR = Fixed charge rate

Q = Annual plant output (i.e, gallons/yr)

O&M = Fixed and variable operating and maintenance costs

E = Externality costs, such as CO_2, , SO_2, and NO_x.

The methodology for calculating the capital cost component is consistent across all technologies in L-CAT. Financing costs assume that capital expenditures are uniformly distributed over the time of construction, and allow the user to include a separate read interest rate during the construction period. As the NETL reports do not include consideration of interest during construction, the default interest rate is set to 0.0% in L-CAT.[2]

Once operational, annual capital costs are determined by multiplying the total capital cost, including finance costs, by a fixed charge rate (FCR), which represents the percentage of capital costs that must be recovered each year:

$$FCR = \frac{CRF[1 - bT\sum_{n=1}^{M} V_n / (1 + d_{WACC})^n - t_c]}{(1 - T)} + p_1 + p_2 \quad (2)$$

where: CRF = capital recovery factor

b = fraction of investment that can be depreciated (initially is 100%)

T = effective tax rate (default 37.6% (federal, 34%; state, 6%))

M = Depreciation period (5 to 20 years)

V_n = fraction of depreciable base in year n

r_{WACC} = real weighted average cost of capital

t_c = tax credit (initially zero)

p_1 = annual insurance cost (initially zero)

p_2 = other taxes (initially zero)

---

[2] All interest and discount rates in L-CAT are expressed in real dollar terms, meaning they are adjusted for inflation. The alternative, not used here, is to use nominal rates in combination with an assumed inflation rate.

The fixed charge rate (FCR) typically ranges from 0.11 and 0.17 and represents the percentage of capital costs that must be recovered each year in order to cover all investment costs, including return on debt and equity. For example, for a $1 million capital investment and a FCR of 0.15, the annual capital requirement for that investment is $150,000.

The real discount rate is based on a weighted average cost of capital (WACC) approach that takes into account the portions of the total cost that is debt (borrowed commercially) or equity (investor) financed. The WACC calculation is given by:

$$WACC = \frac{E}{V} * r_e + \frac{D}{V} * r_d * (1 - T) \quad (3)$$

where: E/V = percent of total project equity financed

r_e = equity financing rate

D/V = percent of total project debt financed

r_d = debt financing rate (pre-tax)

T = effective tax rate

Assumptions about the debt/equity financing split are technology specific. For example, the NGCC option assumes a 50%/50% debt/equity financing, with a debt financing rate of 4.5% and equity financing rate of 12.0%. Based on these values, the default WACC is 7.4%,

The capital recovery factor (CRF) is calculated using:

$$CRF = r_{WACC} * \frac{(1 + r_{WACC})^n}{(1 + r_{WACC})^n - 1} \quad (4)$$

r_{WACC} = real weighted average cost of capital

n = economic plant life (initially 20 years).

Depreciation follows a Modified Accelerated Cost Recovery System (MACRS) methodology. MACRS is an accelerated depreciation method utilized in the U.S. and allows for faster depreciation of capital investments than allowed by straight-line methodologies. Accelerated depreciation methods allow firms to take tax-deductible depreciation expenses earlier in the life of a capital expenditure, giving them an upfront tax advantage for new investments. In the U.S., most utility type investments use either a 15- or 20- year depreciation schedule. Certain investments, such as renewables, are allowed to use a five-year depreciation schedule. Quicker depreciation schedules effectively lower the annual capital requirements for these investments (the CRF (equation 4) is lowered as number of years allowed for depreciation drops).

Environmental Performance

L-CAT tracks the cradle-to-grave emissions of key greenhouse gases, several non-GHG gas pollutants, water withdrawals and consumption for those technologies in Table 1 taken from NETL sources. This level of detail may be added to future versions of L-CAT for the non-NETL specific technologies (nuclear and wind). The greenhouse gases include: carbon dioxide (CO_2), nitrous oxide (N_20), methane (CH_4), and sulfur hexafluoride (SF_6). Each of these gases are multiplied by their global warming potential (GWP) using the 2007 Intergovernmental Panel on Climate Change (IPCC) GWP weights to obtain the total global warming effect in terms of carbon dioxide equivalents (CO_2e) per kWh[3]. Non-greenhouse gases include: lead (Pb), mercury (Hg), ammonia (NH3), oxides of nitrogen (NOx), sulfur oxide (SOx), volatile organic compounds (VOC), and particulate matter (PM). The specific coefficients for each of these pollutants come from the detailed NETL reports.

[3] L-CAT provides users with the option of using the 2001 IPCC GWPs rather than the 2007 values.

Using L-CAT

The overall goal of the Power Systems L-CAT is to provide a high-level tool that allows one to explore the economic and environmental tradeoffs associated with various electricity production options. The opening screen (home page) is shown in *Figure 1*. First time users may want to review the model's assumptions and basic model navigation by clicking on the hyperlinks at the bottom of the screen ("Terms", "Assumptions", "Sources", and "Legend.")

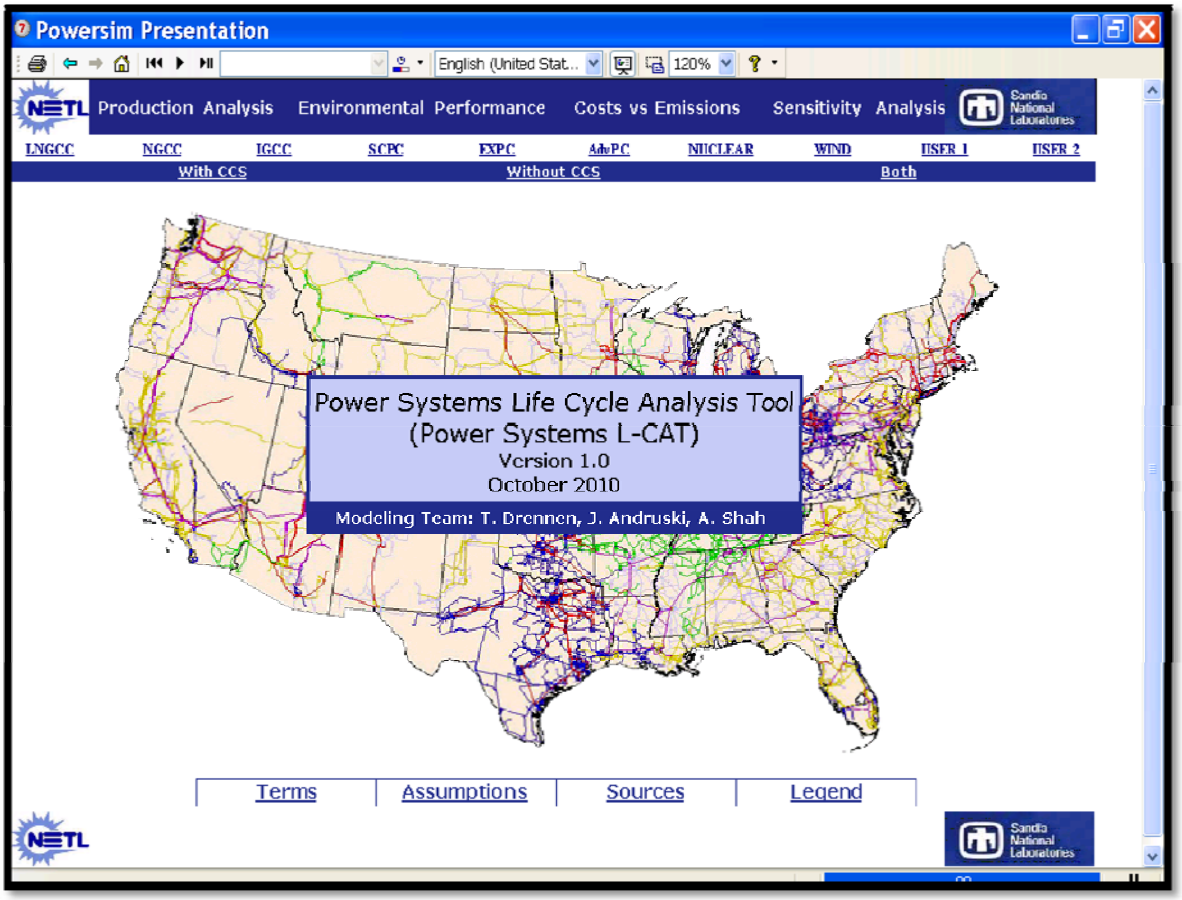


Figure 1. Power Systems L-CAT Home Screen

The L-CAT tool has four main sections, labeled as: "Production Analysis", "Environmental Performance", "Costs vs. Emissions", and "Sensitivity Analysis." The production analysis section is for calculating the LCOE ($/kWh) for each option and for exploring key sensitivities. The environmental performance section estimates both greenhouse and non-greenhouse gas emissions, as well as water useage, at each stage of the life cycle analysis. The "Costs vs. Emissions" section explores the tradeoffs between costs ($/kWh) and greenhouse gas emissions (kg CO_2e/MWh). The "Sensitivity Analysis" section allows one to vary several assumptions simultaneously (capital costs, O&M costs, tax rates, capacity factors, and fuel prices) and view the results graphically as a function of capacity factor.

Figure 1 shows a representative L-CAT main production cost screen (NGCC). Hyperlinks along the top allow the user to change screens. The sliders and text boxes on the bottom of the screen allow the user to change basic assumptions at any time during the model run. The bar graphs illustrate the production costs ($/kWh) for six of the technlogies. The user can select different technologies or change the order in which the results are displayed by using the pull down menus below each column. The same results are available in tabular or percentage terms by clicking the relevant hyperlink on the top left of the column display. Further assumptions about the financing assumptions are available by clicking the "finance" hyperlink in the middle of the screen. This main production screen also includes switches for including switchyard and trunkline costs, decommissioning costs, and CO_2 taxes. The L-CAT graphs and tables are color coded for ease in viewing results; the colors in the graphical output correspond to the color keys given in each slider (such as capital) or data box (such as CO_2 tax). The results, for the default assumptions, show that existing PC plants can produce power for 1.7 cents/kWh. The next cheapest options are supercritical PC plants (5.66 cents/kWh) and then the NGCC plants (5.92 cents/kWh). IGCC (7.39 cents/kWh) and nuclear (8.58 cents/kWh) are more expensive options using the base case assumptions. For nuclear, capital costs are the most important determinant of the LCOE costs (dark blue), whereas for NGCC plants, the fuel cost (lighter blue) is the main component.

