System Analysis Guidance for Assessment of Carbon Capture Technology

Targeting $40/tonne CO_2 Captured Costs

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Objectives

- **Resources for conducting Techno-Economic Analysis (TEA)**
- **Interpreting & Calculating Cost to Capture CO_2**
- **Steps to performing a TEA**
    1. Creating a Model
    2. Performance Modeling
    3. Cost Estimating - COE and Cost of Carbon Captured
- **Reporting Requirements (RR)**
    - Tagged through document as **(RR)**

NETL Baseline TEA Studies Establish A Common Reference and Starting Point

Volume	Title	Description	Notes
1	Bituminous Coal and Natural Gas to Electricity, aka Bituminous Baseline	Establishes performance and cost data for fossil energy power systems for integrated gasification combined cycle (IGCC), pulverized coal (PC), and natural gas combined cycle (NGCC) plants	All plants are modeled with and without carbon capture and sequestration All plants are conducted at International Organization for Standardization (ISO) conditions PC and IGCC plants fire Illinois No. 6 bituminous coal
3	Low-Rank Coal and Natural Gas to Electricity, aka Low Rank Baseline	Establishes performance and cost data for fossil energy power systems for IGCC, PC, and NGCC plants	All plants are modeled with and without carbon capture and sequestration All plants are conducted at Montana elevation (3,400 ft.) and North Dakota elevation (1,900 ft.) PC and IGCC plants fire either Powder River Basin (PRB) sub-bituminous coal or North Dakota lignite (NDL) coal

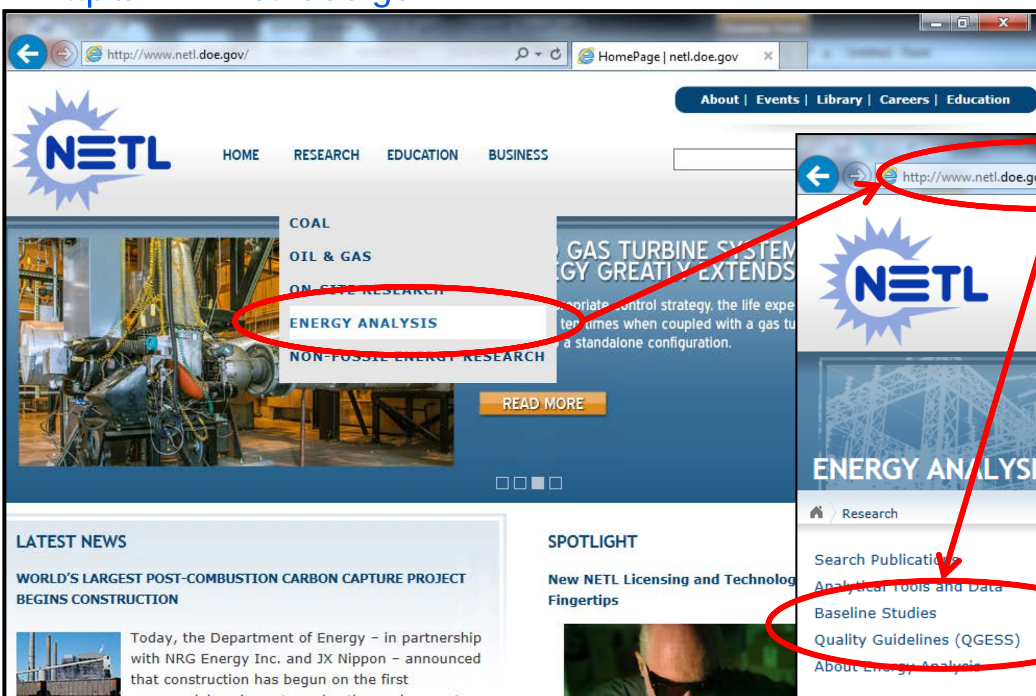
NETL Has Quality Guidelines that Help Define the Design Basis and Modeling Assumptions

