Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 4

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NETL Cost and Performance Baseline for Fossil Energy Plants: Bituminous Baseline

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- **Presents cost and performance estimates of near-term commercial offerings for coal- and natural gas-fired power plants, both with and without current technology for carbon capture and sequestration (CCS)**
  - Integrated gasification combined cycle (IGCC) (7 cases: 4 with capture and 3 without capture)
  - Pulverized coal (PC) (4 cases: 2 with capture and 2 without capture)
  - Natural gas combined cycle (NGCC) (2 cases: 1 with capture and 1 without capture)
- Consistent and transparent design basis and analysis methodology
- Results represent an independent assessment of the power systems considered
- Significant vendor input for performance and capital cost estimates
- Black & Veatch “bottom up” approach to developing capital and operation and maintenance (O&M) estimates

NETL Cost and Performance Baseline for Fossil Energy Plants: Purpose and Use

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **NETL internal uses**
  - Provides a consistent basis to compare existing and developing technologies
  - Informs development of research and development (R&D) goals and targets
  - Guides potential Department of Energy (DOE) investment by quantifying prospective benefits of successful R&D, and for advancing technologies within the DOE Office of Fossil Energy (FE) programs
- **External uses—other agencies (Environmental Information Administration [EIA], Environmental Protection Agency [EPA]), academia, and industry partners)**
  - Reference for technoeconomic analysis (TEA)
  - Benchmark current state-of-the-art (SOA) technology performance and cost, as well as tracking technology development across report revisions
  - Reference for plant configurations, emissions, sub-system descriptions, and others

Tracking Technology Development Through Legacy Report Revisions

Revision 2

Natural Gas Combustion Turbine
2008 F-class: 181 MW-gross

Plant Wastewater
No system considered

MEA CO_2 Capture System
Solvent regeneration energy: 1,530 Btu/lb

17% increase in gross output

N/A

28% reduction

Revision 3

Natural Gas Combustion Turbine
2013 F-class: 211 MW-gross

Plant Wastewater
No system considered

Cansolv CO_2 Capture System – DC103 Solvent
Solvent regeneration energy: 1,100 Btu/lb

13% increase in gross output

Addition

5% reduction

Revision 4

Natural Gas Combustion Turbine
2017 F-class: 238 MW-gross

Plant Wastewater
Spray Dryer Evaporator for ELG Regulation Compliance

Cansolv CO_2 Capture System – DC103 Solvent
Solvent regeneration energy: 1,050 Btu/lb

NETL Cost and Performance Baseline for Fossil Energy Plants: QGESS Documents

- **In addition to the Bituminous Baseline Report, there are a number of supporting documents available that detail underlying assumptions, methodologies, and approaches**
  - Documentation in these sources provides the transparent, repeatable approach
- **Quality Guidelines for Energy System Studies (QGESS)**
  - "Detailed Coal Specifications," "Specifications for Selected Feedstocks"
  - "Fuel Prices for Selected Feedstocks"
  - "Process Modeling Design Parameters"
  - "Cost Estimation Methodology for NETL Assessments of Power Plants"
  - "CO_2 Transport and Storage Costs in NETL Studies"
  - "Performing a Techno-economic Analysis for Power Generation Plants"
  - Others

Regulatory Drivers and Other Relevant Study Assumptions

- **Cases configured to be compliant with key regulatory requirements**
  - Utility Mercury and Air Toxics Standards (MATS)
  - New Source Performance Standards (NSPS)
  - Effluent Limitation Guidelines (ELG)
  - Presumed Best Available Control Technology (BACT)
- **Cases presented are for a generic midwestern, greenfield site**
  - Site specific considerations (e.g., soil issues, water discharge and use restrictions, seismic data, local code for height/noise) are generalized and assumed to not be impactful
- **Performance and cost estimates assume baseload operation**
  - Plant designs do not specifically account for part load, ramping, or similar off-design considerations
  - Levelized cost of electricity (LCOE) results do not account for market pressures relating to these plant operating conditions
- **NETL currently developing reference cases that specifically address flexible plant operation[1]**

[1] NETL. *"Cost and Performance Baseline for Fossil Energy Plants Volume 5: Bituminous Coal Flexible Plant Design," Expected - 2019*