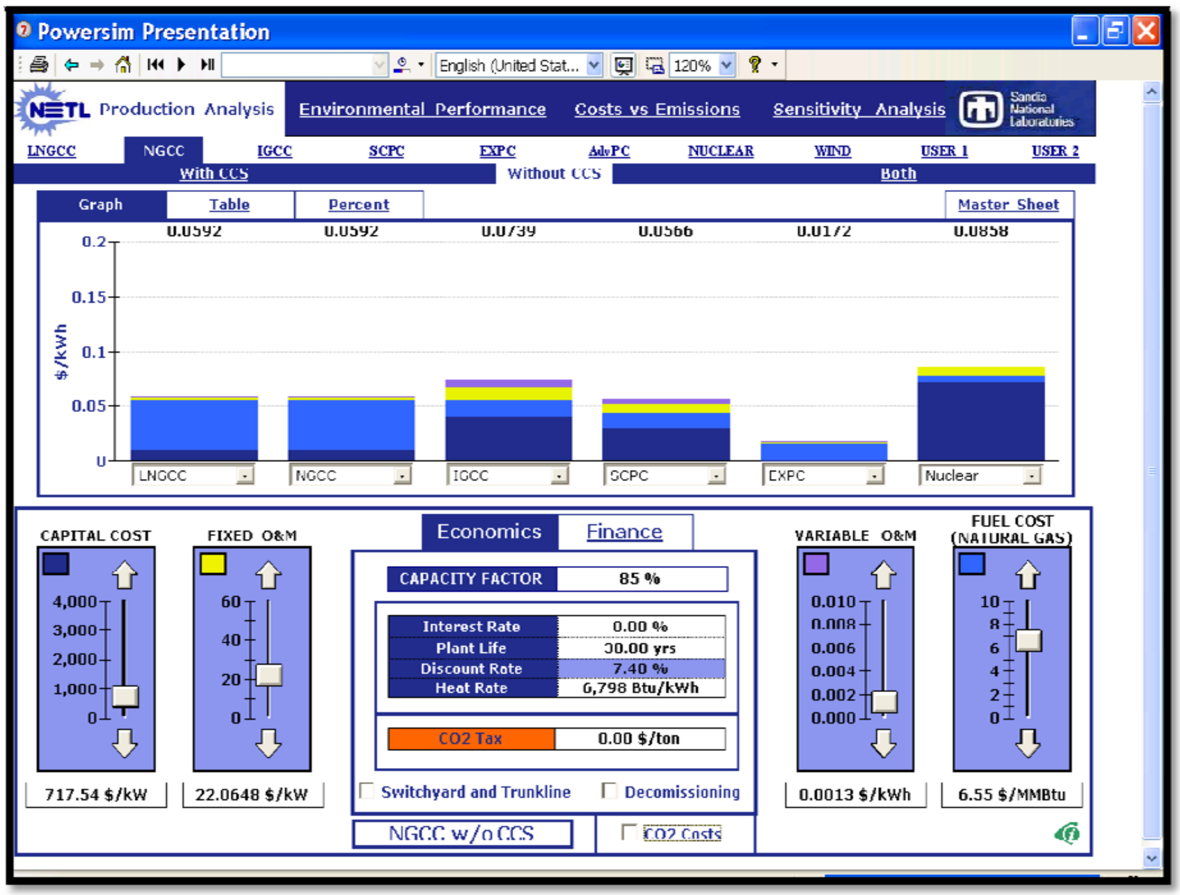


Figure 2. Representative Production Analysis Screen (NGCC w/o CCS)

Users also have the option of using a “master sheet” option to view and change several key assumptions (“Master Sheet” hyperlink on top right of graphical results.) The master sheet is illustrated in *Figure 3*. The LCOE costs are shown in the last column. This screen is useful when making changes to several technologies simultaneously.

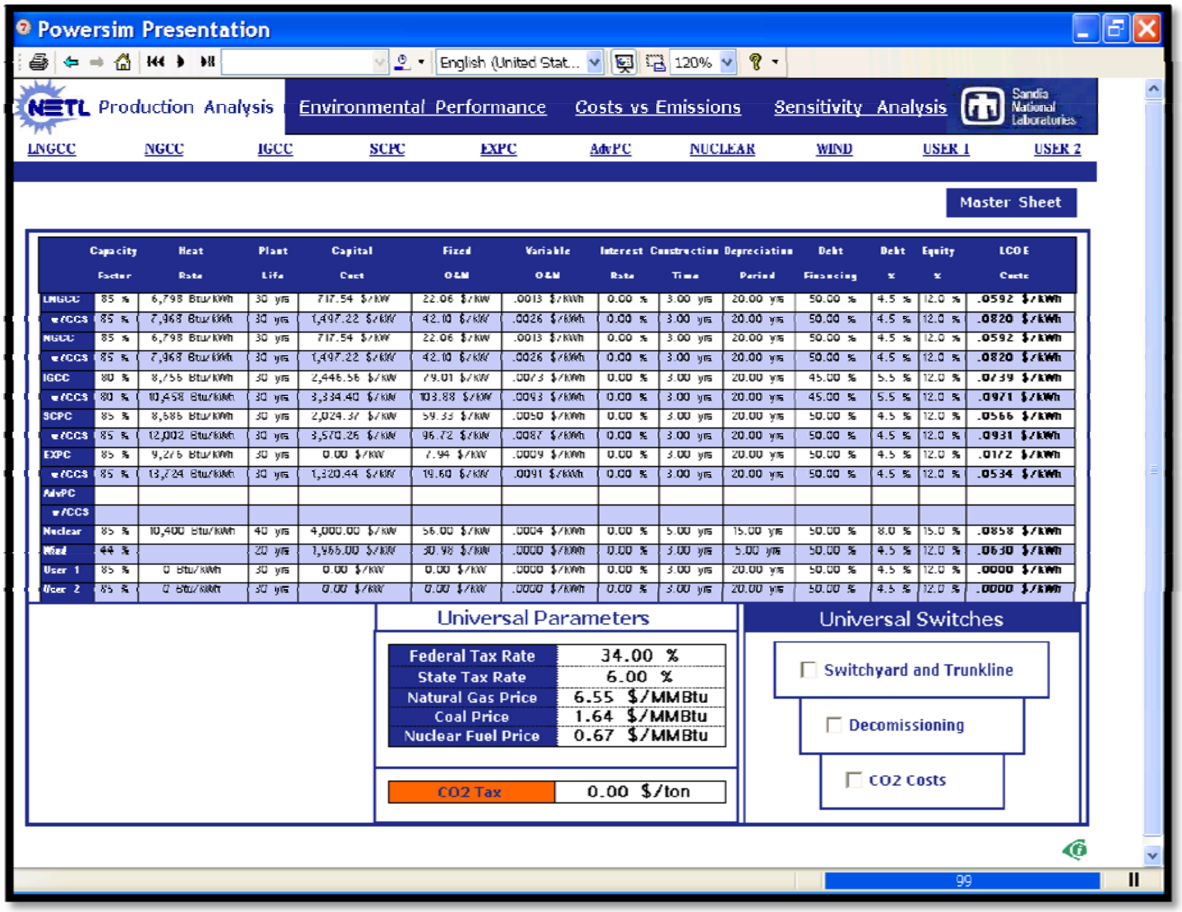


Figure 3. The Master Sheet Option, Used for Changing Assumptions to Multiple Technologies

For the technologies that include a carbon capture and sequestration option (CCS), clicking on the “Both” hyperlink limits the results to the technology specific results with and without CCS, *Figure 4*. For the case of NGCC, adding CCS adds an additional 2.3 cents/kWh.

