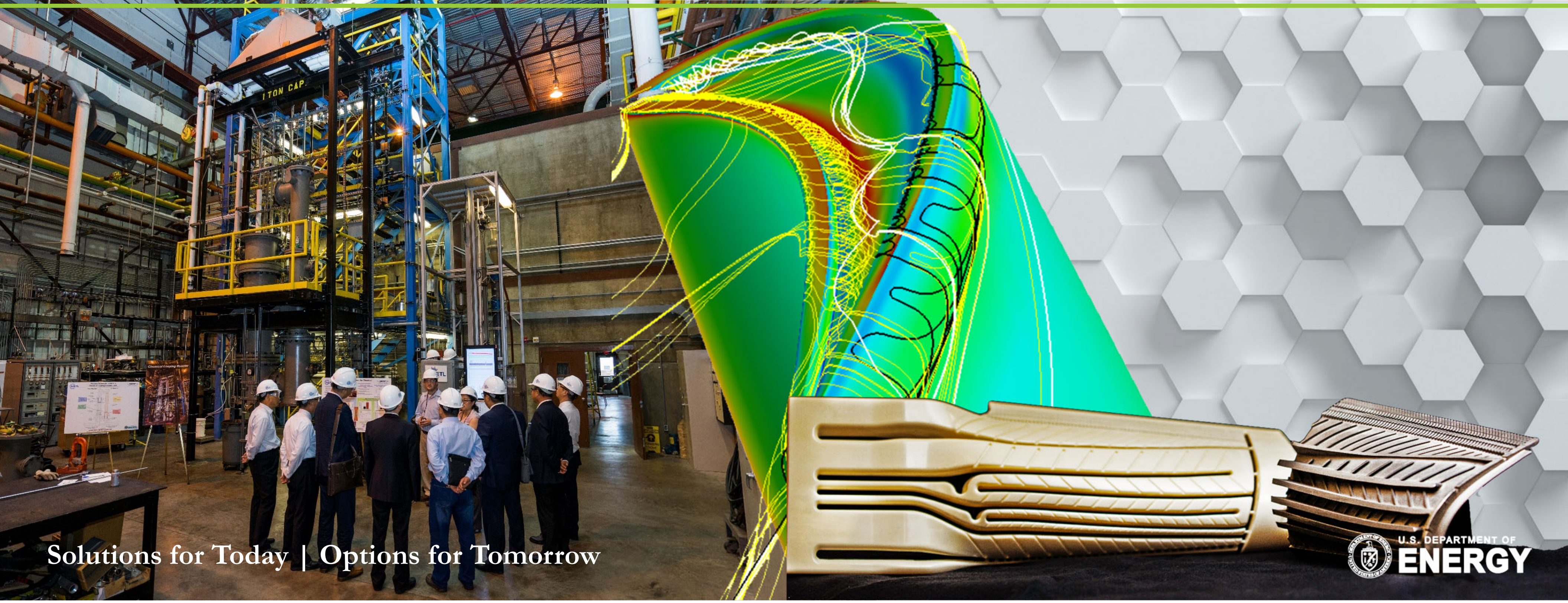
Techno-Economic Analyses for Direct Air Capture (DAC)

Overview

Tim Fout, Strategic Systems Analysis and Engineering (SSAE)

February 24, 2021



Presentation Outline

- **Techno-Economic Analysis (TEA) Process**
- **QGESS Description/Location**
- **Bituminous Baseline Study Overview/Example**

Presentation Outline

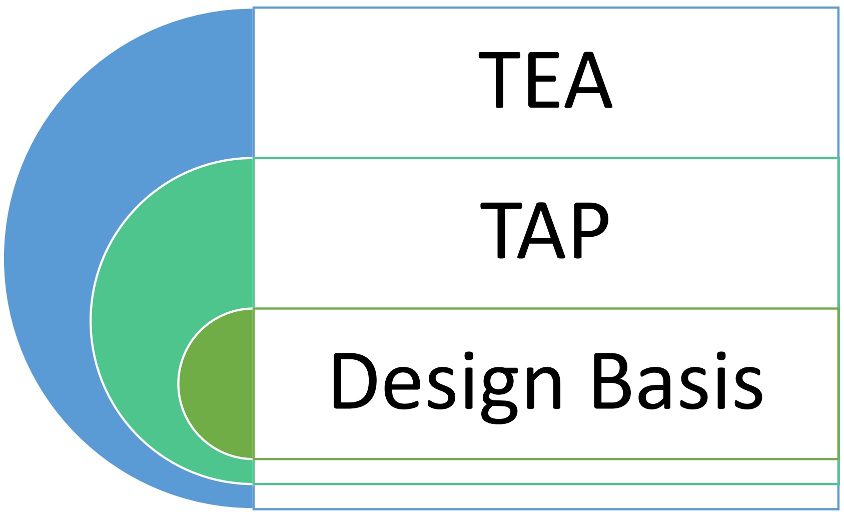
- **Techno-Economic Analysis (TEA) Process**
- **QGESS Description/Location**
- **Bituminous Baseline Study Overview/Example**

Tecno-Economic Analysis Tools

Right tool for TRL level

- **Low TRL Analysis**
  - Mass and Energy Balances
  - Preliminary Spreadsheet Models – Post Combustion Tool, Compression Tool
  - Cost correlations
- **Mid to High TRL (for NETL projects)**
  - Process Simulation Software
    - Aspen Plus
    - CHEMCAD
    - Thermoflow
    - Others

Steps to Performing TEA

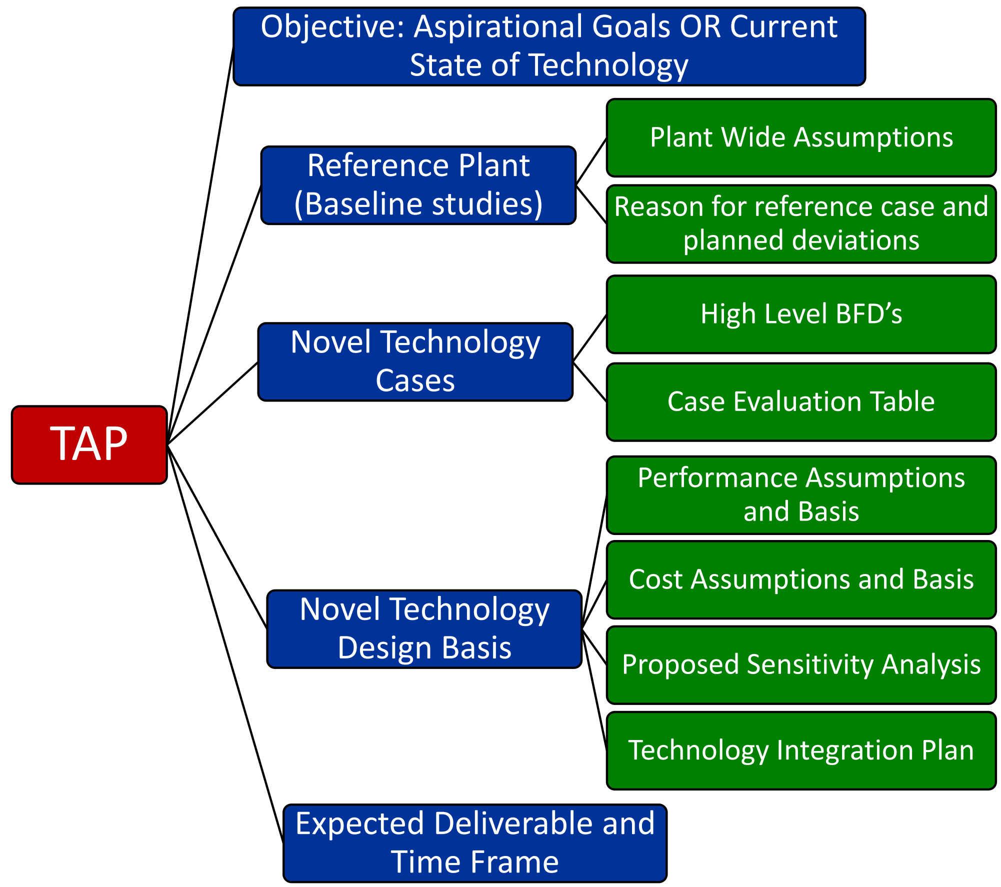


1. Form a Technology Analysis Plan
2. Create a Performance Model
3. Cost Estimating – BSP
4. Reporting Requirements

Technology Analysis Plan (TAP)

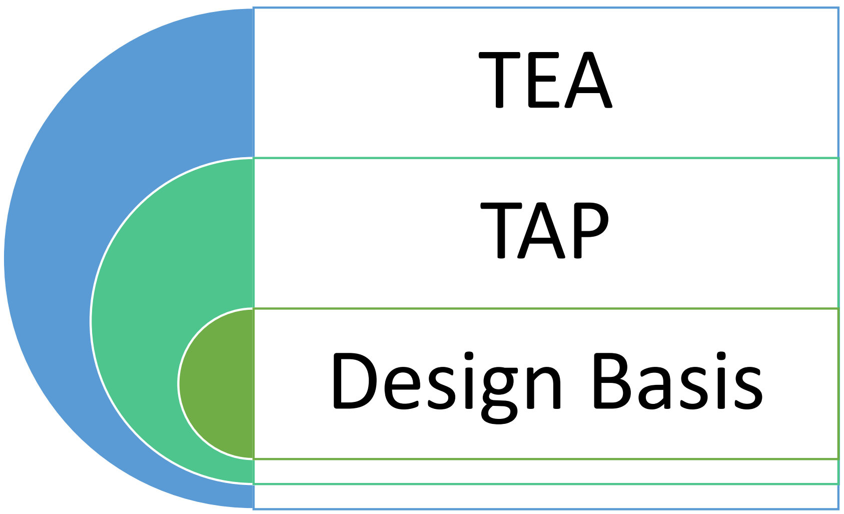
What is a TAP?