Bituminous Baseline Study, Revision 4

Technical Updates

- **Updated bituminous coal characteristics, reducing chlorine content to 1,671 ppmw**
- **Implemented ELG regulation compliance systems for PC and IGCC cases**
  - PC – spray dryer evaporator
  - IGCC – brine concentrator and crystallizer
- **PC net plant electrical output updated from 550 MW_{net} to 650 MW_{net}**
  - Size selection driven by updated NGCC output, and supported by Black & Veatch
- **Updated the mercury control system with data provided by United Conveyor Corporation (UCC)**
- **Updated CO_2 capture system cost and performance for PC and NGCC capture cases**
- **Revised CO_2 compression model to avoid operation near the vapor dome**
- **Updated combustion turbine (CT) and steam turbine (ST) performance estimates for NGCC cases (2017 vintage)**
- **Updates to IGCC cases included:**
  - Water gas shift (WGS) and COS reactor, air separation unit (ASU), steam turbine, Selexol system

Study Matrix

Case Configuration

Case	Unit Cycle	Steam Cycle, psig/°F/°F	Combustion Turbine	Gasifier/Boiler Technology	H_2S Separation	Sulfur Removal	Particulate Matter (PM) Control	CO_2 Separation[A]	Process Water Treatment
B1A	IGCC	1,800/1,050/1,050	2 x State-of-the-art 2008 F-Class	Shell	Sulfinol-M	Claus Plant/Sulfur	Cyclone, candle filter, and water scrubber	N/A	Vacuum flash, brine concentrator, crystallizer
B1B	IGCC	1,800/1,000/1,000	2 x State-of-the-art 2008 F-Class	Shell	Selexol	Claus Plant/Sulfur	Cyclone, candle filter, and water scrubber	Selexol 2nd stage	Vacuum flash, brine concentrator, crystallizer
B4A	IGCC	1,800/1,050/1,050	2 x State-of-the-art 2008 F-Class	CB&I E-Gas™	Refrigerated MDEA	Claus Plant/Sulfur	Cyclone, candle filter, and water scrubber	N/A	Vacuum flash, brine concentrator, crystallizer
B4B	IGCC	1,800/1,000/1,000	2 x State-of-the-art 2008 F-Class	CB&I E-Gas™	Selexol	Claus Plant/Sulfur	Cyclone, candle filter, and water scrubber	Selexol 2nd stage	Vacuum flash, brine concentrator, crystallizer
B5A	IGCC	1,800/1,050/1,050	2 x State-of-the-art 2008 F-Class	General Electric Power (GEP) Radiant	Selexol	Claus Plant/Sulfur	Quench, water scrubber, and acid gas removal (AGR) adsorber	N/A	Vacuum flash, brine concentrator, crystallizer
B5B	IGCC	1,800/1,000/1,000	2 x State-of-the-art 2008 F-Class	General Electric Power (GEP) Radiant	Selexol	Claus Plant/Sulfur	Quench, water scrubber, and acid gas removal (AGR) adsorber	Selexol 2nd stage	Vacuum flash, brine concentrator, crystallizer
B5B-Q	IGCC	1,800/1,000/1,000	2 x State-of-the-art 2008 F-Class	GEP Quench	Selexol	Claus Plant/Sulfur	Quench, water scrubber, and AGR adsorber	Selexol 2nd stage	Vacuum flash, brine concentrator, crystallizer
B11A	PC	2,400/1,050/1,050	N/A	Subcritical PC	N/A	Wet Flue Gas Desulfurization (FGD)/ Gypsum	Baghouse	N/A	Spray dryer evaporator
B11B	PC	2,400/1,050/1,050	N/A	Subcritical PC	N/A	Wet Flue Gas Desulfurization (FGD)/ Gypsum	Baghouse	Cansolv	Spray dryer evaporator
B12A	PC	3,500/1,100/1,100	N/A	Supercritical (SC) PC	N/A	Wet Flue Gas Desulfurization (FGD)/ Gypsum	Baghouse	N/A	Spray dryer evaporator
B12B	PC	3,500/1,100/1,100	N/A	Supercritical (SC) PC	N/A	Wet Flue Gas Desulfurization (FGD)/ Gypsum	Baghouse	Cansolv	Spray dryer evaporator
B31A	NGCC	2,400/1,085/1,085	2 x State-of-the-art 2017 F-Class	Heat Recovery Steam Generator (HRSG)	N/A	N/A	N/A	N/A	N/A
B31B	NGCC	2,400/1,085/1,085	2 x State-of-the-art 2017 F-Class	Heat Recovery Steam Generator (HRSG)	N/A	N/A	N/A	Cansolv	N/A

[A]IGCC cases consider nominal 90 percent removal based on total feedstock minus unburned carbon in slag. PC and NGCC cases consider nominal 90 percent removal based on total feedstock minus unburned carbon in ash (PC).