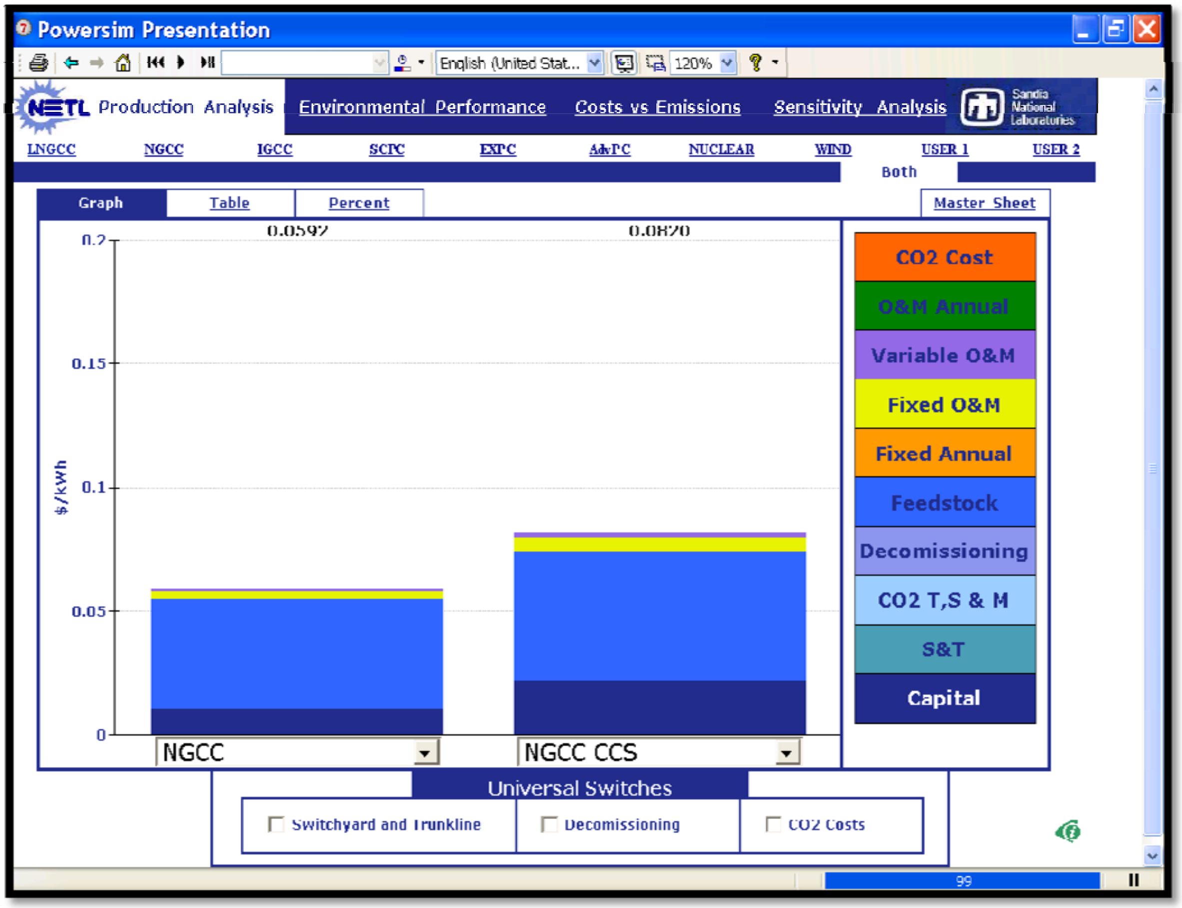


Figure 4. Direct Comparison of Ttechnologies with and without CCS

Environmental Performance

Figure 5 shows the main screen under "Environmental Performance" (the second main section of L-CAT) for the NGCC without CCS case. Clicking on either of the smaller two graphs on the right ("Water Use" or "Non-GHG Emissions") makes that graph replace the "Greenhouse Gas Emissions" graph. Each of these analysis considers emissions (or water use) at each stage: raw material acquisition (RMA), raw material transport (RMT), energy conversion facility (ECF), product tranpsortation and distribution (PT&D), and end use. For the NGCC case without CCS, total life cycle greenhouse gas emissions are 466.64 kg CO2/MWh, the vast majority of which (84%) occur during electricity production, the ECF phase.

Figure 5. Greenhouse Gas Emissions at Each Stage for NGCC without CCS Case

Figure 6 shows the other pollutants released for the NGCC without CCS case. In contrast with the GHG, the majority of these pollutants are released during the earlier stages (RMA and RMT). Viewing these results in tabular form (*Figure 7on the following page*) allows for easier differentiation of the pollutants than is possible with the graphical view. All results can be viewed either in terms of kg/MWh or total kg for that specified plant size.

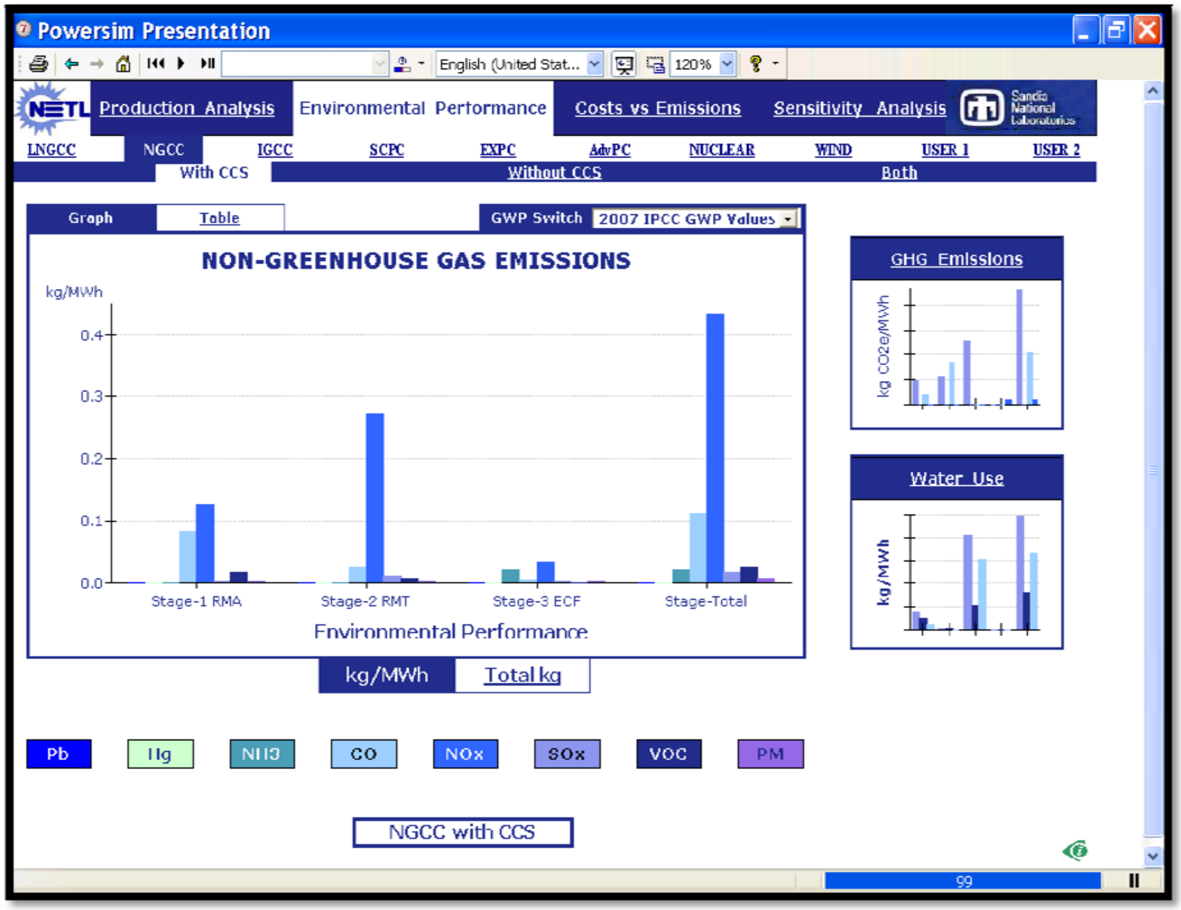
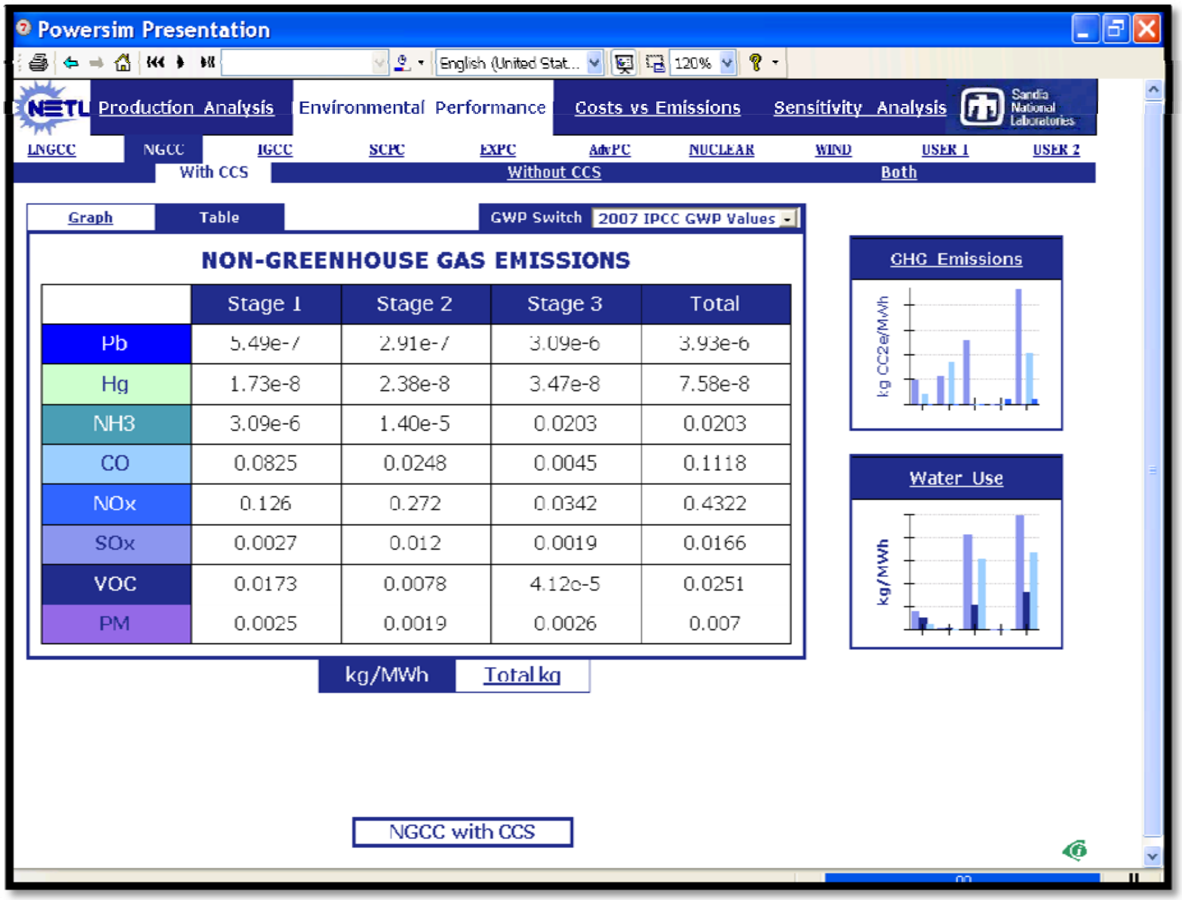


Figure 6. Non-greenhouse Gas Pollutants for the NGCC without CCS Case



	Stage 1	Stage 2	Stage 3	Total
Pb	5.49e-7	2.91e-7	3.09e-6	3.93e-6
Hg	1.73e-8	2.38e-8	3.47e-8	7.58e-8
NH3	3.09e-6	1.40e-5	0.0203	0.0203
CO	0.0825	0.0248	0.0045	0.1118
NOx	0.126	0.272	0.0342	0.4322
SOx	0.0027	0.012	0.0019	0.0166
VOC	0.0173	0.0078	4.12e-5	0.0251
PM	0.0025	0.0019	0.0026	0.007

Figure 7. Tabular Represenation of Non-greenhouse Gas Emissions for NGCC without CCS Case

L-CAT tracks the water withdrawals and ultimate water consumption at each stage. *Figure 8* shows the estimated water withdrawals and use for the case of the supercritical coal plant without CCS. For the SCPC without CCS case, the majority of the water withdrawal and use occurs during the electricity production stage (ECF stage). Specifically, 2514 kg of water are required per MWh. Approximately half of that is eventually returned to the system, for a net consumption of 1291 kg/MWh.

