NATIONAL ENERGY TECHNOLOGY LABORATORY

Power Systems Life Cycle Analysis Tool (Power LCAT)

May 2012

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Disclaimer

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Final Report

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Thomas E. Drennen and Joel Andruski

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185

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Abstract

Power LCAT is a high-level dynamic model that calculates production costs and tracks environmental performance for a range of electricity generation technologies: natural gas combined cycle (NGCC), integrated gasification combined cycle (IGCC), supercritical pulverized coal (SCPC), existing pulverized coal (EXPC), nuclear, and wind (with and without backup power). All of the fossil fuel technologies also include the option of 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. Power LCAT is targeted at helping policy makers, students, and interested stakeholders understand the economic and environmental tradeoffs associated with various electricity production options.

Power LCAT has four main sections: "Production Analysis", "Environmental Performance", "Costs vs. Emissions", and "Sensitivity Analysis." The "Production Analysis" section calculates the cost of electricity (COE) ($/kWh) for each option and allows users to explore key sensitivities. The "Environmental Performance" section estimates aggregate greenhouse gas and non-greenhouse gas emissions, as well as water usage at each stage of the life cycle analysis. The "Costs vs. Emissions" section explores the tradeoffs between costs ($/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.

The Power Systems Life Cycle Analysis Tool (Power LCAT) is a joint effort between Sandia National Laboratories (SNL) and the National Energy Technology Laboratory (NETL). Funding for the project came from the Department of Energy (DOE/NETL).

The technology options are based on detailed life cycle analysis (LCA) reports conducted by the 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 (PT), and end user electricity consumption.

For the default model assumptions, the results show that for the fossil fuel technology options the supercritical pulverized coal plant is the lowest cost option at 6.01 cents/kWh. The next lowest cost fossil fuel option is the natural gas combined cycle plant (6.52 cents/kWh) and then the integrated gasification combined cycle plant (7.90 cents/kWh). Of the nuclear options, the EXNUC plant is the lowest cost option at 1.74 cents /kWh followed by a Gen III+ plant at 10.78 cents/kWh. Power LCAT includes one renewable technology option – a 200 MW wind turbine (with or without backup). For the default assumptions, the COE for the standalone option is 4.91 cents/kWh and 8.11 cents/kWh with a gas turbine simple cycle backup.

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1 Introduction and Overview

Power LCAT 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 version 2.0 of Power LCAT. 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 the wide range of options for conducting sensitivity analysis.

The Power Systems Life Cycle Analysis Tool (Power LCAT) is a joint effort between Sandia National Laboratories (SNL) and the National Energy Technology Laboratory (NETL). Funding for the project came from the Department of Energy (DOE/NETL).

2 Technologies and Input Assumptions

Power LCAT calculates the projected cost of producing electricity[1] for seven electricity generation technologies summarized in **Table 1**: natural gas combined cycle (NGCC), integrated gasification

Table 1: Technologies Included in Power LCAT

Technology Acronym	Technology	Source
Coal		
EXPC	Existing Pulverized Coal	NETL (2010a)
EXPC w/ccs	Existing Pulverized Coal with carbon capture and sequestration	
IGCC	Integrated Gasification Combined Cycle	NETL (2010b)
IGCC w/ccs	Integrated Gasification Combined Cycle with carbon capture and sequestration	
SCPC	Supercritical Pulverized Coal	NETL (2010d)
SCPC w/ccs	Supercritical Pulverized Coal with carbon capture and sequestration	
Natural Gas		
NGCC	Natural Gas Combined Cycle	NETL (2010c)
NGCC w/ccs	Natural Gas Combined Cycle with carbon capture and sequestration	
Nuclear		
EXNUC	Existing Nuclear	NETL (2011c)
Gen III Plus	New Nuclear	NETL (2011c)
Wind	Onshore Wind with Gas Turbine Simple Cycle (GTSC) backup	NETL (2010e)

combined cycle (IGCC), supercritical pulverized coal (SCPC), existing pulverized coal (EXPC)[2], existing (EXNUC)[3] and new (Gen III+) nuclear, and onshore wind[4]. All of the fossil fuel

[1] Sometimes referred to as busbar or production costs.
[2] This technology assumes an existing coal plant for CCS and non-CCS cases (NETL, 2010a).

technologies include the option of incorporating carbon capture and sequestration technologies (CCS).

The technology options are based on detailed life cycle analysis reports conducted by the National Energy Technology Laboratory (NETL). The goal of the NETL studies is to compare existing and future technology options using a life cycle analysis (LCA). 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 (PT), and end user electricity consumption[5]. The NETL analyses consider greenhouse gas emissions (carbon dioxide [CO_2], methane [CH_4], nitrous oxide [N_2O], and sulfur hexafluoride [SF_6]), criteria air pollutants (lead [Pb], carbon monoxide [CO], nitrous oxides [NO_X], sulfur oxides [SO_x], volatile organic compounds [VOC], particulate materials [PM]), mercury (Hg) and ammonia (NH_3) emissions, water withdrawal and consumption, and land use (acreage)[6].

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, CO_2 capture rates, and thermal efficiencies.[7] All values are for new plants and are based on sources given in **Table 1**. While Power LCAT defaults to these assumptions, the user can vary the assumptions and view the implications in terms of projected costs. For example, the user can explore the effects of increased fuel costs, decreased heat rates, or delays in construction time on the projected economics.

Appendix A gives a complete table that includes the main parameters used in Power LCAT. They include technology specific assumptions such as heat rate and capital costs, additional technology assumptions such as tax credits, broader assumptions such as Federal and State tax rates, and assumptions that go into creating relationships between parameter estimates and CO_2 capture rates.

[3] This technology assumes an existing Gen II-II nuclear plant is built between 1969 and 1996 and henceforth referred to in this report as EXNUC (NETL, 2011c).
[4] Wind includes a choice between conventional and advanced turbine construction.
[5] LC Stage #5 considers end user electricity consumption at a 100% efficiency with no cost or environmental burden and is not included in this model (NETL 2010a, 2010b, 2010c, 2010d, 2010e, and 2011c).
[6] Land use is not included in this version of the model.
[7] 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 50.2%.

Table 2: Base Case Assumptions for Power LCAT

Technology Acronym	Capital Cost ($/kW)	Fixed O&M ($/kW)	Variable O&M ($/kWh)	Fuel Price (2008 $/MMBtu)	Years to Construct	Plant Size (MW)	Capacity Factor (%)	Heat Rate (Btu/kWh)	Efficiency (%)	CO_2 Capture Rate (%)
Coal										
EXPC	0	42.10	0.00090	1.51	5	434	85%	9276	36.8%	N/A
EXPC w/ccs	1320	9.34	0.00911	1.51	5	303	85%	13724	24.9%	90%
IGCC	2447	79.01	0.00730	1.51	5	622	80%	8756	39.0%	N/A
IGCC w/ ccs	3359	103.88	0.00933	1.51	5	543	80%	10502	32.5%	90%
SCPC	2024	59.33	0.00504	1.51	5	550	85%	8686	39.3%	N/A
SCPC w/ ccs	3485	96.72	0.00872	1.51	5	550	85%	12099	28.2%	90%
Natural Gas										
NGCC	718	22.06	0.00132	6.76	3	555	85%	6798	50.2%	N/A
NGCC w/ ccs	1497	42.10	0.00256	6.76	3	474	85%	7968	42.8%	90%
Nuclear										
EXNUC*	0	64.00	0.00100	0.4	6	1000	70.7%	10339	33.0%	N/A
Gen III Plus**	4267	69.00	0.00100	0.67	6	1400	90.6%	10216	33.4%	N/A
Wind* **	920 (790)	12.40	0.00810	0	3	200	30%	0	N/A	N/A

** EXNUC represents an existing nuclear plant thus capital costs have been set to zero for this model. An existing nuclear plant assumes a six-year construction period, rounding up from the NETL assumption of 5.6 years.*

*** A Gen III Plus plant assumes a six-year construction period, rounding up from the NETL assumption of 5.6 years.*

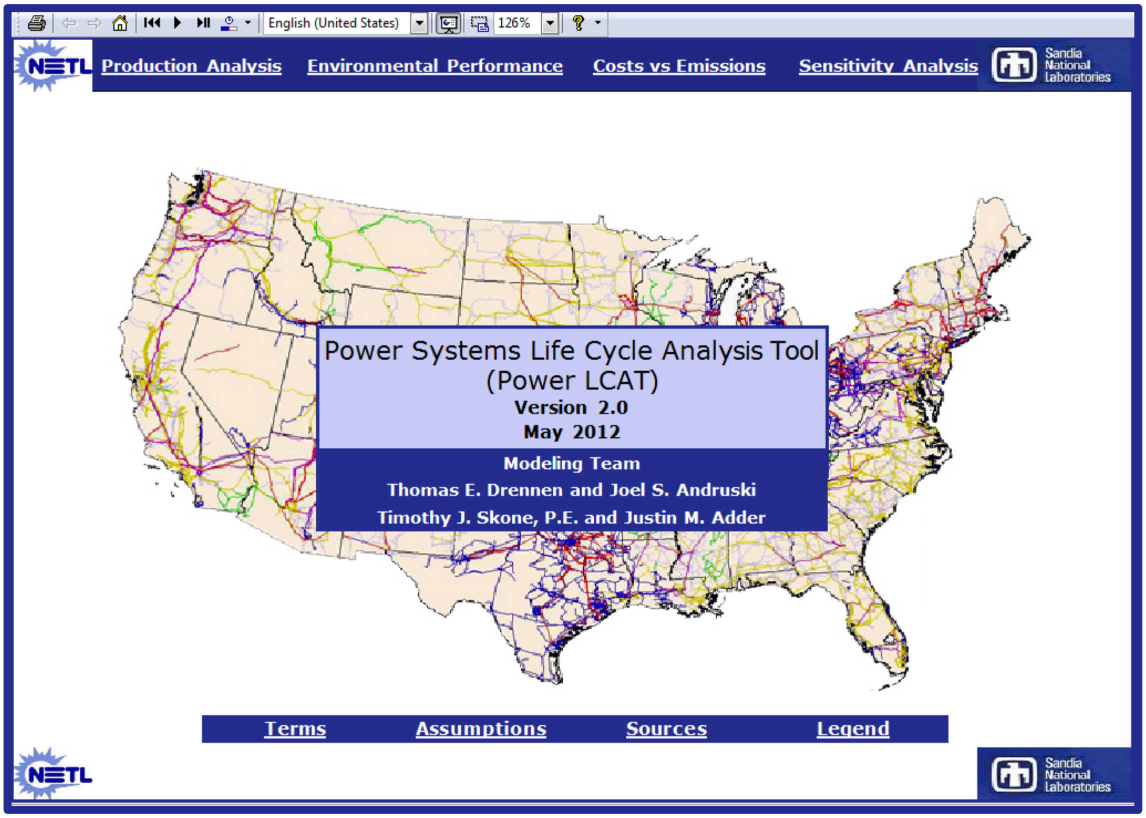
**** Note that under the capital cost for wind the first number is the capital cost assumption for a conventional turbine (920 $/kW), the second number inside the parenthesis is the capital cost assumption for an advanced turbine (790 $/kW).*

3 Model Layout and Assumptions

The overall goal of Power LCAT is to provide a high-level dynamic model 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.")

Power LCAT has four main sections: "Production Analysis", "Environmental Performance", "Costs vs. Emissions", and "Sensitivity Analysis." The "Production Analysis" section calculates the COE ($/kWh) for each option and allows users to explore key sensitivities. The "Environmental Performance" section estimates aggregate greenhouse gas and non-greenhouse gas emissions, as well as water usage at each stage of the life cycle analysis. The "Costs vs. Emissions" section explores the tradeoffs between costs ($/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.

Figure 1: Power LCAT Home Screen



4 Production Analysis

4.1 Cost of Electricity (COE) Calculation Methodology

Production costs are estimated using a levelized cost of energy (COE) approach. COE calculations estimate the per unit ($/kWh) cost of production over the economic lifetime of the technology.[8] Specifically, this calculation takes the capital costs, associated financing costs, O&M, fuel costs, and any externality costs (such as CO_2) and calculates a per unit production cost. The COE 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 levelized COE calculation is given by:

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

where:

I	= total financed capital costs
FCR	= fixed charge rate
Q	= annual plant output (i.e. kWh)
$O\&M$	= fixed and variable operating and maintenance costs
E	= externality costs, such as a $/ ton CO_2e tax

Assumptions about the timing of capital expenditures depend on user-defined assumptions about construction times. Financing costs assume that the distribution of capital expenditures over the time of construction is different.[9] Assuming a three year construction period, the percent breakdown of financed capital is 10%, 60%, and 30% respectively over the three year period. In assuming a five year construction period, the percent breakdown of financed capital is 10%, 30%, 25%, 20% and 15% respectively over the five year period. User specified construction years (1-2, 4, and 6-10) assume a uniform distribution of financed capital over the construction period. The NETL 2010a, 2010b, 2010c, 2010d, and 2010f reports do not include interest rates during construction in their base-case assumptions. Therefore the default interest rate during construction in Power LCAT for those technologies is set to zero. For the nuclear options, NETL assumes a 6.5% interest during construction (NETL, 2011c).

The financed capital cost (I) is multiplied by a fixed charge rate (FCR), which includes assumptions about state and federal taxes, the depreciation period (as defined by the Modified Accelerated Cost Recovery System (MACRS) methodology), and other exogenous costs.

The FCR is calculated using:

$$FCR = \frac{CRF[1 - bT\ \sum_{n=1}^{M} V_n \,/\, (1 + r_{wacc})^n - t_c\,]}{(1 - T)} + p_1 + p_2 \qquad (2)$$

[8] This levelized COE calculation is consistent with the first year COE methodology used in the NETL reports.

[9] The treatment of capital costs comes from the "Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance," Table 4 (NETL 2011b). The purpose of having different cost outlays for different years is based on the assumption that different amounts of capital are needed at different stages of construction. The NETL 2010a, 2010b, 2010c, 2010d reports assume a three or five year construction time for specific technologies, hence the different capital cost percentages needed for only three and five year construction schedules.

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 (3 to 20 years; default depends on technology)
V_n = fraction of depreciable base in year *n* (initially 100%)
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)

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).

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.

An important part of COE calculations is the percentage of the capital investment that is debt or equity financed. The real weighted average cost of capital (r_{wacc}) takes into account the debt-to-equity ratio and their specific financing rates. Debt financing refers to the part of the investment that is financed through traditional financing options, such as those from banks or bonds, and equity financing can include owner or investor financing.

The r_{WACC} is calculated by:

$$r_{wacc} = \frac{E}{V} * r_e + \frac{D}{V} * r_d * (1 - T) \qquad \textbf{(3)}$$

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)
	V	= capital cost
	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 r_{wacc} is 7.4%.

The CRF is calculated using:

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

where:

	r_{wacc}	= real weighted average cost of capital
	n	= economic plant life (initially 20 years).

4.2 Production Analysis for CCS cases

Each fossil fuel option includes possibility of incorporating CCS technologies. CCS options result in added capital and O&M costs which may affect the plant's heat rate. For example, adding a carbon capture technology to an existing pulverized coal plant results in the heat rate increasing from 9,276 to 13,724 Btu/kWh, a 32% penalty.

The relationships between capital costs, heat rates, and CO_2 capture rates are derived from NETL reports (NETL, 2011a) and fit the form of equation 5:

$$y = cx^3 + dx^2 + ex + b \qquad (5)$$

The specific coefficients for each technology for CO_2 capture rate as a function of heat rates and capital costs for all four cases are summarized in **Table 3** and **Table 4**, respectively,

where:

	y	= heat rate (**Table 3**) or capital cost (**Table 4**)
	x	= CO_2 capture rate
	b	= y-intercept.

Table 3: Coefficients for the Derivation of Heat Rate for CCS Cases

	c	d	e	b	R^2
IGCC w/ ccs	338.14	1323	467.71	8726.4	0.99
SCPC w/ ccs	1948.4	-1676.2	3723.5	8685.1	0.99
NGCC w/ ccs	0	0	1300	6798	1
EXPC w/ ccs	0	0	4942.2	9276	1

Table 4: Coefficients for the Derivation of Capital Cost for CCS Cases

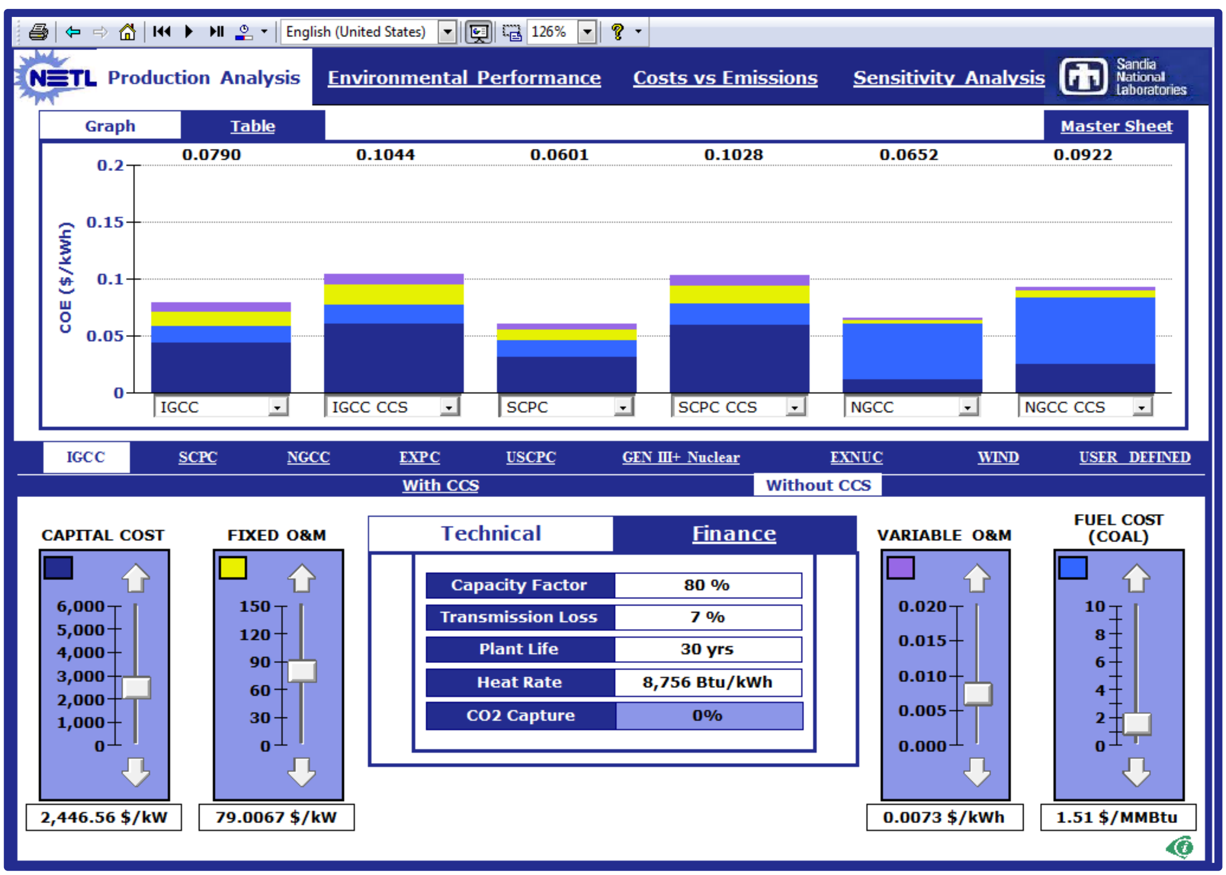
	c	d	e	b	R^2
IGCC w/ ccs	1314.7	-1730.4	1511.7	2441.6	0.99
SCPC w/ ccs	1724.9	-2244.6	2246	2024.7	0.99
NGCC w/ ccs	0	0	866.32	717.54	1
EXPC w/ ccs	0	0	1467.2	0	1

4.3 Production Analysis Screen: Technical Assumptions

Figure 2 shows a representative Power LCAT main production cost screen (IGCC without CCS). Hyperlinks for all of the technology options are located in the middle of the screen. The sliders and text boxes on the bottom of the screen allow the user to change basic assumptions about that specific technology (in this case IGCC without CCS). The bar graphs illustrate the production costs ($/kWh) for six of the technologies. 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 a tabular form, either in terms of $/kWh or percentage terms, by clicking the relevant hyperlink on the top left of the column display. Further financial assumptions are available by clicking the "Finance" hyperlink in the middle of the screen.