Title	Description
Detailed Coal Specifications	Provides data on the coal industry and detailed specifications for seven coals commonly used in energy system studies for NETL.
Specifications for Selected Feedstocks	Provides recommended specifications for various feedstocks that are commonly found in NETL-sponsored energy system studies. Adhering to these specifications should enhance the consistency of such studies. NETL recommends these guidelines be followed in the absence of any compelling market, project, or site-specific requirements in order to facilitate comparison of studies evaluating coal-based technologies.
Process Modeling Design Parameters	Documents the process modeling assumptions most commonly used in systems analysis studies and the basis for those assumptions. The large number of assumptions required for a systems analysis makes it impractical to document the entire set in each report. This document should serve as a comprehensive reference for these assumptions as well as their justification.
Capital Cost Scaling Methodology	Provides a standard basis for scaling capital costs, with specific emphasis on scaling exponents. This document contains a listing of frequently used pieces of equipment and their corresponding scaling exponent for various plant types, along with their ranges of applicability. The intention of having a standardized document is to provide guidelines for proper procedures to reduce the potential for errors and increase credibility through consistency.
Cost Estimation Methodology	Summarizes the cost estimation methodology employed by NETL in its assessment of power plant performance.
Estimating Carbon Dioxide Transport and Storage Costs	Estimates the cost of CO_2 transport and storage (T&S) in a deep saline aquifer for plant locations used in the energy system studies sponsored by NETL. Due to the variances in the geologic formations that make up saline aquifers across the United States, the cost to store CO_2 can vary greatly depending on location. To account for these variances, region-specific results from NETL's CO_2 Saline Storage Cost Model are utilized to represent costs for plant locations used in NETL studies: Midwest, Texas, North Dakota, and Montana. Transport costs are calculated based on a generic 100 km (62 mi) dedicated pipeline for all regions. Storage and monitoring costs represent significant storage potential (up to 25 billion tonnes of CO_2) in local sedimentary basins.
CO_2 Impurity Design Parameters	Provides recommended impurity limits for CO_2 stream components for use in conceptual studies of CO_2 carbon capture, utilization, and storage systems. These limits were developed from information consolidated from numerous studies and are presented by component. Impurity levels are provided for limitations of carbon steel pipelines, enhanced oil recovery (EOR), saline reservoir sequestration, and co-sequestration of CO_2 and H_2S in saline reservoirs.
Fuel Prices for Selected Feedstocks	Provides an estimate of the market price delivered to specific end-use areas of four coals that are commonly used as feedstocks in the energy system studies sponsored by NETL. Also includes the estimated market price for natural gas delivered to three different regions.

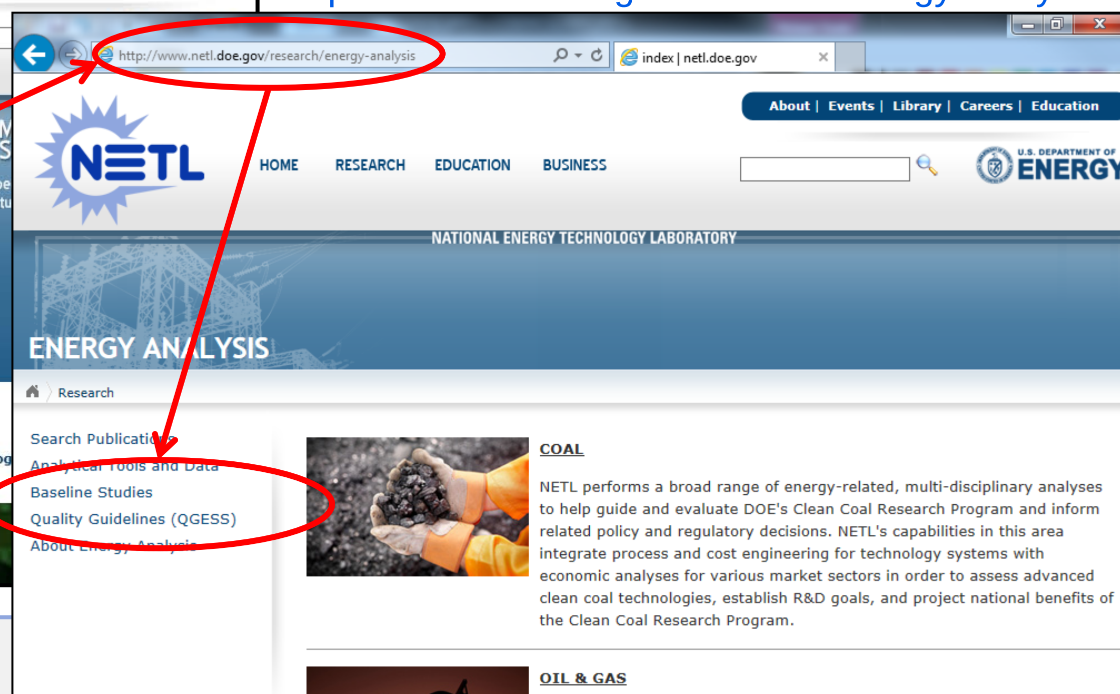
Resources for TEA Development

- **Baseline studies**
  - A Series of documents that provide Baseline's for comparison
  - http://www.netl.doe.gov/research/energy-analysis/energy-baseline-studies
- **Quality Guidelines for Energy System Studies (QGESS) Documents**
  - A series of documents that provide the details to performing TEAs
  - http://www.netl.doe.gov/research/energy-analysis/quality-guidelines-qgess
  - Also includes a manuscript titled "**A proposed methodology for CO_2 capture and storage cost estimates"** that outlines a methodology for costing

