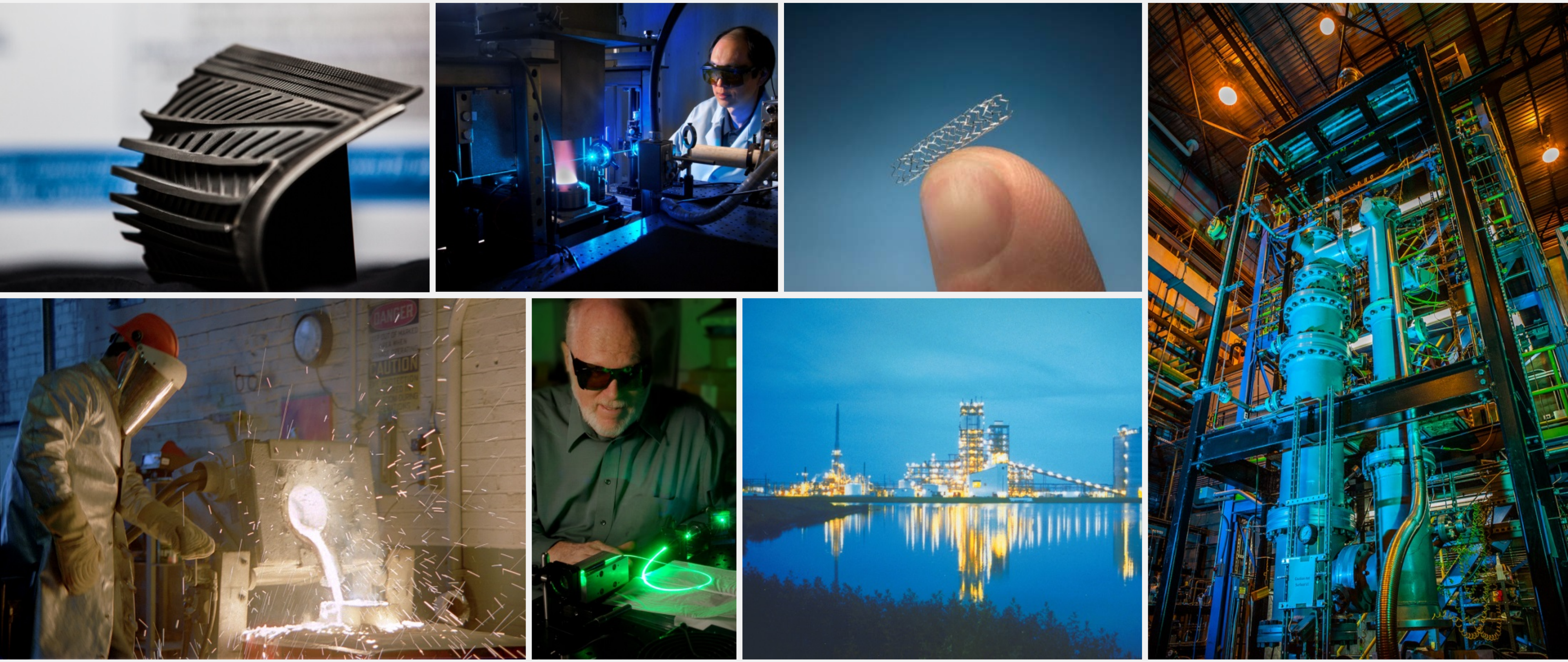
Driving Innovation ♦ Delivering Results



Update on CO_2 Capture Related Systems Analysis Activities

Timothy Fout, Eric Grol

2016 NETL CO_2 Capture Technology Meeting

August 9, 2016

Presentation Outline

- **Outline**
  - Where Systems Engineering & Analysis (SEA) fits in NETL
  - Advanced Ultra-Supercritical (AUSC) Pulverized Coal reference plants
  - Site specific factors
  - Notes on Tools
  - Alternative Scenarios to Meet the Requirements of the Carbon Pollution Standards for New, Coal-Fueled Plants without Carbon Capture

- **Acknowledgements**
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NETL Research and Innovation Center

Core Competencies

Computational Science & Engineering

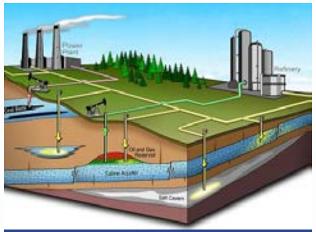
High-Performance Computing

Data Analytics

Materials Engineering & Manufacturing

Structural & Functional

Design, Synthesis & Performance



Geological & Environmental Systems

Air, Water & Geology

Understanding & Mitigation

Energy Conversion Engineering

Component & Device

Design & Validation

Systems Engineering & Analysis

Process & System

Optimization, Validation & Economics

Program Execution & Integration

Strategic Planning

Project Management

Classification Survey and Thermodynamics Studies for Pulverized Coal (PC) Plants

- **Classification of advanced steam conditions for PC plants varies considerably**
  - NETL, EPRI, IEA, Japan, OEMs …..
- **NETL has performed thermodynamic modeling to assess impacts on plant performance**
  - White Paper in preparation

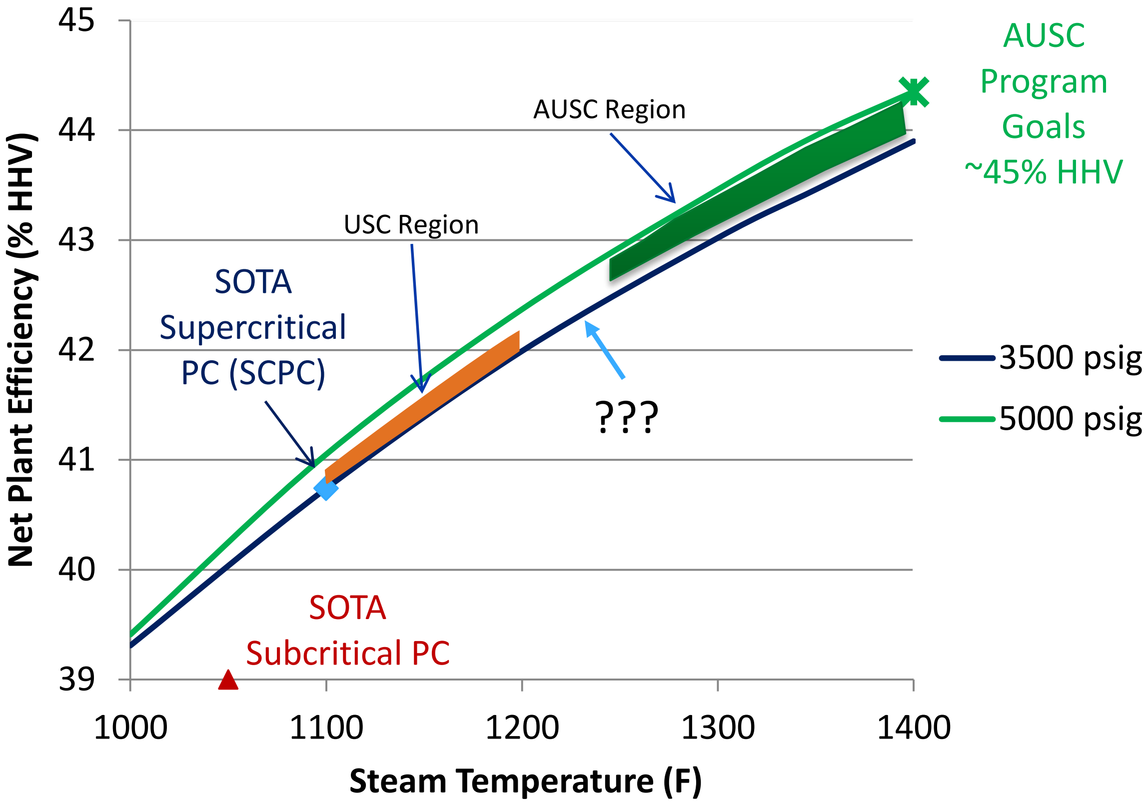
	Main Steam Temperature			Main Steam Pressure		
	Alstom	B&W	EPRI	Alstom[i]	B&W	EPRI[ii]
Supercritical	1,005 ºF (Reheat 1,050 ºF)	-	-	3,480 psia	-	-
Ultrasupercritical	1,075 – 1,100 ºF (Reheat 1,110 – 1,150 ºF)	-	1,100 – 1,200 ºF (Reheat 1,140 – 1,240 ºF)	4,000 psia	-	4,000 – 6,000 psia
Advanced Ultrasupercritical	1,300 – 1,330 ºF (Reheat 1,325 – 1,400 ºF)	1,356 ºF (Reheat 1,402 ºF)	1,300 – 1,400 ºF (Reheat 1,340 – 1,400 ºF)	5,400 psia	5,015 psia[iii]	4,000 – 6,000 psia

[i] *"State-of-the-Art Ultra-Supercritical (USC) and readiness for Advanced Ultra-Supercritical (AUSC) Steam Power Plants,"* Alstom Power, International Conference on Advanced Technologies and Best Practices for Supercritical Thermal Plants, November 22, 2013

[ii] *"Advanced Ultra-Supercritical Steam Cycle Optimization,"* Electric Power Research Institute, Technical Update, January 2014