Power LCAT 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 (seen under the "Table" view). The model is set to NETL default assumptions which can be changed from the "Production Analysis" screen for each technology. The results show that a supercritical PC plant is the lowest cost option at 6.01 cents/kWh. The next lowest cost options are natural gas plants (6.52 cents/kWh) and then the IGCC plants (7.90 cents/kWh). SCPC with CCS (10.28 cents/kWh) and IGCC with CCS (10.44 cents/kWh) are the most expensive CCS options. For coal plants, capital costs are the most important determinant of the COE costs (dark blue), whereas for NGCC plants, the

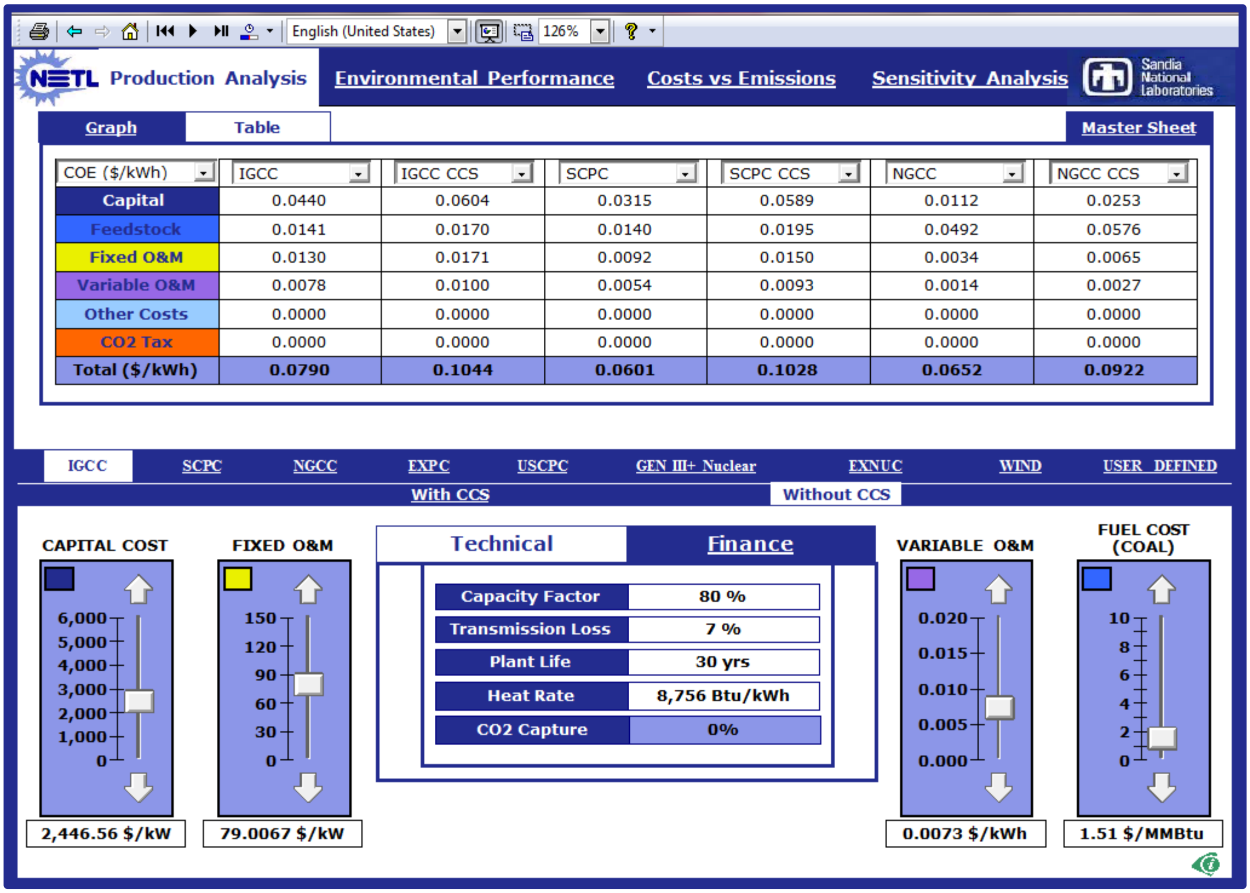
Figure 2: Representative Production Analysis Screen (IGCC w/o CCS)



fuel cost (lighter blue) is the main component.

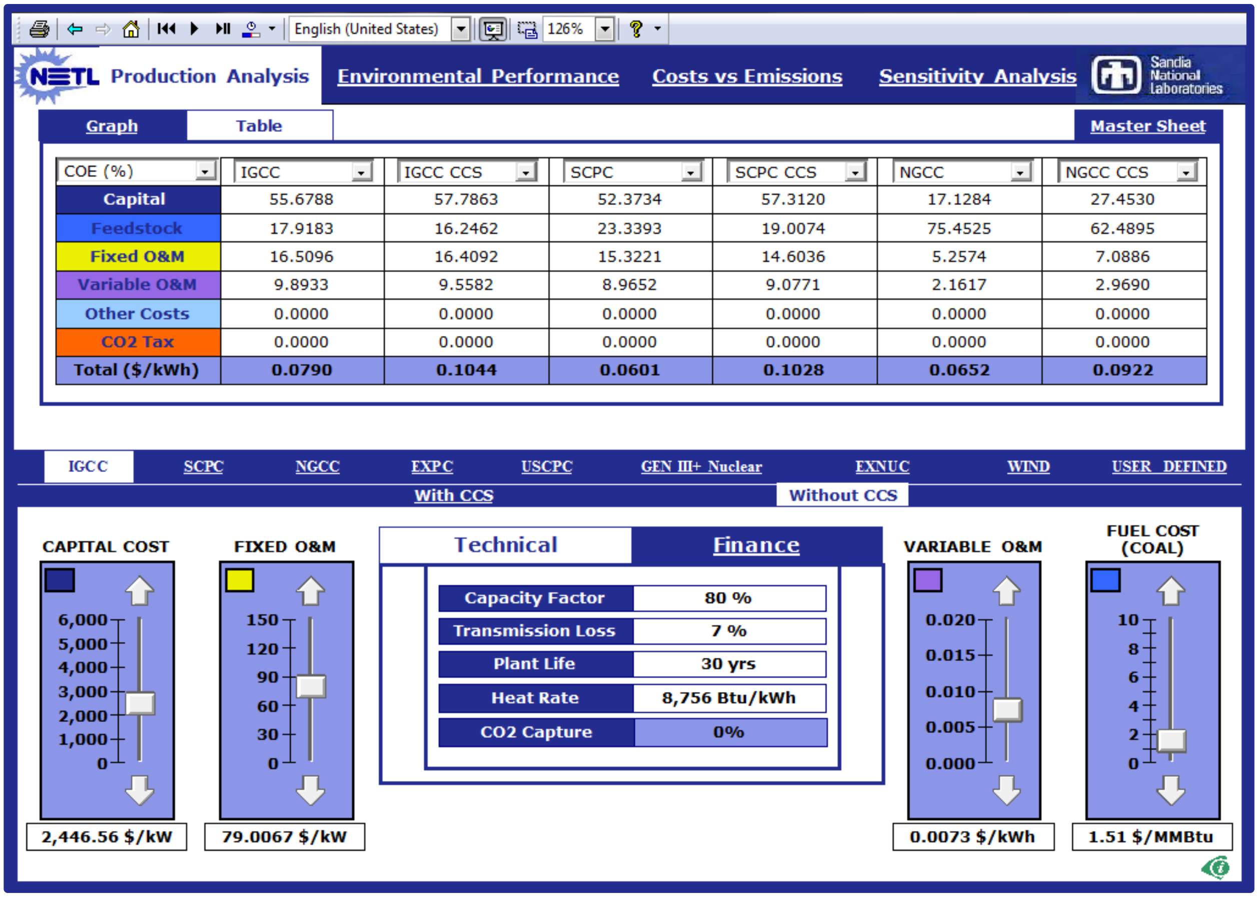
Figure 3 and **Figure 4** show the same "Production Analysis" screen for IGCC in table form in $/kWh and percent.

Figure 3: Representative Production Analysis Screen (IGCC w/o CCS)Table in $/kWh



COE ($/kWh)	IGCC	IGCC CCS	SCPC	SCPC CCS	NGCC	NGCC CCS
Capital	0.0440	0.0604	0.0315	0.0589	0.0112	0.0253
Feedstock	0.0141	0.0170	0.0140	0.0195	0.0492	0.0576
Fixed O&M	0.0130	0.0171	0.0092	0.0150	0.0034	0.0065
Variable O&M	0.0078	0.0100	0.0054	0.0093	0.0014	0.0027
Other Costs	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2 Tax	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total ($/kWh)	0.0790	0.1044	0.0601	0.1028	0.0652	0.0922

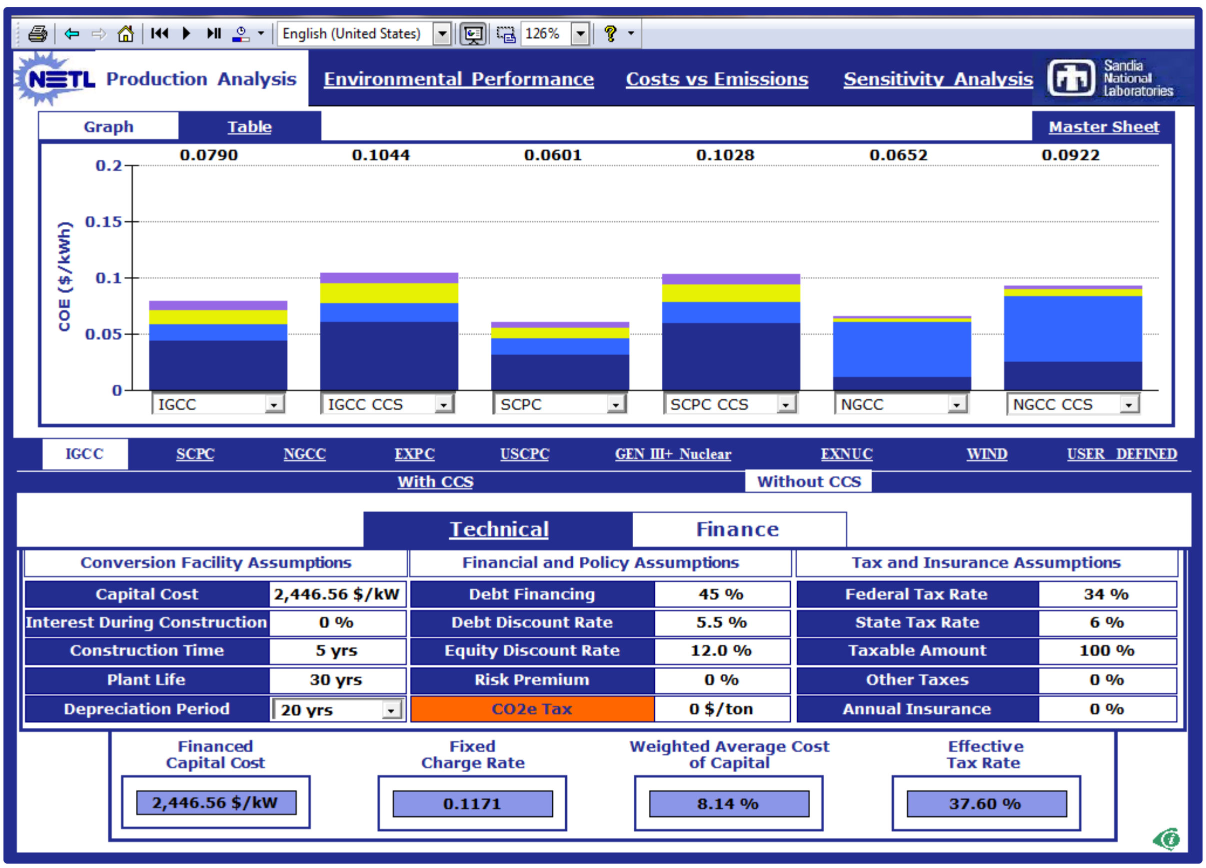
Figure 4: Representative Production Analysis Screen (IGCC w/o CCS) Table in Percent



4.4 Production Analysis Screen: Finance Assumptions

The "Finance" tab separates the inputs into three categories: conversion facility assumptions, financial and policy assumptions, and tax and insurance assumptions, **Figure 5**. Conversion facility assumptions include key parameters associated with plant construction including capital costs, interest during construction, construction time, economic plant life, and depreciation period. Financial and policy assumptions include the debt/equity financing assumptions, risk premium, and whether there is a carbon tax. Tax and insurance assumptions include federal and state taxes as well as the taxable amount, other taxes, and annual insurance. The shaded boxes at the bottom of the screen show the results for the key model calculations based on the user-supplied input; they cannot be changed directly.

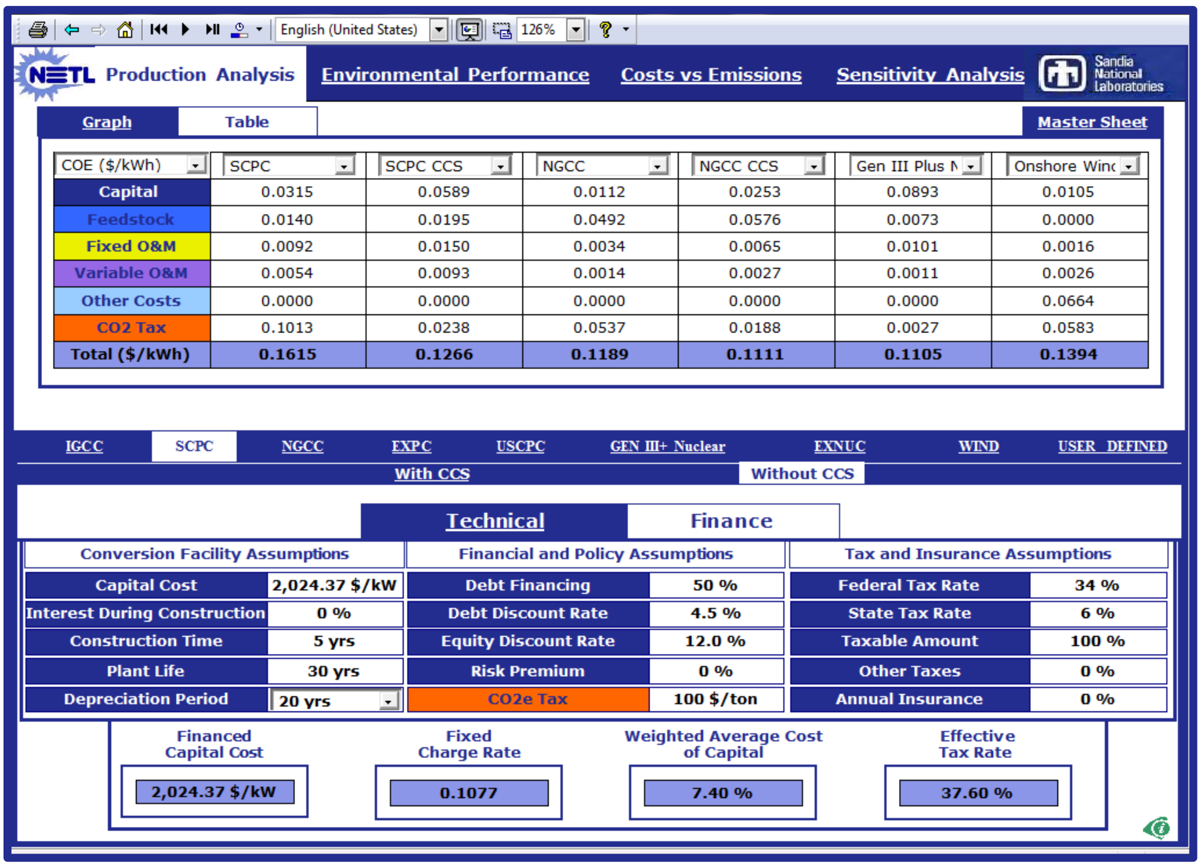
Figure 5: Representative Production Analysis Screen (IGCC w/o CCS) Finance Tab



4.4.1 Effects of Adding a Carbon Tax

Users can also evaluate scenarios for different levels of a carbon tax under the "Finance" tab on the "Production Analysis" screen.[10] **Figure 6** shows the effect of a 100 $/ton tax on several technologies. The tax is applied to the life cycle emissions, however the user can change at which stage to apply the tax under the "Environmental Performance" screen. The results show that with the current assumptions the addition of the carbon tax, shown by the orange bars, makes NGCC with CCS the most economical. The high capital cost for Gen III+ and SCPC CCS limits their economic competitiveness, while the high emissions from the non-CCS cases of SCPC and NGCC subject them to the worst carbon tax penalty. The carbon penalty of 0.0583 $/kWh for wind is attributable almost entirely to the GTSC addition. For comparison, a standalone conventional wind plant with a 100 $/ton tax incurs a penalty of 0.0023 $/kWh, or 4.5% of the total production costs. The next closest technology of Gen III+ has an added cost of 0.0027 $/kWh, or 2.5% of the total production costs.