- **A TAP discusses the approach and methodology required to conduct the TEA**
- **Presented to stakeholders <u>prior</u> to starting the TEA**
  - Document assumptions
  - Ensure valuable product
- **Updated as the TEA is performed - changes should be noted in a final document**



Case	Baseline (Reference)	Case Study		
		Case 1	Case 2	Case 2A
Technology Combinations				
CO_2 Removal	Selexol	Novel Capture Tech.		
Enabling Tech.	Std. Tech.		Enabled Tech.	
CO_2 Purification	No			Yes

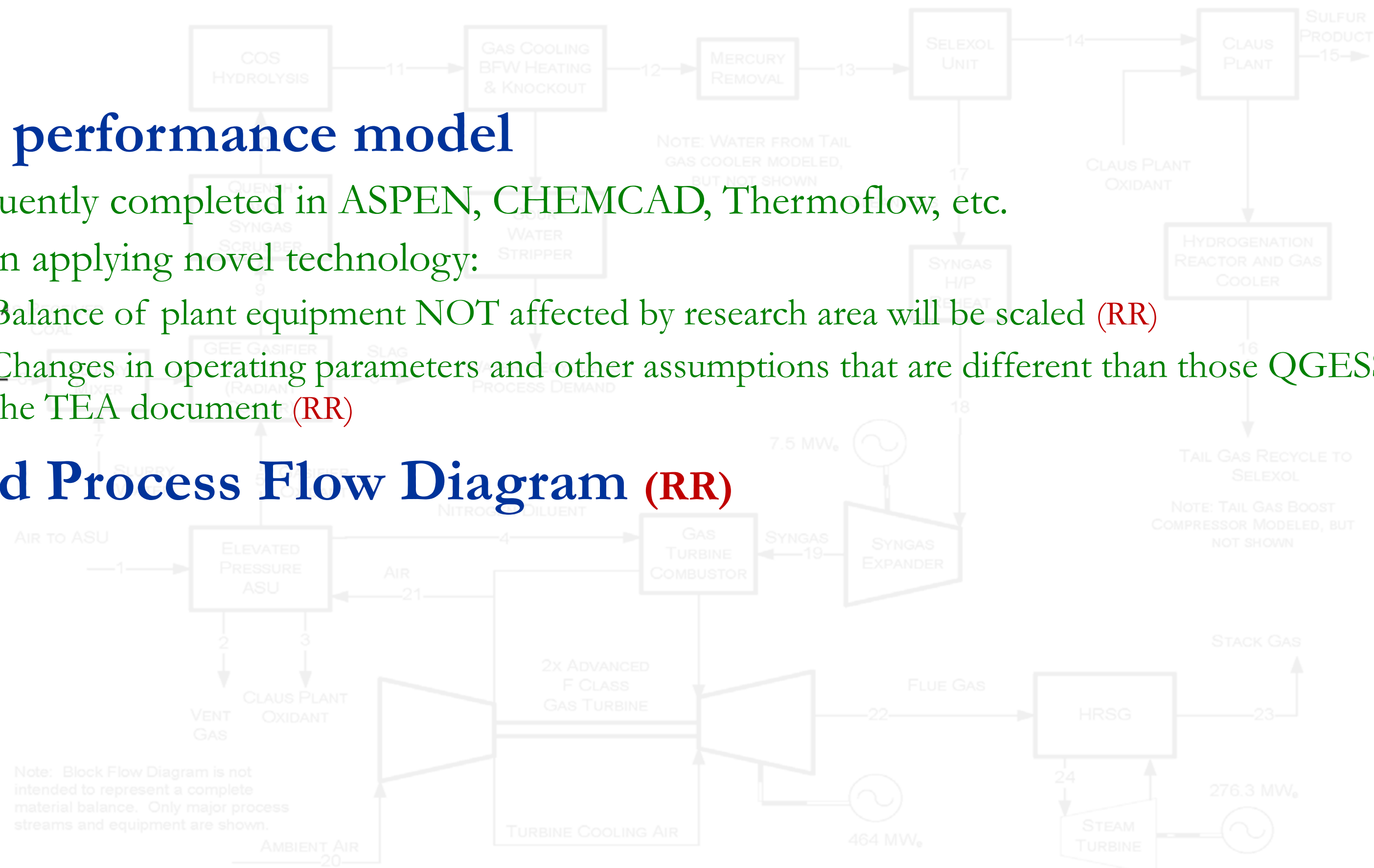
Steps to Performing a TEA



1. Form a Technology Analysis Plan
2. **Create a Performance Model**
3. Cost Estimating – BSP
4. Reporting Requirements

Performance Model Results for Reporting

NATIONAL ENERGY TECHNOLOGY LABORATORY



- **Build a performance model**
  - Frequently completed in ASPEN, CHEMCAD, Thermoflow, etc.
  - When applying novel technology:
    - Balance of plant equipment NOT affected by research area will be scaled (RR)
    - Changes in operating parameters and other assumptions that are different than those QGESS must be justified in the TEA document (RR)
- **Detailed Process Flow Diagram (RR)**

Performance Modeling Inconsistencies

- **Items that are often varied between the reference and novel cases 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

These variations without justification may require further communication or resubmission of report

Performance variations ***NOT*** related to the novel technology between the reference and novel cases should thoroughly explained

Performance Model Results for Reporting

NATIONAL ENERGY TECHNOLOGY LABORATORY

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

Model Results

B5B (GEE Radiant Capture)

- **Total power from turbines (RR)**
- **New auxiliary loads (RR)**
- **Net Power (RR)**
- **Heat rate, efficiencies, etc. (RR)**
  - HHV Commonly used for NETL reporting purposes
- **Water withdraw, consumption, and discharge (RR)**
  - If new technology creates impurities in water discharge, this must be documented
- **CO_2 product composition (RR)**
- **Air emissions**
- **Equipment and auxiliary loads NOT affected by novel technology will be scaled appropriately**

Power Summary	Rev4-PO	Rev4
Combustion Turbine Power, MWe	464	464
Sweet Gas Expander Power, MWe	3	3
Steam Turbine Power, MWe	276	274
Total Gross Power, kWe	**743**	**741**
Auxiliary Load Summary		
Acid Gas Removal, kWe	11,490	11,550
Air Separation Unit Auxiliaries, kWe	1,000	1,000
Air Separation Unit Main Air Compressor, kWe	70,920	71,280
Air Separation Unit Booster Compressor, kWe	5,580	5,610
Ammonia Wash Pumps, kWe	90	90
Circulating Water Pumps, kWe	4,740	4,850
Claus Plant TG Recycle Compressor, kWe	60	1,080
Claus Plant/TGTU Auxiliaries, kWe	250	250
CO_2 Compression, kWe	29,000	31,670
Coal Dryer Air Compressor, kWe	0	0
Coal Handling, kWe	470	470
Coal Milling, kWe	2,240	2,250
Combustion Turbine Auxiliaries, kWe	1,000	1,000
Condensate Pumps, kWe	260	270
Cooling Tower Fans, kWe	2,450	2,510
Feedwater Pumps, kWe	3,810	3,840
Gasifier Water Pump, kWe	0	0
Ground Water Pumps, kWe	490	500
Miscellaneous Balance of Plant[A], kWe	3,000	3,000
Nitrogen Compressors, kWe	35,460	36,580
Nitrogen Humidification Pump, kWe	0	0
Oxygen Pump, kWe	480	480
Auxiliary Load Summary		
Quench Water Pump, kWe	400	400
Shift Steam Pump, kWe	210	210
Slag Handling, kWe	1,150	1,150
Slag Reclaim Water Recycle Pump, kWe	0	0
Slurry Water Pump, kWe	190	190
Sour Gas Compressors, kWe	0	0
Sour Water Recycle Pumps, kWe	10	10
Steam Turbine Auxiliaries, kWe	100	200
Syngas Recycle Compressor, kWe	0	0
Syngas Scrubber Pumps, kWe	140	140
Process Water Treatment Auxiliaries, kWe	1,670	1,320
Transformer Losses, kWe	2,860	2,870
Total Auxiliaries, MWe	**180**	**185**
Net Power, MWe	**564**	**556**

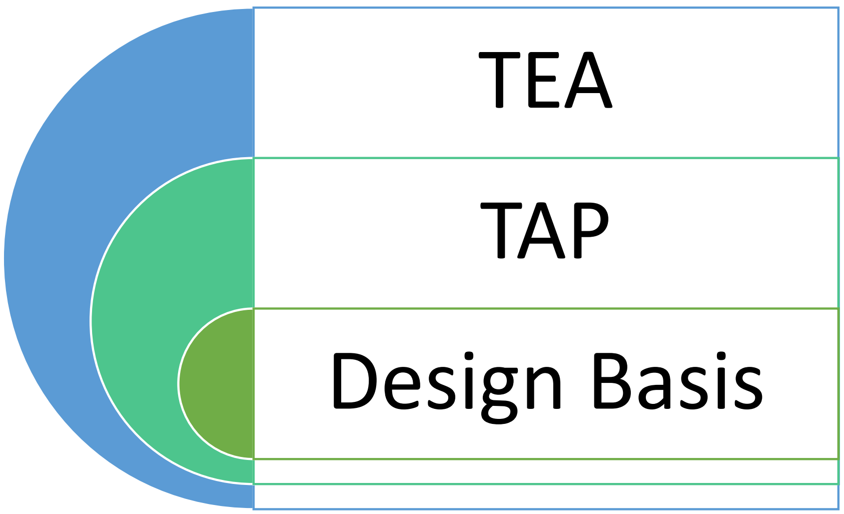
Reporting Novel Equipment

- **Novel equipment should be reported at a greater level of detail than found in the Baseline study**

- **Items to include (RR):**
  - Design equations (if developed)
  - Scaling methodology and equations
  - Design basis (kinetics, volumetric throughput, etc.)
  - How was the data for the above collected (TGA, lab scale bubbling bed, etc.)