Study Matrix

Case Configuration (cont'd)

<table>
<tr><th>Case</th><th>Unit Cycle</th><th>Steam Cycle, psig/°F/°F</th><th>Combustion Turbine</th><th>Boiler Technology</th><th>NOx Removal</th><th>Hg Removal</th><th>Sulfur Removal</th><th>PM Control</th><th>CO_2 Separation[A]</th><th>Process Water Treatment</th></tr>
<tr><td>B11A</td><td rowspan="4">PC</td><td rowspan="2">2,400/1,050/ 1,050</td><td rowspan="4">N/A</td><td rowspan="2">Subcritical PC</td><td rowspan="4">Selective Catalytic Reduction (SCR)</td><td rowspan="4">Dry sorbent injection (DSI)/ activated carbon injection (ACI), co-benefit capture</td><td rowspan="4">Wet FGD/ Gypsum</td><td rowspan="4">Baghouse</td><td>N/A</td><td rowspan="4">Spray dryer evaporator</td></tr>
<tr><td>B11B</td><td>Cansolv</td></tr>
<tr><td>B12A</td><td rowspan="2">3,500/1,100/ 1,100</td><td rowspan="2">SC PC</td><td>N/A</td></tr>
<tr><td>B12B</td><td>Cansolv</td></tr>
<tr><td>B31A</td><td rowspan="2">NGCC</td><td rowspan="2">2,400/1,085/ 1,085</td><td rowspan="2">2 x State-of-the-art 2017 F-Class</td><td rowspan="2">HRSG</td><td rowspan="2">SCR</td><td rowspan="2">N/A</td><td rowspan="2">N/A</td><td rowspan="2">N/A</td><td>N/A</td><td rowspan="2">N/A</td></tr>
<tr><td>B31B</td><td>Cansolv</td></tr>
</table>

[A]IGCC cases consider nominal 90 percent removal based on total feedstock minus unburned carbon in slag. PC and NGCC cases consider nominal 90 percent removal based on total feedstock minus unburned carbon in ash (PC).

Performance Summary

Case Name	IGCC							PC				NGCC	
	Shell		E-Gas™ FSQ		GEP R+Q			Subcritical		Supercritical		State-of-the-art 2017 F-Class	
	B1A	B1B	B4A	B4B	B5A	B5B	B5B-Q	B11A	B11B	B12A	B12B	B31A	B31B
CO_2 Capture Rate (%)	0	90	0	90	0	90	90	0	90	0	90	0	90
PERFORMANCE													
Gross Power Output (MWe)	765	696	763	742	765	741	685	687	776	685	770	740	690
Auxiliary Power Requirement (MWe)	125	177	122	185	131	185	186	37	126	35	120	14	44
Net Power Output (MWe)	640	519	641	557	634	556	499	650	650	650	650	727	646
Coal Flow Rate (lb/hr)	435,418	467,308	456,327	482,173	464,732	482,580	482,918	492,047	634,448	472,037	603,246	N/A	N/A
Natural Gas Flow Rate (lb/hr)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	205,630	205,630
HHV Thermal Input (kW_t)	1,488,680	1,597,710	1,560,166	1,648,535	1,588,902	1,649,926	1,651,082	1,682,291	2,169,156	1,613,879	2,062,478	1,354,905	1,354,905
Net Plant HHV Efficiency (%)	43.0%	32.5%	41.1%	33.8%	39.9%	33.7%	30.2%	38.6%	30.0%	40.3%	31.5%	53.6%	47.7%
Net Plant HHV Heat Rate (Btu/kWh)	7,940	10,497	8,308	10,101	8,554	10,118	11,287	8,832	11,393	8,473	10,834	6,363	7,159
Raw Water Withdrawal (gpm)	4,127	5,080	4,357	5,197	4,799	5,512	6,286	6,485	10,634	6,054	9,911	2,902	4,773
Process Water Discharge (gpm)	922	1,075	944	1,103	1,033	1,123	1,218	1,334	3,090	1,242	2,893	657	1,670
Raw Water Consumption (gpm)	3,206	4,005	3,413	4,093	3,766	4,389	5,068	5,151	7,544	4,811	7,018	2,245	3,103