Figure 6: Illustrative Example of a Carbon Equivalent Tax Using "Production Analysis"



COE ($/kWh)	SCPC	SCPC CCS	NGCC	NGCC CCS	Gen III Plus N	Onshore Winc
Capital	0.0315	0.0589	0.0112	0.0253	0.0893	0.0105
Feedstock	0.0140	0.0195	0.0492	0.0576	0.0073	0.0000
Fixed O&M	0.0092	0.0150	0.0034	0.0065	0.0101	0.0016
Variable O&M	0.0054	0.0093	0.0014	0.0027	0.0011	0.0026
Other Costs	0.0000	0.0000	0.0000	0.0000	0.0000	0.0664
CO2 Tax	0.1013	0.0238	0.0537	0.0188	0.0027	0.0583
Total ($/kWh)	0.1615	0.1266	0.1189	0.1111	0.1105	0.1394

[10] Users can also add a carbon tax under the "Master Sheet."

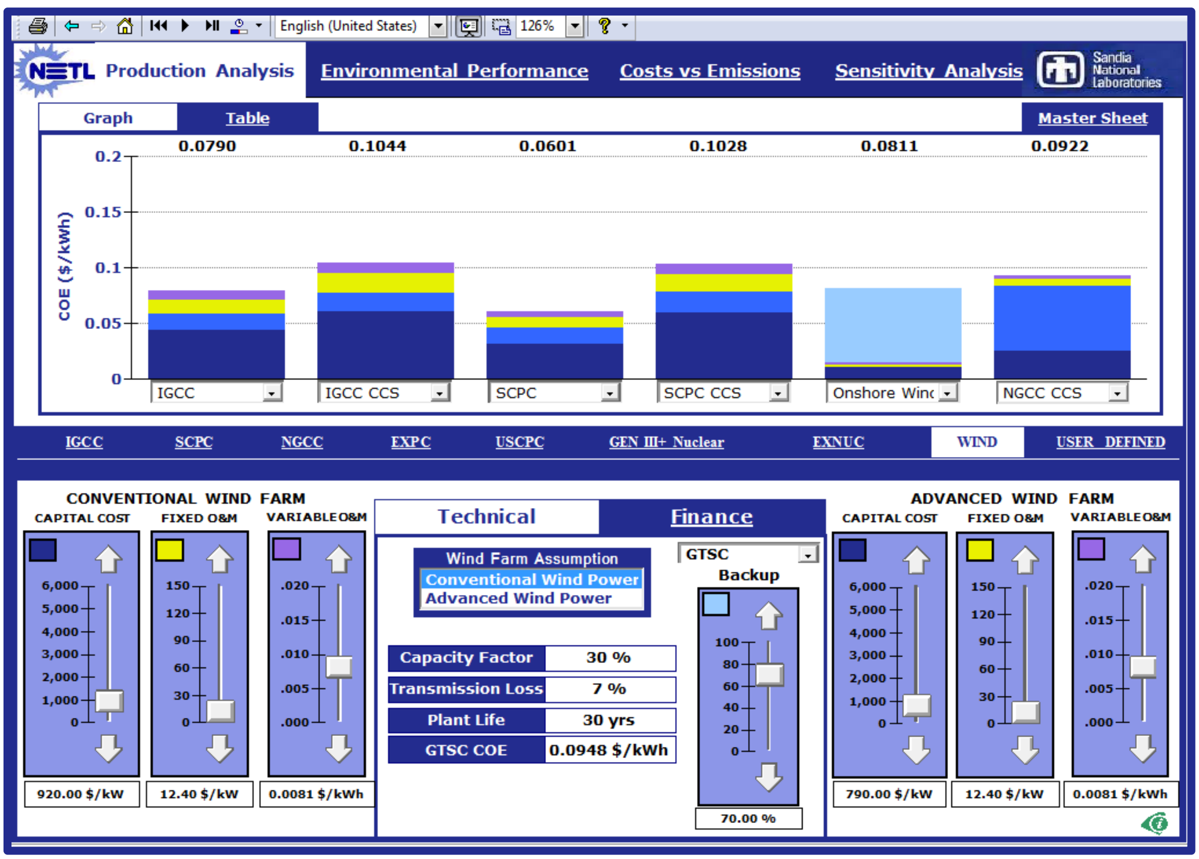
4.5 Production Analysis: Wind with Backup Options

Wind is handled differently in the "Production Analysis" section than other technologies. Users can evaluate wind as a standalone wind farm or with a choice of backup power source. Wind in combination with a Gas Turbine Simple Cycle (GTSC) power plant is the default option. The GTSC plant option assumes a fixed COE of 0.0948 \$/kWh, this can be changed in the middle of the screen but is not subject to the same technical and financial assumptions of the other technology options. This is a model limitation that will be fixed with forthcoming NETL technical reports. Users can also choose any other technology in Power LCAT as a backup source.

Figure 7 shows an example of wind operating at a 30% capacity factor with backup GTSC at 70%. Users can choose the percent addition for backup power using the slider or input box and change the backup power source using the drop-down menu at the top of the slider. Any assumption made about backup power is carried through to the "Environmental Performance" section.

For example, the default case (conventional wind plant with GTSC backup) results in a COE of

Figure 7: Representative Production Analysis Screen (Wind with GTSC backup)



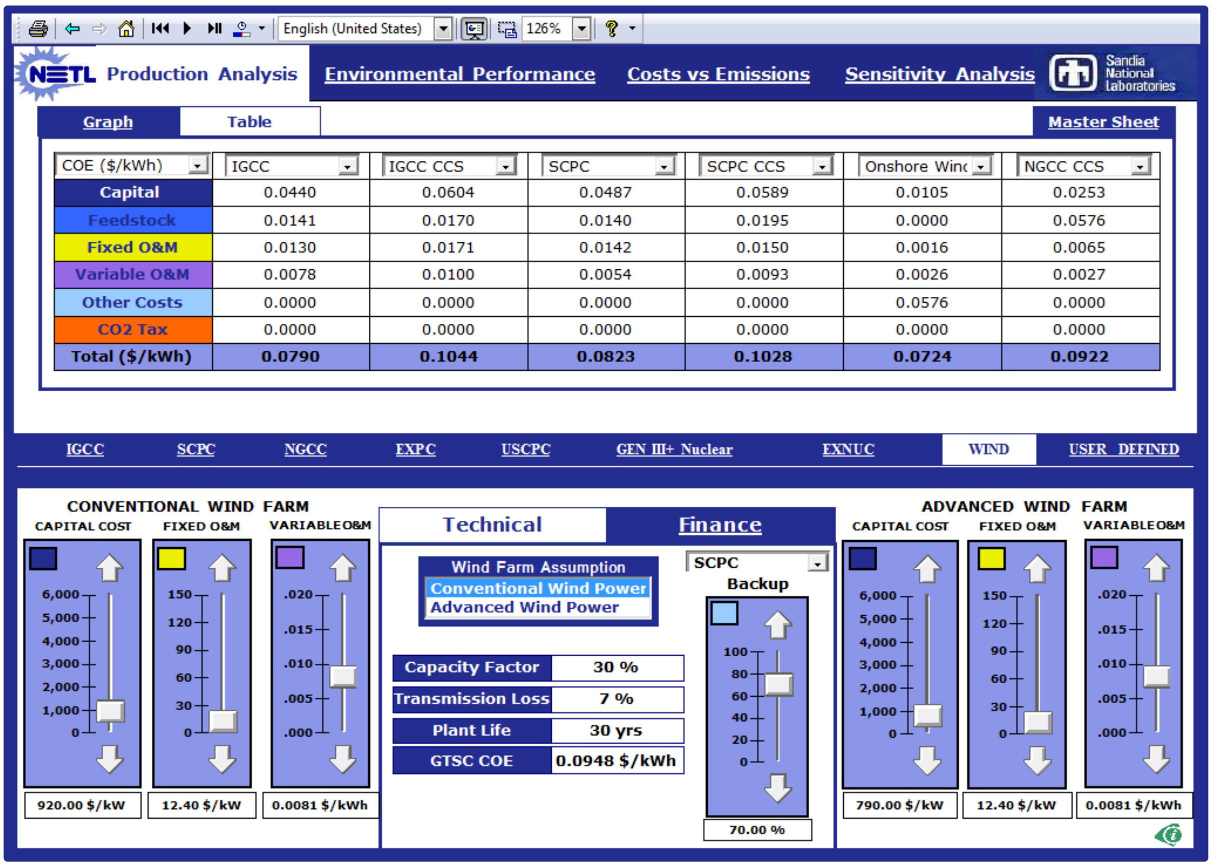
0.0811 \$/kWh and GHG emissions of 542 kg CO_2e/MWh. For comparison, a standalone conventional wind turbine's COE is 0.0491 \$/kWh with associated GHG emissions of 21.45 kg CO_2e/MWh.

To change the backup source, the user must select the backup technology and also adjust the capacity factor of that backup source to meet the desired joint capacity factor. For example, if one wants to use SCPC to backup wind with a combined capacity factor of 85%, the required steps are:

1. Select SCPC from the pull down menu located above the backup addition to COE slider.
2. On the SCPC "Production Analysis" page, lower the capacity factor to 55%.
3. Return to the wind "Production Analysis" page and select the percent addition of the backup generation to the overall COE. Note that the sum of the assumed wind capacity factor and this addition to COE slider must add to 100% as they jointly determine the percentage of the COE attributable to each source (in this case, 30% wind and 70% the backup SCPC operating at 55% capacity factor).[11]

The resulting COE of 0.0724 $/kWh is shown in **Figure 8** in tabular form and which shows the individual additions of cost components for the wind and backup power assumption. In this case, the capital (0.0105 $/kWh), fixed O&M (0.0016 $/kWh), and variable O&M costs (0.0026 $/kWh) are associated with the wind plant, the other costs (0.0576 $/kWh) are the total component costs for the backup SCPC power source.

Figure 8: Representative Production Analysis Screen (Wind with GTSC backup) Table Display



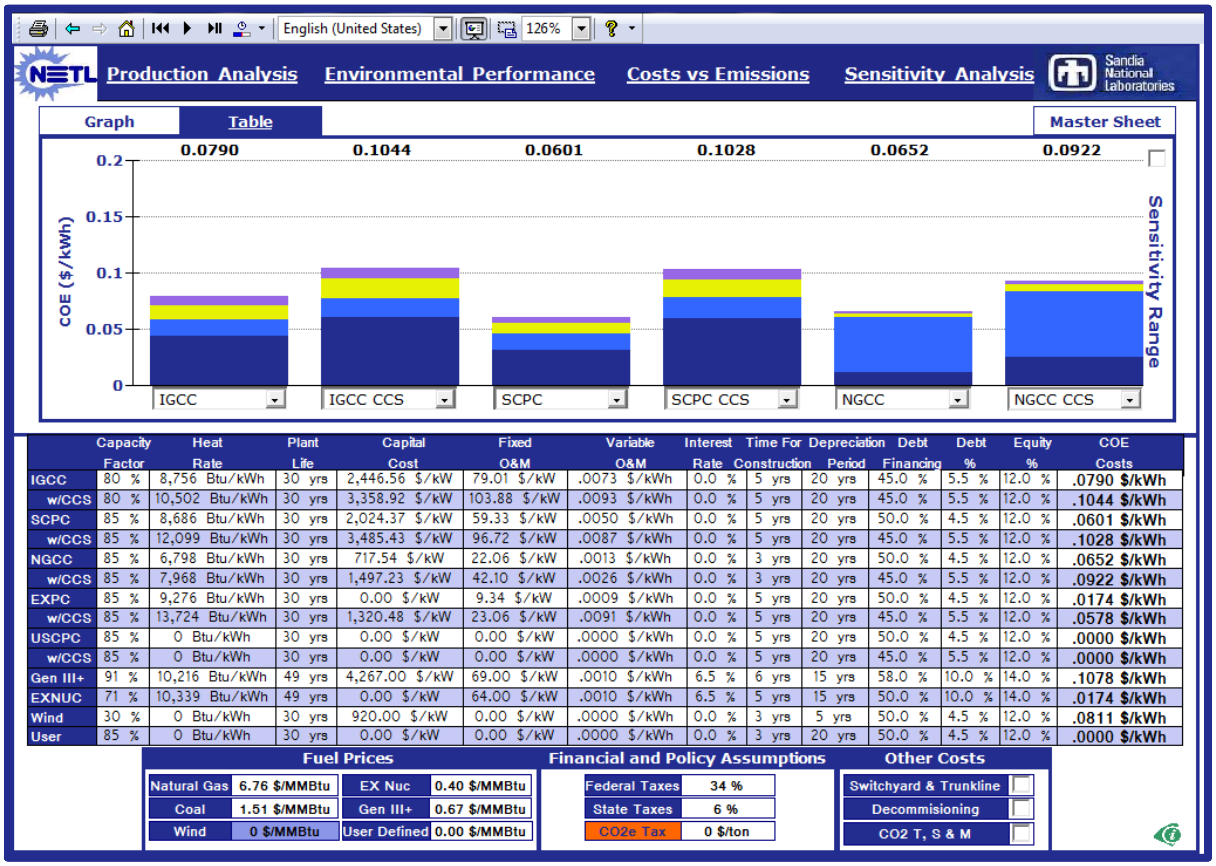
COE ($/kWh)	IGCC	IGCC CCS	SCPC	SCPC CCS	Onshore Winc	NGCC CCS
Capital	0.0440	0.0604	0.0487	0.0589	0.0105	0.0253
Feedstock	0.0141	0.0170	0.0140	0.0195	0.0000	0.0576
Fixed O&M	0.0130	0.0171	0.0142	0.0150	0.0016	0.0065
Variable O&M	0.0078	0.0100	0.0054	0.0093	0.0026	0.0027
Other Costs	0.0000	0.0000	0.0000	0.0000	0.0576	0.0000
CO2 Tax	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total ($/kWh)	0.0790	0.1044	0.0823	0.1028	0.0724	0.0922

[11] User Defined has the same functionality as wind, and users would go through the screen using these same steps. For example, there are two technology options (current and advanced) with the option of a backup power source.

4.6 Production Analysis: Master Sheet

The "Master Sheet" option is an alternative method for varying assumptions and may be particularly useful for those who want to change several key assumptions simultaneously ("Master Sheet" hyperlink on top right of graphical results). The "Master Sheet" is illustrated in **Figure 9**. The COE costs are shown both graphically on top and in the last column of the table. On this screen the user may also include additional costs such as switchyard & trunkline, decommissioning, and CO_2 transportation, storage, and monitoring (T, S & M).

Figure 9: The Master Sheet Option



	Capacity Factor	Heat Rate	Plant Life	Capital Cost	Fixed O&M	Variable O&M	Interest Rate	Time For Construction	Depreciation Period	Debt Financing	Debt %	Equity %	COE Costs
IGCC	80 %	8,756 Btu/kWh	30 yrs	2,446.56 $/kW	79.01 $/kW	.0073 $/kWh	0.0 %	5 yrs	20 yrs	45.0 %	5.5 %	12.0 %	.0790 $/kWh
w/CCS	80 %	10,502 Btu/kWh	30 yrs	3,358.92 $/kW	103.88 $/kW	.0093 $/kWh	0.0 %	5 yrs	20 yrs	45.0 %	5.5 %	12.0 %	.1044 $/kWh
SCPC	85 %	8,686 Btu/kWh	30 yrs	2,024.37 $/kW	59.33 $/kW	.0050 $/kWh	0.0 %	5 yrs	20 yrs	50.0 %	4.5 %	12.0 %	.0601 $/kWh
w/CCS	85 %	12,099 Btu/kWh	30 yrs	3,485.43 $/kW	96.72 $/kW	.0087 $/kWh	0.0 %	5 yrs	20 yrs	45.0 %	5.5 %	12.0 %	.1028 $/kWh
NGCC	85 %	6,798 Btu/kWh	30 yrs	717.54 $/kW	22.06 $/kW	.0013 $/kWh	0.0 %	3 yrs	20 yrs	50.0 %	4.5 %	12.0 %	.0652 $/kWh
w/CCS	85 %	7,968 Btu/kWh	30 yrs	1,497.23 $/kW	42.10 $/kW	.0026 $/kWh	0.0 %	3 yrs	20 yrs	45.0 %	5.5 %	12.0 %	.0922 $/kWh
EXPC	85 %	9,276 Btu/kWh	30 yrs	0.00 $/kW	9.34 $/kW	.0009 $/kWh	0.0 %	5 yrs	20 yrs	50.0 %	4.5 %	12.0 %	.0174 $/kWh
w/CCS	85 %	13,724 Btu/kWh	30 yrs	1,320.48 $/kW	23.06 $/kW	.0091 $/kWh	0.0 %	5 yrs	20 yrs	45.0 %	5.5 %	12.0 %	.0578 $/kWh
USCPC	85 %	0 Btu/kWh	30 yrs	0.00 $/kW	0.00 $/kW	.0000 $/kWh	0.0 %	5 yrs	20 yrs	50.0 %	4.5 %	12.0 %	.0000 $/kWh
w/CCS	85 %	0 Btu/kWh	30 yrs	0.00 $/kW	0.00 $/kW	.0000 $/kWh	0.0 %	5 yrs	20 yrs	45.0 %	5.5 %	12.0 %	.0000 $/kWh
Gen III+	91 %	10,216 Btu/kWh	49 yrs	4,267.00 $/kW	69.00 $/kW	.0010 $/kWh	6.5 %	6 yrs	15 yrs	58.0 %	10.0 %	14.0 %	.1078 $/kWh
EXNUC	71 %	10,339 Btu/kWh	49 yrs	0.00 $/kW	64.00 $/kW	.0010 $/kWh	6.5 %	5 yrs	15 yrs	50.0 %	10.0 %	14.0 %	.0174 $/kWh
Wind	30 %	0 Btu/kWh	30 yrs	920.00 $/kW	0.00 $/kW	.0000 $/kWh	0.0 %	3 yrs	5 yrs	50.0 %	4.5 %	12.0 %	.0811 $/kWh
User	85 %	0 Btu/kWh	30 yrs	0.00 $/kW	0.00 $/kW	.0000 $/kWh	0.0 %	3 yrs	20 yrs	50.0 %	4.5 %	12.0 %	.0000 $/kWh

5 Environmental Performance

5.1 LC Greenhouse Gases

Power LCAT tracks the life cycle emissions of key greenhouse gases, several pollutants, and water withdrawals and consumption for those technologies in **Table 1**. The greenhouse gases include: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20), and sulfur hexafluoride (SF_6). Each of these gases are multiplied by their global warming potential (GWP), using either the 2007 and 2001 Intergovernmental Panel on Climate Change (IPCC) GWP weights for various time horizons (**Table 5**) to obtain the total greenhouse gas contribution in terms of carbon dioxide equivalents (CO_2e) per kWh (IPCC 2001, IPCC 2007) . As an example, **Table 6** summarizes greenhouse gas emissions (GHGs) for IGCC without CCS; similar tables for the other technologies appear in Appendix B.