Steps to Performing TEA

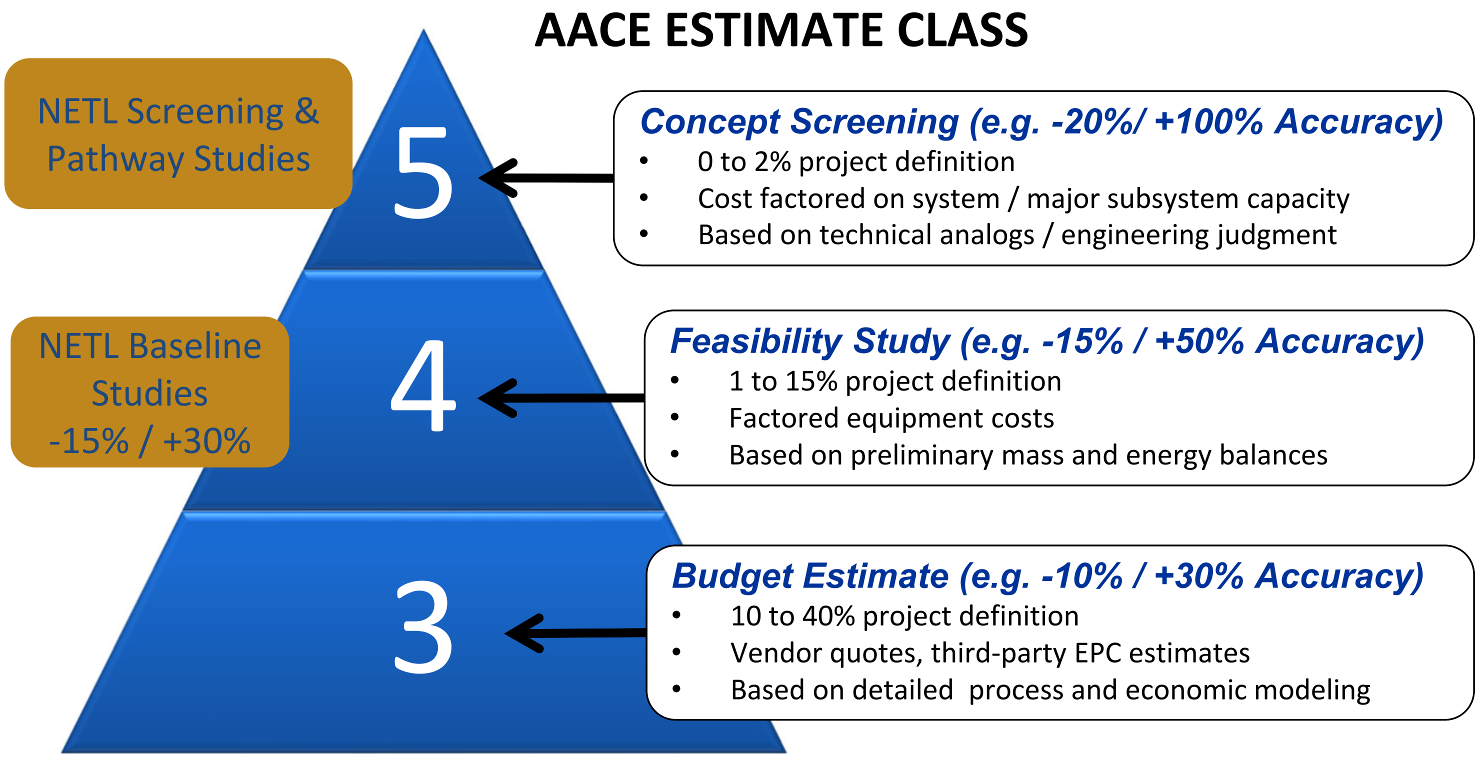
NATIONAL ENERGY TECHNOLOGY LABORATORY



1. Form a Technology Analysis Plan
2. Create a Performance Model
3. Cost Estimating – BSP
4. Reporting Requirements

Classes of NETL Cost Estimates

NATIONAL ENERGY TECHNOLOGY LABORATORY

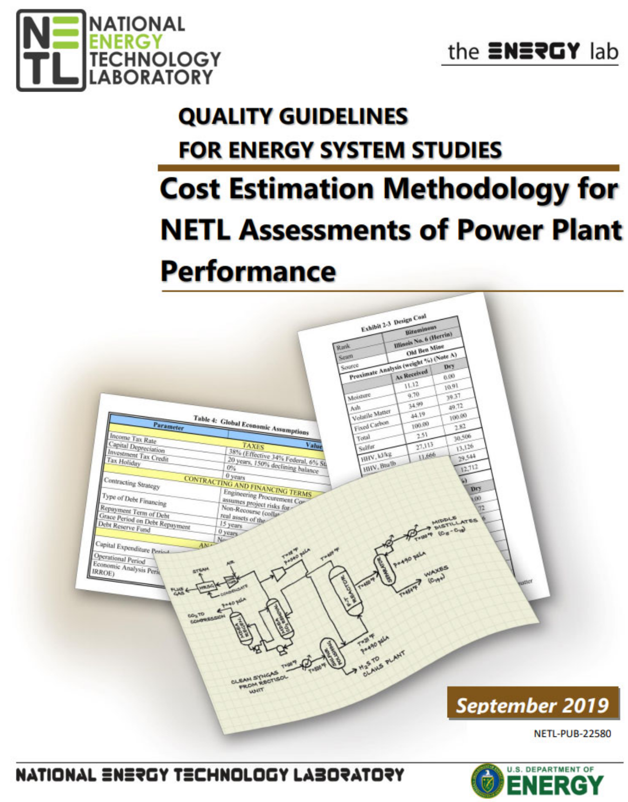


Process flow diagrams (PFDs) and piping and instrument diagrams (P&IDs) are the primary documents that define project scope. Association for the Advancement of Cost Engineering International (AACE) Recommended Practice No. 18R-97 describes the AACE cost estimate classification system.

QGESS: 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 BSP



https://netl.doe.gov/projects/files/QGESSCostEstMethodforNETLAssessmentsofPowerPlantPerformance_090119.pdf

Economic Analysis – Breakeven CO_2 Sales Price

Cost of Capture

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **Breakeven CO_2 Sales Price (BSP) is the minimum revenue a power plant must receive for the CO_2 captured and sent to storage in order to cover cost and stated IRROE**
  - Determining involves a complex set of financial assumptions
  - To simplify the calculation, a Fixed Charge Rate (for capital) has been developed.
    - Simplifies and unifies common financial terms and assumptions
    - Annualizes the capital cost over the life of the plant
- **A simplified equation can be utilized to determine the BSP to unify assumptions**

$$\mathbf{BSP} = \frac{\begin{matrix}\text{Annualized}\\ \text{capital charge}\end{matrix} + \begin{matrix}\text{Annual}\\ \text{fixed operating}\\ \text{costs}\end{matrix} + \begin{matrix}\text{Annual}\\ \text{variable operating}\\ \text{costs}\end{matrix}}{\begin{matrix}\text{annual } CO_2 \text{ captured and}\\ \text{sent to storage}\end{matrix}}$$

Economic Analysis - BSP

(RR)

$$BSP = \frac{\mathbf{FCR} \cdot TASC + OC_{FIX} + \mathbf{CF} \cdot OC_{VAR} + \mathbf{CF} \cdot \mathbf{FP}}{\mathbf{CF} \cdot \mathbf{FCO_2}}$$

- The **FCR** takes into account the financial aspects of the plant and represents them in a single factor that can then be used to annualize the capital over the life of the plant. Greater detail can be found in the QGESS documents.
- The **FCO_2** parameter is the annual flow of CO_2 from the plant (at 100% CF);
  - NET removal = is the net CO_2 removed from the atmosphere
  - GROSS = is the gross CO_2 removed from the atmosphere by the DAC system
  - PLANT GROSS = gross DAC removal plus and other CO_2 product flow from the overall plant including power generation
- The **CF** parameter Capacity Factor, which is assumed to be equal to the availability
- The **FP** is the sum of annual fuel costs (if in plant boundary)

Fixed Operating Costs (OC_{FIX})	Variable Operating Costs (OC_{VAR})
Annual Operating Labor Cost	Maintenance Material Cost
Maintenance Labor Cost	Other Consumables
Administrative & Support Labor	Waste Disposal
Property Taxes and Insurance	Emission Costs
Additional OC_{Fix} for new technology	Byproduct Revenues
	Additional OC_{Var} for new technology
	*Energy Costs, if outside plant

Economic Analysis – Capital Costs

(RR)

$$BSP = \frac{FCR \cdot \mathbf{TASC} + OC_{FIX} + CF \cdot OC_{VAR} + CF \cdot FP}{CF \cdot FCO_2}$$

- **TASC**
  - **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.

Capital Cost Basis of Novel Equipment

- **Capital costs (projected commercial costs) for unique equipment may be calculated by several methods: (RR)**
  - Scaled: The equipment can be scaled if analogous equipment is available either in an NETL baseline study or otherwise
  - Bottom-up: Build cost from metal and manufacturing cost estimates
  - If neither a scaled approach or a bottom-up estimate can be produced - research goals or bearable costs can be estimated
    - This approach is occasionally used at laboratory scale projects
  - Report what the basis is for cost (experimental scale)
- **The methodology, reference equipment, and sources of data should be documented in detail within the TEA**
- **Balance of plant will be directly used or scaled from the Baseline reports**

Contingency Estimation

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **Contingency is to cover the known-unknowns or costs that will likely occur based on past experience due to incomplete engineering design**
  - Example: early in the design phase, the plant will have high contingencies, future plants should have lower contingencies, but more known costs
- **Two types of contingencies are used:**
  - Project Contingency: AACE 16R-90 states that project contingency for a "budget-type" estimate (AACE Class 4 or 5) should be 15 percent to 30 percent of the sum of BEC, EPC fees and process contingency.
  - Process Contingency: intended to compensate for uncertainty in cost estimates caused by performance uncertainties associated with the development status of a technology.