[iii] *"Advanced Ultra-Supercritical Power Plant (700 to 760C) Design for Indian Coal,"* Weitzel et. al. (Babcock & Wilcox), Okita et. al. (Toshiba Corporation), Presented to Power-Gen Asia, October 3 – 5, 2012

Impact of Steam Conditions on PC Plant Efficiencies



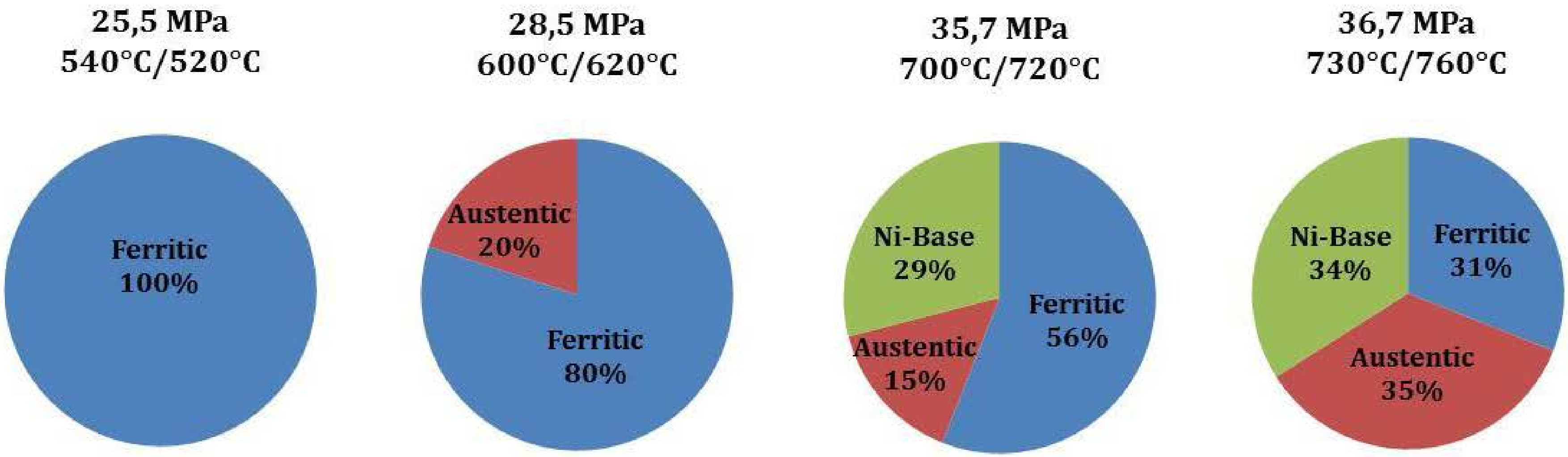
Net plant efficiencies above are based on an example plant operating on Bituminous coal, at ISO conditions, with 50°F reheat, wet flue gas desulfurization, and wet cooling towers. Other design parameters and site conditions will also impact the efficiency of a specific plant.

Source: NETL, Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 3, 2015; and other internal assessments of USC and AUSC steam conditions.

- **Steam temperature drives efficiency benefits**
- **Steam pressure has a secondary effect on efficiency, but a significant effect on cost**
- **Commercially available USC/AUSC technology currently falls to the far left of the range shown here**
- **Program goals target AUSC steam conditions as shown**

Classification Survey and Thermodynamics Studies for Pulverized Coal (PC) Plants

Classification of advanced power plant steam conditions is driven by the boiler and turbine materials utilized*



Subcritical (SubC)
Supercritical (SC)

Ultra-supercritical
(USC)

Advanced Ultra-supercritical
(AUSC)

*** Contemporary Engineering Sciences, Vol. 7, 2014, no. 34, 1807 - 1825**
HIKARI Ltd, www.m-hikari.com
http://dx.doi.org/10.12988/ces.2014.410191

Impact of Steam Conditions on PC Plant Efficiencies

	Temperature	Pressure (absolute)	Net Plant Efficiency (% HHV)**
Subcritical	540 - 565°C 1000 - 1050°F	16 - 22 MPa 2300 - 3200 psi	38.3 - 39.6%
Supercritical (SC)	565 - 600°C 1050 - 1112°F	22 - 27 MPa 3200 - 4000 psi	39.6 - 40.6%
Ultra-supercritical (USC)*	600 - 640°C 1112 - 1184°F	24 - 31 MPa 3500 - 4500 psi	41.3 - 42.0%
Advanced USC (DOE Program Goals)	700 - 760°C 1292 - 1400°F	24 - 35 MPa 3500 - 5000 psi	43.4 - 44.4%

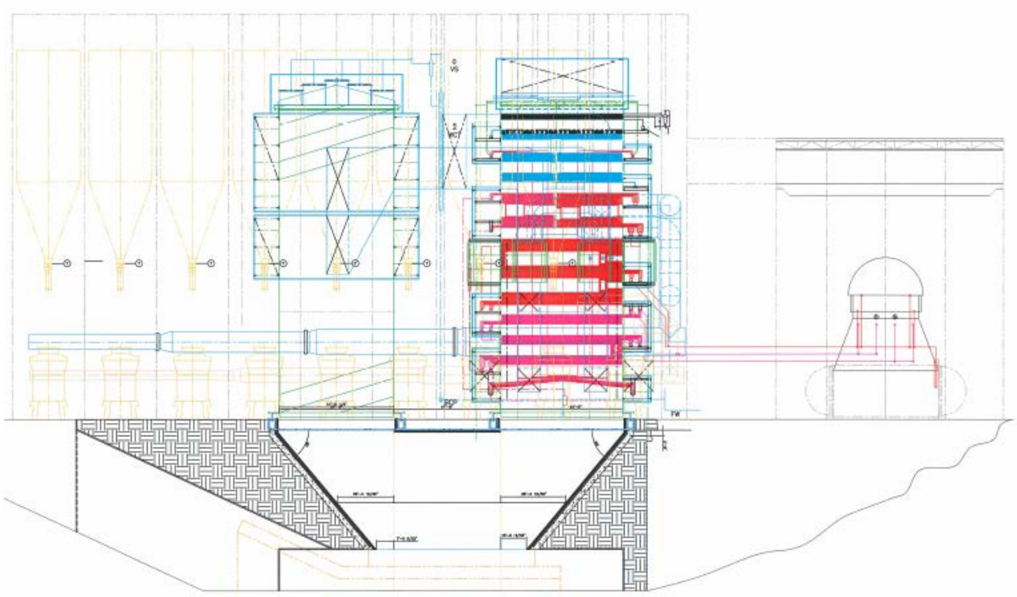
*USC represents a broad range of steam conditions; criteria on what constitutes USC are not consistent (especially internationally). Commercially available USC technology results in efficiencies similar to or slightly above the state-of-the-art SCPC plant provided here.

**Net plant efficiencies above are based on an example plant operating on Bituminous coal, at ISO conditions, with 50°F reheat, wet flue gas desulfurization, and wet cooling towers. Other design parameters and site conditions will also impact the efficiency of a specific plant.

Source: NETL, Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 3, 2015; and other internal assessments of AUSC steam conditions.

Advanced Ultra-Supercritical (AUSC) Pulverized Coal Reference Plants

- **Objective: Develop AUSC reference cases**
  - Enabled by DOE/Ohio Coal Development Office (OCDO) AUSC Materials Consortia
    - Steam boilers (DE-FG26-01NT41175)
    - Steam turbines (DE-FE0000234)
  - Supported by NETL Crosscutting program
  - Evaluate three steam pressures and effect of CCS
  - Conduct economic analysis based on an Inverted Tower Boiler Design (B&W)*



*_Advanced Ultra-Supercritical Pulverized Coal Power Plant with and without Post-Combustion Carbon Capture_. EPRI, Palo Alto, CA: 2015.

Advanced Ultra-Supercritical (AUSC) Pulverized Coal Reference Plants

Case Matrix

Case	Steam Conditions	Capacity (MW-net)	CO_2 Capture (Cansolv)	CO_2 Capture Heat Integration
1	3500 psig / 1350°F / 1400°F	550	0%	-
2	3500 psig / 1350°F / 1400°F	550	90%	No
3	4250 psig / 1350°F / 1400°F	550	0%	-
4	4250 psig / 1350°F / 1400°F	550	90%	No
5	5000 psig / 1350°F / 1400°F	550	0%	-
6	5000 psig / 1350°F / 1400°F	550	90%	No