Table 5: Global Warming Potential (IPCC 2001, IPCC 2007)

	Time Horizon			GWP
	20 Year	100 Year	500 Year	Year
CO_2	1	1	1	2007
CH_4	72	25	7.6	
N_2O	289	298	153	
SF_6	16,300	22,800	32,600	
CO_2	1	1	1	2001
CH_4	62	23	7	
N_2O	275	296	156	
SF_6	15,100	22,200	32,400	

Table 6: LC Greenhouse Gases for IGCC without CCS

kg/MWh		CO_2	CH_4	N_2O	SF_6	Total (kg CO_2e/MWh)
IGCC	Stage #1: RMA	2.83E+00	2.77E+00	4.40E-05	6.50E-11	7.22E+01
	Stage #2: RMT	1.31E+01	2.00E-02	3.13E-05	3.52E-11	1.36E+01
	Stage #3: ECF	8.42E+02	0.00E+00	2.10E-05	3.10E-07	8.42E+02
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.40E-04	3.19E+00
	Total	8.58E+02	2.79E+00	9.63E-05	1.40E-04	9.31E+02

For those technologies that include a CCS option, Power LCAT allows the user to vary the CO_2 capture percentage.[12] Power LCAT uses third-order polynomial equations for CO_2 emissions for SCPC and IGCC plants. NGCC and EXPC cases use a linear relationship derived from the base case with CCS. These relationships apply only for CO_2 emissions for stage #3 at the energy conversion facility. The default capture rate is 90%, with options for 0, 30, 50, 70, 85, 90, 95, and 99% capture.

[12] NETL has derived relationships for CO_2 emissions as a function of CO_2 capture rates which are summarized in Exhibit ES-14 (SCPC) and Exhibit ES-15 (IGCC) of the "Cost and Performance of PC and IGCC Plants for a Range of Carbon Dioxide Capture" (Grol 2011a).

The relationships between CO_2 emissions and CO_2 capture rates are derived from NETL reports (NETL, 2011a) and fit the form of equation 6:

$$y = cx^3 + dx^2 + ex + b \quad (6)$$

The coefficients for each technology for CO_2 capture rate as a function of CO_2 emissions for all five cases are summarized in **Table 7**[13],

where: y = CO_2 emissions
x = CO_2 capture rate
b = y-intercept.

Table 7: Coefficients for the Derivation of CO_2 Emissions for CCS Cases

	c	d	e	b	R^2
IGCC w/ ccs	-202.112	190.4997	-767.796	780.0882	0.99
SCPC w/ ccs	-60.30057	-231.545	-507.978	800.9534	1
NGCC w/ ccs	0	0	-379.71	393	1
EXPC w/ ccs	0	0	-338.684	462.6642	1

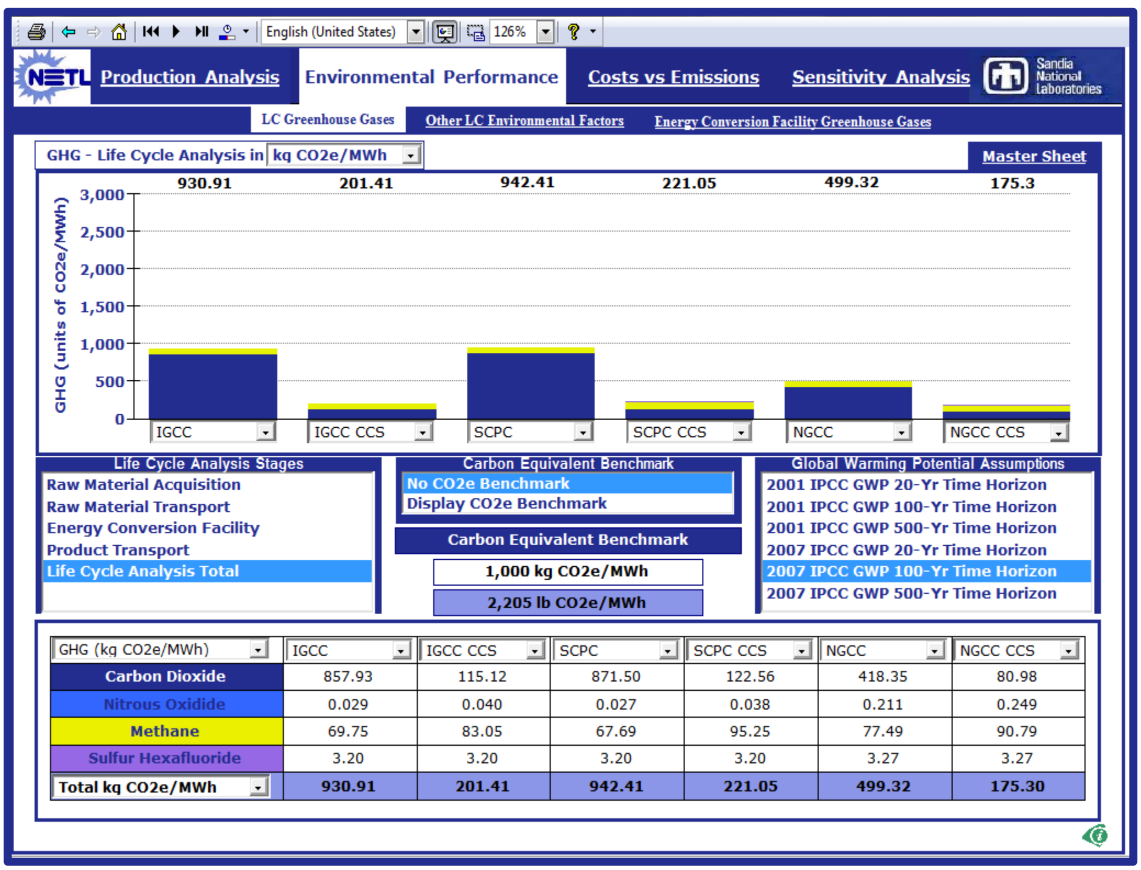
[13] Note that for NGCC the environmental profile for the ECF does not change based on the source of natural gas. Emissions related to raw material acquisition and material transport differ based on the increased plant size and coal throughput for the CCS case. Furthermore, natural gas is considered a commodity and hence the source of natural gas does not affect the fuel price assumption.

5.2 Environmental Performance Screen

The second main section of Power LCAT is "Environmental Performance" (**Figure 10**). This section tracks greenhouse gases and other environmental factors which can be chosen towards the top of the screen. The default screen for "Environmental Performance" includes both a graphical and tabular display of the greenhouse gases associated with each technology option (**Figure 10**). Greenhouse gas values are reported in terms of CO_2e calculated using 2007 IPCC GWP values for a 100 year time horizon, an assumption that can be changed in the table at the bottom of the screen. Users can evaluate emissions based on individual LCA stages in kg and lb. of CO_2e/MWh[14], choosing the stage at the middle-left of the screen and the unit choice at the top of the graph. Users can also set a CO_2e benchmark to see how various technology options compare to a specified policy target applied to any stage, such as 1000 kg/MWh.[15]

Major reductions in a plant's emissions can be achieved with CCS technologies. For example, with a 90% capture rate, emissions for the IGCC option are reduced from 930.9 to 201.4 kg CO_2e/MWh, a reduction of 80%. Changes to the GWP assumptions primarily affect methane emission profiles. For example, for an IGCC plant under 2007 IPCC GWP 20 year time horizon assumptions, methane

Figure 10: Environmenal Performance for Greenhouse Gases 2007 IPCC GWP 100-Yr Time Horizon



[14] Emissions on this screen are on a net generation basis and include a 7% transmission and distribution loss (i.e., a 1MWh demand by an end user requires 1.07MWh at the plant level).
[15] This option is explained further in the Energy Conversion Facility Greenhouse Gases section.

accounts for 19% of total emissions. Using the 100 and 500 year time horizons reduces methane's contribution to 7% and 2% respectively.

5.3 Other LC Environmental Factors

Non-greenhouse gases, water withdrawal, and water consumption are included in Power LCAT on a kilogram (kg) or liter (L) per MWh basis. Non-greenhouse gases include: lead (Pb), mercury (Hg), ammonia (NH_3), oxides of nitrogen (NO_X), sulfur oxide (SO_X), volatile organic compounds (VOC), and particulate matter (PM). Emissions or water use for each technology is categorized by stage: raw material acquisition (RMA), raw material transport (RMT), energy conversion facility (ECF), product transportation (PT), and end use.[16] As an example of Power LCAT's capabilities, **Table 8** summarizes the non-greenhouse gas emissions for the case of IGCC without CCS. Similar tables for other technologies are included in Appendix C.

Table 8: Other LC Environmental Factors for IGCC without CCS

kg/MWh	Pb	Hg	NH_3	CO	NO_X	SO_X	VOC	PM	Water Withdrawal	Water Consumption
Stage #1: RMA	2.90E-07	4.30E-08	2.40E-05	3.50E-03	5.20E-03	1.40E-02	1.00E-04	8.80E-04	1.50E+02	-5.94E+02
Stage #2: RMT	1.70E-07	1.40E-08	4.80E-04	4.00E-02	3.50E-02	7.80E-03	3.30E-03	4.40E-02	6.86E+00	2.16E+00
Stage #3: ECF	1.30E-05	2.40E-06	3.30E-06	5.10E-03	2.60E-01	8.40E-03	2.60E-04	3.10E-02	1.86E+03	1.48E+03
Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	1.35E-05	2.46E-06	5.07E-04	4.86E-02	3.00E-01	3.02E-02	3.66E-03	7.59E-02	2.02E+03	8.83E+02

[16] LC Stage #5 considers end user electricity consumption at a 100% efficiency with no environmental burden and is not included in this model (NETL 2010a, 2010b, 2010c, 2010d, 2010e, and 2011c).

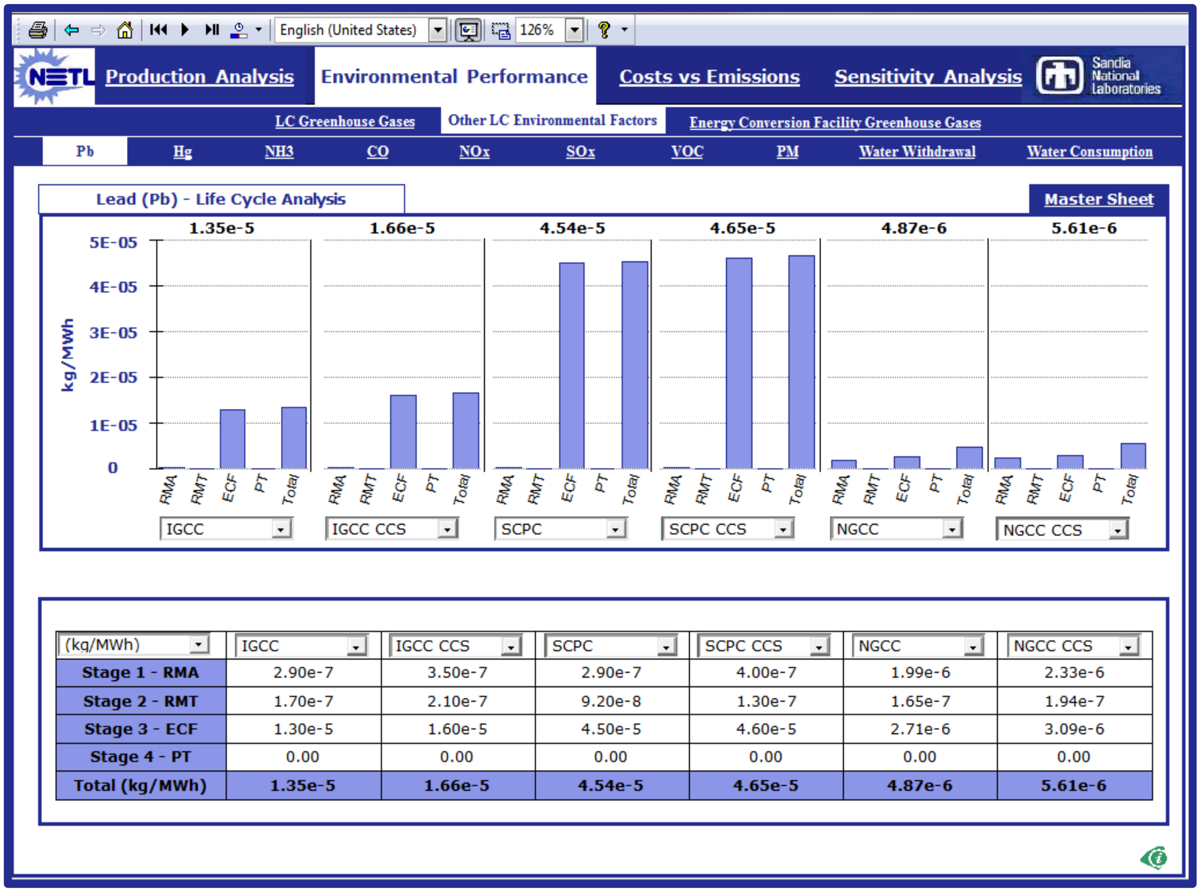
5.4 Other LC Environmental Factors Screen

Under the “Environmental Performance” tab, the user can choose “Other LC Environmental Factors” which shows the respective non-GHG emissions or water metrics using the technology choices similar to those found in “Production Analysis.” These metrics are given for each stage in both graphical and tabular form.

5.4.1 Other LC Environmental Factors: Lead

Figure 11 shows lead (Pb) emissions for the six default technologies indicating the majority of lead emissions occur from the energy conversion facility (ECF). For IGCC and SCPC, lead emissions at the ECF account for 97% and 99% of total LCA lead emissions. For an NGCC plant, lead emissions at the ECF account for 79% of total lead emissions. Similar screens exist for each of the other included pollutants as well as water withdrawal and consumption.

Figure 11: Environmental Performance for Other LC Environmental Factors: Pb

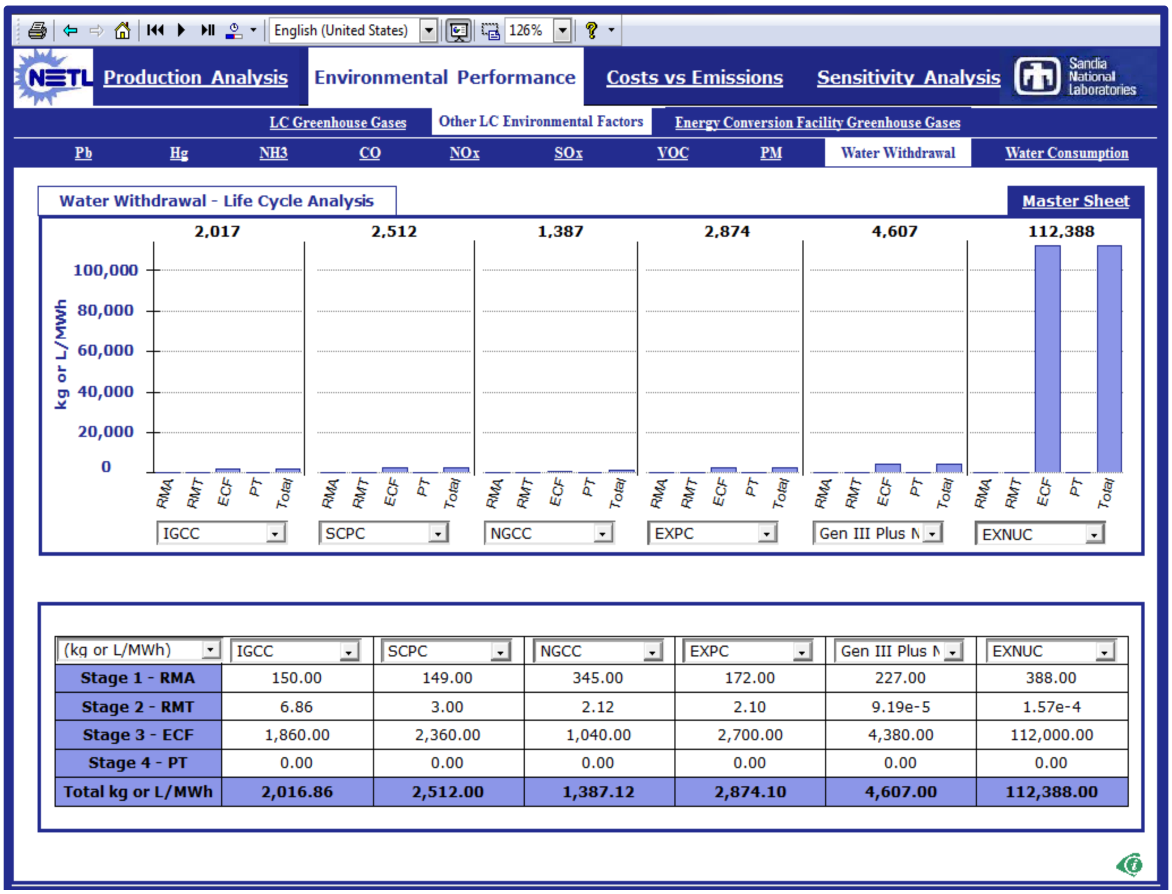


(kg/MWh)	IGCC	IGCC CCS	SCPC	SCPC CCS	NGCC	NGCC CCS
Stage 1 - RMA	2.90e-7	3.50e-7	2.90e-7	4.00e-7	1.99e-6	2.33e-6
Stage 2 - RMT	1.70e-7	2.10e-7	9.20e-8	1.30e-7	1.65e-7	1.94e-7
Stage 3 - ECF	1.30e-5	1.60e-5	4.50e-5	4.60e-5	2.71e-6	3.09e-6
Stage 4 - PT	0.00	0.00	0.00	0.00	0.00	0.00
Total (kg/MWh)	1.35e-5	1.66e-5	4.54e-5	4.65e-5	4.87e-6	5.61e-6

5.4.2 Other LC Environmental Factors: Water Withdrawal

An existing nuclear plant (EXNUC) has very similar environmental emissions as a new nuclear plant (Gen III+). For example, the GHG emissions from a EXNUC plant are 38.82 kg CO_2e/MWh versus 25.28 kg CO_2e/MWh for a Gen III+ plant. The differences are of the same magnitude for all other environmental factors except for water withdrawals due to major differences in cooling methods. The EXNUC nuclear plant is modeled with a once-through cooling method which results in greater water withdrawal.[17] For example, **Figure 12** shows the water withdrawal for IGCC, SCPC, NGCC, EXPC, Gen III+, and EXNUC. An EXNUC nuclear plant is two orders of magnitude larger than the next closest technology (Gen III+), 112,388 L/MWh compared to 4,607 L/MWh. The other non-CCS technologies shown in **Figure 12** are closer in magnitude to a Gen III+ nuclear plant, though the water withdrawal of EXPC, the next closest technology, is still considerably less at 2,874 L/MWh.