- **Each "process" in the TEA is assigned a contingency**

Technology Status	Process Contingency
New Concept – limited data	40+%
Concept with bench scale data	30-70%
Small Pilot scale data	20-35%
Full sized modules tested	5-20%
Commercial process	0-10%

Contingency Estimation

- Generally, novel technology should have a higher contingency than those in the Baseline studies
- Level of Contingency used should be relative to the development level and engineering completeness of the cost estimate for the novel technology.
- If R&D cost targets, if applicable, contingency might be inclusive
  - When assessing progress towards R&D targets, appropriate contingencies should be included

- Contingency is not:
  - To cover poor engineering or poor estimates
  - Accuracy
  - Cover a scope change
  - Account for delays
  - Unexpected cost escalation
  - Plant performance after startup

Process contingencies range between 2-5% of overall TPC

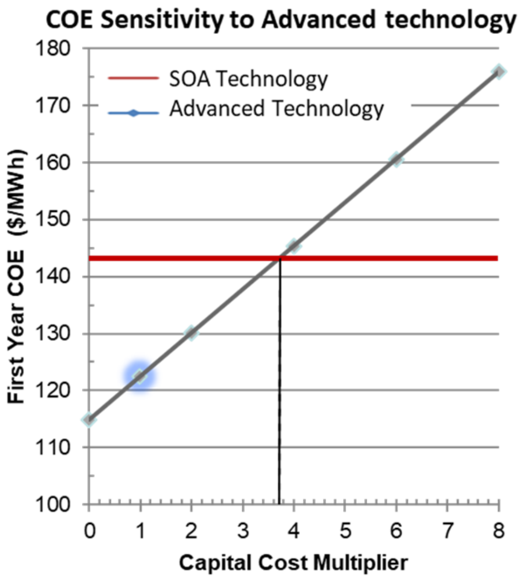
Process Contingency	
Slurry prep and Feed pump	5%
Gasifier and syngas cooler	15%
Two stage Selexol	20%
Mercury Removal	5%
CO_2 removal (PC & NGCC)	20%
Combustion Turbine	5%
AHT in IGCC	10%
Instrumentation and controls	5%

Economic Analysis - BSP

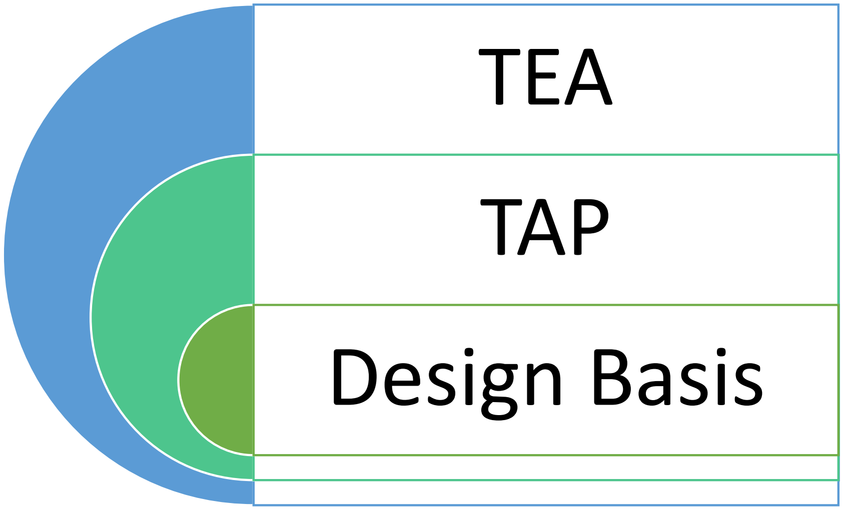
Once BSP has been calculated:

- **Compared to reference to novel cases(RR)**
- **Sensitivity analysis can be conducted to guide research or suggest future goals (RR)**

  Examples include:
  - Capital cost,
  - changes in kinetics
  - reduced pressure drop,
  - reduced heat of reaction to reduce regeneration duties
- **This information can be utilized to determine if a parameter is critical.**
- **Warning: Do not compare BSP from different developer TEA's. BSP's should only be compared when from the same TEA with the same assumptions and basis**



Steps to Performing TEA



1. Form a Technology Analysis Plan
2. Create a Performance Model
3. Cost Estimating – BSP
4. Reporting Requirements

Reporting Requirements

- **TAP – share with stakeholders**
  - State Design and Cost Assumptions and Basis

→ **Stakeholders**

- **Updated TAP**
- **Performance Modeling**
  - Block Flow diagram
  - Detailed Simulation Model
  - Material and Energy Balance
- **Cost Estimating – Capital Cost and Breakeven CO_2 Sales Price ($/tonne)**
  - Detailed TOC cost estimates
  - Sensitivity Studies
  - Breakeven Sales Price
    - Focus on $/tonne NET
    - May also calculate on GROSS or PLANT GROSS basis

- **The TEA report should:**
  - Provide reasoning for new equipment design basis – experimental data is preferred
  - Have a level a detail equal or greater than that outlined in the Bituminous Baseline (particularly for novel equipment)
  - Provide a basis for both design and costing of novel equipment
- **Remember to:**
  - Justify any variations from the QGESS/Baseline outside of the new technology
  - Provide enough detail to reproduce stated number
  - Once complete, use the information to guide research

Presentation Outline

- TEA Process
- **QGESS Description/Location**
- Bituminous Baseline Study Overview/Example

NETL Quality Guidelines for Energy System Studies

QGESS

NATIONAL ENERGY TECHNOLOGY LABORATORY

Title	Description
Detailed Coal Specifications	Provides detailed specifications for seven coals commonly used with detailed production information
Specifications for Selected Feedstocks	Provides recommended specifications for natural gas and coal that are commonly found in NETL energy system studies.
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 serves as a comprehensive reference for these assumptions as well as their justification.
CO_2 Impurity Design Parameters	Summarizes the impurity limits for CO_2 stream components for use in carbon steel pipelines, enhanced oil recovery (EOR), saline formation sequestration, and co-sequestration of CO_2 and H_2S in saline formations.
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.
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	Addresses the cost of CO_2 transport and storage (T&S) in a deep saline formation with respect to plant location and region-specific aquifers.
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.

Examples of Information Used in TEA

QGESS Documents Frequently Referenced

- **QGESS on Process Modeling Design**
  - Site Conditions
  - Steam Cycle Conditions
  - Coal Combustion Parameters
  - Gasifier Performance
  - Syngas Processing
  - Sulfur Processing
  - Equations of State
  - Cooling Water Parameters

- **Feedstock Specification QGESS**
  - Natural Gas Composition
  - Coal Compositions – by type
  - Limestone Analysis
  - Lime Analysis
  - LHV and HHV

- **QGESS on CO_2 Impurities**
  - CO_2 Delivery Pressure
  - Individual Contaminate Concentration Limits
  - CO_2 minimum concentration
  - Specifications for intended use (Saline, EOR, etc.)
  - Venting concerns

Energy Analysis Website
NETL Webpage: Library: Energy Analysis

NATIONAL ENERGY TECHNOLOGY LABORATORY

ABOUT ENERGY ANALYSIS

NETL conducts a variety of energy analyses to identify and evaluate promising research and development (R&D) opportunities in order to provide balanced solutions in support of economic sustainability, energy supply security, mitigation of global climate change, and improved environmental performance.

NETL-conducted studies require a multi-disciplinary approach to the assessment of large, complex energy systems encompassing energy production, distribution, and use. Strategic assessments and planning efforts also incorporate the evaluation of current status, near-term trends, and futuristic scenarios.

KEY ANALYSIS AREAS

TECHNOLOGY ANALYSIS

Technology analyses estimate and assess the performance and cost of current, state-of-the-art as well as future energy technologies and systems that result from successful NETL RD&D. Example energy technologies and systems include advanced carbon capture technologies and systems that store captured carbon dioxide in deep geologic formations. The outputs from technology analyses are used to inform larger scale energy-economic models that place these technologies in context within the larger energy portfolio. The analyses also provide insights into the anticipated competitiveness of these technologies, as well as the potential economic, environmental, and energy security impacts and benefits that result from successful NETL RD&D under a variety of possible future scenarios.

BENEFITS ANALYSIS

Focuses on quantifying both prospective and retrospective benefits of energy R&D programs using economic models. These studies deliver an understanding of the potential economic competitiveness of advanced energy technologies being developed at NETL, both in the near term and over the next several decades.

The extent to which benefits are realized is a function of several factors, including:

- Success at meeting R&D goals
- Competition with other technologies
- Future energy prices
- Future regulatory actions

Since the future of markets and regulations is uncertain, alternative scenarios must be considered. NETL analysts use economic models to forecast the market penetration of advanced energy systems for a variety of possible futures. Impacts are evaluated and associated benefits quantified across three areas: economic, environmental, and energy security.

INTEGRATED ELECTRIC POWER SYSTEMS INFRASTRUCTURE EVALUATION

Studies involve analyzing the interdependencies of electric power systems with other critical infrastructures, such as transportation networks and water infrastructure. Analyses evaluate options for generation, transmission, distribution, and consumption of electricity considering the value of electric power to industry, consumers, and society.

ENERGY DATA AND TRENDS ANALYSIS

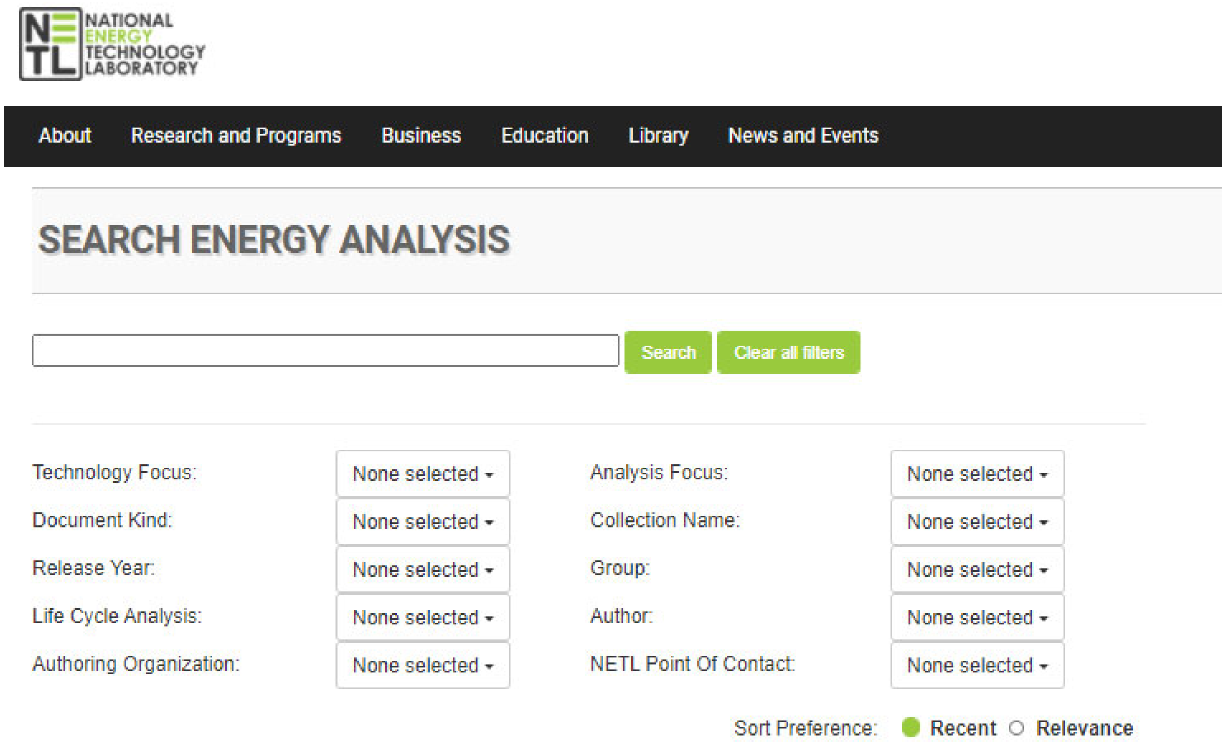
Energy analyses include assessments of near- and long-term trends within the U.S. and world energy industries that may impact energy price, availability, and security while influencing the choice of fuels and energy production technologies.