http://www.netl.doe.gov



http://www.netl.doe.gov/research/energy-analysis



CO_2 Captured Cost *Interpretation*

$$Cost\ of\ CO_2\ Captured = \frac{(COE_{With\ CC} - COE_{Without\ CC})}{CO_2\ Captured}$$

- **Plant gate revenue required to incentivize carbon capture**
- **Assumes the CC plant and the reference plant <u>receive</u> their associated COE required to realize 12% ROE**
- **Does not include:**
  - TS&M
  - Risk/Uncertainty
- **Is NOT:**
  - Avoided cost (not covered here)
  - Equivalent to motivating CO_2 tax on emissions

Economic Analysis – Cost of CO_2 Captured

- **The cost of CO_2 capture is formally:**

$$Cost\ of\ CO_2\ Captured = \frac{(COE_{With\ CC} - COE_{Without\ CC})}{CO_2\ Captured}$$

- **Where:**
  - $COE_{with\ CC}$: The plant modeled with novel technology
  - $COE_{without\ CC}$: Reference non-capture plant
    - Generally Case 11 in the Bituminous Baseline
    - COE = $81/MWh (2011 $)
  - CO_2 captured (denominator) equals the rate of CO_2 captured with units [$tonne/MWh_{with\ cc}$]

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Economic Analysis – Breaking Down COE

- Cost of electricity (COE) is the required revenue a power plant must receive for the electricity generated.
  - An increase in the COE represents an increase in the publics' electricity bill
  - Capital Charge Factor (CCF) has been developed to aggregate financial assumptions like financial structures, tax structures, loan interest, etc. and allows a more straightforward comparison between Baseline and newly modeled plants
- A simplified equation can be utilized to determine the COE for Baseline comparison purposes

$$\mathbf{COE} = \frac{\substack{\textit{First year} \\ \textit{capital charge}} + \substack{\textit{first year} \\ \textit{fixed operating} \\ \textit{costs}} + \substack{\textit{first year} \\ \textit{variable operating} \\ \textit{costs}}}{\substack{\textit{annual net megawatt hours} \\ \textit{of power generation}}}$$

$$\mathbf{COE} = \frac{\mathbf{CCF \cdot TOC + OC_{FIX} + CF \cdot OC_{VAR}}}{\mathbf{CF \cdot MWh}}$$

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Economic Analysis – COE

$$\mathbf{COE} = \frac{\mathbf{CCF \cdot TOC + OC_{FIX} + CF \cdot OC_{VAR}}}{\mathbf{CF \cdot MWh}}$$

- **Where (all items below are to be reported (RR)):**
  - COE = Revenue required by the generator during the power plant's first year of operation
  - CCF = Capital charge factor
  - TOC = Total overnight capital
  - OC_{FIX} = Sum of all fixed annual operating costs
  - OC_{VAR} = Sum of all variable annual operating costs at 100 percent capacity
  - CF = Plant capacity factor
  - MWh = Annual net megawatt-hours

COE Requires Multiple Significant Calculations

Term	Variable(s)	Calculation Requirement(s)	Instruction Source(s)
Capital Cost	TOC	• Baseline costs • Scaling • Contingency • “Bearable costs”	• BB Study Capital Reference • QGESS: Scaling Equipment Costs • Goal Requirement
Operating Costs	OC_{FIX}, OC_{VAR}	• Baseline costs • Scaling • Contingency • “Bearable costs”	• BB Study Operating Cost Reference
Power Output	MWh	• Full System Analysis	• BB Case 11 • QGESS website

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Capital Costs

- **Equipment that is not affected by implementation of new capture technology can be directly used or scaled from the Baseline reports**
- **Capital costs for unique equipment may be calculated by several methods:**
  - If analogous equipment is available either in an NETL baseline study or otherwise, the scaling method is preferred
  - If analogs are not available, the developer should do a bottom-up estimate of the unique equipment
  - If neither an analog-based nor a bottom-up estimate can be produced, research goals or bearable costs should be provided
- **The methodology, reference equipment, and sources of data should be documented in detail within the TEA**