Performance Summary – PC and NGCC

Case Name	PC				NGCC	
	Subcritical		Supercritical		State-of-the-art 2017 F-Class	
	B11A	B11B	B12A	B12B	B31A	B31B
CO_2 Capture Rate (%)	0	90	0	90	0	90
PERFORMANCE						
Gross Power Output (MWe)	687	776	685	770	740	690
Net Power Output (MWe)	650	650	650	650	727	646
Coal Flow Rate (lb/hr)	492,047	634,448	472,037	603,246	N/A	N/A
Natural Gas Flow Rate (lb/hr)	N/A	N/A	N/A	N/A	205,630	205,630
HHV Thermal Input (kW_t)	1,682,291	2,169,156	1,613,879	2,062,478	1,354,905	1,354,905
Net Plant HHV Efficiency (%)	38.6%	30.0%	40.3%	31.5%	53.6%	47.7%
Raw Water Consumption (gpm)	5,151	7,544	4,811	7,018	2,245	3,103

Emissions Summary – PC and NGCC

Case Name	PC				NGCC	
	Subcritical		Supercritical		State-of-the-art 2017 F-Class	
	B11A	B11B	B12A	B12B	B31A	B31B
CO_2 Capture Rate (%)	0	90	0	90	0	90
EMISSIONS						
CO_2 Emissions (lb/MWh-gross)	1,691	193	1,627	185	741	80
SO_2 Emissions (lb/MWh-gross)	0.67	-	0.65	-	0.01	-
NOx Emissions (lb/MWh-gross)	0.70	0.70	0.70	0.70	0.02	0.02
PM Emissions (lb/MWh-gross)	0.09	0.09	0.09	0.09	0.01	-
Hg Emissions (lb/MWh-gross)	3.00E-06	3.00E-06	3.00E-06	3.00E-06	-	-

Capital and O&M Cost Estimation

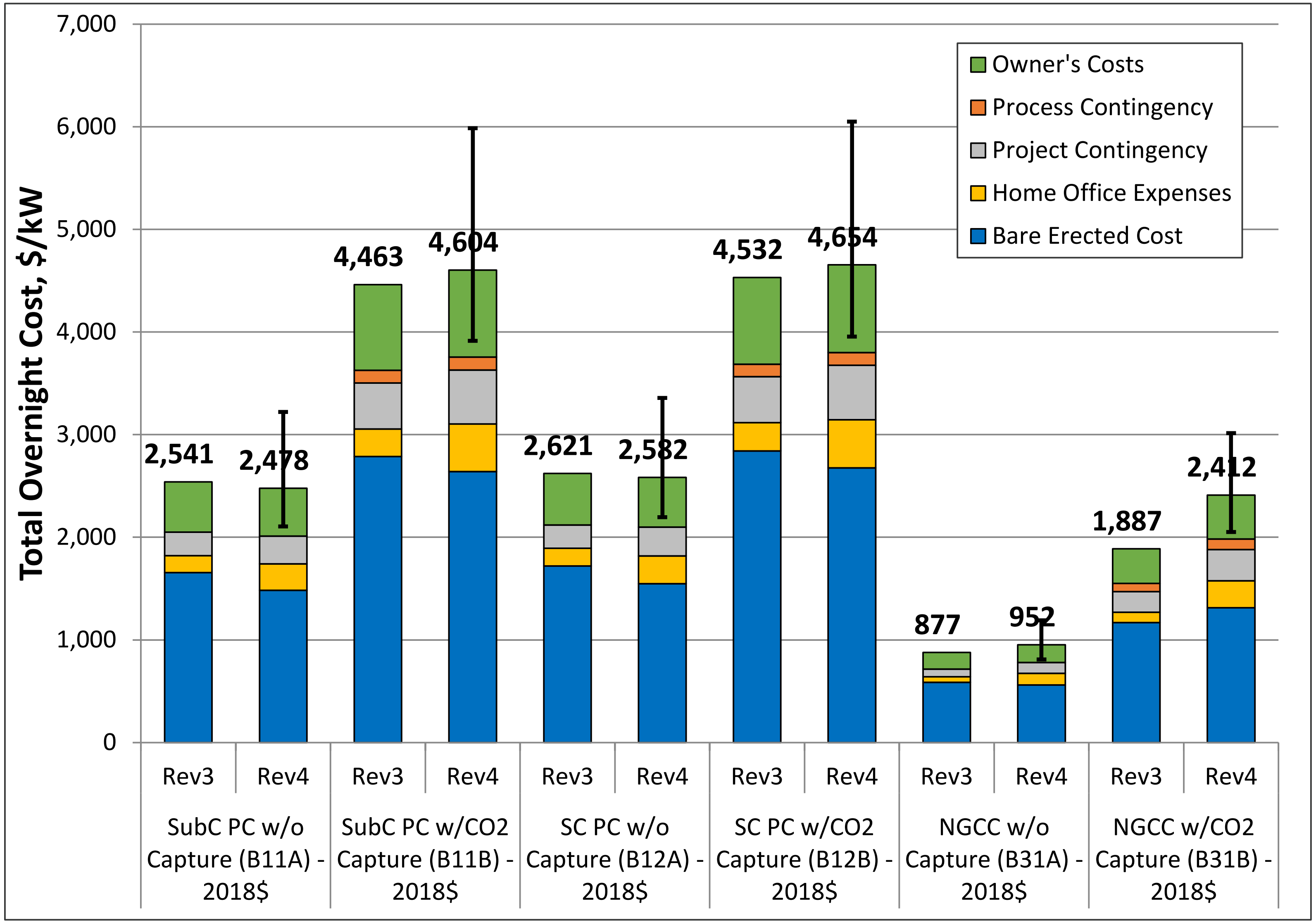
- **Capital cost results are broken into 14 accounts, and further partitioned by relevant sub-systems**
  - 2018$ estimation basis
  - Itemized owner's costs
- **Total costs for equipment through total as-spent costs (TASC) are reported**
- **O&M tables breakout fixed, variable, and fuel costs, as well as initial and daily consumable rates**