LIFE CYCLE ASSESSMENT

Life Cycle Analysis (LCA) is a comprehensive form of analysis that utilizes the principles of Life Cycle Assessment, Life Cycle Cost Analysis, and various other methods to evaluate the environmental, economic, and social attributes of energy systems ranging from the extraction of raw materials from the ground to the use of the energy carrier to perform work (commonly referred to as the "life cycle" of a product). Results are used to inform research at NETL and evaluate energy options from a National perspective.

https://netl.doe.gov/ea/about

Energy Analysis Website
Search Energy Analysis



https://netl.doe.gov/energy-analysis/search

QGESS Examples

Site Characteristics

Site Characteristics

Parameter	Value
Location	Greenfield, Midwestern U.S.
Topography	Level
Size (PC), acres	300
Size (NGCC), acres	100
Transportation	Rail or Highway
Ash Disposal	Off-Site
Water	50% Municipal and 50% Ground Water

Site Ambient Conditions

Parameter	Value
Elevation, m (ft)	0 (0)
Barometric Pressure, MPa (psia)	0.101 (14.696)
Average Ambient Dry Bulb Temperature, °C (°F)	15 (59)
Average Ambient Wet Bulb Temperature, °C (°F)	10.8 (51.5)
Design Ambient Relative Humidity, %	60
Cooling Water Temperature, °C (°F)[A]	15.6 (60)
Air composition based on published psychrometric data, mass %	
N_2	75.055
O_2	22.998
Ar	1.280
H_2O	0.616
CO_2	0.050
Total	100.00

QGESS Examples

Fuel Specification

Coal Specifications

	Volume 1a and Volume 1b Rev3		Volume 1 Rev4	
Rank	**Bituminous**		**Bituminous**	
Seam	**Illinois No. 6 (Herrin)**		**Illinois No. 6**	
Source	Old Ben Mine		-	
Proximate Analysis (weight %)[A]				
	As Received	**Dry**	**As Received**	**Dry**
Moisture	11.12	0.00	11.12	0.00
Ash	9.70	10.91	9.70	10.91
Volatile Matter	34.99	39.37	34.99	39.37
Fixed Carbon	44.19	49.72	44.19	49.72
Total	100.00	100.00	100.00	100.00
Sulfur	2.51	2.82	2.51	2.82
HHV, kJ/kg (Btu/lb)	27,113 (11,666)	30,506 (13,126)	27,113 (11,666)	30,506 (13,126)
LHV, Btu/lb (Btu/lb)	26,151 (11,252)	29,544 (12,712)	26,151 (11,252)	29,544 (12,712)
Ultimate Analysis (weight %)				
	As Received	**Dry**	**As Received**	**Dry**
Moisture	11.12	0.00	11.12	0.00
Carbon	63.75	71.72	63.75	71.72
Hydrogen	4.50	5.06	4.50	5.06
Nitrogen	1.25	1.41	1.25	1.41
Chlorine	0.29	0.33	0.15	0.17
Sulfur	2.51	2.82	2.51	2.82
Ash	9.70	10.91	9.70	10.91
Oxygen[B]	6.88	7.75	7.02	7.91
Total	100.00	100.00	100.00	100.00

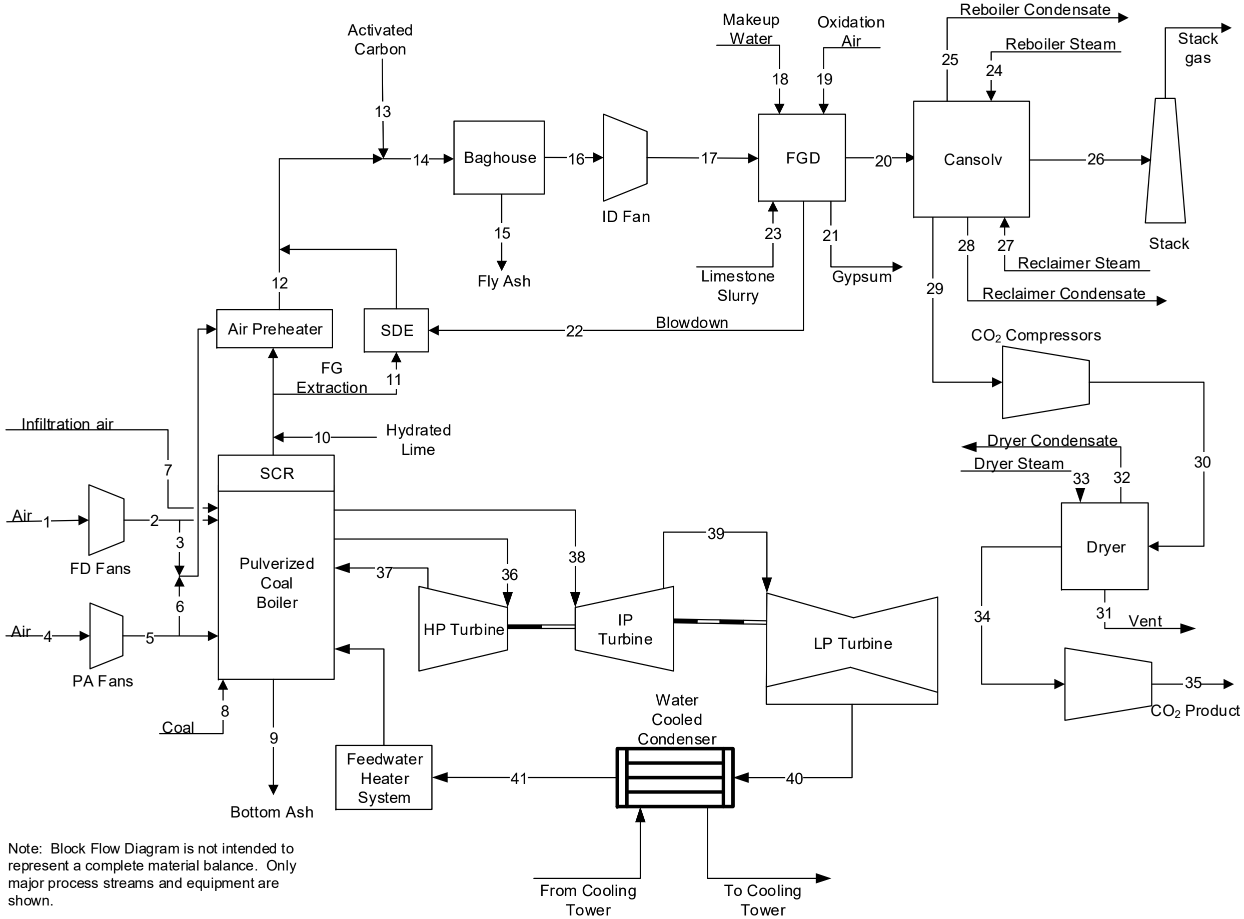
Natural Gas Specification

	Volume 1a Rev3		Volume 1 Rev4	
Component	**Volume Percentage**		**Volume Percentage**	
Basis	QGESS		Aspen: QVAL GRS/NET @ 25C	
Methane	93.1		93.1	
Ethane	3.2		3.2	
Propane	0.7		0.7	
n-Butane	0.4		0.4	
Carbon Dioxide	1.0		1.0	
Nitrogen	1.6		1.6	
Methanethiol[A]	5.75×10^{-6}		5.75×10^{-6}	
Total	100.00		100.00	
	LHV	**HHV**	**LHV**	**HHV**
kJ/kg (Btu/lb)	47,454 (20,410)	52,581 (22,600)	47,201 (20,293)	52,295 (22,483)
MJ/scm (Btu/scf)	34.71 (932)	38.46 (1,032)	34.52 (927)	38.25 (1,027)

Presentation Outline

- TEA Process
- QGESS Description/Location
- **Bituminous Baseline Study Overview/Example**
  - Type of content to include
  - DAC baseline not available yet

Final Block Flow Diagram – B12B



B31B NGCC Stream Tables

NATIONAL ENERGY TECHNOLOGY LABORATORY

	1	2	3	4	5	6	7	8	9	10	11	12
V-L Mole Fraction												
Ar	0.0092	0.0000	0.0089	0.0089	0.0000	0.0000	0.0000	0.0098	0.0000	0.0000	0.0000	0.0000
CH_4	0.0000	0.9310	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0320	0.0000	0.0000	0.000							
C_3H_8	0.0000	0.0070	0.0000	0.0000	0.000							
C_4H_{10}	0.0000	0.0040	0.0000	0.0000	0.000							
CO_2	0.0003	0.0100	0.0408	0.0408	0.000							
H_2O	0.0099	0.0000	0.0875	0.0875	1.000							
N_2	0.7732	0.0160	0.7428	0.7428	0.000							
O_2	0.2074	0.0000	0.1200	0.1200	0.000							
SO_2	0.0000	0.0000	0.0000	0.0000	0.000							
Total	1.0000	1.0000	1.0000	1.0000	1.000							
V-L Flowrate (kg_{mol}/hr)	132,867	5,383	138,406	138,406	14,3							
V-L Flowrate (kg/hr)	3,834,126	93,272	3,927,398	3,927,398	259,2							
Solids Flowrate (kg/hr)	0	0	0	0	0							
Temperature (°C)	15	27	625	111	308							
Pressure (MPa, abs)	0.10	2.96	0.11	0.10	0.51							
Steam Table Enthalpy (kJ/kg)[A]	30.23	22.04	832.66	255.52	3,080.							
AspenPlus Enthalpy (kJ/kg)[B]	-97.58	-4,487.18	-644.47	-1,221.61	-12,900							
Density (kg/m³)	1.2	22.1	0.4	0.9	1.9							
V-L Molecular Weight	28.857	17.328	28.376	28.376	18.01							
V-L Flowrate (lb_{mol}/hr)	292,921	11,867	305,132	305,132	31,72							
V-L Flowrate (lb/hr)	8,452,800	205,630	8,658,430	8,658,430	571,5							
Solids Flowrate (lb/hr)	0	0	0	0	0							
Temperature (°F)	59	80	1,156	231	586							
Pressure (psia)	14.7	430.0	15.5	14.8	73.5							
Steam Table Enthalpy (Btu/lb)[A]	13.0	9.5	358.0	109.9	1,324							
AspenPlus Enthalpy (Btu/lb)[B]	-42.0	-1,929.1	-277.1	-525.2	-5,546							
Density (lb/ft³)	0.076	1.380	0.025	0.057	0.11							