Capital Costs – Research Goals and Bearable Costs

- **If a scaled or bottom-up costing approach is not applicable, a cost for novel technology can be reported as either research goals or bearable costs**
- **Research goals – Intended targets for the costs of technology under development**
  - Detailed descriptions as to the reason for the selection of the targets should be provided
  - Available data that supports the goal selection should be provided
- **Bearable costs – The costs at which the technology meets a specific goal**
  - If a goal has been provided (e.g. < 30 percent increase in COE), the bearable cost to meet the goal can be calculated

Scope of Capital Costs (RR)

$$\mathrm{COE} = \frac{\mathrm{CCF} \cdot \mathbf{TOC} + \mathrm{OC_{FIX}} + \mathrm{CF} \cdot \mathrm{OC_{VAR}}}{\mathrm{CF} \cdot \mathrm{MWh}}$$

- **TASC / TCR**
  - **TOC**
    - **TPC**
      - **EPCC**
        - **BEC**
          - process equipment
          - supporting facilities
          - direct and indirect labor
        - EPC contractor services
      - process contingency
      - project contingency
    - pre-production costs
    - inventory capital
    - financing costs
    - other owner's costs
  - escalation during capital expenditure period
  - interest on debt during capital expenditure period

Bare Erected Cost
Engineering, Procurement and Construction Cost
Total Plant Cost
Total Overnight Cost
Total As-Spent Cost

BEC, EPCC, TPC, TOC and TCR are all "overnight" costs expressed in base-year dollars.

TASC is expressed in mixed-year current dollars, spread over the capital expenditure period.

Economic Analysis – Operating Costs (RR)

$$\text{COE} = \frac{\text{CCF} \cdot \text{TOC} + \mathbf{OC_{FIX}} + \text{CF} \cdot \mathbf{OC_{VAR}}}{\text{CF} \cdot \text{MWh}}$$

Fixed Operating Costs (OC_{FIX})	Variable Operating Costs (OC_{VAR})
Annual Operating Labor Cost	Maintenance Material Cost
Maintenance Labor Cost	Fuel
Administrative & Support Labor	Other Consumables
Property Taxes and Insurance	Waste Disposal
	Emission Costs
	Byproduct Revenues

OC costs reported should be similar to those found in the Baseline Reports

Power Output Calculation Requires TEA

- **Very complex – Usually requires process simulator**
- **Requires lots of steps, analysis, assumptions**
- **Equipment and operations not directly involved in the CO_2 Capture technology research should be modeled according to QGESS documentation**
  - Standardizes “apples-to-apples” comparison
  - Very thorough QGESS library addresses virtually all assumptions necessary for TEA

Instructions for TEA
Calculating CO_2 Captured Cost

- **These are success criteria – take them seriously!**
- **Two (2) TEA's required – ideally:**
  1. Baseline plant without CC
  2. Baseline plant with ***your*** CC technology
     - No other changes to BOP are permitted in analysis
- **You should produce in-house TEA #1 and match BB performance/cost**
- **For TEA #2, use BB and QGESS documentation as detailed within**
  – Estimate "bearable cost" (or performance) for capture technology that cannot be adequately estimated consistent with DOE goal

Creating a Performance Model

- **Determine a baseline case from the Baseline Studies (RR)**
  - Choose a Baseline that the technology can be applied to
  - Reduce costing and modeling efforts with the correct baseline
- **Non-research related units should remain constant with Baseline and QGESS documents.**
  - If non-research units require size adjustment, QGESS for Capital Cost Scaling Methodology should be used **(RR)**
  - http://www.netl.doe.gov/File%20Library/research/energy%20analysis/publications/QGESS_CapitalCostScalingMethodology_Final_20130201.pdf
- **Variation must be well justified in the TEA document (RR)**

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Performance Modeling - Design Basis

- **QGESS on Process Modeling Design**
  http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/QGESS_ProcessModDesignParameters_Public_Rev2_20140513.pdf
  - Site Conditions
  - Steam cycle conditions
  - Coal Combustion parameters
  - Gasifier Performance
  - Syngas processing
  - Sulfur processing
  - Equations of State
  - Cooling water parameters
- **Items to hold constant (RR)**
  - PC application hold net power output constant
  - IGCC application hold combustion turbine output constant

Performance Modeling - Design Basis

- **Feedstock: QGESS on Feedstock Specifications**
  http://www.netl.doe.gov/File%20Library/research/energy%20analysis/publications/QGESSSec1.pdf
  - Natural Gas Composition
  - Various Coal Compositions
  - Limestone analysis
  - Lime analysis
  - LHV and HHV
- **CO_2 Specifications: QGESS on CO_2 impurities**
  http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/QGESS_CO2Purity_Rev3_20130927_1.pdf
  - CO_2 delivery pressure
  - Individual contaminate concentration limits
  - CO_2 minimum concentration
  - Specifications for intended use (Saline, EOR, etc.)
  - Venting concerns
  - CCUS specifications