	Case:	B12B	– SC PC w/ CO_2				Estimate Type:			Conceptual	
	Plant Size (MW, net):	650					Cost Base:			Dec 2018	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/kW
4.13	Secondary Air System	$2,571	$0	$1,465	$0	$4,035	$706	$0	$711	$5,453	$8
4.14	Induced Draft Fans	$5,479	$0	$3,122	$0	$8,601	$1,505	$0	$1,516	$11,622	$18
4.15	Major Component Rigging	$93	$0	$53	$0	$146	$26	$0	$26	$197	$0
4.16	Boiler Foundations	$0	$399	$351	$0	$751	$131	$0	$132	$1,014	$2
	Subtotal	**$309,869**	**$399**	**$176,913**	**$0**	**$487,181**	**$85,257**	**$0**	**$85,866**	**$658,303**	**$1,013**
	5										
5.1	Cansolv Carbon Dioxide (CO_2) Removal System	$199,653	$86,357	$181,351	$0						
5.2	WFGD Absorber Vessels & Accessories	$79,398	$0	$16,976	$0						
5.3	Other FGD	$356	$0	$401	$0						
5.4	Carbon Dioxide (CO_2) Compression & Drying	$41,405	$6,211	$13,844	$0						
5.5	Carbon Dioxide (CO_2) Compressor Aftercooler	$455	$72	$195	$0						
5.6	Mercury Removal (Dry Sorbent Injection/Activated Carbon Injection)	$2,634	$579	$2,590	$0						
5.9	Particulate Removal (Bag House & Accessories)	$1,522	$0	$959	$0						
5.12	Gas Cleanup Foundations	$0	$198	$173	$0						
5.13	Gypsum Dewatering System	$764	$0	$129	$0						
	Subtotal	**$326,187**	**$93,417**	**$216,617**	**$0**						
	7										
7.3	Ductwork	$0	$747	$519	$0						
7.4	Stack	$8,767	$0	$5,094	$0						
7.5	Duct & Stack Foundations	$0	$210	$249	$0						
	Subtotal	**$8,767**	**$957**	**$5,862**	**$0**						
	8										
8.1	Steam Turbine Generator & Accessories	$73,354	$0	$8,175	$0						
8.2	Steam Turbine Plant Auxiliaries	$1,665	$0	$3,544	$0						
8.3	Condenser & Auxiliaries	$11,298	$0	$3,833	$0						
8.4	Steam Piping	$43,139	$0	$17,484	$0						
8.5	Turbine Generator Foundations	$0	$260	$430	$0						
	Subtotal	**$129,456**	**$260**	**$33,465**	**$0**						
	9										
9.1	Cooling Towers	$20,110	$0	$6,219	$0						
9.2	Circulating Water Pumps	$2,849	$0	$209	$0						