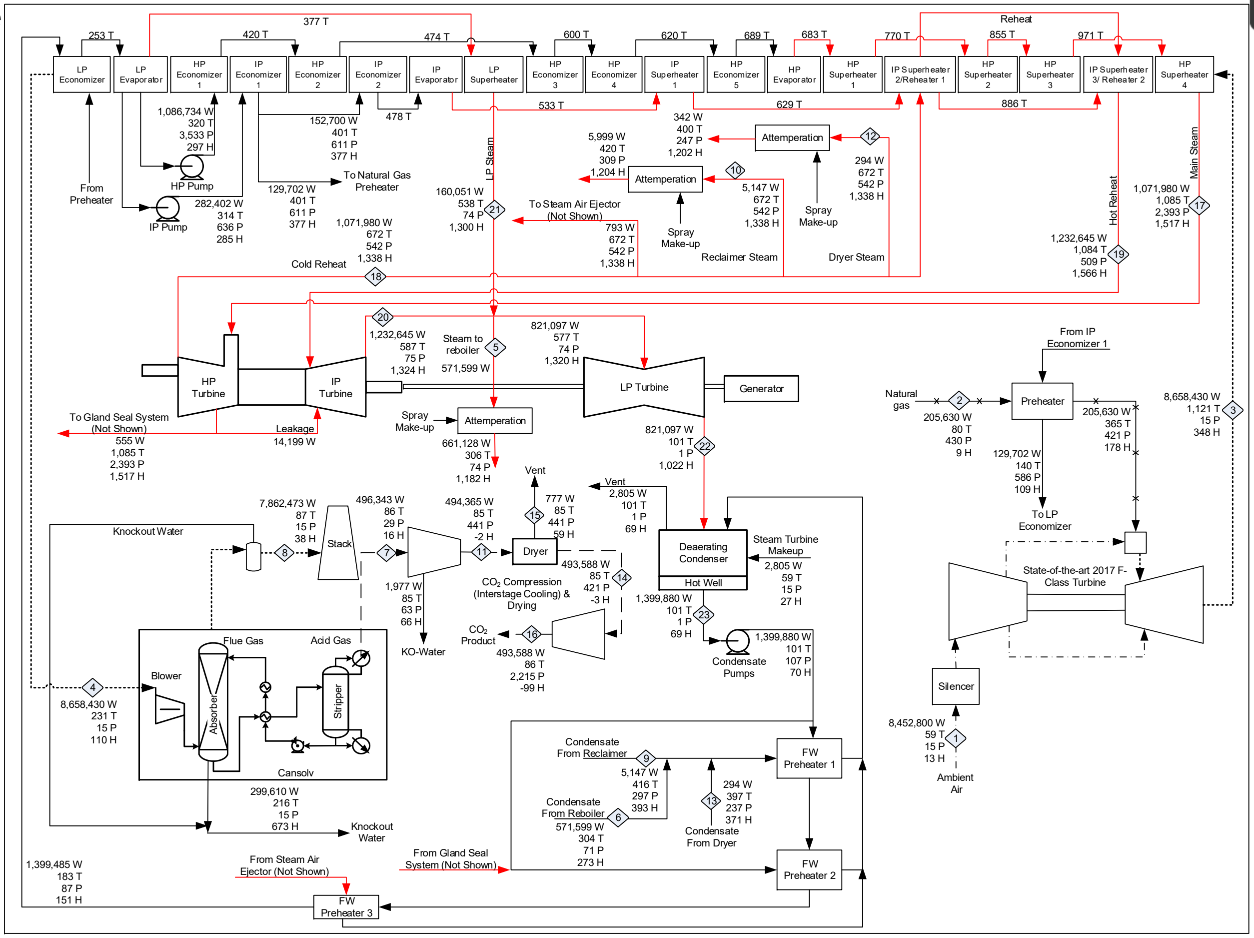
	13	14	15	16	17	18	19	20	21	22	23
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.9995	0.0500	0.9995	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	1.0000	0.0005	0.9500	0.0005	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
N_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	7	5,089	18	5,089	26,991	26,991	31,036	31,036	4,030	20,674	35,246
V-L Flowrate (kg/hr)	133	223,888	353	223,888	486,242	486,242	559,118	559,118	72,598	372,443	634,975
Solids Flowrate (kg/hr)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	203	29	29	30	585	356	584	308	281	38	38
Pressure (MPa, abs)	1.64	2.90	3.04	15.27	16.50	3.74	3.51	0.52	0.51	0.01	0.01
Steam Table Enthalpy (kJ/kg)[A]	863.65	-6.32	137.79	-231.09	3,528.08	3,112.11	3,642.67	3,080.20	3,024.62	2,376.09	160.78
AspenPlus Enthalpy (kJ/kg)[B]	-15,116.65	-8,969.87	-15,225.37	-9,194.65	-12,452.22	-12,868.18	-12,337.62	-12,900.10	-12,955.67	-13,604.20	-15,819.51
Density (kg/m³)	861.8	60.1	375.2	630.1	45.6	13.8	9.0	2.0	2.0	0.1	992.8
V-L Molecular Weight	18.015	43.997	19.315	43.997	18.015	18.015	18.015	18.015	18.015	18.015	18.015
V-L Flowrate (lb_{mol}/hr)	16	11,219	40	11,219	59,504	59,504	68,422	68,422	8,884	45,578	77,705
V-L Flowrate (lb/hr)	294	493,588	777	493,588	1,071,980	1,071,980	1,232,645	1,232,645	160,051	821,097	1,399,880
Solids Flowrate (lb/hr)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	397	85	85	86	1,085	672	1,084	587	538	101	101
Pressure (psia)	237.4	421.1	441.1	2,214.7	2,393.1	542.3	508.6	75.0	73.5	1.0	1.0
Steam Table Enthalpy (Btu/lb)[A]	371.3	-2.7	59.2	-99.4	1,516.8	1,338.0	1,566.1	1,324.2	1,300.4	1,021.5	69.1
AspenPlus Enthalpy (Btu/lb)[B]	-6,499.0	-3,856.4	-6,545.7	-3,953.0	-5,353.5	-5,532.3	-5,304.2	-5,546.0	-5,569.9	-5,848.8	-6,801.2
Density (lb/ft³)	53.801	3.755	23.421	39.338	2.849	0.863	0.563	0.122	0.125	0.003	61.977

[A]Steam table reference conditions are 32.02°F & 0.089 psia

[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

B31B (NGCC Capture)

Heat & Mass Balance



B12B (SC PC Capture)

Performance Summary

Power Summary	Rev4 – 650 MW
Steam Turbine Power, MWe	770
Total Gross Power, MWe	**770**
Auxiliary Load Summary	
Activated Carbon Injection, kWe	40
Ash Handling, kWe	880
Baghouse, kWe	120
Circulating Water Pumps, kWe	9,610
CO_2 Capture/Removal Auxiliaries, kWe	27,300
CO_2 Compression, kWe	44,380
Coal Handling and Conveying, kWe	530
Condensate Pumps, kWe	790
Cooling Tower Fans, kWe	4,970
Dry Sorbent Injection, kWe	80
Flue Gas Desulfurizer, kWe	4,230
Forced Draft Fans, kWe	2,560
Ground Water Pumps, kWe	900
Induced Draft Fans, kWe	10,440
Miscellaneous Balance of Plant[A,B], kWe	2,250
Primary Air Fans, kWe	2,010
Pulverizers, kWe	4,100
SCR, kWe	50
Sorbent Handling & Reagent Preparation, kWe	1,280
Spray Dryer Evaporator, kWe	300
Steam Turbine Auxiliaries, kWe	500
Transformer Losses, kWe	2,680
Total Auxiliaries, MWe	**120**
Net Power, MWe	**650**

Performance Summary	Rev4 – 650 MW
Total Gross Power, MWe	**770**
CO_2 Capture/Removal Auxiliaries, kWe	27,300
CO_2 Compression, kWe	44,380
Balance of Plant, kWe	48,320
Total Auxiliaries, MWe	**120**
Net Power, MWe	**650**
HHV Net Plant Efficiency, %	31.5%
HHV Net Plant Heat Rate, kJ/kWh (Btu/kWh)	11,430 (10,834)
LHV Net Plant Efficiency, %	32.7%
LHV Net Plant Heat Rate, kJ/kWh (Btu/kWh)	11,024 (10,449)
HHV Boiler Efficiency, %	88.1%
LHV Boiler Efficiency, %	91.3%
Steam Turbine Cycle Efficiency, %	57.5%
Steam Turbine Heat Rate, kJ/kWh (Btu/kWh)	6,256 (5,930)
Condenser Duty, GJ/hr (MMBtu/hr)	2,127 (2,016)
AGR Duty, GJ/hr (MMBtu/hr)	2,344 (2,222)
As-Received Coal Feed, kg/hr (lb/hr)	273,628 (603,246)
Limestone Sorbent Feed, kg/hr (lb/hr)	26,469 (58,354)
HHV Thermal Input, kWt	2,062,478
LHV Thermal Input, kWt	1,989,286
Raw Water Withdrawal, $(m^3/min)/MW_{net}$ (gpm/MW_{net})	0.058 (15.3)
Raw Water Consumption, $(m^3/min)/MW_{net}$ (gpm/MW_{net})	0.041 (10.8)
Excess Air, %	20.3%

Rev4 Footnotes:
[A]Boiler feed pumps are turbine driven
[B]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