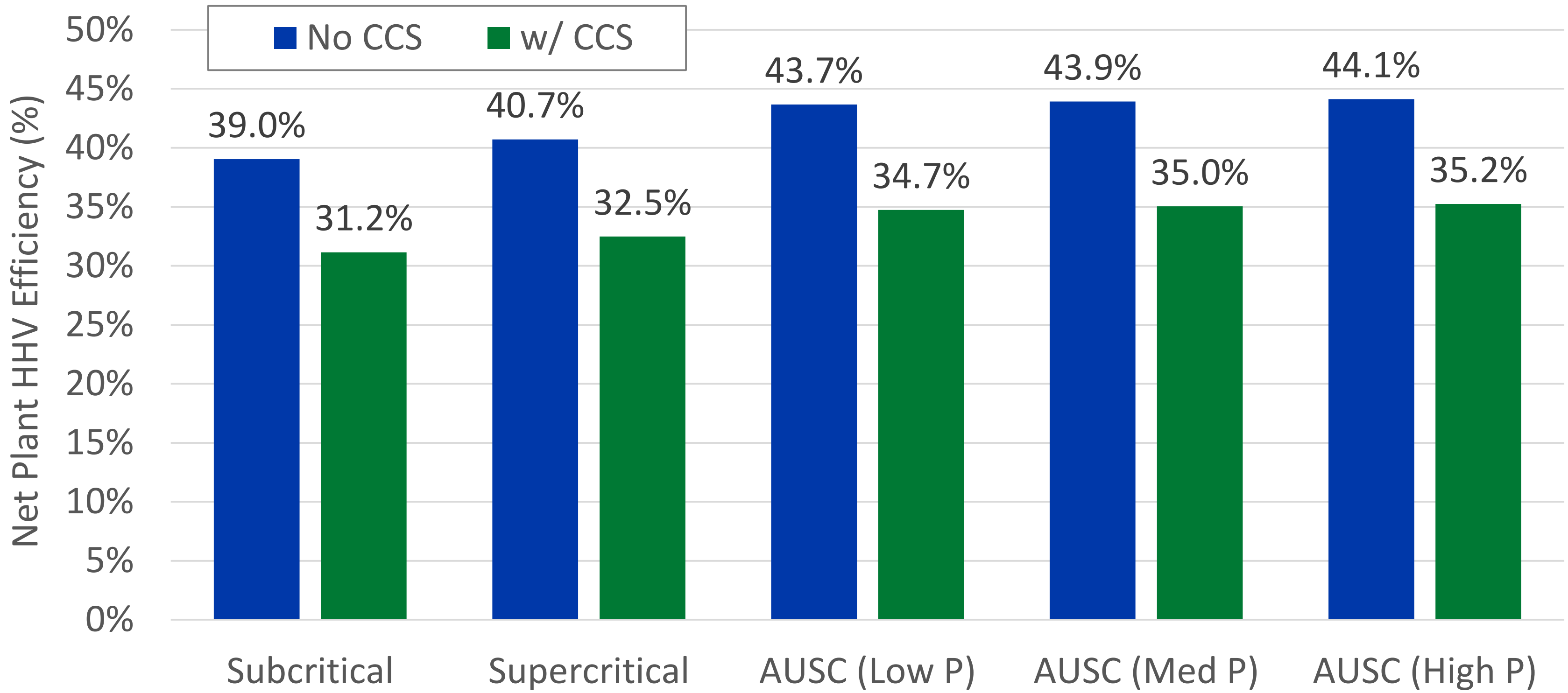
- **Performance for all cases now reflect the steam turbine stage efficiencies extracted from steam flow diagrams provided in the A-USC Consortium literature[1] rather than those from the Bituminous Baseline Report[2]**
- **Boiler and steam piping costs reflect the conceptual B&W inverted tower boiler design**
  - Steam piping costs assume a reduced steam lead length to 150’ from 450’ for a conventional boiler

AUSC PC Plant Performance Results

	PC Subcritical		PC Supercritical		PC A-USC					
	Case B11A	Case B11B	Case B12A	Case B12B	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Nominal CO_2 Capture	**0%**	**90%**	**0%**	**90%**	**0%**	**90%**	**0%**	**90%**	**0%**	**90%**
Gross Power Output (MWe)	581	644	580	642	578	635	578	634	578	633
Auxiliary Power Requirement (MWe)	31	94	30	91	27	85	27	84	27	84
Net Power Output (MWe)	550	550	550	550	550	550	550	550	550	550
HHV Thermal Input (MW_{th})	1,409	1,765	1,351	1,694	1,260	1,583	1,253	1,569	1,247	1,559
Net Plant HHV Efficiency (%)	39.0%	31.2%	40.7%	32.5%	43.7%	34.7%	43.9%	35.0%	44.1%	35.2%
Raw Water Withdrawal, gpm	5,538	8,441	5,105	7,882	4,508	7,124	4,461	7,025	4,422	6,960
Process Water Discharge, gpm	1,137	1,920	1,059	1,813	930	1,638	919	1,615	911	1,600
Raw Water Consumption, gpm	4,401	6,521	4,045	6,069	3,578	5,486	3,541	5,410	3,511	5,360
CO_2 Emissions (lb/MWhgross)	1,683	190	1,618	183	1,515	173	1,506	172	1,500	171

- **Design basis for AUSC Study enables direct comparison to subcritical and supercritical PC plants from the Bituminous Baseline Study:**
  - National Energy Technology Laboratory. *Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3,* DOE/NETL-2015/1723. July 2015.

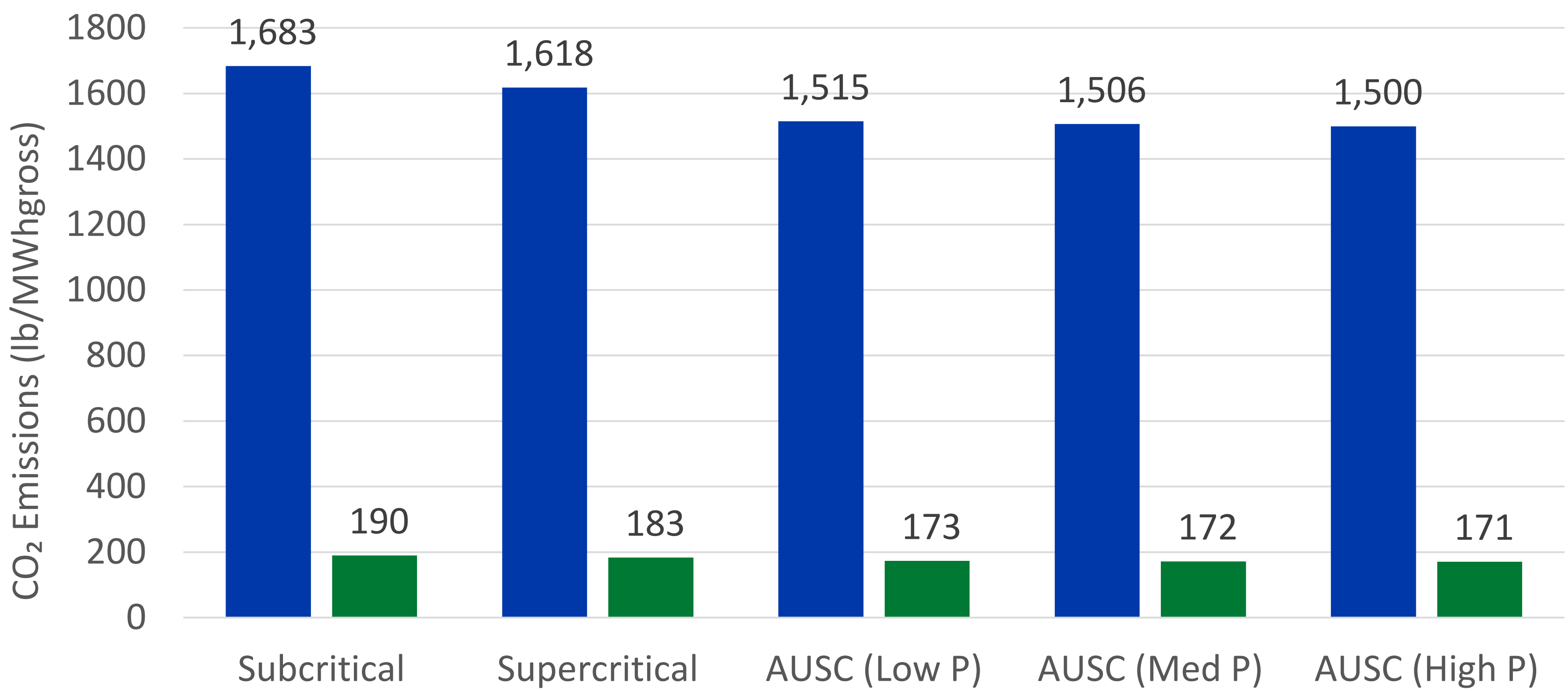
AUSC PC Plant Performance Results



Case	B11A/B*	B12A/B*	1 & 2	3 & 4	5 & 6
Pressure (psig)	2400	3500	3500	4250	5000
Main Steam (°F)	1050	1100	1350	1350	1350
Reheat (°F)	1050	1100	1400	1400	1400

AUSC PC Plant Performance Results

CO_2 Emissions



Case	**B11A/B***	**B12A/B***	**1 & 2**	**3 & 4**	**5 & 6**
Pressure (psig)	2400	3500	3500	4250	5000
Main Steam (°F)	1050	1100	1350	1350	1350
Reheat (°F)	1050	1100	1400	1400	1400

Advanced Ultra-Supercritical (AUSC) Pulverized Coal Reference Plants

Conclusions

- AUSC PC plants provide 3.0-3.5% points efficiency improvement over baseline supercritical (SC) PC plants
  - Improvement of only 2.2-2.7% points efficiency for CCS cases
- Efficiency gains due to increasing main steam pressure above 3500 psig provide diminishing benefit to plant costs
- Greater confidence in AUSC steam turbine efficiency and cost has been gained due to work performed by AUSC Materials Consortium

Future Work

- Economic analysis for all six cases nearing completion
- A COE sensitivity on high-nickel-alloy components can be performed once the weight fraction of the inverted tower design boiler for these materials is estimated