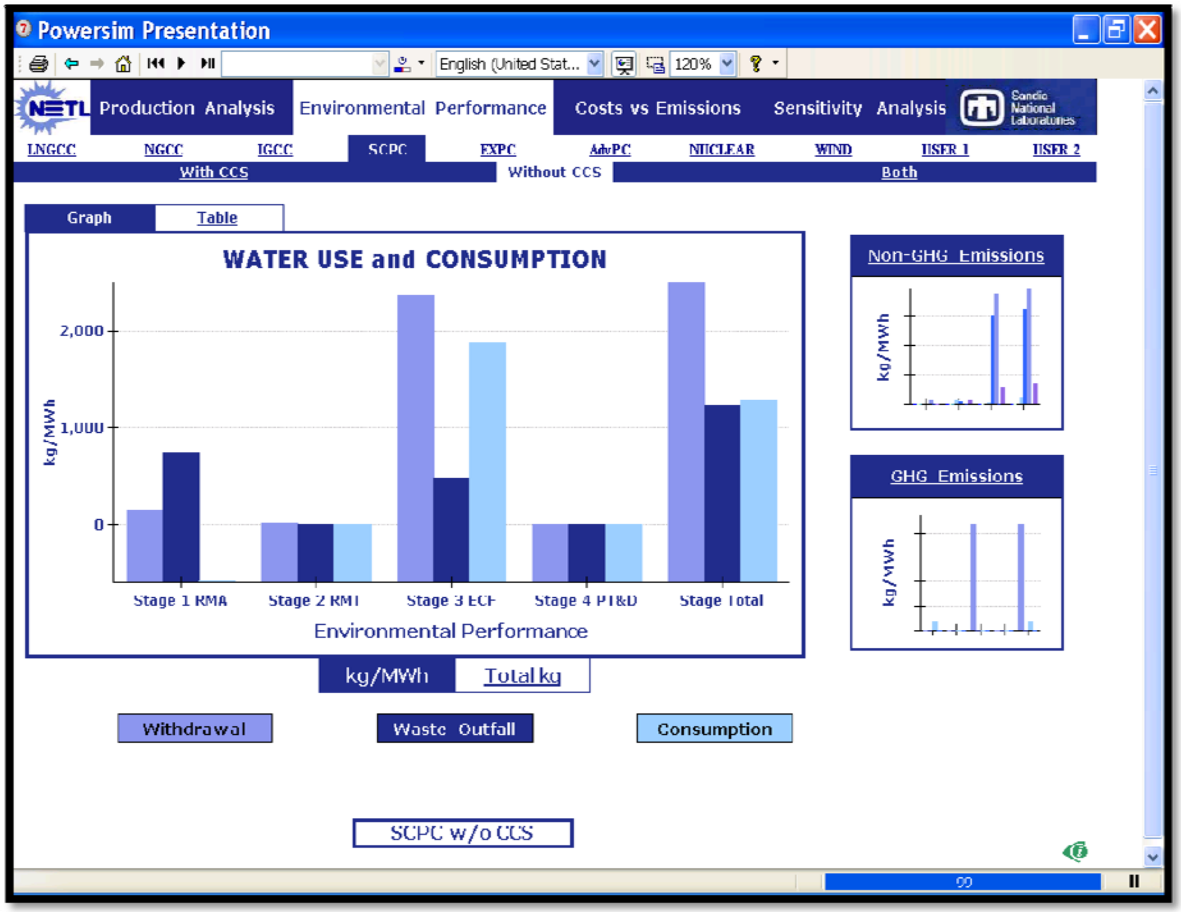


Figure 8. Estimated Water Withdrawals and Consumption for SCPC without CCS Case

Costs vs. Emissions

The "Costs vs. Emissions" section (the third of the major sections in L-CAT) explores the tradeoffs between costs ($/kWh) and greenhouse gas emissions (kg CO2e/MWh), *Figure 9*. At present, the results shown in this section are only dynamic for the cost estimates. The emission estimates are static, meaning the estimated emissions in terms of kg CO2e/MWh is constant for all capacity factors. In reality, a plant operating at lower capacity factors or one that is cycled more rapidly (ramped up and down to meet peak demand, for example) may have higher average emmissions per MWh. The results show that existing pulverized coal plants are low cost, but very high in emissions. Adding CCS to existing PC plants lowers the emissions (from 1109 to 444 CO2e/MWh), but increases the costs significantly (4.7 cents/kWh) to a level higher than those for a new NGCC plant without sequestration with comparable emissions (466 kg CO2e/MWh). Those options with lower emission profiles all include CCS. The lowest emission rate (137 kgCO2/MWh) is for the NGCC with CCS option.

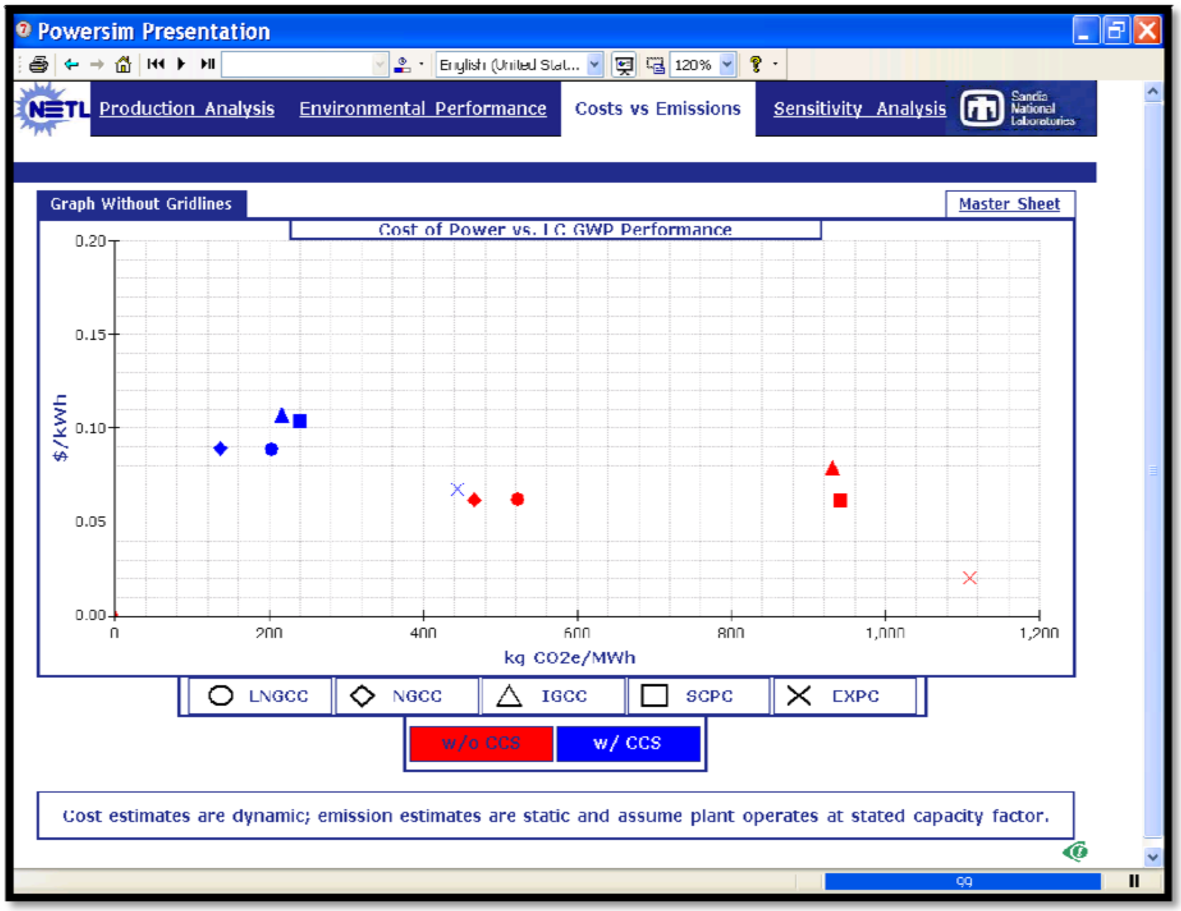


Figure 9. "Cost vs Emissions" Section

The “Cost vs. Emission” section can also provide valuable insights about how carbon taxes can change the relative competiveness of the various options. *Figure 10* illustrates the effect of a 65 $/ton CO2 tax, the tax level at which NGCC with CCS becomes cost competitive with NGCC without CCS. Note at this tax level, options such as SCPC and IGCC (both without CCS) are signficantly more expensive than the options such as NGCC with CCS.