Design Basis - Inconsistencies

- **Items that are often inconsistently reported that create issues without justification:**
  - Condenser pressure
  - Steam cycle conditions (e.g. reheat temperature)
  - Combustion turbine conditions (e.g. turbine inlet temperature)
  - Cooling water temperature
  - ASU performance and oxygen quality
  - Emissions levels
  - Equipment selection
- **Inconsistencies without justification may require further communication or resubmission of report**
  - Creates over-budget & schedule slip risks

Model Results for Reporting

- **Block Flow diagram (RR)**
- **Material and Energy Balances consistent with the level of detail found in the Baseline reports (RR)**
  - Material balance should including
    - All inputs feedstock, catalyst, limestone, etc.
    - All outputs such as stack gas, waste water, solid waste disposal
    - Steam compositions
  - Energy Balance should include
    - Thermal energy input from fuel
    - Major auxiliary loads
    - Detailed loads for new technology

Model Results

Other performance metrics to be calculated and reported

- **Total power from turbines (RR)**
- **New auxiliary loads (RR)**
- **Net Power (RR)**
- **Equipment NOT affected by CC can be scaled**
  - Capital Cost Scaling Methodology
  - http://www.netl.doe.gov/File%20Library/research/energy%20analysis/publications/QGESS_CapitalCostScalingMethodology_Final_20130201.pdf

POWER SUMMARY (Gross Power at Generator Terminals, kWe)	
Gas Turbine Power	464,000
Sweet Gas Expander Power	7,500
Steam Turbine Power	276,300
TOTAL POWER, kWe	**747,800**
AUXILIARY LOAD SUMMARY, kWe	
Coal Handling	460
Coal Milling	2,180
Sour Water Recycle Slurry Pump	180
Slag Handling	1,120
Air Separation Unit Auxiliaries	1,000
Air Separation Unit Main Air Compressor	53,820
Oxygen Compressor	10,260
Nitrogen Compressors	33,340
Boiler Feedwater Pumps	3,980
Condensate Pump	230
Quench Water Pump	520
Circulating Water Pump	4,200
Ground Water Pumps	430
Cooling Tower Fans	2,170
Scrubber Pumps	220
Acid Gas Removal	2,590
Gas Turbine Auxiliaries	1,000
Steam Turbine Auxiliaries	100
Claus Plant/TGTU Auxiliaries	250
Claus Plant TG Recycle Compressor	2,090
Miscellaneous Balance of Plant[2]	3,000
Transformer Losses	2,610
TOTAL AUXILIARIES, kWe	**125,750**
NET POWER, kWe	**622,050**
Net Plant Efficiency, % (HHV)	39.0
Net Plant Heat Rate, kJ/kWh (Btu/kWh)	9,238 (8,756)
CONDENSER COOLING DUTY 10^6 kJ/hr (10^6 Btu/hr)	**1,540 (1,460)**
CONSUMABLES	
As-Received Coal Feed, kg/hr (lb/hr)	211,783 (466,901)
Thermal Input[1], kWt	1,596,320
Raw Water Withdrawal, m^3/min (gpm)	17.9 (4,735)
Raw Water Consumption, m^3/min (gpm)	14.2 (3,755)

Model Results

Other performance metrics to be calculated and reported

- **CO_2 impurities (RR)**
- **Air emissions**
- **Water withdraw, consumption, and discharge (RR)**
  - If new technology creates impurities in water discharge, this must be documented
- **Heat rate, efficiencies, etc. (RR)**
  - HHV Commonly used for NETL reporting purposes

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COE Also Requires Assumptions