Site Specific Study: Objective

- **Effect on Cost of Electricity (COE) by varying parameters for three plant configurations:**
  - Supercritical PC with 90% capture (B12B, Rev 3)
  - IGCC with 90% capture (B5B, Rev 2b)
  - NGCC with 90% capture (B31B, Rev 3)
  - http://www.netl.doe.gov/research/energy-analysis/baseline-studies
- **Parameters being considered are:**
  - Specifically excluding changes to scope and schedule

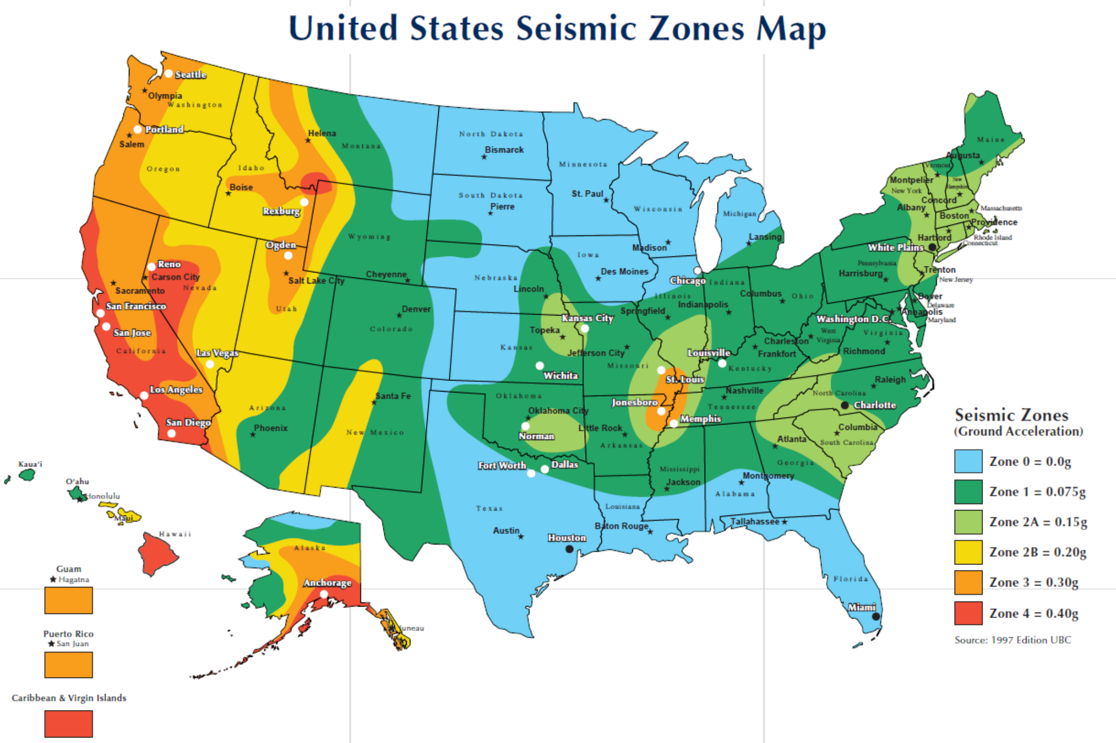
Construction Cost

- site geology issues that necessitate the use of piles
- costs of steel
- cost of concrete
- seismic zone
- labor productivity
- Labor cost (i.e. union vs merit, location, etc.)
- project and process contingencies

Performance Cost

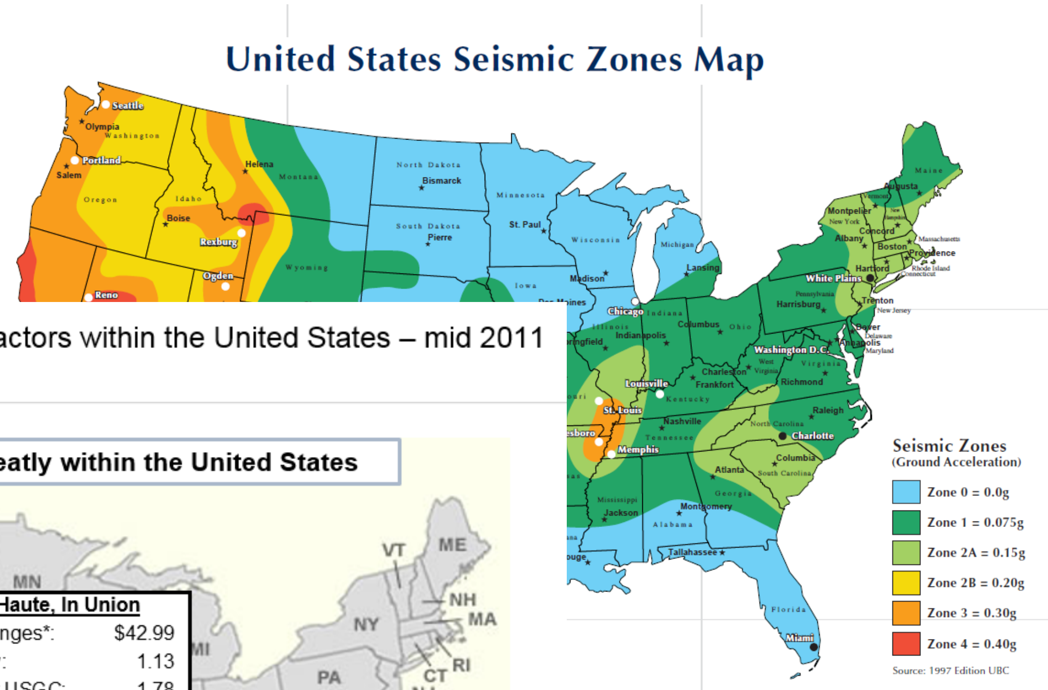
- elevation (atmospheric pressure)
- relative humidity (including the impact on cooling water temperature)
- ambient temperature
- coupled humidity + temperature