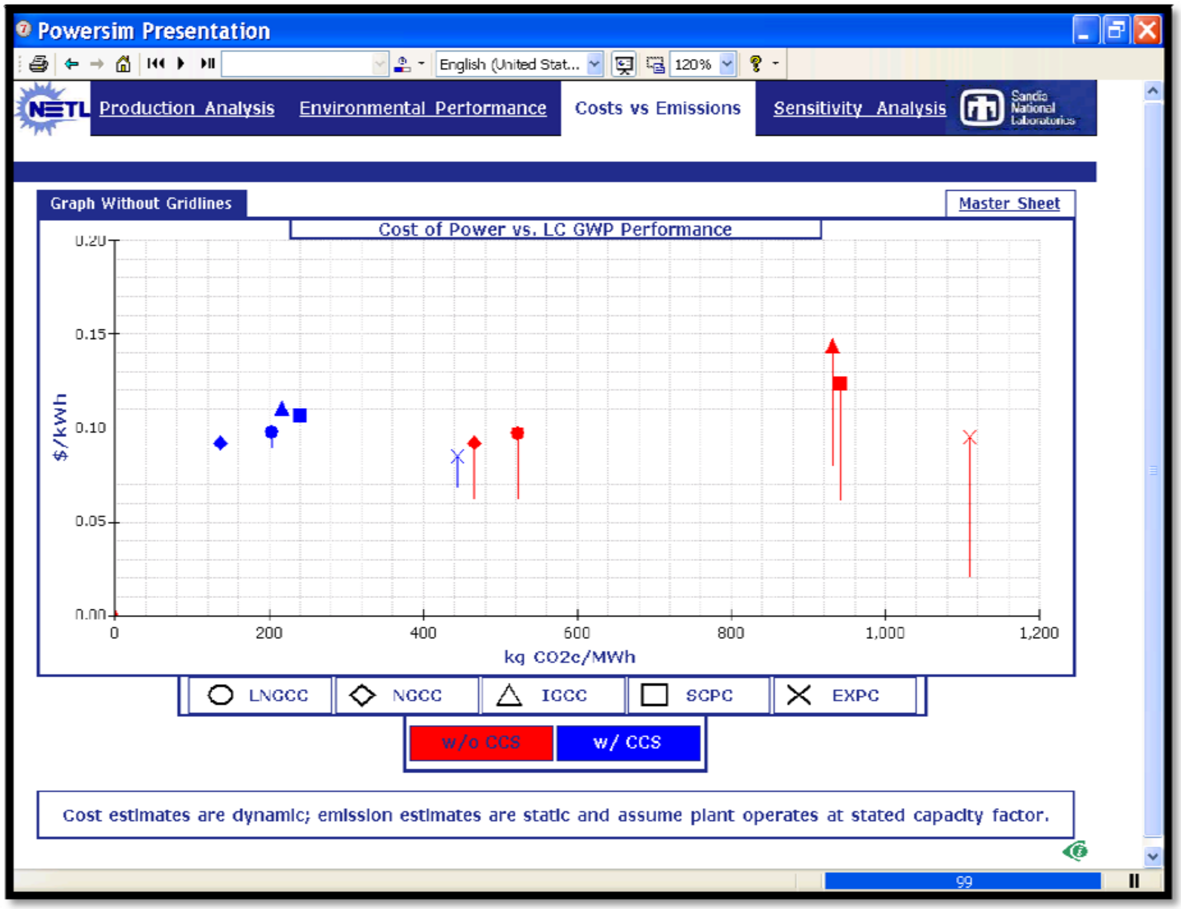


Figure 10. Using the “Cost vs. Emission” Screen to Demonstrate Effect of a \$65/ton CO_2 Tax

Sensitivity Analysis

The "Sensitivity Analysis" section (the fourth of the major sections in L-CAT) allows one to vary several assumptions simultaneously (capital costs, O&M costs, tax rates, capacity factors, and fuel prices) and view the results graphically as a function of capacity factor. *Figure 11* shows an example for nuclear. In this example, the sensitivity of the LCOE costs to assumptions about capital costs are shown. The base case assumes capital costs of 4000 $/kW which results in estimated production costs of 0.0858 $/kWh. This example shows that if capital costs are either 30% higher or lower, the production costs capital increase/decrease by 24.79%, production costs would range from 0.1071 to 0.0645 $/kWh. The range is more pronounced at lower capacity factors.

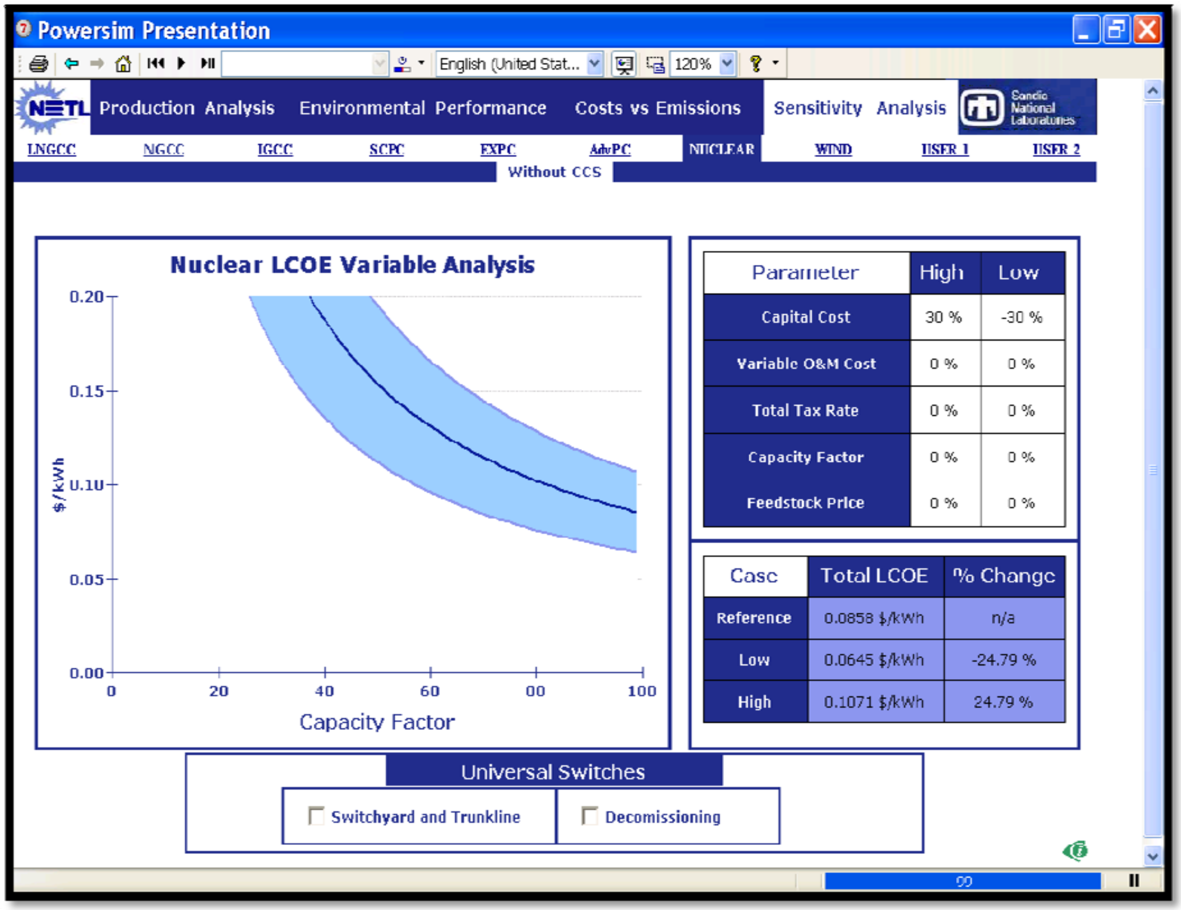


Figure 11. Illustrative Example Using "Sensitivity Analysis" Section for Nuclear

Comparison to NETL Results

The previous section illustrated results using the default assumptions in L-CAT. To compare the overall results with the NETL results, it was necessary to make minor adjustments to some of the financial assumptions. Specifically, it is necessary to change the percentage for debt financing for the CCS cases to 45% instead of 50% and the assumed rate for debt financing from 4.5% to 5.5%. NETL assumes these CCS cases are higher risk and therefore carry a higher cost of financing.

Table 3 summarizes the L-CAT results using the same financing assumptions as NETL, as summarized in their forthcoming Bituminous Baseline report (NEED APPROVAL FROM NETL BEFORE CAN CITE).

Table 3. Summary of L-CAT Results for With and Without $50 per ton CO_2 Tax

Technology	Base Case LCOE ($/kWh)	LCOE with $50 per ton CO_2e tax ($/kWh)
Natural Gas		
NGCC	0.0592	0.0883
NGCC w/CCS	0.0839	0.0894
LNGCC	0.0592	0.0883
LNGCC w/CCS	0.0839	0.0894
Coal		
ExPC	0.0172	0.0772
ExPC w/CCS	0.0551	0.0756
SCPC	0.0566	0.1078
SCPC w/CCS	0.0976	0.1059
IGCC	0.0739	0.1275
IGCC w/CCS	0.0971	0.1052
Nuclear	0.0858	0.0858
Wind	0.0630	0.0630

The NETL studies use a more detailed financial method for calculating levelized production costs. The NETL methodology uses a cash-flow methodology that projects future annual revenue requirements necessary to cover all expenses including returns on investment. These revenue requirement streams are then used to calculate the levelized annual costs of electricity production. The NETL methodology also includes consideration of future inflation rates, whereas L-CAT uses a real dollar approach (adjusted for inflation). While the NETL methodology is used by financial investors, it can be less transparent for non-financial types, including most policy makers. The reason for the lack of transparency in the NETL methodology is that it is an iterative process and key variables cannot be changed as easily as is possible with L-CAT. Specifically, the L-CAT methodology allows for the recalculation of the fixed charge rate (FCR), Equation 2, after changes to assumptions about financing and taxes, and te NETL methodology does not. While ideally, the L-CAT results would equal the NETL results, for this project, it was decided that there was added value in an approach that allowed for such changes, as long as the final results were reasonably close, or within 5%. This section demonstrates that this goal has been met.