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						
Maintenance Material:						
			Consum			
	Initial Fill	**Per Day**	**Per**			
Water (/1000 gallons):	0	7,136				
Makeup and Waste Water Treatment Chemicals (ton):	0	21.3				
Brominated Activated Carbon (ton):	0	1.56				
Enhanced Hydrated Lime (ton):	0	39.9				
Limestone (ton):	0	700				
Ammonia (19 wt%, ton):	0.00	69.0				
SCR Catalyst (ft³):	17,414	15.9				
CO_2 Capture System Chemicals[A]			Proprie			
Triethylene Glycol (gal):	w/equip.	544				
Subtotal:						
			Waste D			
Fly Ash (ton)	0	657				
Bottom Ash (ton)	0	146				
SCR Catalyst (ft³):	0	16				
Triethylene Glycol (gal):		544				
Thermal Reclaimer Unit Waste (ton)	0	3.51				
Prescrubber Blowdown Waste (ton)	0	52.1				
Subtotal:						
			By-Pro			
Gypsum (ton)	0	1064				
Subtotal:						
Variable Operating Costs Total:						
			Fuel			
Illinois Number 6 (ton):	0	7,239				
Total:						

Description	$/1,000	$/kW
Pre-Production Costs		
6 Months All Labor	$14,349	$22
1 Month Maintenance Materials	$2,323	$4
1 Month Non-Fuel Consumables	$3,322	$5
1 Month Waste Disposal	$999	$2
25% of 1 Months Fuel Cost at 100% CF	$2,860	$4
2% of TPC	$49,367	$76
Total	**$73,221**	**$113**
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	$28,700	$44
0.5% of TPC (spare parts)	$12,342	$19
Total	**$41,042**	**$63**
Other Costs		
Initial Cost for Catalyst and Chemicals	$2,612	$4
Land	$900	$1
Other Owner's Costs	$370,256	$570
Financing Costs	$66,646	$103
Total Overnight Costs (TOC)	**$3,023,051**	**$4,654**
TASC Multiplier (IOU, 35 year)	1.154	
Total As-Spent Cost (TASC)	**$3,488,911**	**$5,371**

PC and NGCC Capital Cost Results



- **PC and NGCC capital estimates represent AACE Class 4**
  - PC uncertainty range is -15%/+30%
  - NGCC uncertainty range is -15%/+25%
- **Recent experience with NGCC allows for a tighter uncertainty range compared to PC**
- **The methodology for calculating COE will be detailed in the QGESS[1]**

[1]NETL. *"Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessment of Power Plant Performance." Pending - 2019.*

Cost of Electricity Methodology

- **Revision 4 will utilize an updated cost of electricity (COE) methodology**
  - Transition from *project* approach to *corporate* approach
  - Reporting an LCOE
  - Real dollar basis
- **Relevant parameter updates will include:**
  - Tax rates
  - Debt/equity splits
  - Fuel price and transport and storage cost

Parameter	Rev3 Value	Rev4 Value
Coal Price, \$/MMBtu, \$/tonne	2.94 (68.54) – 2011\$	2.23 (51.96) – 2018\$
Natural Gas Price, \$/MMBtu	6.13 – 2011\$	4.42 – 2018\$
CO_2 Transport & Storage Cost, \$/tonne	11.0 – 2011\$	10.0 – 2018\$

Conclusions and Takeaways

- NETL's Bituminous Baseline Report presents a transparent and independent assessment of the cost and performance of near-term commercial offerings for coal- and natural gas-fired power plants, both with and without CCS
- The report serves many purposes including to benchmark SOA technology, guide DOE R&D, develop technology goals, and identify opportunities for beneficial R&D investment, among others
- Performance estimates are based on significant sub-system vendor input
- Cost estimates are generated with a "bottom-up" approach, and based on recent and historical engineering, procurement, and construction (EPC) experience with power plant projects

Conclusions and Takeaways (cont'd)

- The study methodology is well-documented and reproducible via supplemental QGESS references that provide guidance on model development, parameter selection, cost evaluation, LCOE calculation methodology, and several other key areas
- The absolute capital estimates (and future LCOE results) reported are not developed in an effort to match any single real-world project scenario; rather, the value of the results are that they are developed on a consistent basis, and facilitate technology comparison

Thank You

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