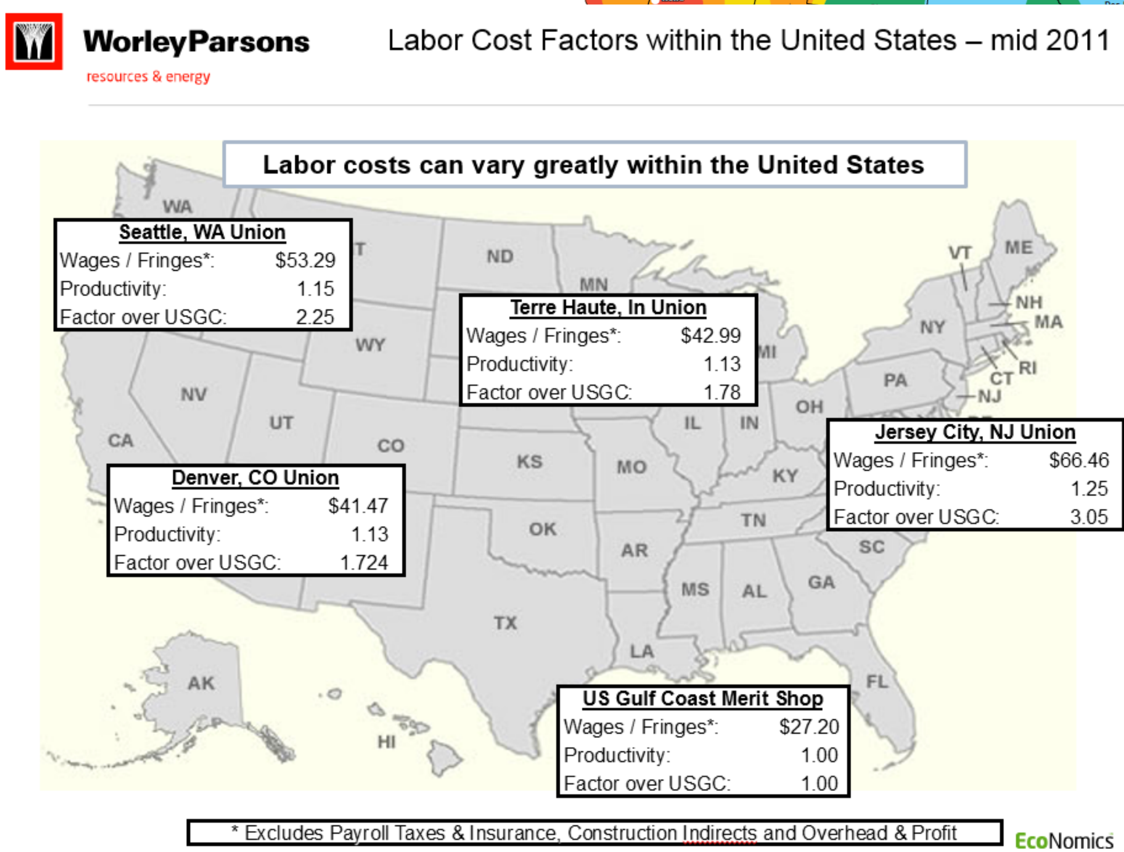
Factors Considered



Source: USGS

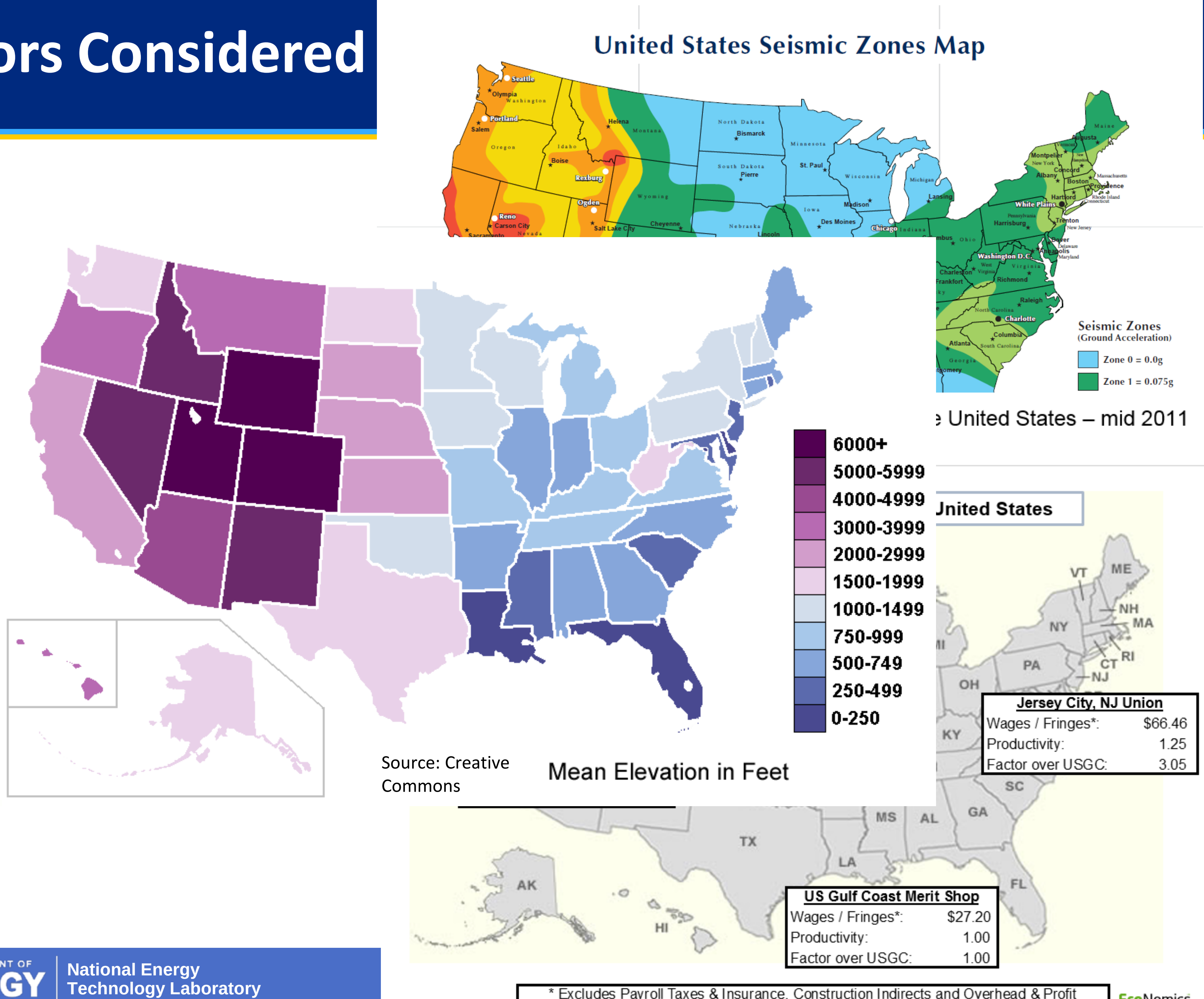
Factors Considered



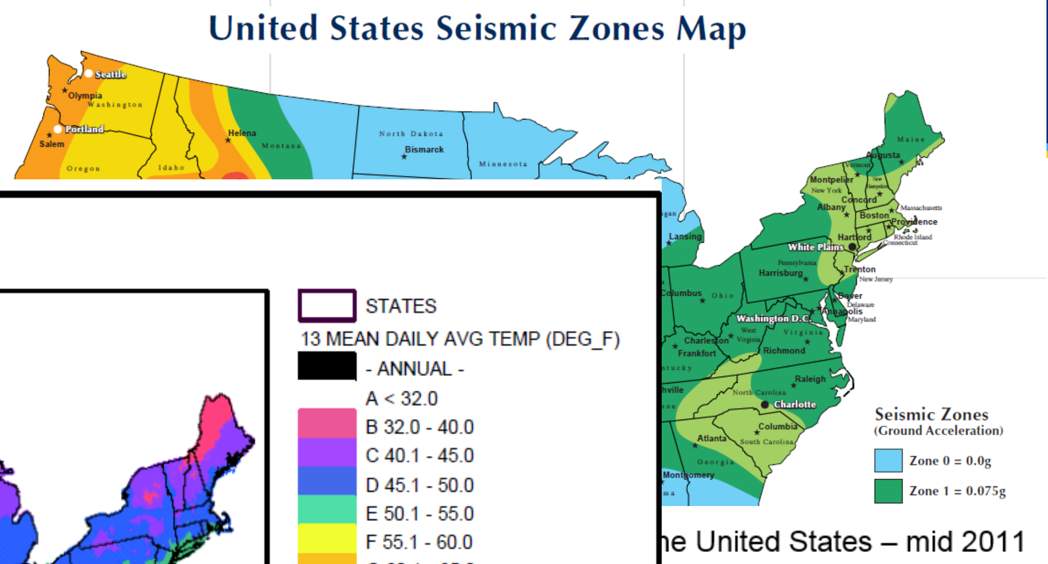


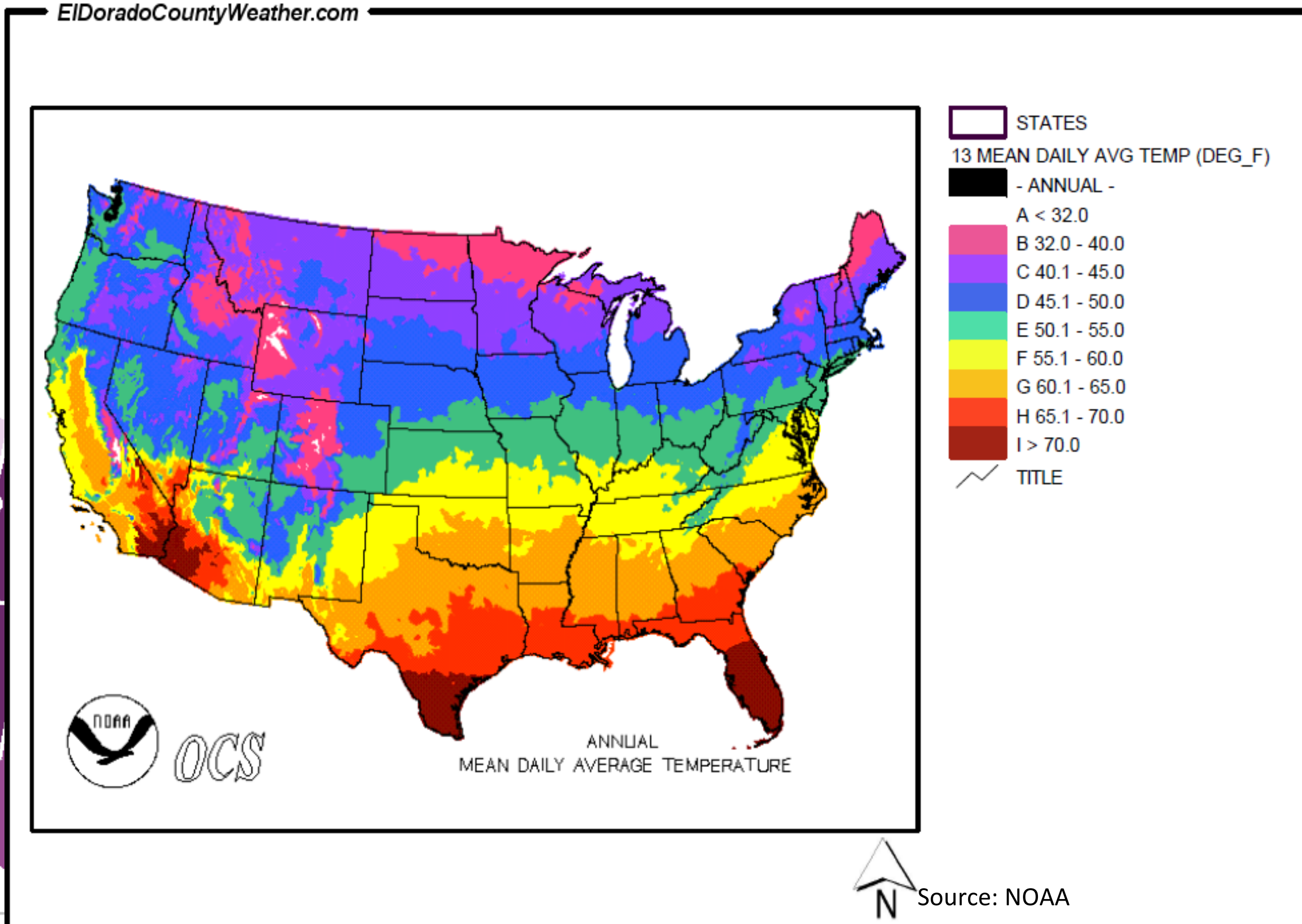
Source: USGS

Factors Considered

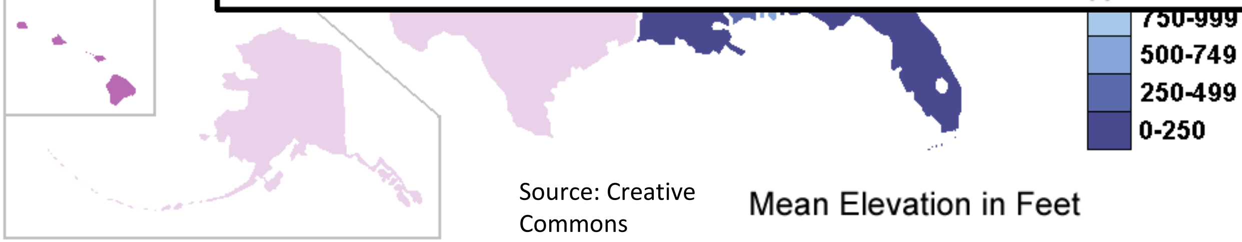


Factors Considered

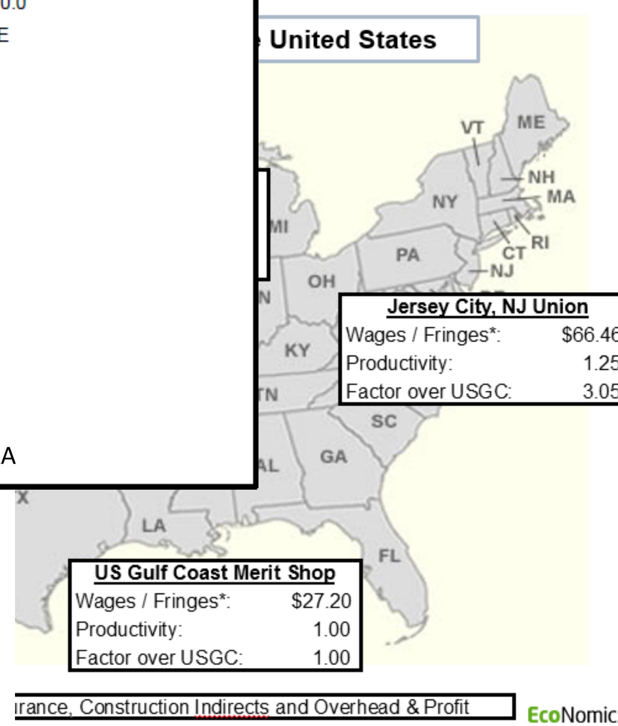


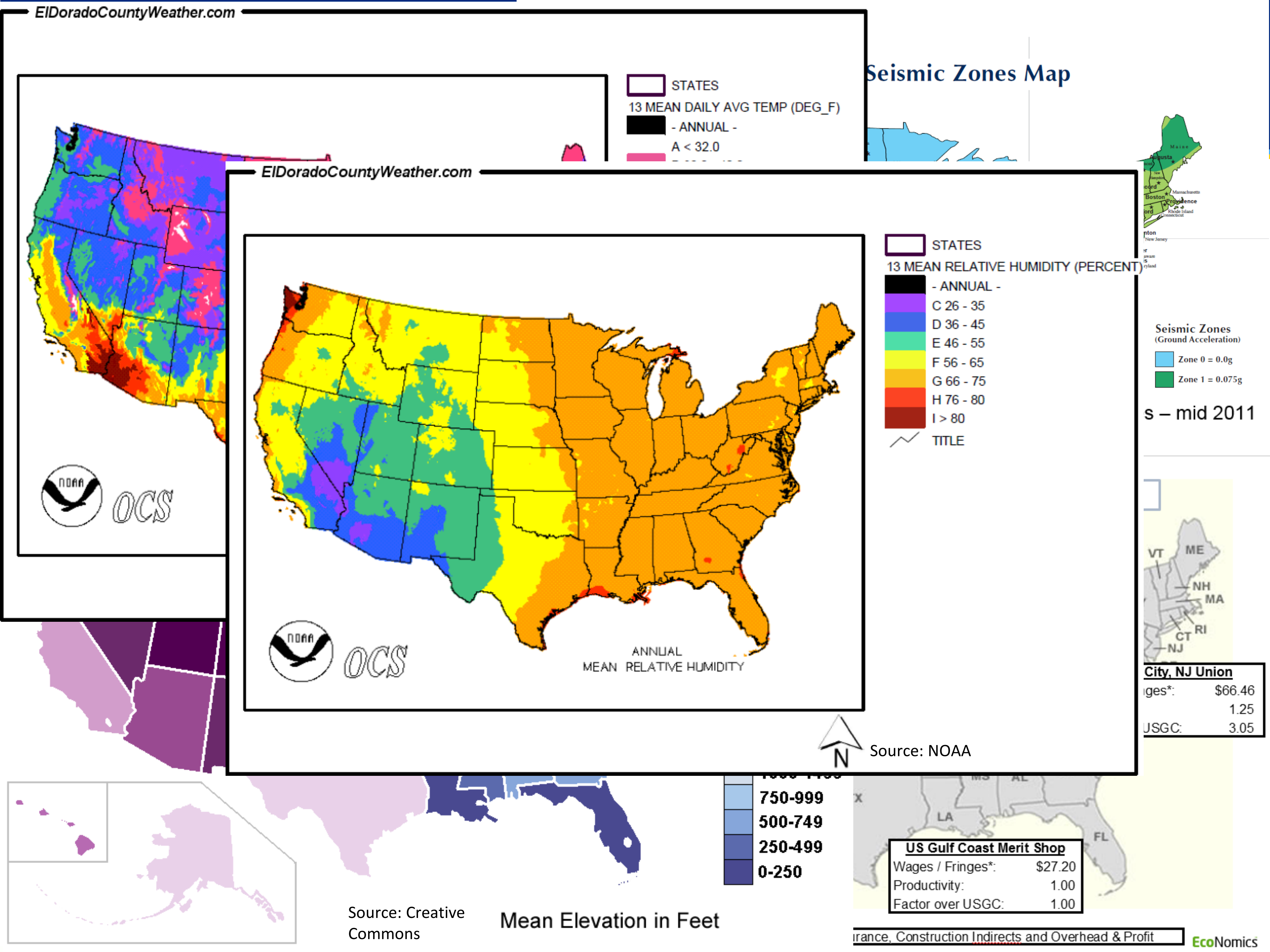


Source: NOAA



Source: Creative Commons




ElDoradoCountyWeather.com
STATES
13 MEAN DAILY AVG TEMP (DEG_F)
- ANNUAL -
A < 32.0
OCS
Seismic Zones Map
Seismic Zones
(Ground Acceleration)
Zone 0 = 0.0g
Zone 1 = 0.075g
s – mid 2011
ElDoradoCountyWeather.com
STATES
13 MEAN RELATIVE HUMIDITY (PERCENT)
- ANNUAL -
C 26 - 35
D 36 - 45
E 46 - 55
F 56 - 65
G 66 - 75
H 76 - 80
I > 80
TITLE
OCS
ANNUAL
MEAN RELATIVE HUMIDITY
N
Source: NOAA
VT
ME
NH
MA
RI
CT
NJ
City, NJ Union
ges*: $66.46
1.25
USGC: 3.05
750-999
500-749
250-499
0-250
LA
FL
US Gulf Coast Merit Shop
Wages / Fringes*: $27.20
Productivity: 1.00
Factor over USGC: 1.00
rance, Construction Indirects and Overhead & Profit
EcoNomics
Source: Creative Commons
Mean Elevation in Feet