Tables 4 – 6 compare the assumptions and results for the NETL technologies included in L-CAT: NGCC with and without CCS (*Table 4*), IGCC with and without CCS (*Table 5*), and SCPC with and without CCS (*Table 6*). The NETL assumptions and results are from the Bituminous Baseline Report (Need NETL approval for cite).

Table 4. Comparison of NETL Bituminous Baseline and Power Systems L-CAT for NGCC

	NGCC w/o CCS	L-CAT Calc	Difference	NGCC w/ CCS	L-CAT Calc	Difference
Capital Expenditure Period	3.00	3.00	0.00%	3.00	3.00	0.00%
COE Levelization Period	33.00	30.00		33.00	30.00	
ATWCC	0.07	0.07	0.14%	0.08	0.08	0.07%
Heat Rate (Btu/kWh)	6798.00	6798.00	0.00%	7968.00	7968.00	0.00%
Net MW	555.08	555.08	0.00%	473.57	473.57	0.00%
Capacity Factor	0.85	0.85	0.00%	0.85	0.85	0.00%
TOC ($/kW)	717.54	717.54	0.00%	1497.22	1497.22	0.00%
Current-Dollar 30-Year FYCOE						
Capital, $/MWh	10.10	10.35	2.46%	22.33	23.55	5.44%
Fixed O&M, $/MWh	2.96	2.96	0.00%	5.65	5.65	0.00%
Non-fuel Var. O&M, $/MWh	1.32	1.32	0.00%	2.56	2.56	0.00%
Fuel O&M (variable), $/MWh	44.51	44.51	0.00%	52.17	52.17	0.00%
CO2 Tax Cost, $/MWh	0.00	0.00	0.00%	0.00	0.00	0.00%
CO2 TSM, $/MWh	0.00	0.00	0.00%	0.00	0.00	0.00%
Total Current-Dollar 30-Year FYCOE, $/MWh	58.89	59.17	0.47%	82.72	83.93	1.47%

For the NGCC cases (*Table 4*), the NETL and L-CAT results are very similar. NETL's estimate for first year LCOE for the NGCC withou CCS case is 5.89 cents/kWh, compared to 5.92 cents/kWh using L-CAT, a 0.47% difference. L-CAT appears to overestimate the capital cost component compared to NETL (2.46% higher). However, L-CAT is not consistently higher on capital costs. In the IGCC case (Table 6), L-CAT underestimate capital costs relative to NETL (5.75%). However, the first year LCOE cost estimates are within 5%; NETL is at 7.63 cents/kWh compared to 7.39 cents/kWh for L-CAT (3.18% difference).

Table 5. Comparison of NETL Bituminous Baseline and Power Systems L-CAT for IGCC

	GE IGCC w/o CCS	L-CAT Calc	Difference	GE IGCC w/ CCS	L-CAT Calc	Difference
Capital Expenditure Period	5.00	5.00	**0.00%**	5.00	5.00	**0.00%**
COE Levelization Period	35.00	30.00		35.00	30.00	
ATWCC	0.08	0.08	**0.07%**	0.08	0.08	**0.07%**
Heat Rate (Btu/kWh)	8756.00	8756.00	**0.00%**	10458.00	10458.00	**0.00%**
Net MW	622.05	622.05	**0.00%**	543.25	543.25	**0.00%**
Capacity Factor	0.80	0.80	**0.00%**	0.80	0.80	**0.00%**
TOC ($/kW)	2446.56	2446.56	**0.00%**	3334.40	3334.40	**0.00%**
Current-Dollar 30-Year FYCOE						
Capital, $/MWh	43.38	40.88	**-5.75%**	59.12	55.72	**-5.75%**
Fixed O&M, $/MWh	11.27	11.27	**0.00%**	14.82	14.82	**0.00%**
Non-fuel Var. O&M, $/MWh	7.30	7.30	**0.00%**	9.33	9.33	**0.00%**
Fuel O&M (variable), $/MWh	14.33	14.40	**0.50%**	17.12	17.20	**0.48%**
CO2 Tax Cost, $/MWh	0.00	0.00	**0.00%**	0.00	0.00	**0.00%**
CO2 TSM, $/MWh	0.00	0.00	**0.00%**	0.00	0.00	**0.00%**
Total Current-Dollar 30-Year FYCOE, $/MWh	76.28	73.86	**-3.18%**	100.39	97.07	**-3.31%**

Table 6. Comparison of NETL Bituminous Baseline and Power Systems L-CAT for SCPC

	PC Super w/o CCS	L-CAT Calc	Difference	PC Super w/ CCS	L-CAT Calc	Difference
Capital Expenditure Period	5.00	5.00	**0.00%**	5.00	5.00	**0.00%**
COE Levelization Period	35.00	30.00		35.00	30.00	
ATWCC	0.07	0.07	**0.14%**	0.08	0.08	**0.07%**
Heat Rate (Btu/kWh)	8686.00	8686.00	**0.00%**	12002.00	12002.00	**0.00%**
Net MW	550.02	550.02	**0.00%**	550.00	550.00	**0.00%**
Capacity Factor	0.85	0.85	**0.00%**	0.85	0.85	**0.00%**
TOC ($/kW)	2024.37	2024.37	**0.00%**	3570.26	3570.26	**0.00%**
Current-Dollar 30-Year FYCOE						
Capital, $/MWh	31.68	29.29	**-7.55%**	59.58	56.15	**-5.75%**
Fixed O&M, $/MWh	7.97	7.97	**0.00%**	12.99	12.99	**0.00%**
Non-fuel Var. O&M, $/MWh	5.04	5.04	**0.00%**	8.72	8.72	**0.00%**
Fuel O&M (variable), $/MWh	14.22	14.27	**0.40%**	19.64	19.70	**0.29%**
CO2 Tax Cost, $/MWh	0.00	0.00	**0.00%**	0.00	0.00	**0.00%**
CO2 TSM, $/MWh	0.00	0.00	**0.00%**	0.00	0.00	**0.00%**
Total Current-Dollar 30-Year FYCOE, $/MWh	58.90	56.57	**-3.96%**	100.94	97.57	**-3.34%**

Sensitivity Analysis in L-CAT

L-CAT's structure makes several types of sensitivity analysis straightforward. First, the production analysis screens allow for quick changes to key technical, economic, and financial assumptions. The screens are color-coded so it is easy to see the relative importance of capital, O&M, and fuel costs. For example, nuclear is is clearly more capital intensive than a NGCC plant and so a 10% change in capital costs for both nuclear and natural gas will result in a bigger change in the projected LCOE for the nuclear option.

The production analysis screens are also ideal for answering "what-if?" type questions. For example, using the default assumptions, the IGCC technology is about 1.8 cents/kWh more than the NGCC option. A typical type of "what-if" type question might be: at what real natural gas price over the life of the plant does the IGCC option become cheaper? By using the sliders on fuel prices, one can find that the breakeven natural gas price is 9.11 $/MMBtu; above that price, the IGCC plant produces cheaper power, all else constant, *Figure 12*.

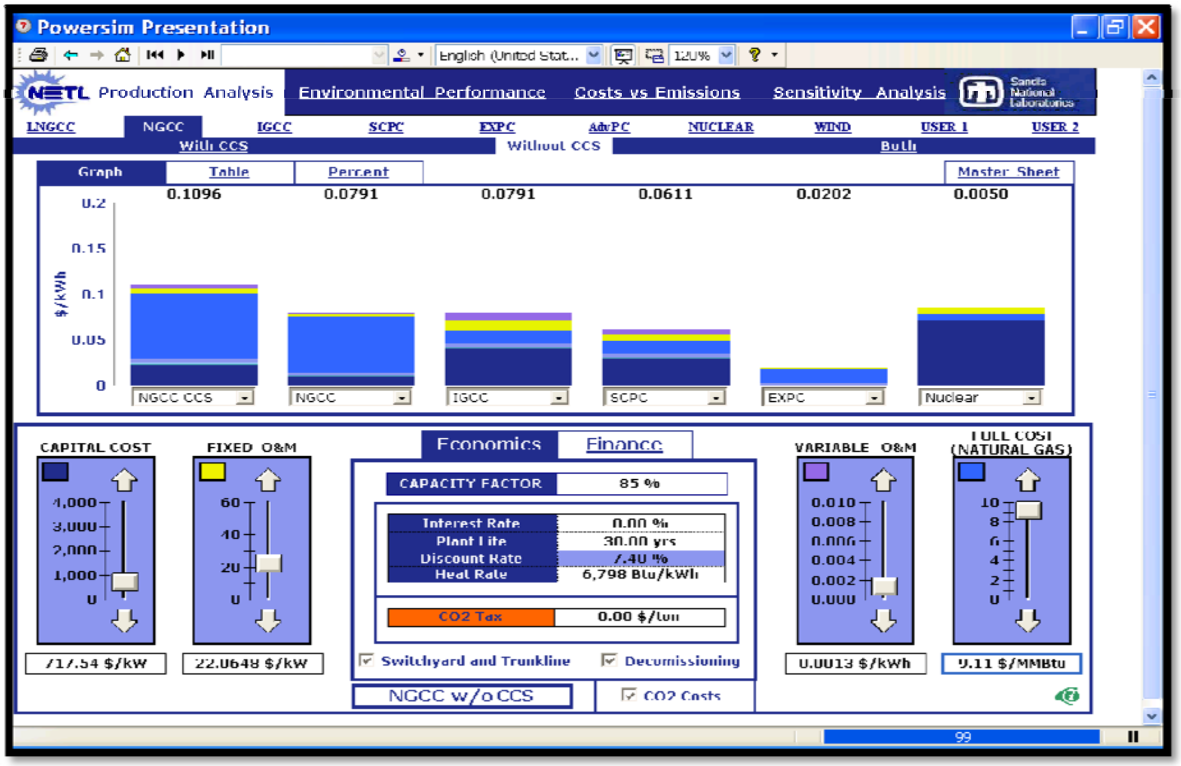


Figure 12. Using Production Analysis Screen to Find Natural Gas Price that Makes IGCC Competitive with NGCC Price

The following three sections provide a more detailed sensitivity analyses, derived from L-CAT. In the first section, production costs for various technologies are plotted against specific fuel prices. This type of analysis is useful for determining fuel price breakeven costs, such as the coal price at which nuclear is cost competitive. The next section determines capital cost breakeven points, such as at what capital costs nuclear becomes competitive with coal, gas, or wind.