Figure 12: Environmental Performance for Other LC Environmental Factors: Water Withdrawal



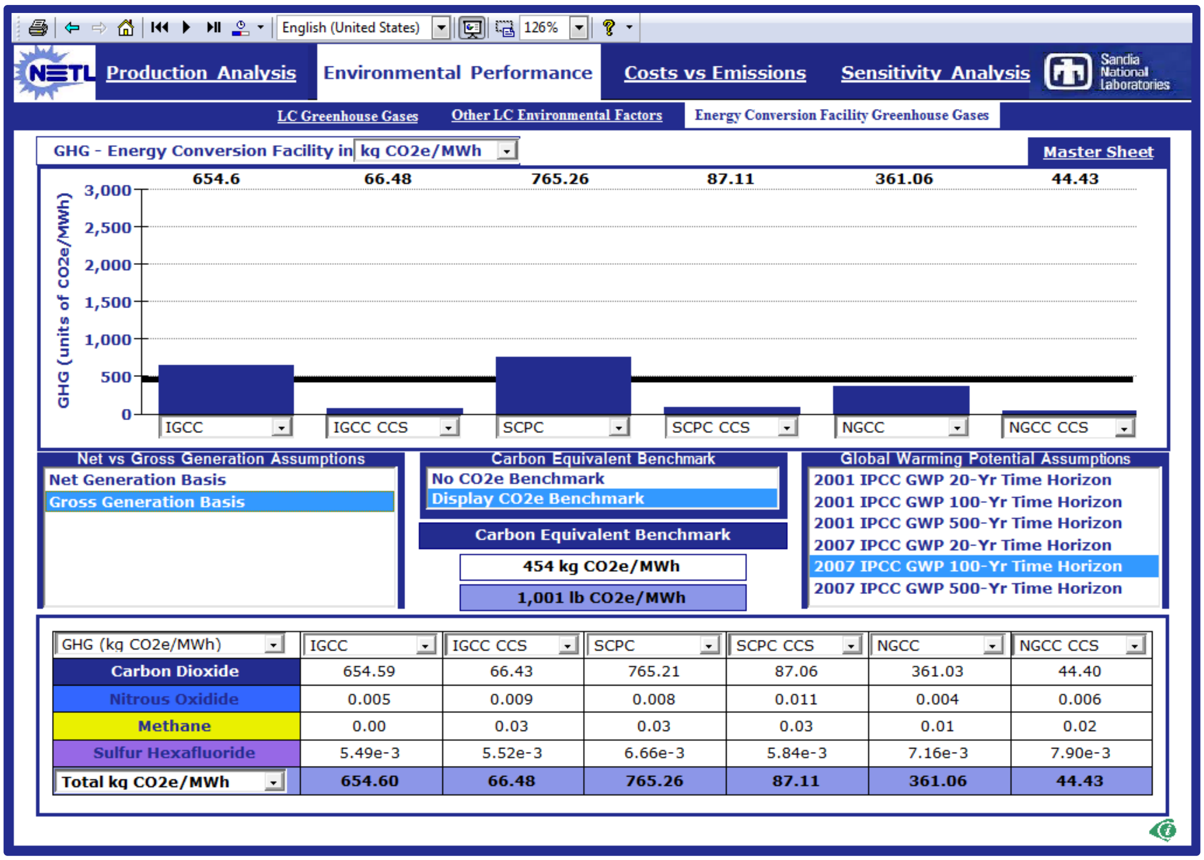
(kg or L/MWh)	IGCC	SCPC	NGCC	EXPC	Gen III Plus N	EXNUC
Stage 1 - RMA	150.00	149.00	345.00	172.00	227.00	388.00
Stage 2 - RMT	6.86	3.00	2.12	2.10	9.19e-5	1.57e-4
Stage 3 - ECF	1,860.00	2,360.00	1,040.00	2,700.00	4,380.00	112,000.00
Stage 4 - PT	0.00	0.00	0.00	0.00	0.00	0.00
Total kg or L/MWh	**2,016.86**	**2,512.00**	**1,387.12**	**2,874.10**	**4,607.00**	**112,388.00**

[17] The existing nuclear power fleet (EXNUC) uses once-through cooling technology. The EXNUC design in this model and the NETL report (referred to as Gen II-III [NETL, 2011c]) represent a plant with once-through cooling technology only. A comparison to a closed-loop cooling system for water withdrawal and consumption only can be performed by evaluating the Gen III+ plant type.

5.5 Energy Conversion Facility Greenhouse Gases

This section lets users evaluate how various technology options compare to specified policy targets applied at the energy conversion facility on either a net or gross kg or lb. of CO_2e/MWh basis, **Figure 13**. Emissions on this screen exclude any transmission and distribution losses assigned to this stage in other sections of the model (the default cases assume that a 7% loss in getting the power from the plant to the end user). The net basis considers only the electricity delivered to the grid at the plant gate, whereas the gross basis includes the power consumed within the plant itself.

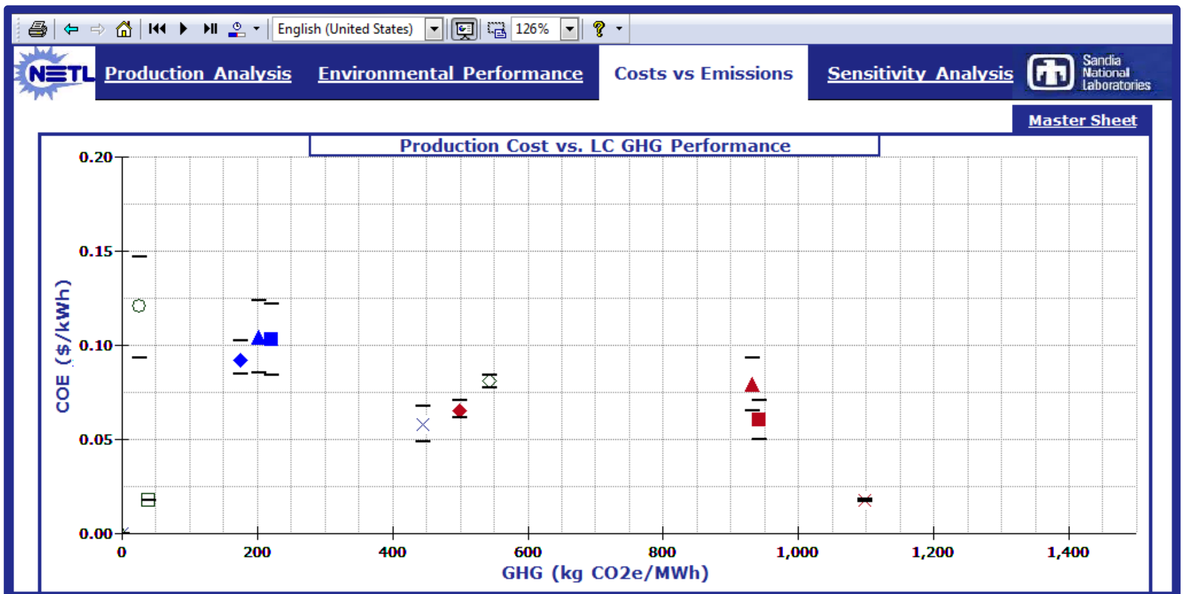
Figure 13: Energy Conversion Facility Greenhouse Gases with Carbon Equivalent Benchmark on a Gross Generation Basis



6 Costs vs. Emissions

The "Costs vs. Emissions" section (the third major section in Power LCAT) explores the tradeoffs between production costs ($/kWh) and Life Cycle (LC) GHG performance (kg CO_2e/MWh), **Figure 14**. The results shown in this section are dynamic for the cost and emission estimates. The emission estimates are based on the relationships explained in the previous section. 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 1097 to 444 kg CO_2e/MWh), but increases the costs significantly (4.04 cents/kWh) to a level comparable to a new NGCC plant without sequestration with comparable emissions (499 kg CO_2e/MWh). Those options with lower emission profiles all include CCS. The lowest emission rate (25 kg CO_2/MWh) is for the Gen III+ nuclear option although the costs are slightly above an IGCC with CCS plant, 10.78 cents/kWh versus 10.44 cents/kWh, the next most costly option.

Figure 14: Costs vs. Emissions (labels added showing technologies discussed in text)



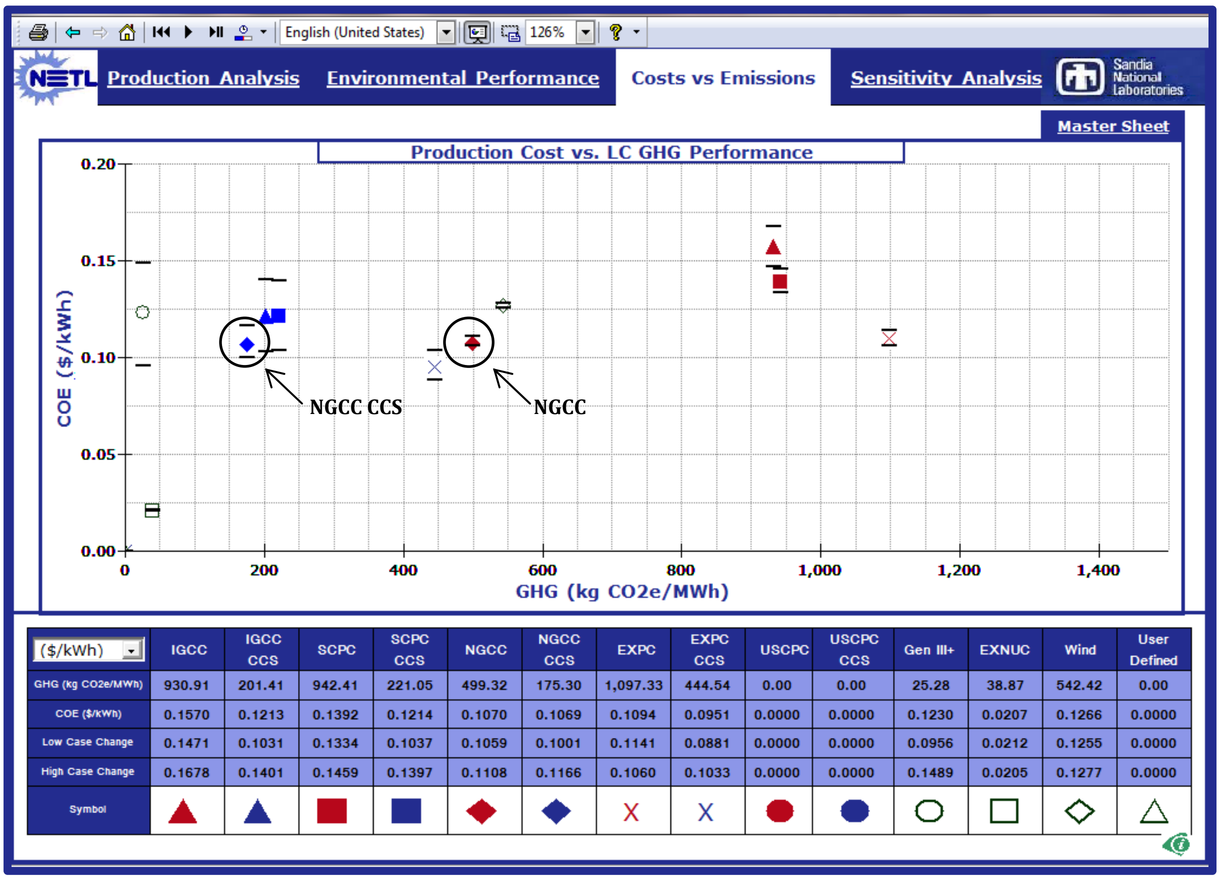
($/kWh)	IGCC	IGCC CCS	SCPC	SCPC CCS	NGCC	NGCC CCS	EXPC	EXPC CCS	USCPC	USCPC CCS	Gen III+	EXNUC	Wind	User Defined
GHG (kg CO2e/MWh)	930.91	201.41	942.41	221.05	499.32	175.30	1,097.33	444.54	0.00	0.00	25.28	38.87	542.42	0.00
COE ($/kWh)	0.0790	0.1044	0.0601	0.1028	0.0652	0.0922	0.0174	0.0578	0.0000	0.0000	0.1208	0.0174	0.0811	0.0000
Low Case Change	0.0649	0.0853	0.0502	0.0842	0.0618	0.0846	0.0172	0.0488	0.0000	0.0000	0.0934	0.0178	0.0776	0.0000
High Case Change	0.0934	0.1240	0.0706	0.1220	0.0709	0.1025	0.0184	0.0678	0.0000	0.0000	0.1469	0.0174	0.0844	0.0000
Symbol														

The black bars in **Figure 14** represent the sensitivity of the total COE based on assumptions made in the "Sensitivity Analysis" section of Power LCAT. Based on those assumptions, the plant with the highest sensitivity to changes in estimates is a Gen III+ nuclear plant with a high and low estimated change of 21% and -22% of total COE respectively. Of the CCS options, IGCC with CCS is most sensitive to changes in estimates with high and low estimates of 19% and -18% of total COE respectively. For IGCC with CCS and Gen III+, the most sensitive parameter and representing the largest addition to COE is capital cost. "Sensitivity Analysis" is explained in the next section.

6.1 Costs vs Emissions Including a Carbon Tax

The "Cost vs. Emission" section can also provide valuable insights about how carbon taxes can change the relative competiveness of the various options. **Figure 15** illustrates the effect of a 78 \$/ton CO_2e tax, the tax level at which NGCC with CCS becomes cost competitive with NGCC without CCS. The user can change the carbon tax from the "Financial" tab on the "Production Analysis" or "Master Sheet" screen. Note at this tax level, options such as SCPC and IGCC (both without CCS) are significantly more expensive than the options such as NGCC with CCS.

Figure 15: Using the "Cost vs. Emission" Screen to Demonstrate Effect of a \$78/ton CO_2e Tax

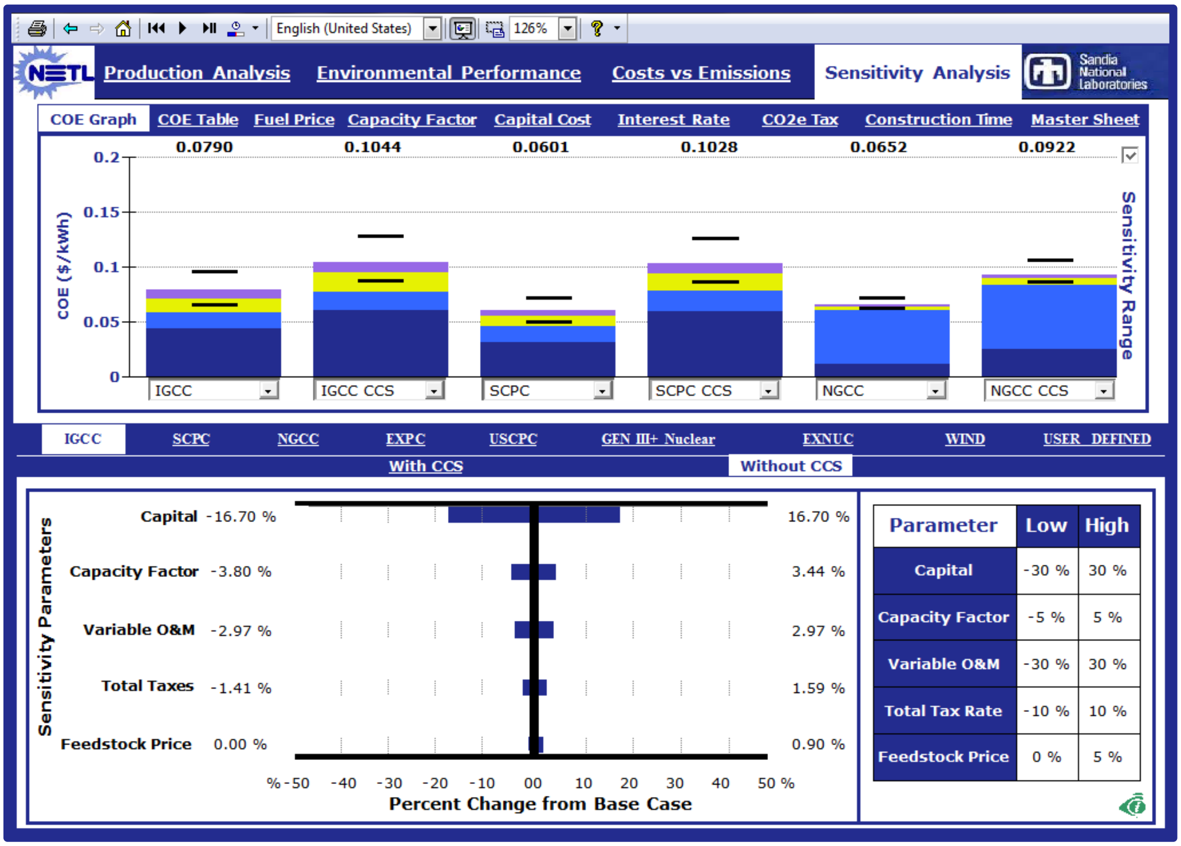


($/kWh)	IGCC	IGCC CCS	SCPC	SCPC CCS	NGCC	NGCC CCS	EXPC	EXPC CCS	USCPC	USCPC CCS	Gen III+	EXNUC	Wind	User Defined
GHG (kg CO2e/MWh)	930.91	201.41	942.41	221.05	499.32	175.30	1,097.33	444.54	0.00	0.00	25.28	38.87	542.42	0.00
COE ($/kWh)	0.1570	0.1213	0.1392	0.1214	0.1070	0.1069	0.1094	0.0951	0.0000	0.0000	0.1230	0.0207	0.1266	0.0000
Low Case Change	0.1471	0.1031	0.1334	0.1037	0.1059	0.1001	0.1141	0.0881	0.0000	0.0000	0.0956	0.0212	0.1255	0.0000
High Case Change	0.1678	0.1401	0.1459	0.1397	0.1108	0.1166	0.1060	0.1033	0.0000	0.0000	0.1489	0.0205	0.1277	0.0000
Symbol	▲	▲	■	■	◆	◆	X	X	●	●	○	□	◇	△

7 Sensitivity Analysis

The "Sensitivity Analysis" section (the fourth major section in LCAT) allows one to vary several assumptions simultaneously (capital costs, capacity factors, variable O&M costs, tax rates, and fuel prices) and view the results graphically as a 'tornado plot' on the bottom left of the screen and as "Sensitivity Range" bars on the graph located on the top of the screen. **Figure 16** shows an example for IGCC without CCS. The base case assumes capital costs of 2,446 $/kW which results in estimated production costs of 0.0790 $/kWh. If capital costs either increase or decrease by 30% from the base, capital costs change by +/-16.7%. A 5% increase in assumed capacity factor decreases estimated production costs by 3.44%. The cumulative effect of the uncertainty ranges shown in this example ranges from 0.0934 to 0.0649 $/kWh shown by the black bars on the graph at the top of the screen. The black bars can be turned on and off by clicking the check box at the far right of the graph labeled "Sensitivity Range."