Selected Ambient Condition Ranges

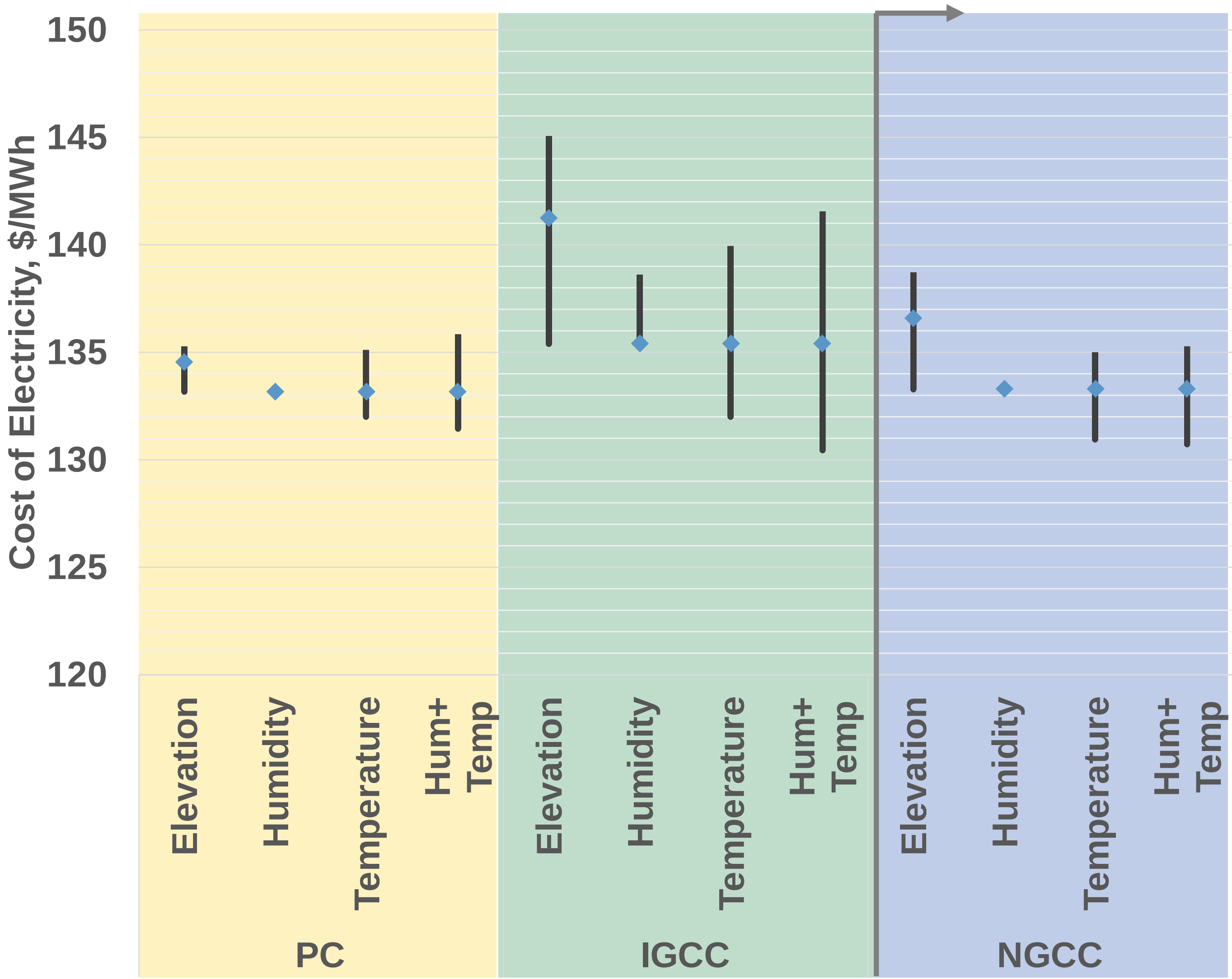
Elevation		
0 ft	ISO Site; 14.7 psia	
3,400 ft	Montana Site; 13.0 psia	-MID
5,280 ft	Denver, CO; 12.1 psia	-HIGH
Ambient Temperature , Dry Bulb		
59 F	ISO Site; 14.7 psia	
36 F	Anchorage, AK Annual Average	-COLD
73 F	Phoenix, AZ Annual Average	-HOT
Ambient Relative Humidity		
25%	Low US State Annual Average Humidity, NOAA	-DRY, -COLDRY
60%	ISO Site; 14.7 psia	
80%	High US State Annual Average Humidity, NOAA	-HUM, -HOTHUM

Source: NETL

Ambient Condition Impacts

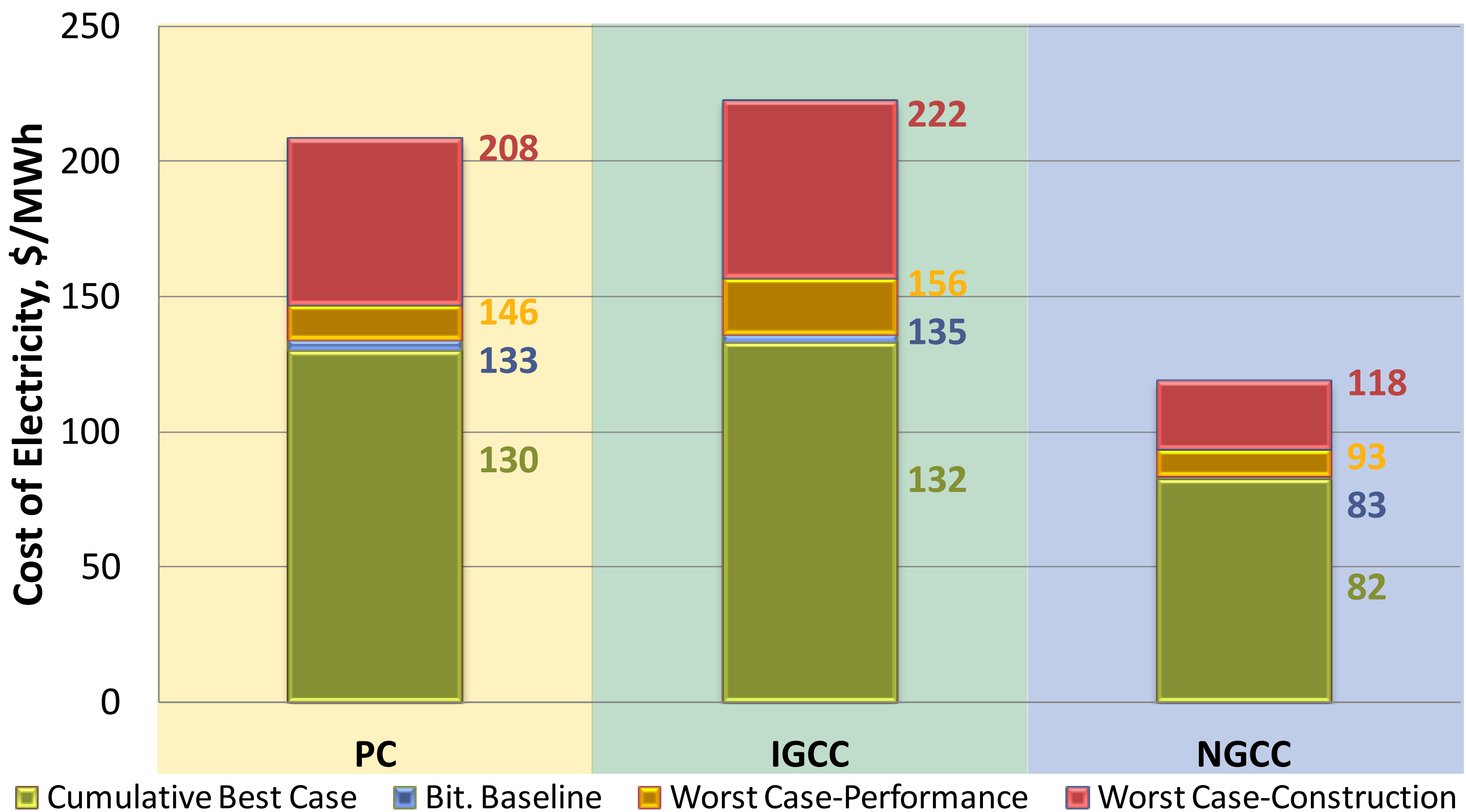
- **Combustion Turbine**
  - Pressure, density, and composition of air
  - Ambient density ranges from 0.060 to 0.077 lb/cuft
- **Cooling Tower / Water**
  - Minimum temperature limited by wet bulb temperature
  - Wet bulb temperature ranges from 27.3 to 68.5 F, resulting cooling water temperatures range from 35.8 to 77 F
  - Steam Turbine Condenser, SWS, Syngas Cooling, AGR, ASU, CO_2 Compressor
- **Sensible Heat of Ambient Streams**
  - Temperature set by ambient temperature

Cost of Electricity Sensitivity



Source: NETL

Combined Performance and Cost Sensitivity



Source: NETL

Conclusions

- **NETL's Bituminous Baseline reference cases are within 3% of the "best case"**
  - lower steel costs
  - gulf coast merit wages
  - improved productivity
  - lower ambient temperature and humidity
- **Construction cost parameters have the largest effect on plant cost and COE in the following order**
  1. labor costs (merit vs union, location, etc.)
  2. steel price
  3. labor productivity
  4. seismic zone
  5. requirement for piles
  6. concrete costs.
- **Ambient conditions changes affect the COE less**
  - turbine performance (IGCC and NGCC) are most sensitive to elevation changes
  - PC is affected most by cooling water and condenser pressure

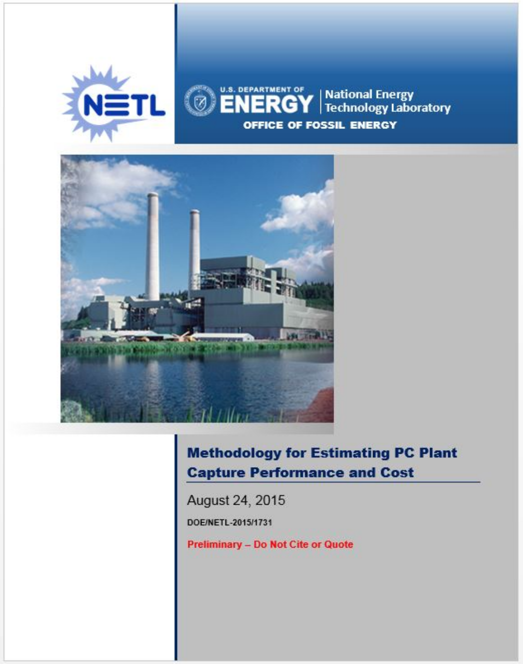
Conclusions (continued)

- **Many variables can impact project costs**
  - focus on common variables
  - not intended to be all inclusive
- **Changes in project scope can have a significant impact on project costs; in many cases, far greater than any of the variables considered in this study.**
  - Improved scope definition equals less cost risk.