Fuel Price Sensitivity Results

Figure 13 illustrates the sensitivity of the results to natural gas prices. For example, for nuclear to be cost competitive with NGCC, natural gas prices would have to be above 10.50 $/MMBtu (the reference natural gas price is 6.55 $/MMBtu). The NGCC option is not competitive with the existing PC plants, as the capital costs are already paid off. IGCC with CCS would only be competitive with NGCC for natural gas prices above 12.15 $/MMBtu. Adding CCS to the NGCC option increases the projected electricity costs. For the default assumptions, NGCC with CCS costs an additional 2.48 cents/kWh over NGCC without CCS. For the case of NGCC with CCS, nuclear would become competitive for natural gas prices above 6.80 $/MMBtu.

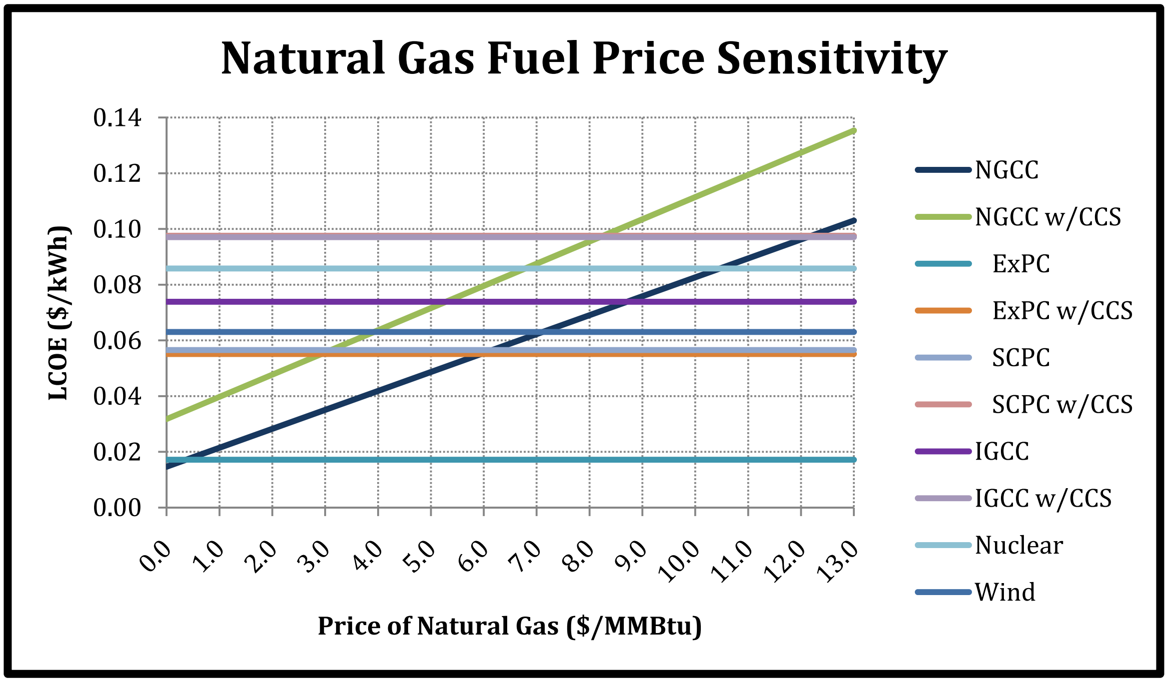


Figure 13. Natural Gas Fuel Price Sensitivity Analysis

Figure 14 illustrates a similar analysis for coal prices. The base case assumes a coal price of 1.64 $/MMBtu. This analysis shows that for a supercritical coal plant the breakeven coal prices for nuclear, wind, and NGCC technologies are 5.00 $/MMBtu, 2.38 $/MMBtu, and 1.94 $/MMBtu, respectively. As with the previous example, these results indicate that coal's competitiveness is very dependent on assumed fuel prices. Adding CCS to the supercritical PC significantly increases the costs per kWh (4.1cents/kWh for the base case), but therefore lowers the coal price at which nuclear or other options can compete. For nuclear, the breakeven coal price for SCPC with CCS is 0.66 $/MMBtu.

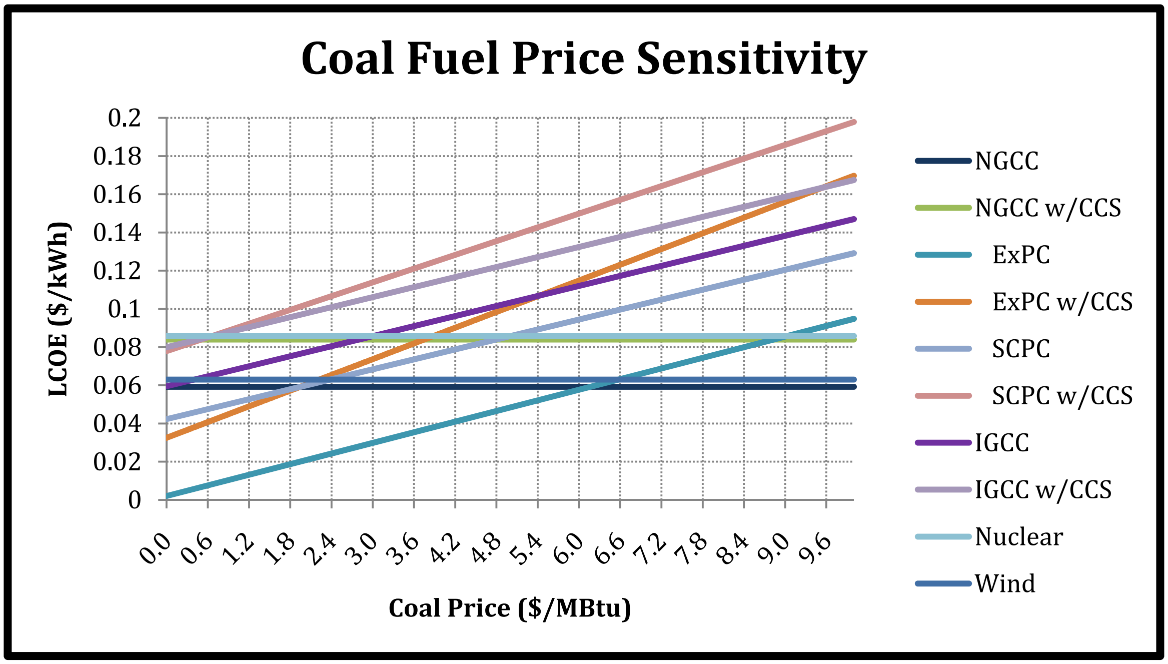


Figure 14. Coal Fuel Price Sensitivity Analysis

Capital Costs Sensitivity Analysis

Figures 15 through 17 illustrate breakeven points based on varying capital costs.

Figure 15 shows the results for natural gas combined cycle plants. The default capital cost for NGCC without CCS is 717.54 $/kWh. Holding all else constant, the capital cost at which IGCC, nuclear, and wind become cost competitive are 1725, 2550, and 975 $/kW, respectively.

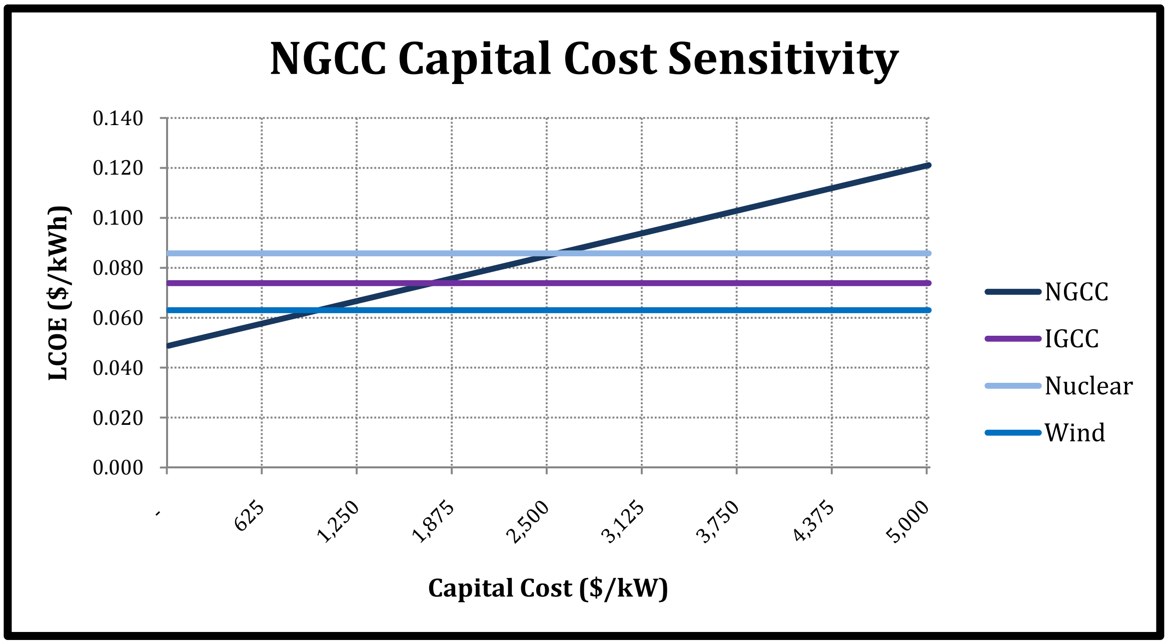


Figure 15. Gas Combined Cycle Capital Cost Sensitivity

The base case assumes IGCC facilities have a capital cost of 2446 $/kW. As *Figure 16* shows, those costs would have to be reduced to below 1570 $/kW to compete with NGCC at assumed fuel prices. Alternatively, IGCC is cost competitive with nuclear for capital costs below 3160 $/kW.