Figure 16: Illustrative Example Using "Sensitivity Analysis" Section for IGCC

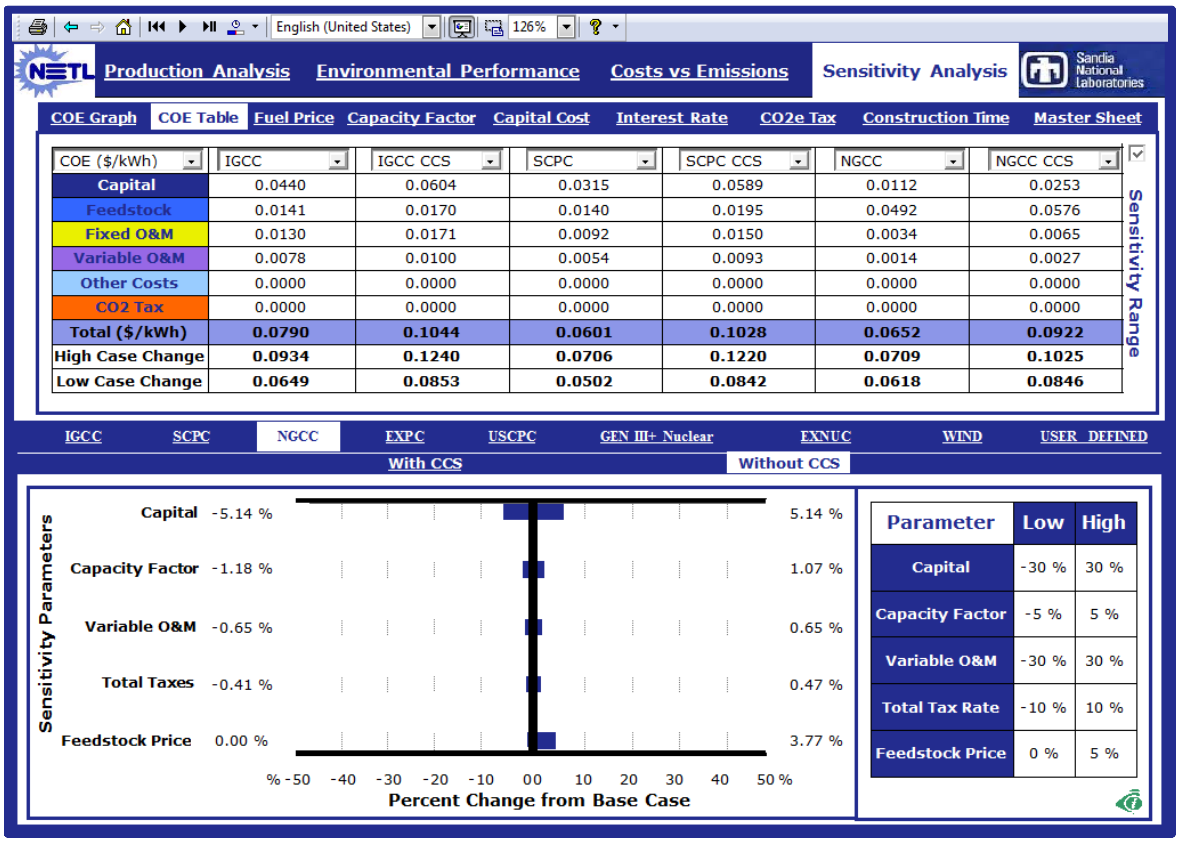


7.1 Tornado Plot and High/Low Sensitivity Table

The sensitivity results can also be displayed in tabular form, **Figure 17**. This example focuses on NGCC. For the NGCC technology, a 30% increase or decrease in capital costs results in a +/- 5.14% change in estimated production costs. The cumulative uncertainty associated with the sensitivities in this example result in a high and low change of 8.82% and -5.18%.

Figure 17 shows the sensitivity results in tabular format and shows that the percent contribution of certain cost components and the percent uncertainty around those estimates affect certain technologies more than others. The +/- 16% sensitivity to a +/- 30% change in capital cost for an IGCC plant shown in **Figure 17** results in a greater overall change to the COE compared to the overall change in COE for a NGCC plant on account of capital costs comprising a larger part of production costs. For the NGCC plant, the largest addition to an NGCC plant can be found in the feedstock costs, 62% to 75%. Since natural gas plants have lower capital costs and are subject to larger fuel prices, the modest default assumption for changes in natural gas feedstock price explains the smaller change in total COE.

Figure 17: Illustrative Example Using "Sensitivity Analysis" Section for NGCC



7.2 Sensitivity and Break-Even Analysis for Different Parameters

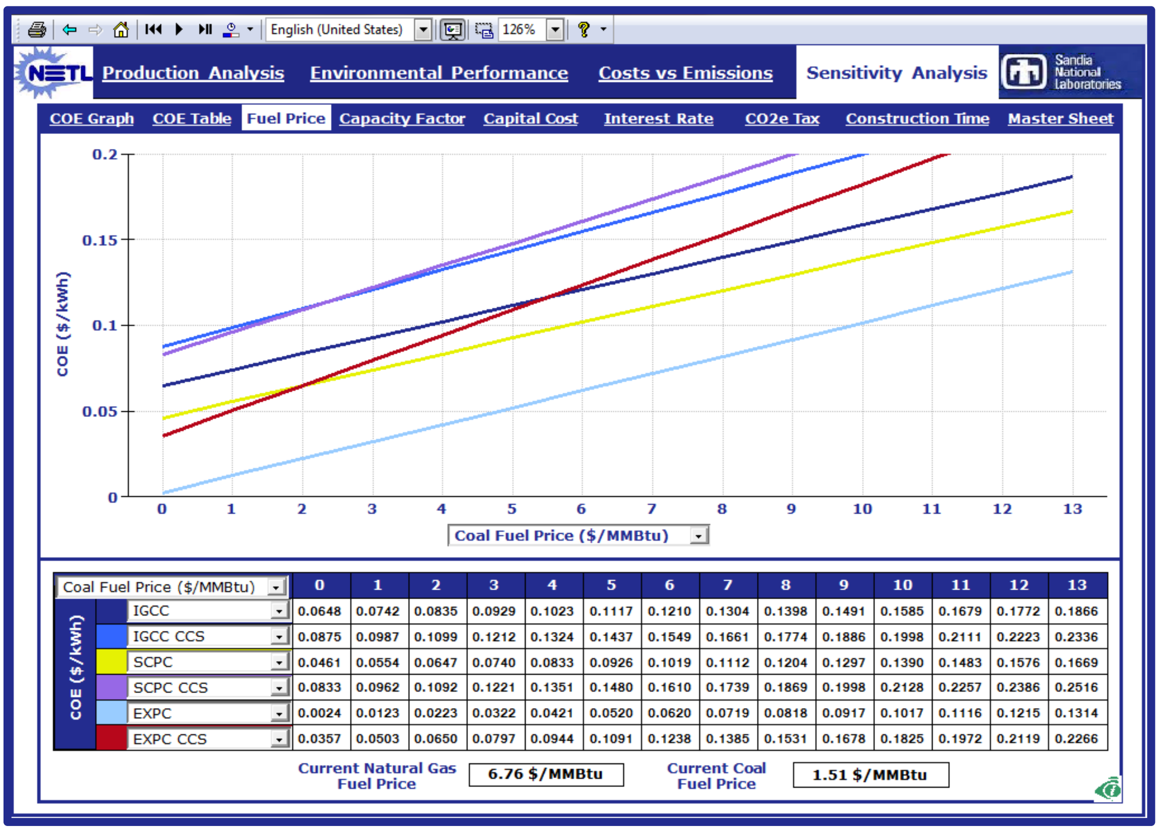
The “Sensitivity Analysis” section also provides the option for evaluating the sensitivity of COE as a function of fuel price, capacity factor, capital cost, interest rate, CO_2e tax, and construction time.

7.2.1 Sensitivty Analysis: Coal Fuel Price

Figure 18 illustrates the production cost sensitivity to coal prices over a range of 0 to 13 $/MMBtu. The EXPC plant with a carbon capture and sequestration retrofit is most sensitive (has the steepest slope in **Figure 18**) to fuel prices. The SCPC plant is least sensitive to coal price changes. For reference, the assumed coal and natural gas fuel prices are shown at the bottom of the screen.

This type of analysis is useful for understanding the fuel price ranges over which technologies are economically competitive, holding all else constant. For example, for the case of coal prices, the results suggest that retrofitting an EXPC plant with CCS is the lowest cost option for coal prices below 2.00 $/MMBtu. However, none of the other price relationships change, suggesting that coal prices alone will not affect relative competitiveness of the coal technologies.

Figure 18: Illustrative Example Using “Sensitivity Analysis” Section for Coal Fuel Price

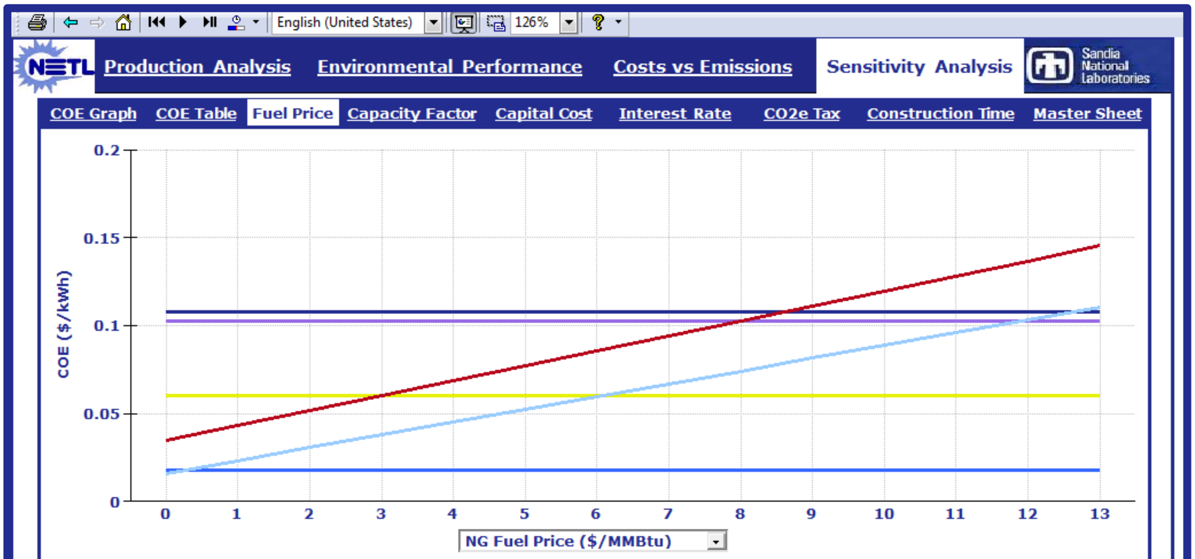


Coal Fuel Price ($/MMBtu)	0	1	2	3	4	5	6	7	8	9	10	11	12	13
IGCC	0.0648	0.0742	0.0835	0.0929	0.1023	0.1117	0.1210	0.1304	0.1398	0.1491	0.1585	0.1679	0.1772	0.1866
IGCC CCS	0.0875	0.0987	0.1099	0.1212	0.1324	0.1437	0.1549	0.1661	0.1774	0.1886	0.1998	0.2111	0.2223	0.2336
SCPC	0.0461	0.0554	0.0647	0.0740	0.0833	0.0926	0.1019	0.1112	0.1204	0.1297	0.1390	0.1483	0.1576	0.1669
SCPC CCS	0.0833	0.0962	0.1092	0.1221	0.1351	0.1480	0.1610	0.1739	0.1869	0.1998	0.2128	0.2257	0.2386	0.2516
EXPC	0.0024	0.0123	0.0223	0.0322	0.0421	0.0520	0.0620	0.0719	0.0818	0.0917	0.1017	0.1116	0.1215	0.1314
EXPC CCS	0.0357	0.0503	0.0650	0.0797	0.0944	0.1091	0.1238	0.1385	0.1531	0.1678	0.1825	0.1972	0.2119	0.2266

7.2.2 Sensitivity Analysis: Natural Gas Fuel Price

Figure 19 shows the sensitivity of natural gas plants to changes in fuel price. Omitting EXNUC which excludes capital costs, NGCC is the lowest cost option for natural gas prices below 6 \$/MMBtu (0.0596 \$/kWh). For natural gas prices below 8 \$/MMBtu, the NGCC with CCS option is the lowest CCS option (0.1028 \$/kWh). Natural gas prices would have to rise above 9 \$/MMBtu for a new Gen III+ nuclear plant to be competitive with NGCC with CCS.

Figure 19: Illustrative Example Using "Sensitivity Analysis" Section for Natural Gas Fuel Price



NG Fuel Price ($/MMBtu)	0	1	2	3	4	5	6	7	8	9	10	11	12	13
Gen III Plus Nucle	0.1078	0.1078	0.1078	0.1078	0.1078	0.1078	0.1078	0.1078	0.1078	0.1078	0.1078	0.1078	0.1078	0.1078
EXNUC	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174
SCPC	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601
SCPC CCS	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028
NGCC	0.0160	0.0233	0.0305	0.0378	0.0451	0.0524	0.0596	0.0669	0.0742	0.0815	0.0887	0.0960	0.1033	0.1106
NGCC CCS	0.0346	0.0431	0.0516	0.0602	0.0687	0.0772	0.0858	0.0943	0.1028	0.1113	0.1199	0.1284	0.1369	0.1454

COE ($/kWh)

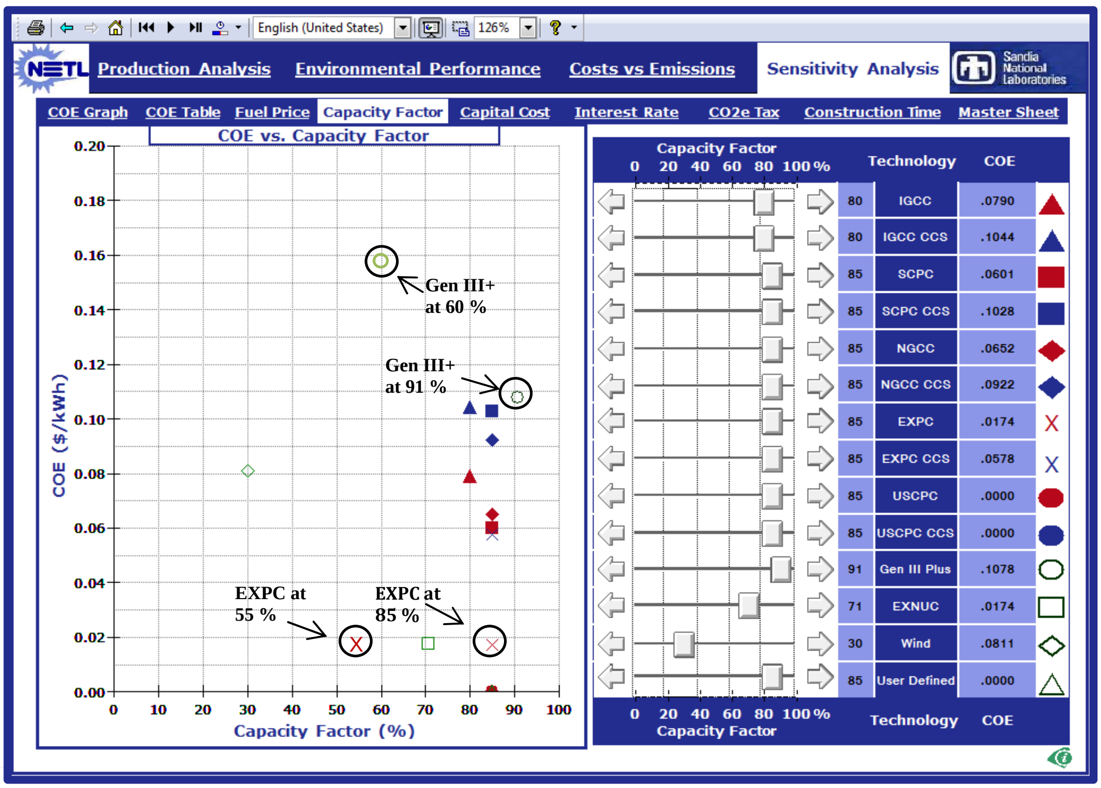
Current Natural Gas Fuel Price: 6.76 $/MMBtu

Current Coal Fuel Price: 1.51 $/MMBtu

7.2.3 Sensitivity Analysis: Capacity Factor

The user can also see the sensitivity to varying capacity factor assumptions by using an interactive slider. **Figure 20** shows the production cost of all technologies as a function of capacity factor starting at their default assumptions. By using the sliders, the user can quickly see how changes in capacity factor affect the COE in a non-linear manner. For example, by changing the capacity factor assumptions for Gen III+ from 91% to 60%, the COE increases from to 0.1208 to 0.1796 $/kWh, or 49% .[18] For an EXPC plant the capital costs have already been recovered, therefore changing the capacity factor from 85% to 55% results in the COE increasing from 0.0174 to 0.0182 $/kWh, or 6%.