B12B Equipment Summaries

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
8	Vacuum Filter Belt	Horizontal belt	44 tonne/hr (49 tph) of 50 wt% slurry	2	1
9	Filtrate Water Return Pumps	Horizontal centrifugal	850 lpm @ 13 m H_2O (220 gpm @ 40 ft H_2O)	1	1
10	Filtrate Water Return Storage Tank	Vertical, lined	560,000 lpm (150,000 gal)	1	0
11	Process Makeup Water Pumps	Horizontal centrifugal	1,990 lpm @ 21 m H_2O (530 gpm @ 70 ft H_2O)	1	1
12	Activated Carbon Injectors	---	60 kg/hr (140 lb/hr)	1	0
13	Hydrated Lime Injectors	---	1,660 kg/hr (3,650 lb/hr)	1	0
14	Cansolv	Amine-based CO2 capture technology	3,724,000 kg/hr (8,211,000 lb/hr) 19.1 wt% CO_2 concentration	1	0
15	Cansolv LP Condensate Pump	Centrifugal	1,287 lpm @ 1 m H_2O (340 gpm @ 4 ft H_2O)	1	1
16	Cansolv IP Condensate Pump	Centrifugal	6 lpm @ 4.6 m H_2O (2 gpm @ 15 ft H_2O)	1	1
17	CO_2 Dryer	Triethylene glycol	Inlet: 152 m³/min @ 3.0 MPa (5,381 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 487 kg/hr (1,074 lb/hr)	1	0
18	CO_2 Compressor	Integrally geared, multi-stage centrifugal	8.0 m³/min @ 15.3 MPa, 80°C (299 acfm @ 2,217 psia, 176°F)	2	0
19	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15.3 MPa, 30°C (2,215psia, 86°F) Duty: 88 MMkJ/hr (84 MMBtu/hr)	1	0

Case B12B – Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	Reinforced concrete with FRP liner	152 m (500 ft) high x 6.0 m (20 ft) diameter	1	0

Case B12B – Account 8: Steam Turbine and Accessories

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Steam Turbine	Commercially available advanced steam turbine	798 MW 24.1 MPa/593°C/593°C (3500 psig/ 1100°F/1100°F)	1	0
2	Steam Turbine Generator	Hydrogen cooled, static excitation	890 MVA @ 0.9 p.f., 24 kV, 60 Hz, 3-phase	1	0
3	Surface Condenser	Single pass, divided waterbox including vacuum pumps	1,170 GJ/hr (2,220 MMBtu/hr), Inlet water temperature 16°C (60°F), Water temperature rise 11°C (20°F)	1	0

B12B Capital Cost Summary

Item No.	Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies Process	Contingencies Project	Total Plant Cost $/1,000	Total Plant Cost $/kW
	Case:	B31B	– 2x1 CT NGCC w/ CO_2					Estimate Type:		Conceptual	
	Plant Size (MW, net):	646						Cost Base:		Dec 2018	
3	Feedwater & Miscellaneous BOP Systems										
3.1	Feedwater System	$1,698	$2,910	$1,455	$0	$6,063	$1,213	$0	$1,091	$8,367	$13
3.2	Water Makeup & Pretreating	$5,347	$535	$3,030	$0	$8,912	$1,782	$0	$2,139	$12,834	$20
3.3	Other Feedwater Subsystems	$966	$317	$301	$0	$1,583	$317	$0	$285	$2,185	$3
3.4	Service Water Systems	$1,623	$3,098	$10,031	$0	$14,752	$2,950	$0	$3,540	$21,243	$33
3.5	Other Boiler Plant Systems	$230	$84	$209	$0	$523	$105	$0	$94	$722	$1
3.6	Natural Gas Pipeline and Start-Up System	$9,304	$400	$300	$0	$10,005	$2,001	$0	$1,801	$13,807	$21
3.7	Waste Water Treatment Equipment	$9,693	$0	$5,941	$0	$15,634	$3,127	$0	$3,752	$22,512	$35
3.9	Miscellaneous Plant Equipment	$14,217	$1,865	$7,225	$0	$23,306	$4,661	$0	$5,594	$33,561	$52
	Subtotal	$43,078	$9,208	$28,493	$0	$80,778	$16,156	$0	$18,296	$115,230	$178
5	Flue Gas Cleanup										
5.1	Cansolv Carbon Dioxide (CO_2) Removal System	$148,215	$72,722	$152,716	$0	$373,652	74,730	67,257	103,128	$618,768	$958
5.4	Carbon Dioxide (CO_2) Compression & Drying	$26,481	$3,972	$10,986	$0	$41,440	$8,288	$0	$9,946	$59,674	$92
5.5	Carbon Dioxide (CO_2) Compressor Aftercooler	$218	$35	$93	$0	$346	$69	$0	$83	$498	$1
5.12	Gas Cleanup Foundations	$0	$382	$413	$0	$795	$159	$0	$191	$1,145	$2
	Subtotal	$174,914	$77,111	$164,208	$0	$416,233	$83,247	$67,257	$113,347	$680,085	$1,053
6	Combustion Turbine & Accessories										
6.1	Combustion Turbine Generator	$72,224	$0	$4,395	$0	$76,619	$15,324	$0	$13,791	$105,735	$164
6.3	Combustion Turbine Accessories	$2,626	$0	$160	$0	$2,786	$557	$0	$501	$3,845	$6
6.4	Compressed Air Piping	$0	$867	$196	$0	$1,063	$213	$0	$191	$1,467	$2
6.5	Combustion Turbine Foundations	$0	$906	$979	$0	$1,885	$377	$0	$452	$2,714	$4
	Subtotal	$74,850	$1,773	$5,730	$0	$82,353	$16,471	$0	$14,937	$113,760	$176
7	HRSG, Ductwork, & Stack										
7.1	Heat Recovery Steam Generator	$34,545	$0	$8,636	$0	$43,181	$8,636	$0	$7,773	$59,590	$92
7.2	Heat Recovery Steam Generator Accessories	$12,307	$0	$2,283	$0	$14,590	$2,918	$0	$2,626	$20,134	$31
7.3	Ductwork	$0	$852	$592	$0	$1,445	$289	$0	$260	$1,994	$3
7.4	Stack	$8,150	$0	$1,512	$0	$9,662	$1,932	$0	$1,739	$13,333	$21
7.5	Heat Recovery Steam Generator, Ductwork & Stack Foundations	$0	$635	$597	$0	$1,232	$246	$0	$296	$1,774	$3
7.6	Selective Catalytic Reduction System	$1,465	$616	$859	$0	$2,940	$588	$0	$529	$4,057	$6
	Subtotal	$56,467	$2,104	$14,479	$0	$73,049	$14,610	$0	$13,223	$100,882	$156

Report Capital by Account and Sub Account

Additional Accounts in Baseline include:

8 – Steam Turbine & Accessories
9 – Cooling Water System
11 – Accessory Electric Plant
12 – Instrumentation & Controls
13 – Improvements to Site
14 – Buildings & Structures

Build up of Capital Costs

B31B Example

Description	$/1,000	$/kW
Pre-Production Costs		
6 Months All Labor	$7,822	$12
1 Month Maintenance Materials	$1,432	$2
1 Month Non-Fuel Consumables	$1,211	$2
1 Month Waste Disposal	$12	$0
25% of 1 Months Fuel Cost at 100% CF	$3,729	$6
2% of TPC	$25,626	$40
Total	**$39,833**	**$62**
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	$2,026	$3
0.5% of TPC (spare parts)	$6,407	$10
Total	**$8,432**	**$13**
Other Costs		
Initial Cost for Catalyst and Chemicals	$847	$1
Land	$300	$0
Other Owner's Costs	$192,199	$298
Financing Costs	$34,596	$54
Total Overnight Costs (TOC)	**$1,557,531**	**$2,412**
TASC Multiplier (IOU, 33 year)	1.093	
Total As-Spent Cost (TASC)	**$1,701,831**	**$2,635**

Fixed and Variable Operating Costs

B12B Example

Case:	**B12B**	**– SC PC w/ CO_2**			**Cost Base:**	**Dec 2018**
Plant Size (MW, net):	**650**	**Heat Rate-net (Btu/kWh):**		**10,834**	**Capacity Factor (%):**	**85**
			Operating & Maintenance Labor			
Operating Labor				Operating Labor Requirements per Shift		
Operating Labor Rate (base):		38.50	$/hour	Skilled Operator:		2.0
Operating Labor Burden:		30.00	% of base	Operator:		11.3
Labor O-H Charge Rate:		25.00	% of labor	Foreman:		1.0
				Lab Techs, etc.:		2.0
				Total:		**16.3**
			Fixed Operating Costs			
					Annual Cost	
					($)	**($/kW-net)**
Annual Operating Labor:					$7,161,008	$11.024
Maintenance Labor:					$15,797,590	$24.319
Administrative & Support Labor:					$5,739,649	$8.836
Property Taxes and Insurance:					$49,367,468	$75.997
Total:					**$78,065,715**	**$120.175**
			Variable Operating Costs			
					($)	**($/MWh-net)**
Maintenance Material:					$23,696,385	$4.89906
			Consumables			
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1000 gallons):	0	7,136	$1.90	$0	$4,206,523	$0.86967
Makeup and Waste Water Treatment Chemicals (ton):	0	21.3	$550.00	$0	$3,627,291	$0.74992
Brominated Activated Carbon (ton):	0	1.56	$1,600.00	$0	$772,686	$0.15975
Enhanced Hydrated Lime (ton):	0	39.9	$240.00	$0	$2,967,412	$0.61349
Limestone (ton):	0	700	$22.00	$0	$4,779,570	$0.98814
Ammonia (19 wt%, ton):	0.00	69.0	$300.00	0.00	$6,420,577	$1.32741
SCR Catalyst (ft^3):	17,414	15.9	$150.00	$2,612,120	$740,101	$0.15301
CO_2 Capture System Chemicals[A]		Proprietary			$9,225,455	$1.90730
Triethylene Glycol (gal):	w/equip.	544	$6.80	$0	$1,147,315	$0.23720
Subtotal:				$2,612,120	$33,886,930	$7.00589
			Waste Disposal			
Fly Ash (ton)	0	657	$38.00	$0	$7,744,619	$1.60115
Bottom Ash (ton)	0	146	$38.00	$0	$1,720,404	$0.35568
SCR Catalyst (ft^3):	0	16	$2.50	$0	$12,335	$0.00255
Triethylene Glycol (gal):		544	$0.35	$0	$59,053	$0.01221
Thermal Reclaimer Unit Waste (ton)	0	3.51	$38.00	$0	$41,395	$0.00856
Prescrubber Blowdown Waste (ton)	0	52.1	$38.00	$0	$614,467	$0.12704
Subtotal:				$0	$10,192,273	$2.10718
			By-Products			
Gypsum (ton)	0	1064	$0.00	$0	$0	$0.00000
Subtotal:				$0	$0	$0.00000
Variable Operating Costs Total:				$2,612,120	$67,775,588	$14.01213
			Fuel Cost			
Illinois Number 6 (ton):	0	7,239	$51.96	$0	$116,691,765	$24.12521
Total:				$0	$116,691,765	$24.12521