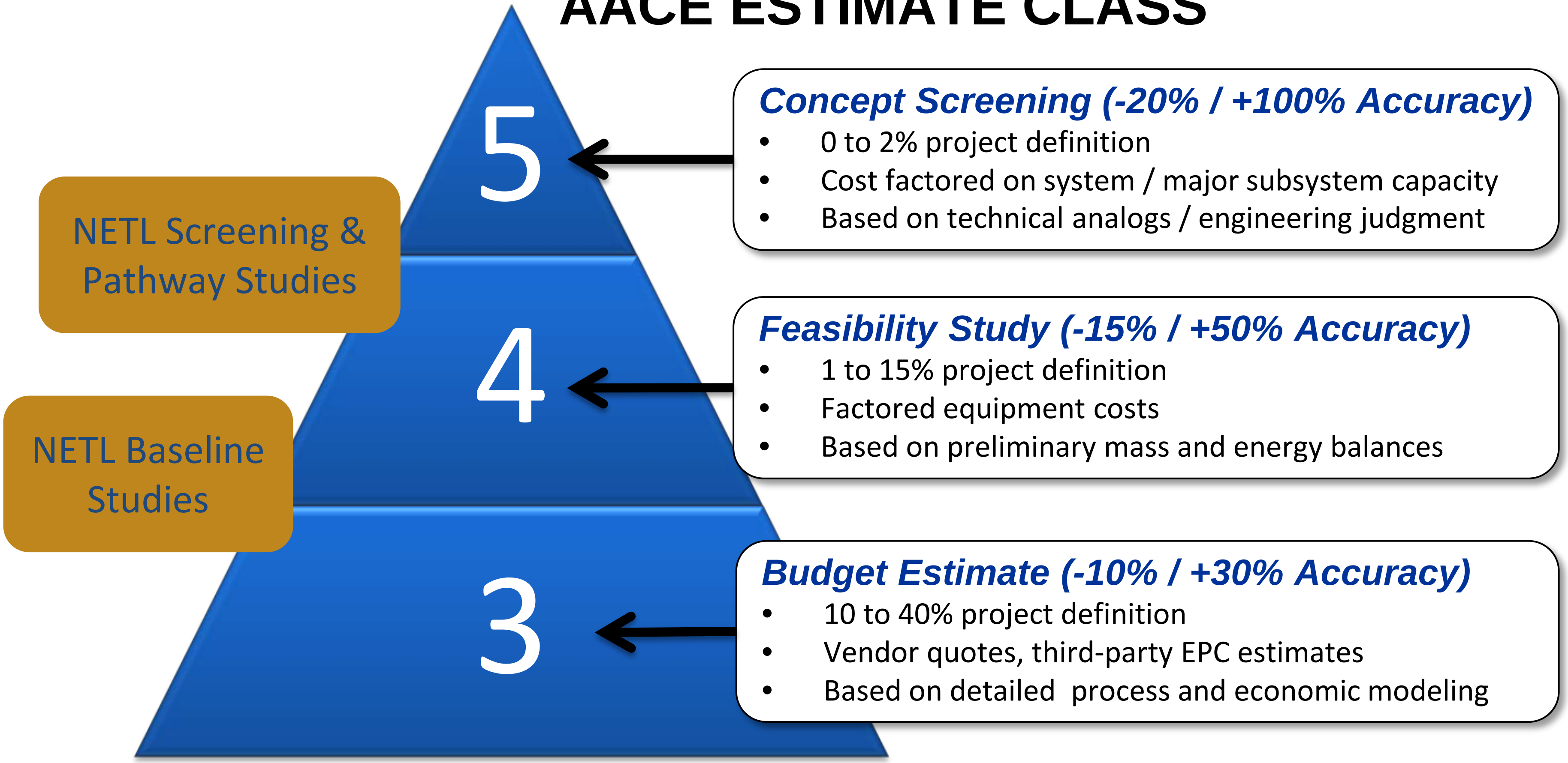
$$\mathrm{COE} = \frac{\mathbf{CCF} \cdot \mathrm{TOC} + \mathrm{OC_{FIX}} + \mathbf{CF} \cdot \mathrm{OC_{VAR}}}{\mathbf{CF} \cdot \mathbf{MWh}}$$

Plant Type	CCF w/ CC	CF
PC	0.124	0.85
IGCC	0.124	0.80
NGCC	0.111	0.85

- The **CCF** is a term that takes into account the financial aspects of the plant and simplifies them to a single term for simplicity. Greater detail can be found in the QGESS documents.
- The **CF** is a term that accounts for the fraction of the year that the power plant is producing electricity for the grid. This is in general a variable value with a moderate range, but is fixed per the above for purposes of comparison.