Figure 20: Illustrative Example Using "Sensitivity Analysis" Section for Capacity Factor



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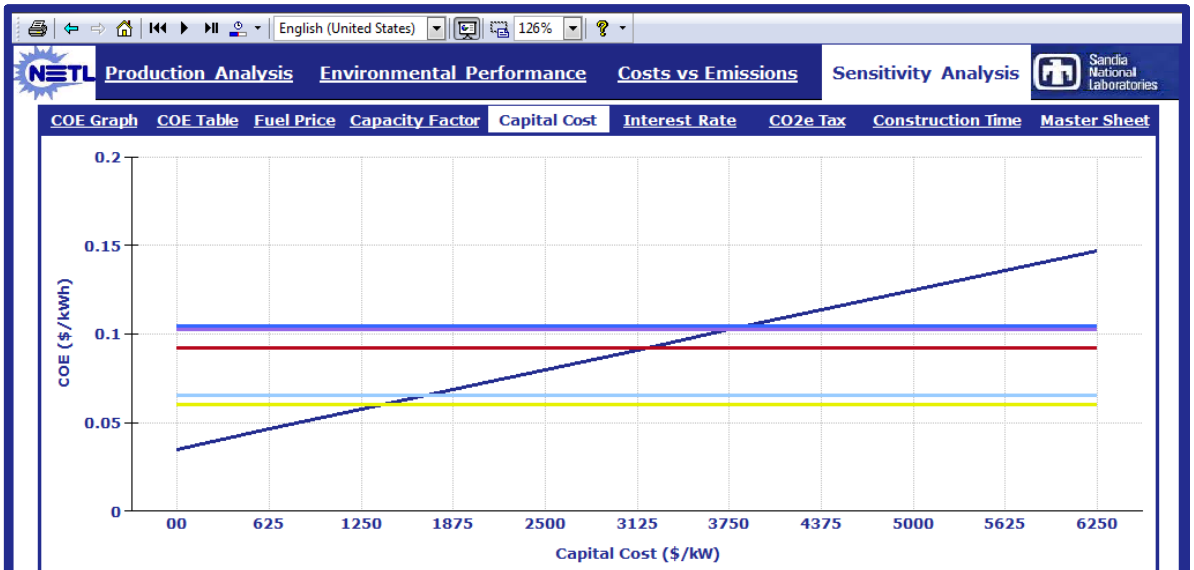
[18] Note that the marker indicating Gen III+ and EXPC respectively at 55% and 60% capacity factor is included for comparison. When using the interactive slider, the original marker will move and the user will no longer see the original position.

7.2.4 Break-Even Analysis: IGCC Capital Cost

An additional option in the "Sensitivity Analysis" section of the model is referred to as "Break-Even Analysis." This option lets users identify the point at which one technology becomes cost competitive with the other technology choices holding those technologies constant. When doing break even analysis, the only technology changing is the first technology in the table. For example, **Figure 21** shows a break-even analysis for the IGCC option indicating that an IGCC plant is cost competitive with a NGCC plant for the capital costs below 1,680 $/kW. The default capital cost for an IGCC plant is 2,446 $/kW, meaning that holding all else constant, the capital costs for the IGCC plant would have to be reduced below 766 $/kW, or 31%, to be economically competitive with a new natural gas plant. For IGCC capital costs above 3,175 $/kW, the technologies with CCS become competitive.

Figure 21: Illustrative Example Using "Break-Even Analysis" Option for IGCC Capital Cost



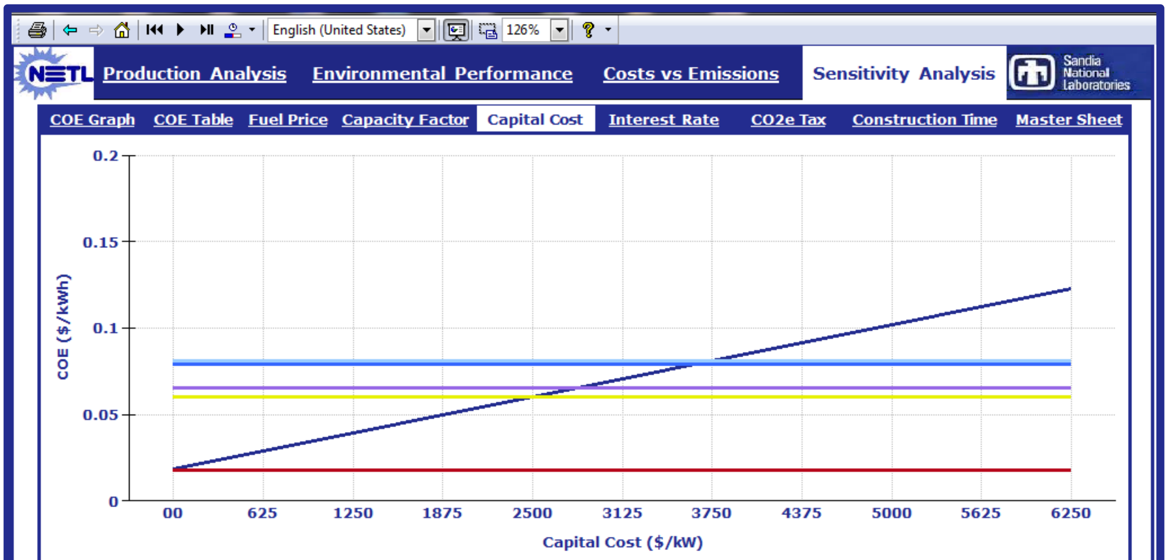
Capital Cost ($/kW) — Break-Even Analysis	0	625	1,250	1,875	2,500	3,125	3,750	4,375	5,000	5,625	6,250
IGCC	0.0350	0.0462	0.0575	0.0687	0.0799	0.0911	0.1024	0.1136	0.1248	0.1361	0.1473
IGCC CCS	0.1044	0.1044	0.1044	0.1044	0.1044	0.1044	0.1044	0.1044	0.1044	0.1044	0.1044
SCPC	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601
SCPC CCS	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028	0.1028
NGCC	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652
NGCC CCS	0.0922	0.0922	0.0922	0.0922	0.0922	0.0922	0.0922	0.0922	0.0922	0.0922	0.0922

COE ($/kWh)

7.2.5 Break-Even Analysis: Nuclear Capital Cost

A Gen III+ nuclear plant has the highest capital cost of all the technologies (4,500 $/kW). **Figure 22** shows the break-even point for a Gen III+ nuclear plant capital cost against IGCC, SCPC, NGCC, wind with GTSC backup, and EXNUC nuclear plant.[19] The results show that a new nuclear plant would have to bring its capital costs below 2,500 $/kW to be economically competitively with the non-CCS technologies. Capital costs would have to fall below 1,250 $/kW for the Gen III+ nuclear plant option to be competitive with a new SCPC plant, all else constant. EXNUC is the lowest cost option under this scenario due to the lack of capital costs.

Figure 22: Illustrative Example Using "Break-Even Analysis" Option for Gen III+ Nuclear Capital Cost



Capital Cost ($/kW) Break-Even Analysis	0	625	1,250	1,875	2,500	3,125	3,750	4,375	5,000	5,625	6,250
COE ($/kWh) Gen III Plus Nucle	0.0184	0.0289	0.0393	0.0498	0.0602	0.0706	0.0811	0.0915	0.1019	0.1124	0.1228
IGCC	0.0790	0.0790	0.0790	0.0790	0.0790	0.0790	0.0790	0.0790	0.0790	0.0790	0.0790
SCPC	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601	0.0601
NGCC	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652	0.0652
Onshore Wind	0.0811	0.0811	0.0811	0.0811	0.0811	0.0811	0.0811	0.0811	0.0811	0.0811	0.0811
EXNUC	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174	0.0174

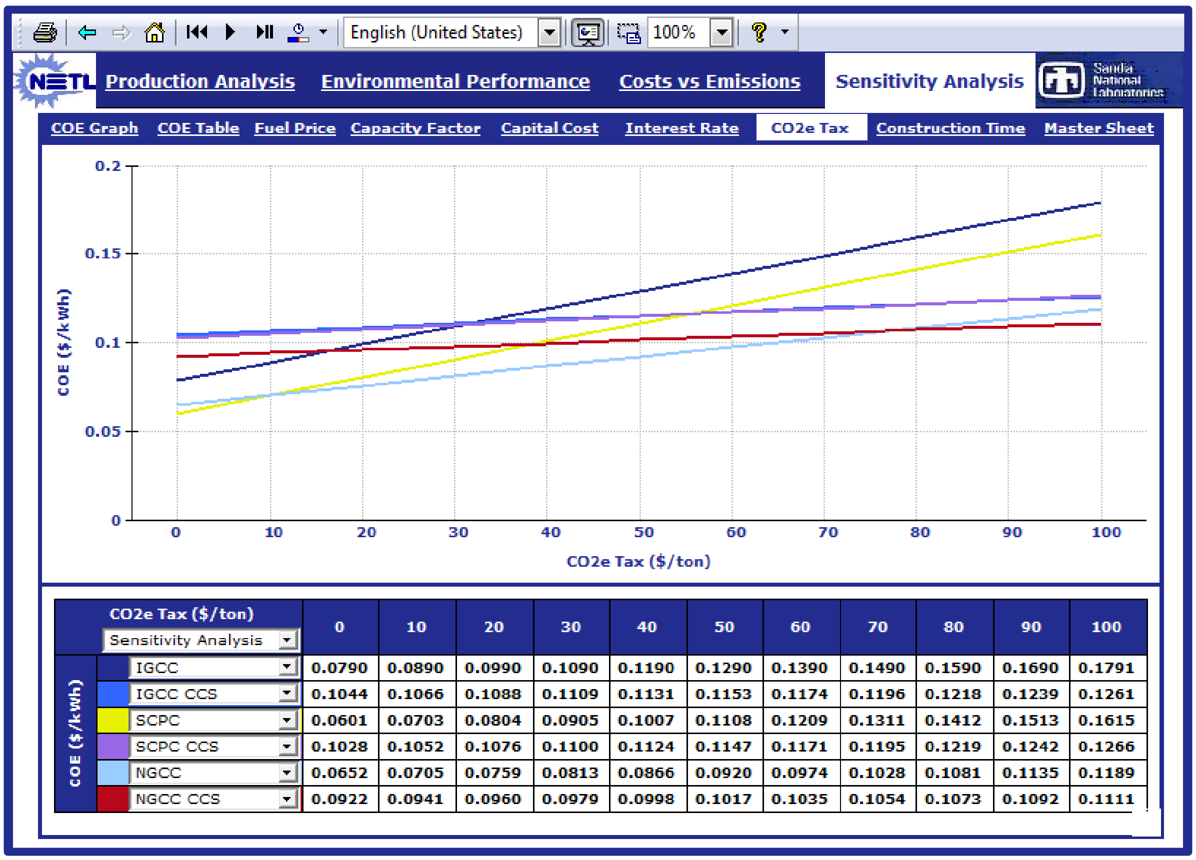
[19] NETL assumes a capital cost for existing nuclear plants to reflect an industry average for existing plants NETL (NETL 2011c). EXNUC represents a currently operating nuclear plant thus capital costs have been set to zero for a relative assessment similar to EXPC plants for this model.

7.2.6 Break-Even Analysis: CO_2e Tax

Users can evaluate scenarios for different levels of a carbon tax under the “Finance” tab on the “Production Analysis” screen. In addition, in the section discussing the “Costs vs Emissions” screen, the effects of a carbon equivalent tax showed the carbon equivalent tax at which an NGCC with a carbon sequestration option became cost competitive with an NGCC plant (78 $/ton). Users can also use the “Sensitivity Analysis” screen to evaluate the addition of a CO_2e tax.

Figure 23 shows a range of carbon equivalent taxes from 0 to 100 $/ton on the life cycle emissions of the default technologies. The results show that IGCC, SCPC, and NGCC with carbon capture and sequestration become cost competitive with their CCS counterparts at 33, 55, and 78 $/ton respectively. Of the non-CCS default technologies, NGCC is the least sensitive when subjected to the current tax scenario, evident by having the slope with the least amount of change.

Figure 23: Illustrative Example Using “Break-Even Analysis” Option for CO_2e Tax



CO2e Tax ($/ton) Sensitivity Analysis	0	10	20	30	40	50	60	70	80	90	100
IGCC	0.0790	0.0890	0.0990	0.1090	0.1190	0.1290	0.1390	0.1490	0.1590	0.1690	0.1791
IGCC CCS	0.1044	0.1066	0.1088	0.1109	0.1131	0.1153	0.1174	0.1196	0.1218	0.1239	0.1261
SCPC	0.0601	0.0703	0.0804	0.0905	0.1007	0.1108	0.1209	0.1311	0.1412	0.1513	0.1615
SCPC CCS	0.1028	0.1052	0.1076	0.1100	0.1124	0.1147	0.1171	0.1195	0.1219	0.1242	0.1266
NGCC	0.0652	0.0705	0.0759	0.0813	0.0866	0.0920	0.0974	0.1028	0.1081	0.1135	0.1189
NGCC CCS	0.0922	0.0941	0.0960	0.0979	0.0998	0.1017	0.1035	0.1054	0.1073	0.1092	0.1111

8 Conclusion

The Power LCAT is a high-level dynamic model that calculates production costs and tracks environmental performance for a range of electricity generation technologies: natural gas combined cycle (NGCC), integrated gasification combined cycle (IGCC), supercritical pulverized coal (SCPC), existing pulverized coal (EXPC), nuclear, and wind (with and without backup power). 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. Power LCAT is targeted at helping policy makers, students, and interested stakeholders understand the economic and environmental tradeoffs associated with various electricity production options.

Power LCAT has four main sections: "Production Analysis", "Environmental Performance", "Costs vs. Emissions", and "Sensitivity Analysis." The "Production Analysis" section calculates the COE ($/kWh) for each option and allows users to explore key sensitivities. The "Environmental Performance" section estimates aggregate greenhouse gas and non-greenhouse gas emissions, as well as water usage at each stage of the life cycle analysis. The "Costs vs. Emissions" section explores the tradeoffs between costs ($/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.

The technology options are based on detailed life cycle analysis (LCA) 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 (PT), and end user electricity consumption.

For the default model assumptions, the results show that for the fossil fuel technology options the supercritical pulverized coal plant is the lowest cost option at 6.01 cents/kWh. The next lowest cost fossil fuel option is the natural gas combined cycle plant (6.52 cents/kWh) and then the integrated gasification combined cycle plant (7.90 cents/kWh). Of the nuclear options, the EXNUC plant is the lowest cost option at 1.74 cents /kWh followed by a Gen III+ plant at 10.78 cents/kWh. Power LCAT currently includes one renewable technology option – a 200 MW wind turbine (with or without backup). For the default assumptions, the COE for the standalone option is 4.91 cents/kWh and 8.11 cents/kWh with a gas turbine simple cycle backup.

9 References

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IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

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Appendix A

List of Tables

Appendix A: New Technology Assumptions for Power LCAT Version 2.0

Template for adding a new technology to Power LCAT

Unit	Parameter	
$/kW	Total Overnight Cost	-----
$/kW	Fixed O&M Base Year Cost	-----
$/kWh	Variable O&M Base Year Cost	-----
Years	Capital Expenditure Period	-----
MW	Electricity Net	-----
%	Capacity Factor	-----
Btu/kWh	Heat Rate	-----
$/kWh	Decommissioning Constant	-----
$/kWh	CO_2 T, S & M Costs	-----
%	CO_2 Capture Rate	-----
$/kWh	Switchyard & Trunkline Constant	-----
Years	Depreciation Period	-----
Years	Economic Plant Life (levelization period)	-----
%	Interest Rate During Construction	-----
%	Cost of Equity Financing	-----
%	Cost of Debt Financing	-----
%	Debt Financing Percent	-----

Other parameters included in Power LCAT, but not considered in NETL LCA reports

%	Fraction To Be Depreciated	-----
%	Risk Assessment	-----
%	Annual Insurance Cost	-----
%	Tax Credit	-----
%	Other Taxes	-----

Template for including dynamic parameters based on CO_2 capture rate to Power LCAT

Units	Parameter *	c	d	e	y-intercept
Btu/kWh	Heat Rate	-----	-----	-----	-----
$/kW	Total Overnight Cost	-----	-----	-----	-----
lb. or kg/MWh	CO_2 Emissions	-----	-----	-----	-----

* These are based on equation:

$$y=cx^3+dx^2+ex+b$$

where:

y = parameter
x = CO_2 capture rate
b = y-intercept

Derived from NETL study:
National Energy Technology Laboratory. *Cost and Performance of PC and IGCC Plants for a Range of Carbon Dioxide Capture.* DOE/NETL-2011/1498. May 27, 2011.