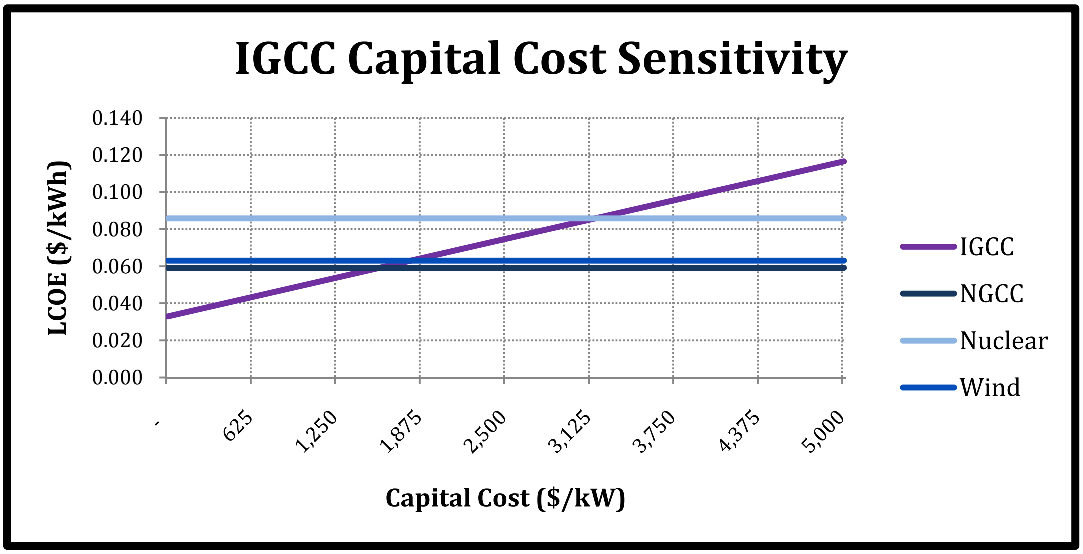


Figure 16. IGCC Capital Cost Sensitivity

The base case assumes a capital cost for nuclear of 4000 $/kW. At that capital cost, nuclear is not cost competitive with NGCC, IGCC, or wind. As *Figure 17* shows, nuclear becomes cost competive with NGCC, IGCC, and wind at capital costs of 2500, 3330, and 2715 $/kW, respectively.

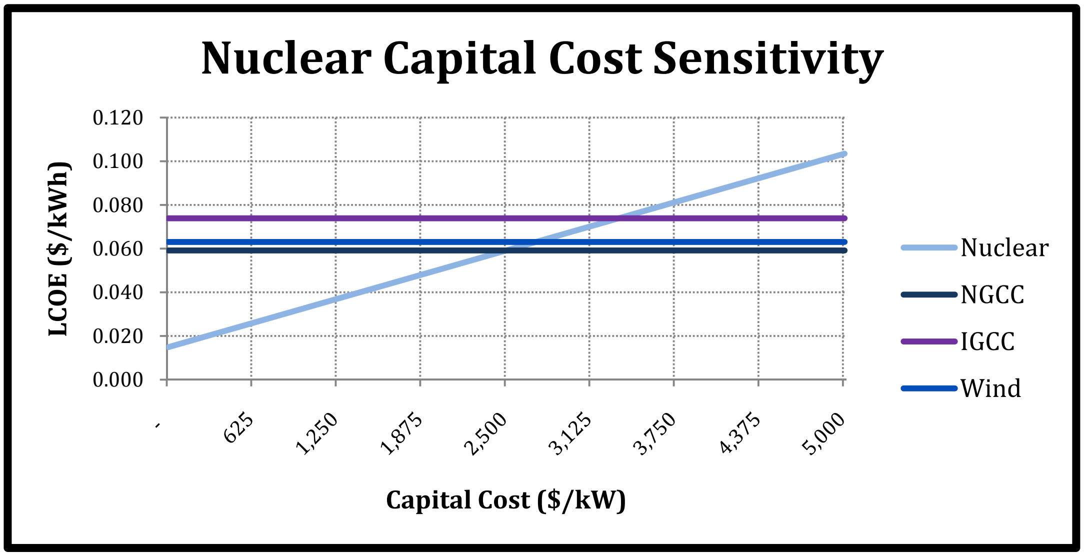


Figure 17. Nuclear Capital Cost Sensitivity Analysis

Capacity Factor Sensitivity

L-CAT can also be used to test the sensitivity of assumptions about available capacity factor. For example, the default assumptions for wind assume an average capacity of 44%, which is used by the DOE in their *Annual Energy Outlook 2010*. At this capacity factor, wind production costs are 6.3 cents/kWh. However, this capacity factor is at the upper end of what is actually available at most locations. The AEO notes that this capacity factor "represents the highest quality resource available"[4]. For a capacity factor of 33%, production costs increase 2.1 cents/kWh to 8.4 cents/kWh, *Figure 18*.

Figure 18 also illustrates the effect of the capacity factor assumptions on capital cost sensitivities. The base case assumes the capital cost of wind is 1966 $/kW. At the higher capacity factor, wind becomes cost competitive with NGCC for capital costs below 1830 $/kW. However, for the lower capacity factor, capital costs would have to fall below 1300 $/kW.

Wind-generated electricity is eligible for a 1.9 cents/kWh production tax credit (PTC), which makes a significant difference to the estimated production costs. For the case of 44% capacity factor, the effect of the PTC is comparable to lowering the capital cost from 1966 to 1300 $/kW, *Figure 18*.

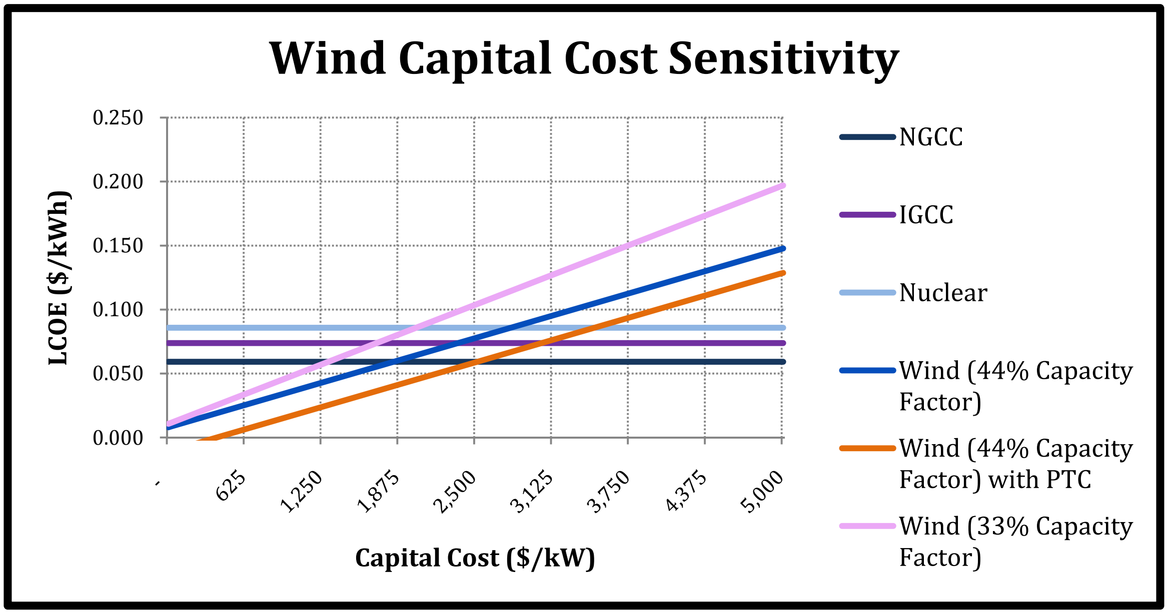


Figure 18. Wind Capital Cost Sensitivity Analysis

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[4] DOE, 2010, Table 13.2.

Conclusion and Next Steps

The Power Systems L-CAT is a high-level dynamic model that calculates production costs and tracks environmental performance for a range of electricity generation technologies. This report summarizes key assumptions and results for the first generation of L-CAT. As development of L-CAT is a work in progress, results or conclusions presented in this report are likely to change or evolve as the model is reviewed and improved.

This report demonstrates the differences between the L-CAT and NETL approach for calculating levelized costs of energy. The simplified approach used in L-CAT allows one to change assumptions in a model such as this and view the results instantly. While the results differ slightly from the NETL results (less than 5%), we believe the value added of being able to change key assumptions and view the results makes the L-CAT approach appealing for this type of model. L-CAT should be used for comparing and contrasting electricity production choices and for understanding the trade-offs between economics and the environment. The NETL methodology is more appropriate for investors who need to understand the annual cash flow requirements for various plant options.

L-CAT is a work in progress. Recommended next steps (not in any particular order) include:

- Add detail on carbon taxation options to allow user to specify taxation policies at different stages (i.e., raw material acquisition, end use)
- Explore options for inclusion of uncertainty analysis (Monte Carlo/probabilistic approaches)
- Expand technologies options (biomass, solar, offshore wind)
- Add consideration of land use requirements as additional metric to environmental performance section
- Research feasibility of including construction indices that incorporate price swings in steel and cement
- Consider regrouping of technologies by fuel type (natural gas, coal, nuclear, renewable)
- Refining current display options which accurately mirror the NETL methodologies, in terms of cost components, but which clutter the graphics (too many categories (graphs now have 10 categories).
- Decouple the financing assumptions for CCS and non-CCS cases so as to allow different financing assumptions
- Add production and other tax credits
- Explore the use of "tornado graphs" similar to NETL LCA reports to show sensitivity to changes in variables.

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Timothy Skone
SkoneT@netl.doe.gov
National Energy Technology Laboratory
(electronic copy)

Sandia National Laboratories