Expected Accuracy of NETL Cost Estimates

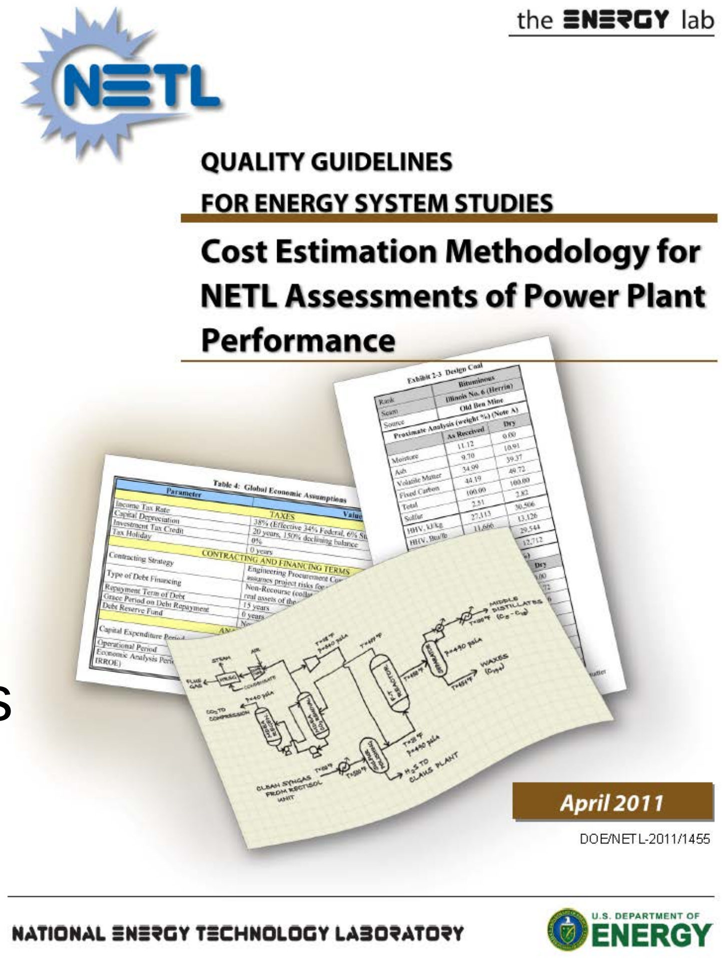
AACE ESTIMATE CLASS



Process flow diagrams (PFDs) and piping and instrument diagrams (P&IDs) are the primary documents that define project scope. Association for the Advancement of Cost Engineering International (AACE) Recommended Practice No. 18R-97 describes the AACE cost estimate classification system.

Cost Estimation Methodology

- **Capital Cost Breakdown**
  - Estimate Class
  - Contingency Guidelines
  - Owner's Cost Recommendations
  - Estimate Scope
  - Project Scope
- **Economic Analysis**
  - Global Economic Assumptions
  - Recommended Financing Structures
  - Estimation of COE



Cost Estimation Methodology: http://www.netl.doe.gov/File%20Library/research/energy%20analysis/publications/QGESSNETLCostEstMethod.pdf

Economic Analysis – COE

$$COE = \frac{CCF \cdot TOC + OC_{FIX} + CF \cdot OC_{VAR}}{CF \cdot MWh}$$

Once COE has been calculated:

- **Compare to Baseline studies (RR)**
- **Sensitivity analysis can be conducted to guide research or suggest future goals (RR)**

  Examples include:
  - reduced cost of manufacturing of capture material,
  - changes in kinetics reduce pressure drop,
  - reduced heat of reaction to reduce regeneration duties
- **Cost of CO_2 Captured can be determined for base and alternative cases (RR)**

REPORTING REQUIREMENTS

Reporting Requirements

- Creating a Model
  - State base case that will be used
  - State Design Basis parameters (Items held constant, feedstock, CO_2 specifications, etc.)
- Performance Modeling
  - Block Flow diagram
  - Material and Energy Balance
  - Water usage
  - Heat Rates, efficiencies, etc.
- Cost Estimating - COE and Cost of Carbon Captured
  - Detailed COE calculations
  - Detailed TOC cost estimates
  - Sensitivity Studies
  - Cost of CO_2 Captured

Reporting Requirements

- **Remember to:**
  - Choose a Baseline study that can easily use the new technology
  - Justify any variations from the Baseline outside of the new material
  - Provide enough detail to reproduce stated number
  - Once complete, use the information to guide research

- **Consider as a reference:**
  - http://www.sciencedirect.com/science/article/pii/S1750583613002521

Acknowledgements

- **OPPB**
  - Kristin Gerdes
  - James Fisher
  - Morgan Summers
- **ESPA**
  - Vince Chou
  - Mark Turner
  - Mark Woods

QUESTIONS?