Additional Assumptions to Power LCAT

$/MMBtu	Fuel Price	-----
%	Federal Taxes	-----
%	State Taxes	-----
%	Transmission Loss	-----

Appendix B

List of Tables

Appendix B: Greenhouse Gas Metrics for Environmental Performance

Natural Gas Plants: Greenhouse Gases						
kg/MWh		CO_2	CH_4	N_2O	SF_6	Total (kg CO_2e/MWh)
NGCC with Domestic NG	Stage #1: RMA	2.14E+01	2.33E+00	6.68E-04	1.77E-07	7.97E+01
	Stage #2: RMT	3.95E+00	7.69E-01	2.51E-05	8.99E-09	2.32E+01
	Stage #3: ECF	3.93E+02	5.94E-04	1.51E-05	3.42E-07	3.93E+02
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.43E-04	3.27E+00
	Total	4.18E+02	3.09E+00	7.08E-04	1.44E-04	4.99E+02
NGCC CCS with Domestic NG	Stage #1: RMA	2.51E+01	2.73E+00	7.83E-04	2.07E-07	9.34E+01
	Stage #2: RMT	4.62E+00	9.01E-01	2.95E-05	1.05E-08	2.72E+01
	Stage #3: ECF	5.13E+01	7.78E-04	2.35E-05	4.00E-07	5.13E+01
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.43E-04	3.27E+00
	Total	8.10E+01	3.63E+00	8.36E-04	1.44E-04	1.75E+02
NGCC with Imported NG	Stage #1: RMA	1.06E+02	9.99E-01	1.23E-03	1.46E-07	1.31E+02
	Stage #2: RMT	3.95E+00	7.69E-01	2.51E-05	8.99E-09	2.32E+01
	Stage #3: ECF	3.93E+02	5.94E-04	1.51E-05	3.42E-07	3.93E+02
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.43E-04	3.27E+00
	Total	5.03E+02	1.77E+00	1.27E-03	1.44E-04	5.50E+02
NGCC CCS with Imported NG	Stage #1: RMA	1.24E+02	1.17E+00	1.44E-03	1.71E-07	1.53E+02
	Stage #2: RMT	4.62E+00	9.01E-01	2.95E-05	1.05E-08	2.72E+01
	Stage #3: ECF	5.13E+01	7.78E-04	2.35E-05	4.00E-07	5.13E+01
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.43E-04	3.27E+00
	Total	1.80E+02	2.07E+00	1.49E-03	1.44E-04	2.35E+02
GTSC Domestic NG	Stage #1: RMA	3.30E+01	3.58E+00	1.03E-03	2.72E-07	1.23E+02
	Stage #2: RMT	6.08E+00	1.18E+00	3.88E-05	1.38E-08	3.57E+01
	Stage #3: ECF	6.04E+02	1.20E-03	1.30E-05	1.97E-08	6.04E+02
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.43E-04	3.27E+00
	Total	6.43E+02	4.77E+00	1.08E-03	1.44E-04	7.65E+02
Nuclear Plants: Greenhouse Gases						
Existing Nuclear	Stage #1: RMA	3.10E+01	6.30E-02	4.95E-04	2.79E-07	3.28E+01
	Stage #2: RMT	5.50E-05	1.05E-07	1.13E-09	3.66E-17	5.80E-05
	Stage #3: ECF	2.84E+00	1.64E-03	1.35E-05	1.98E-08	2.88E+00
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.43E-04	3.27E+00
	Total	3.39E+01	6.46E-02	5.08E-04	1.44E-04	3.89E+01
Gen III Plus Nuclear	Stage #1: RMA	1.81E+01	3.68E-02	2.89E-04	1.63E-07	1.91E+01
	Stage #2: RMT	3.21E-05	6.14E-08	6.58E-10	2.14E-17	3.39E-05
	Stage #3: ECF	2.86E+00	1.77E-03	1.31E-05	4.83E-08	2.91E+00
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.43E-04	3.27E+00
	Total	2.10E+01	3.86E-02	3.02E-04	1.44E-04	2.53E+01

Appendix B: Greenhouse Gas Metrics for Environmental Performance (Continued)

Onshore Wind Power: Greenhouse Gases						
kg/MWh		**CO_2**	**CH_4**	**N_2O**	**SF_6**	**Total (kg CO_2e/MWh)**
Conventional Wind	Stage #1: RMA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Stage #2: RMT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Stage #3: ECF	1.71E+01	3.38E-02	7.24E-04	1.11E-06	1.82E+01
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.43E-04	3.26E+00
	Total	1.71E+01	3.38E-02	7.24E-04	1.44E-04	2.14E+01
Advanced Wind	Stage #1: RMA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Stage #2: RMT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Stage #3: ECF	1.17E+01	3.11E-02	7.77E-04	8.55E-07	1.27E+01
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.43E-04	3.26E+00
	Total	1.17E+01	3.11E-02	7.77E-04	1.44E-04	1.59E+01

Appendix B: Greenhouse Gas Metrics for Environmental Performance (Continued)

Coal Plants – Greenhouse Gases						
kg/MWh		CO_2	CH_4	N_2O	SF_6	Total (kg CO_2e/MWh)
IGCC	Stage #1: RMA	2.83E+00	2.77E+00	4.40E-05	6.50E-11	7.22E+01
	Stage #2: RMT	1.31E+01	2.00E-02	3.13E-05	3.52E-11	1.36E+01
	Stage #3: ECF	8.42E+02	0.00E+00	2.10E-05	3.10E-07	8.42E+02
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.40E-04	3.19E+00
	Total	8.58E+02	2.79E+00	9.63E-05	1.40E-04	9.31E+02
IGCC CCS	Stage #1: RMA	3.38E+00	3.30E+00	5.30E-05	7.80E-11	8.59E+01
	Stage #2: RMT	1.57E+01	2.00E-02	3.80E-05	4.20E-11	1.62E+01
	Stage #3: ECF	1.11E+02	2.00E-03	4.20E-05	3.50E-07	9.61E+01
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.40E-04	3.19E+00
	Total	1.30E+02	3.32E+00	1.33E-04	1.40E-04	2.01E+02
SCPC	Stage #1: RMA	2.80E+00	2.70E+00	4.40E-05	6.50E-11	7.03E+01
	Stage #2: RMT	4.70E+00	6.00E-03	1.30E-05	2.10E-11	4.85E+00
	Stage #3: ECF	8.64E+02	1.50E-03	3.20E-05	3.30E-07	8.64E+02
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.40E-04	3.19E+00
	Total	8.72E+02	2.71E+00	8.90E-05	1.40E-04	9.42E+02
SCPC CCS	Stage #1: RMA	3.90E+00	3.80E+00	6.10E-05	9.00E-11	9.89E+01
	Stage #2: RMT	6.40E+00	8.20E-03	1.80E-05	2.90E-11	6.61E+00
	Stage #3: ECF	1.32E+02	1.80E-03	4.80E-05	3.30E-07	1.12E+02
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.40E-04	3.19E+00
	Total	1.42E+02	3.81E+00	1.27E-04	1.40E-04	2.21E+02
EXPC	Stage #1: RMA	3.20E+00	3.20E+00	4.70E-05	1.89E-11	8.32E+01
	Stage #2: RMT	5.20E+00	7.60E-03	1.24E-04	2.63E-12	5.43E+00
	Stage #3: ECF	1.00E+03	1.12E-02	1.71E-02	2.76E-07	1.01E+03
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.45E-04	3.31E+00
	Total	1.01E+03	3.22E+00	1.73E-02	1.45E-04	1.10E+03
EXPC CCS	Stage #1: RMA	3.20E+00	3.20E+00	4.70E-05	1.89E-11	8.32E+01
	Stage #2: RMT	5.20E+00	7.60E-03	1.24E-04	2.63E-12	5.43E+00
	Stage #3: ECF	3.40E+02	2.64E-01	2.01E-02	1.97E-07	3.53E+02
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	1.45E-04	3.31E+00
	Total	3.48E+02	3.47E+00	2.03E-02	1.45E-04	4.45E+02

Appendix C

List of Tables

Appendix C: Other Environmental Factors for Environmental Performance

Natural Gas Plants: Other Environmental Factors											
kg/MWh		Pb	Hg	NH_3	CO	NO_X	SO_X	VOC	PM	Water Withdrawal	Water Consumption
NGCC with Domestic NG	Stage #1: RMA	1.99E-06	6.83E-08	8.99E-07	4.39E-02	4.85E-01	5.07E-03	4.75E-01	1.04E-03	3.45E+02	1.43E+02
	Stage #2: RMT	1.65E-07	5.17E-09	1.99E-06	6.23E-04	7.79E-04	3.15E-04	1.59E-05	6.50E-05	2.12E+00	7.53E-01
	Stage #3: ECF	2.71E-06	2.46E-08	1.88E-02	3.12E-03	3.05E-02	1.19E-03	3.72E-05	3.74E-04	1.04E+03	8.03E+02
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	4.87E-06	9.80E-08	1.88E-02	4.76E-02	5.16E-01	6.57E-03	4.75E-01	1.48E-03	1.39E+03	9.47E+02
NGCC CCS with Domestic NG	Stage #1: RMA	2.33E-06	8.00E-08	1.05E-06	5.14E-02	5.68E-01	5.94E-03	5.57E-01	1.22E-03	4.04E+02	1.68E+02
	Stage #2: RMT	1.94E-07	6.06E-09	2.33E-06	7.31E-04	9.13E-04	3.69E-04	1.86E-05	7.61E-05	2.48E+00	8.83E-01
	Stage #3: ECF	3.09E-06	3.50E-08	2.03E-02	4.50E-03	3.42E-02	1.66E-03	4.74E-05	5.53E-04	2.06E+03	1.54E+03
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	5.62E-06	1.21E-07	2.03E-02	5.66E-02	6.03E-01	7.97E-03	5.57E-01	1.84E-03	2.47E+03	1.71E+03
NGCC with Imported NG	Stage #1: RMA	6.81E-07	4.33E-08	9.67E-02	9.29E-02	2.32E-01	1.31E-02	5.41E-02	5.12E-04	1.80E+02	2.07E+01
	Stage #2: RMT	1.65E-07	5.17E-09	1.99E-06	6.23E-04	7.79E-04	3.15E-04	1.59E-05	6.50E-05	2.12E+00	7.53E-01
	Stage #3: ECF	2.71E-06	2.46E-08	1.88E-02	3.12E-03	3.05E-02	1.19E-03	3.72E-05	3.74E-04	1.04E+03	8.03E+02
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	3.56E-06	7.30E-08	1.16E-01	9.66E-02	2.64E-01	1.46E-02	5.41E-02	9.51E-04	1.22E+03	8.25E+02
NGCC CCS with Imported NG	Stage #1: RMA	7.98E-07	5.08E-08	1.13E-01	1.09E-01	2.72E-01	1.54E-02	6.34E-02	6.00E-04	2.11E+02	2.43E+01
	Stage #2: RMT	1.94E-07	6.06E-09	2.33E-06	7.31E-04	9.13E-04	3.69E-04	1.86E-05	7.61E-05	2.48E+00	8.83E-01
	Stage #3: ECF	3.09E-06	3.50E-08	2.03E-02	4.50E-03	3.42E-02	1.66E-03	4.74E-05	5.53E-04	2.06E+03	1.54E+03
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	4.08E-06	9.19E-08	1.34E-01	1.14E-01	3.07E-01	1.74E-02	6.35E-02	1.23E-03	2.28E+03	1.57E+03
GTSC	Stage #1: RMA	3.07E-06	1.05E-07	1.39E-06	6.76E-02	7.47E-01	7.81E-03	7.32E-01	1.60E-03	5.31E+02	2.21E+02
	Stage #2: RMT	2.55E-07	7.96E-09	3.07E-06	9.61E-04	1.20E-03	4.85E-04	2.45E-05	1.00E-04	3.26E+00	1.16E+00
	Stage #3: ECF	6.27E-07	7.08E-09	2.90E-02	5.48E-03	4.87E-02	1.53E-03	1.63E-04	5.77E-04	5.06E+00	1.08E+00
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	3.95E-06	1.20E-07	2.90E-02	7.40E-02	7.97E-01	9.83E-03	7.32E-01	2.27E-03	5.40E+02	2.23E+02

Appendix C: Other Environmental Factors for Environmental Performance (Continued)

Coal Plants – Other Environmental Factors											
kg/MWh		Pb	Hg	NH_3	CO	NO_X	SO_X	VOC	PM	Water Withdrawal	Water Consumption
IGCC	Stage #1: RMA	2.90E-07	4.30E-08	2.40E-05	3.50E-03	5.20E-03	1.40E-02	1.00E-04	8.80E-04	1.50E+02	-5.94E+02
	Stage #2: RMT	1.70E-07	1.40E-08	4.80E-04	4.00E-02	3.50E-02	7.80E-03	3.30E-03	4.40E-02	6.86E+00	2.16E+00
	Stage #3: ECF	1.30E-05	2.40E-06	3.30E-06	5.10E-03	2.60E-01	8.40E-03	2.60E-04	3.10E-02	1.86E+03	1.48E+03
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	1.35E-05	2.46E-06	5.07E-04	4.86E-02	3.00E-01	3.02E-02	3.66E-03	7.59E-02	2.02E+03	8.83E+02
IGCC CCS	Stage #1: RMA	3.50E-07	5.20E-08	2.90E-05	4.10E-03	6.20E-03	1.70E-02	1.20E-04	1.10E-03	1.79E+02	-7.10E+02
	Stage #2: RMT	2.10E-07	1.60E-08	5.70E-04	4.80E-02	4.20E-02	9.30E-03	3.90E-03	5.20E-02	8.20E+00	2.60E+00
	Stage #3: ECF	1.60E-05	2.80E-06	4.80E-06	8.40E-03	2.50E-01	1.50E-02	3.70E-04	3.70E-02	2.62E+03	2.13E+03
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	1.66E-05	2.87E-06	6.04E-04	6.05E-02	2.98E-01	4.13E-02	4.39E-03	9.01E-02	2.81E+03	1.42E+03
SCPC	Stage #1: RMA	2.90E-07	4.30E-08	2.40E-05	3.40E-03	5.10E-03	1.40E-02	1.00E-04	8.80E-04	1.49E+02	-5.90E+02
	Stage #2: RMT	9.20E-08	7.00E-09	1.70E-04	1.50E-02	1.20E-02	3.20E-03	1.10E-03	1.50E-02	3.00E+00	1.00E+00
	Stage #3: ECF	4.50E-05	4.50E-06	2.40E-03	7.00E-03	3.00E-01	3.70E-01	3.00E-04	5.60E-02	2.36E+03	1.88E+03
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	4.54E-05	4.55E-06	2.59E-03	2.54E-02	3.17E-01	3.87E-01	1.50E-03	7.19E-02	2.51E+03	1.29E+03
SCPC CCS	Stage #1: RMA	4.00E-07	6.00E-08	3.30E-05	4.70E-03	7.10E-03	1.90E-02	1.40E-04	1.20E-03	2.05E+02	-8.15E+02
	Stage #2: RMT	1.30E-07	9.70E-09	2.30E-04	2.00E-02	1.70E-02	4.40E-03	1.60E-03	2.10E-02	4.20E+00	1.30E+00
	Stage #3: ECF	4.60E-05	7.20E-06	2.70E-03	9.30E-03	4.10E-01	1.40E-02	3.60E-04	7.80E-02	4.48E+03	3.44E+03
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	4.65E-05	7.27E-06	2.96E-03	3.40E-02	4.34E-01	3.74E-02	2.10E-03	1.00E-01	4.69E+03	2.63E+03
EXPC	Stage #1: RMA	1.40E-07	3.90E-08	2.80E-05	3.10E-03	5.70E-03	1.60E-02	1.00E-04	5.50E-04	1.72E+02	-2.67E+02
	Stage #2: RMT	3.10E-08	2.90E-09	1.90E-04	1.50E-02	1.40E-02	2.80E-03	1.30E-03	1.70E-02	2.10E+00	6.50E-01
	Stage #3: ECF	6.30E-06	5.20E-05	2.20E-04	1.10E-01	2.00E+00	2.40E+00	1.30E-02	6.70E-01	2.70E+03	2.09E+03
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	6.47E-06	5.20E-05	4.38E-04	1.28E-01	2.02E+00	2.42E+00	1.44E-02	6.88E-01	2.88E+03	1.83E+03
EXPC CCS	Stage #1: RMA	1.40E-07	3.90E-08	2.80E-05	3.10E-03	5.70E-03	1.60E-02	1.00E-04	5.50E-04	1.72E+02	-2.67E+02
	Stage #2: RMT	3.10E-08	2.90E-09	1.90E-04	1.50E-02	1.40E-02	2.80E-03	1.30E-03	1.70E-02	2.10E+00	6.50E-01
	Stage #3: ECF	1.87E-05	5.49E-05	1.29E-03	2.04E-01	4.63E-01	1.30E+00	1.30E-02	9.89E-05	5.49E+03	3.41E+03
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	1.89E-05	5.49E-05	1.51E-03	2.22E-01	4.83E-01	1.32E+00	1.44E-02	1.76E-02	5.66E+03	3.14E+03

Appendix C: Other Environmental Factors for Environmental Performance (Continued)

Nuclear Plants: Other Environmental Factors											
kg/MWh		Pb	Hg	NH_3	CO	NO_X	SO_X	VOC	PM	Water Withdrawal	Water Consumption
Gen III Plus Nuclear	**Stage #1: RMA**	**9.04E-07**	**1.99E-07**	**9.22E-04**	**1.33E-02**	**4.16E-02**	**1.10E-01**	**2.53E-03**	**2.30E-03**	**2.27E+02**	**4.77E+01**
	Stage #2: RMT	**3.10E-13**	**3.61E-14**	**1.06E-10**	**4.10E-08**	**2.79E-08**	**3.75E-08**	**2.82E-08**	**7.09E-10**	**9.19E-05**	**7.82E-05**
	Stage #3: ECF	**2.28E-07**	**1.64E-08**	**8.93E-06**	**1.23E-02**	**1.94E-02**	**6.50E-03**	**1.88E-03**	**9.73E-04**	**4.38E+03**	**2.90E+03**
	Stage #4: PT	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
	Total	**1.13E-06**	**2.15E-07**	**9.31E-04**	**2.56E-02**	**6.10E-02**	**1.16E-01**	**4.41E-03**	**3.27E-03**	**4.60E+03**	**2.94E+03**
Existing Nuclear	**Stage #1: RMA**	**1.55E-06**	**3.40E-07**	**1.58E-03**	**2.28E-02**	**7.13E-02**	**1.88E-01**	**4.33E-03**	**3.93E-03**	**3.88E+02**	**8.16E+01**
	Stage #2: RMT	5.30E-13	6.18E-14	1.81E-10	7.02E-08	4.78E-08	6.41E-08	4.82E-08	1.21E-09	1.57E-04	1.34E-04
	Stage #3: ECF	4.92E-07	1.78E-08	1.13E-05	1.40E-02	1.82E-03	5.57E-03	5.90E-04	3.26E-04	1.12E+05	2.59E+03
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	2.04E-06	3.58E-07	1.59E-03	3.68E-02	7.31E-02	1.93E-01	4.92E-03	4.26E-03	1.12E+05	2.67E+03
Onshore Wind Power: Other Environmental Factors											
Conventional Wind	Stage #1: RMA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Stage #2: RMT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Stage #3: ECF	-1.18E-05	1.34E-07	8.64E-04	5.59E-02	5.65E-02	2.56E-02	5.92E-03	5.35E-02	1.99E+02	2.57E+01
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	-1.18E-05	1.34E-07	8.64E-04	5.59E-02	5.65E-02	2.56E-02	5.92E-03	5.35E-02	1.99E+02	2.57E+01
Advanced Wind	Stage #1: RMA	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Stage #2: RMT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Stage #3: ECF	-3.20E-07	1.39E-07	5.97E-04	4.35E-02	3.36E-02	2.57E-02	5.43E-03	3.36E-02	1.70E+02	2.22E+01
	Stage #4: PT	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	-3.20E-07	1.39E-07	5.97E-04	4.35E-02	3.36E-02	2.57E-02	5.43E-03	3.36E-02	1.70E+02	2.22E+01