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

Revision 4 Cost Estimate Results

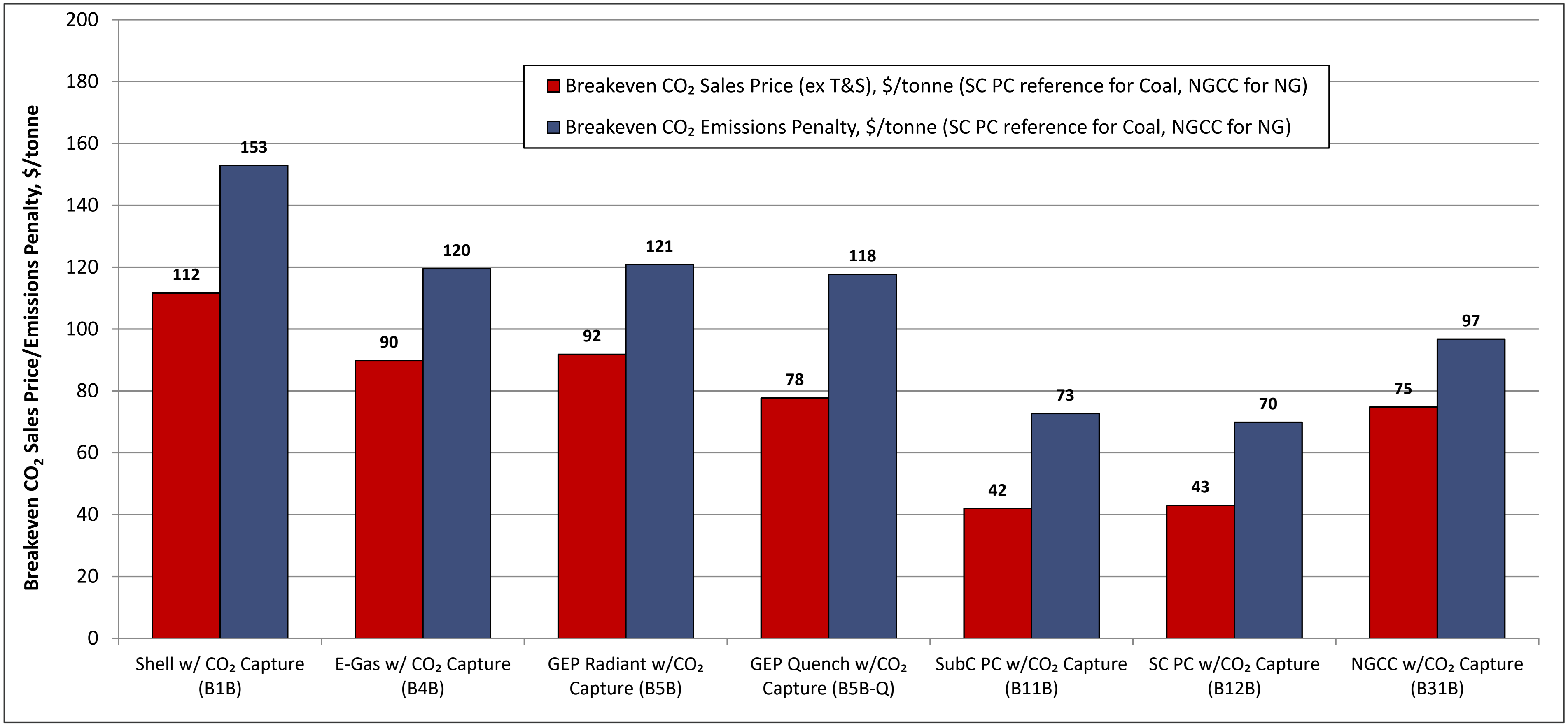
PC and NGCC Cases

Case Name	PC				NGCC	
	PC Subcritical		PC Supercritical		State-of-the-art 2017 F-Class	
	B11A	B11B	B12A	B12B	B31A	B31B
COST						
Total Plant Cost (2018$/kW)	2,011	3,756	2,099	3,800	780	1,984
Bare Erected Cost	1,482	2,641	1,548	2,677	561	1,312
Home Office Expenses	259	462	271	469	112	262
Project Contingency	269	526	280	531	107	304
Process Contingency	0	127	0	123	0	105
Total Overnight Cost (2018$M)	1,611	2,991	1,678	3,023	692	1,558
Total Overnight Cost (2018$/kW)	2,478	4,604	2,582	4,654	952	2,412
Owner's Costs	467	848	484	854	172	428
Total As-Spent Cost (2018$/kW)	2,860	5,314	2,980	5,371	1,040	2,635
LCOE ($/MWh) (excluding T&S)	60.9	100.8	61.3	99.7	42.2	68.2
Capital Costs	24.2	45.0	25.2	45.4	8.8	22.3
Fixed Costs	9.1	16.0	9.5	16.1	3.6	8.6
Variable Costs	7.9	14.5	7.7	14.0	1.7	5.6
Fuel Costs	19.7	25.4	18.9	24.1	28.1	31.6
LCOE ($/MWh) (including T&S)	60.9	110.2	61.3	108.7	42.2	71.6
CO_2 T&S Costs	0.0	9.4	0.0	8.9	0.0	3.5
Breakeven CO_2 Sales Price (ex. T&S), $/tonne[A]	N/A	42.0	N/A	42.9	N/A	74.8
Breakeven CO_2 Emissions Penalty (incl. T&S), $/tonne[A]	N/A	72.7	N/A	69.9	N/A	96.7

[A] Both the breakeven CO_2 sales price and emissions penalty were calculated based on the non-capture SC PC Case B12A for all coal cases, and the non-capture NGCC Case B31A for natural gas cases

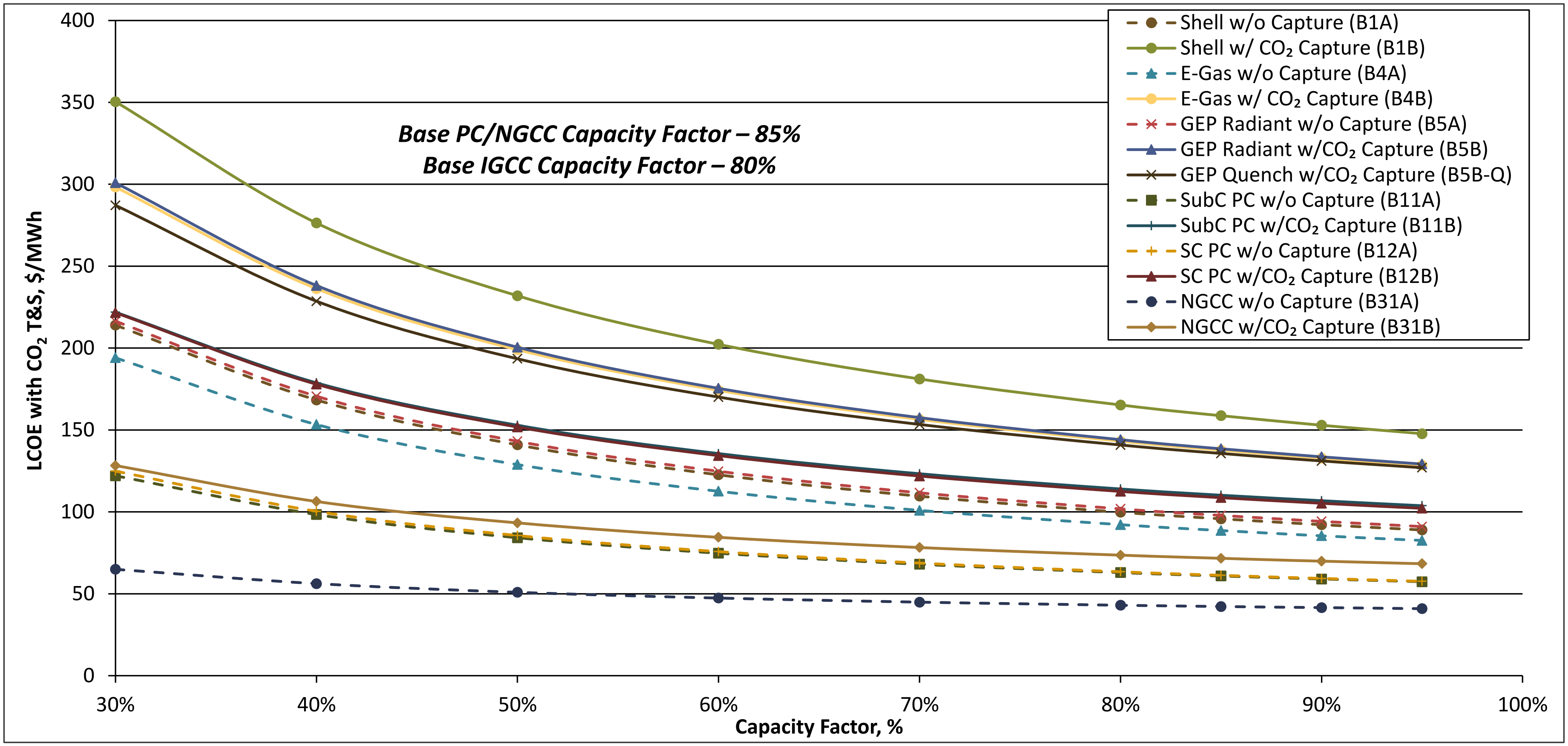
Revision 4 Cost Estimate Results

Breakeven CO_2 Sales Price/Emissions Penalty



Revision 4 Cost Estimate Results

Sensitivities – Capacity Factor



Questions ?

Tim Fout

Strategic Systems Analysis and Engineering

Timothy.Fout@netl.doe.gov

304-285-1341