For More Information About the NETL Carbon Capture Program

- ***NETL Website:***
  - ***www.netl.doe.gov***
- ***Capture Program Website:***
  - ***www.netl.doe.gov/technologies/coalpower/ewr/co2/index.html***

Reference Shelf

- ***Annual CO_2 Capture Meeting***

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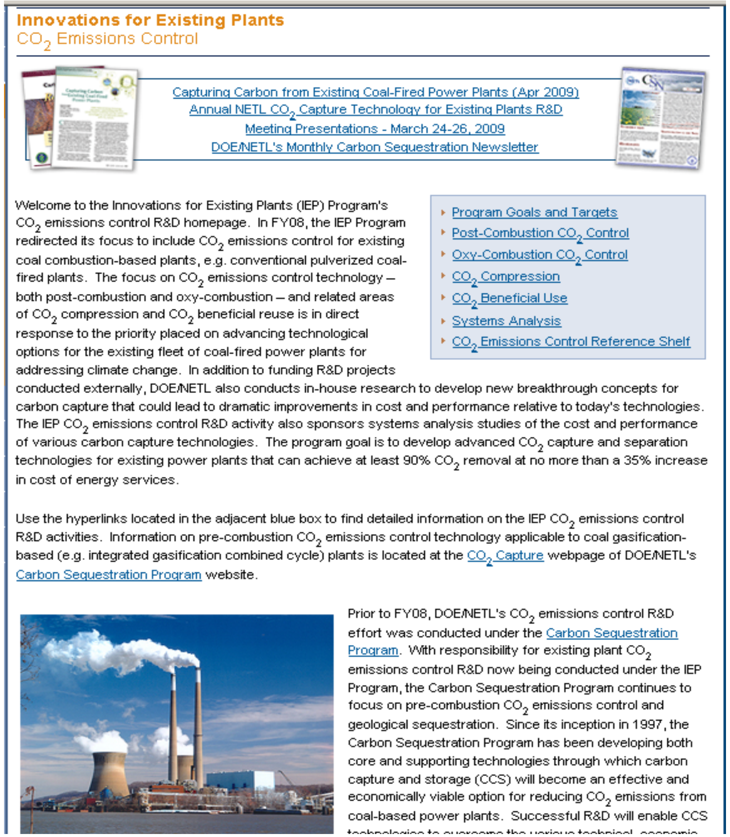
- ***Office of Fossil Energy website:***
  - ***www.fe.doe.gov***



Innovations for Existing Plants
CO_2 Emissions Control

Capturing Carbon from Existing Coal-Fired Power Plants (Apr 2009)
Annual NETL CO_2 Capture Technology for Existing Plants R&D
Meeting Presentations - March 24-26, 2009
DOE/NETL's Monthly Carbon Sequestration Newsletter

- Program Goals and Targets
- Post-Combustion CO_2 Control
- Oxy-Combustion CO_2 Control
- CO_2 Compression
- CO_2 Beneficial Use
- Systems Analysis
- CO_2 Emissions Control Reference Shelf

Welcome to the Innovations for Existing Plants (IEP) Program's CO_2 emissions control R&D homepage. In FY08, the IEP Program redirected its focus to include CO_2 emissions control for existing coal combustion-based plants, e.g. conventional pulverized coal-fired plants. The focus on CO_2 emissions control technology – both post-combustion and oxy-combustion – and related areas of CO_2 compression and CO_2 beneficial reuse is in direct response to the priority placed on advancing technological options for the existing fleet of coal-fired power plants for addressing climate change. In addition to funding R&D projects conducted externally, DOE/NETL also conducts in-house research to develop new breakthrough concepts for carbon capture that could lead to dramatic improvements in cost and performance relative to today's technologies. The IEP CO_2 emissions control R&D activity also sponsors systems analysis studies of the cost and performance of various carbon capture technologies. The program goal is to develop advanced CO_2 capture and separation technologies for existing power plants that can achieve at least 90% CO_2 removal at no more than a 35% increase in cost of energy services.

Use the hyperlinks located in the adjacent blue box to find detailed information on the IEP CO_2 emissions control R&D activities. Information on pre-combustion CO_2 emissions control technology applicable to coal gasification-based (e.g. integrated gasification combined cycle) plants is located at the CO_2 Capture webpage of DOE/NETL's Carbon Sequestration Program website.

Prior to FY08, DOE/NETL's CO_2 emissions control R&D effort was conducted under the Carbon Sequestration Program. With responsibility for existing plant CO_2 emissions control R&D now being conducted under the IEP Program, the Carbon Sequestration Program continues to focus on pre-combustion CO_2 emissions control and geological sequestration. Since its inception in 1997, the Carbon Sequestration Program has been developing both core and supporting technologies through which carbon capture and storage (CCS) will become an effective and economically viable option for reducing CO_2 emissions from coal-based power plants. Successful R&D will enable CCS