Toolset Components

- **CO_2 Capture Methodology Spreadsheet**
  - Input: performance and cost estimates from developer models
  - Spreadsheet estimates performance and cost of base plant and provides overall plant metrics
    - Performance and cost calculations based upon model developed from Bituminous Baseline Study, Rev 3 Case B12B
    - Detailed description of model contained in methodology document

	A	B	C	D	E
1	POST-COMBUSTION CO_2 CAPTURE TECHNOLOGY ASSESSMENT METHODOLOGY				
54					
55	BASE PLANT CO_2 CAPTURE PROCESS PERFORMANCE & COST INPUTS		Input Cells	Calculation Cells	PRESS F9 TO
56	Developing CO_2 Capture Technology Identifier	Base Case Example	Adsorbent	Membrane	
57		BBR B12B Cansolv	Example	Example	
58	CO_2 Capture Process Performance Inputs (Inputs generated using prescribed design basis)				
59	No. 1 Extracted steam heating duty: Q_H (MMBtu/hr)	1,129	1,000	0	
60	No. 1 Extracted steam heating temperature (F)	293.5	284	230	
61	No. 2 Extracted steam heating duty: Q_H (MMBtu/hr)	0	0	0	
62	No. 2 Extracted steam heating temperature (F)	230	230	230	
63	CO_2 Capture Process cooling duty: Q_C (MMBtu/hr)	1,868	200	350	
64	CO_2 Separation System pressure drop: DP_{sep} (psi)	0	0.9	2	
65	FD-fan pressure boost above Base value of 0.6 psia: DP_{FDfan} (psi)	0	0	1	
66	CO_2 Capture Process CO_2 removal efficiency (%)	90	91	90	
67	CO_2 Separation System power: A_{sep} (kW)	16,000	10,900	30,000	
68	CO_2 CPU power: A_{CPU} (kW)	35,690	49,000	51,000	
69	CO_2 Capture Process Cost Inputs (Inputs generated using prescribed design basis)				
70	CO_2 Separation System cost ($1000: Cost Base June 2011, TPC basis)	533,757	400,000	350,000	
71	CO_2 CPU cost ($1000; Cost Base June 2011, TPC basis)	98,381	100,000	140,000	
72	Key CO_2 Capture Process variable cost items	Makeup solvent	Makeup adsorbent	Membrane surface	
73	CO_2 Capture Process variable cost: C_{varCO2} ($1000/yr)	0	5,000	8,000	



Toolset Components

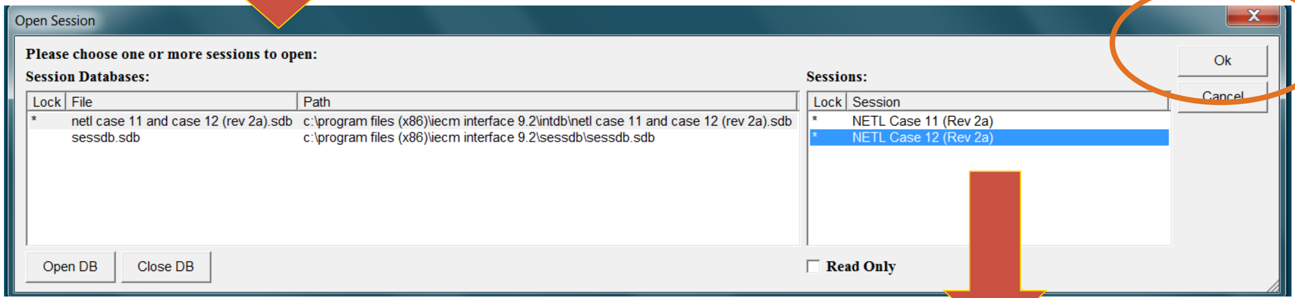
- **CO_2 Purification and Compression Spreadsheet**
  - Input: composition and conditions of CO_2 product from the capture system
  - Spreadsheet estimates performance and cost of CO_2 compression and (if required) CO_2 purification system
    - Performance and cost calculations based upon Aspen model of CO_2 purification and compression system for performance and Aspen Economic Analyzer for costs
  - Results can be used as inputs to CO_2 Methodology spreadsheet
  - Detailed description of model contained in methodology document

1	RAW CO_2 GAS FINAL PROCESSING SYSTEM PERFORMANCE AND COST SPREADSHEET				
2	Application	PC Post-Combustion (coal rate fixed at BBR Case B12B)			
3					
4		STUDY	Correlation	BASELINE	
5		PROCESS	Limits	PROCESS	
6	Raw CO_2 Gas Composition (mole fraction)				
7	CO_2	0.6	OK	0.9824	
8	H_2O	0.3	OK	0.0176	Developer Input Data for Raw CO_2 Gas
9	O_2	0	OK	0	Calculated Results
10	N_2	0.1	OK	0	PRESS F9 TO RECALCULATE
11	Ar	0		0	
12	Total	1		1	
13	Raw CO_2 Gas Inlet Pressure (psia)	15	OK	28.7	
14	Raw CO_2 Gas Inlet Temperature (°F)	85	OK	86	
15	Separation System CO_2 Efficiency (%)	90.0		91.5	
16					
17	Raw CO_2 Gas Flow (lbmol/hr)				
18	CO_2	24,060		24,461	
19	H_2O	12,030		438	
20	O_2	0		0	
21	N_2	4,010		0	
22	Ar	0		0	
23	Total	40,100		24,899	
24					
25	Raw CO_2 Gas Processing Needed	CPU		Compression	
26	Power Consumed (kW)	57,336		33,997	
27	Cooling-Water Load (MMBtu/hr)	537		230	
28	CO_2 Loss Rate (% of inlet CO_2)	6.5		0.0	
29	Separation System CO_2 Efficiency Needed (%)	96.3		90.0	
30	Total Plant Cost (Million June 2011$)	193		98	

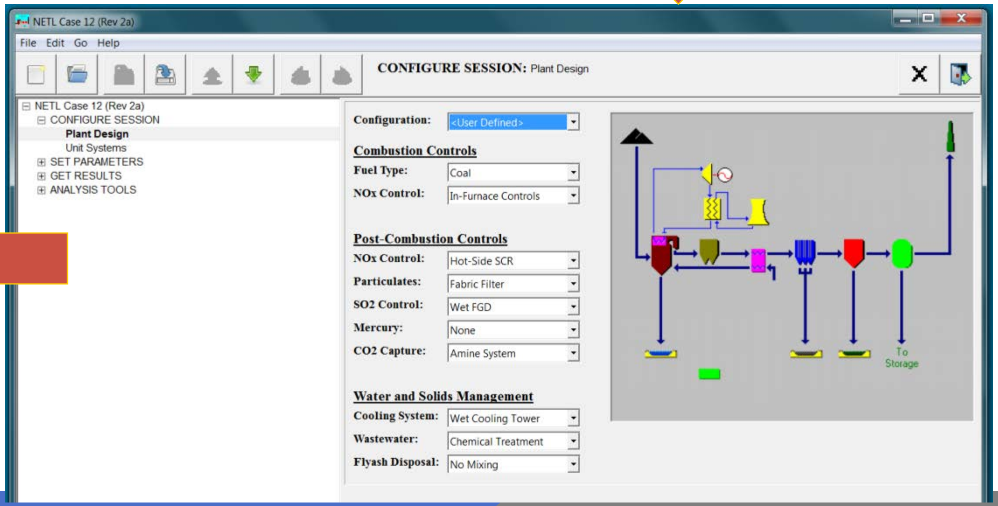
Bituminous Baseline Rev.2 Case Implementation in IECM (v.9.2)

Click "Open Session" to access NETL Case 11 or 12

Use "New Session" to access IECM defaults



View or change model parameters and results. Use "Save as" to keep a copy of your changes in a "New Database" with your new sessions.



Source: Carnegie Mellon University

Carbon Pollution Standard (CPS) – CO_2 NSPS

- **All new coal sources must achieve emission limit of 1,400 Lb CO_2/MWh gross**
- **New Source Performance Standard - Section 111(b) of Clean Air Act**
- **Application of best system of emission reduction (BSER)**

CPS Compliance Options

- **BSER for coal: New supercritical PC with partial CCS**

- **Emission limit not to exceed 1,400 Lb CO_2/MWh gross**

- **BSER not required – coal/gas co-firing, combined heat and power also discussed (neither selected as BSER)**

Coal – natural gas cofiring

- **Gas less C intensive fuel than coal**
- **Blend coal and gas to achieve 1,400 Lb CO_2/MWh g**
- **Plant exposed to both coal and natural gas prices**

	C Content	Lb CO_2/MWh gross
Bituminous coal	56 Lb C/MBtu bit.	1,636[a]
Natural gas	32 Lb C/MBtu gas	763[b]

a) 7,960 Btu/kWh
b) 6,517 Btu/kWh

Combined Heat and Power

- **Coal based power plant that sells a portion of its thermal energy (steam) to industrial takers**

- **Increase gross power to reduce emission rate (Lb CO_2/MWh g)**

$$P_{gross\,/net} = \frac{(Pe)ST + (Pe)CT + (Pe)IE - (PE)FW - (Pe)A}{TDF} + [(Pt)PS + (Pt)HR + (Pt)IE]$$

- **Challenge will be finding sufficient steam users**

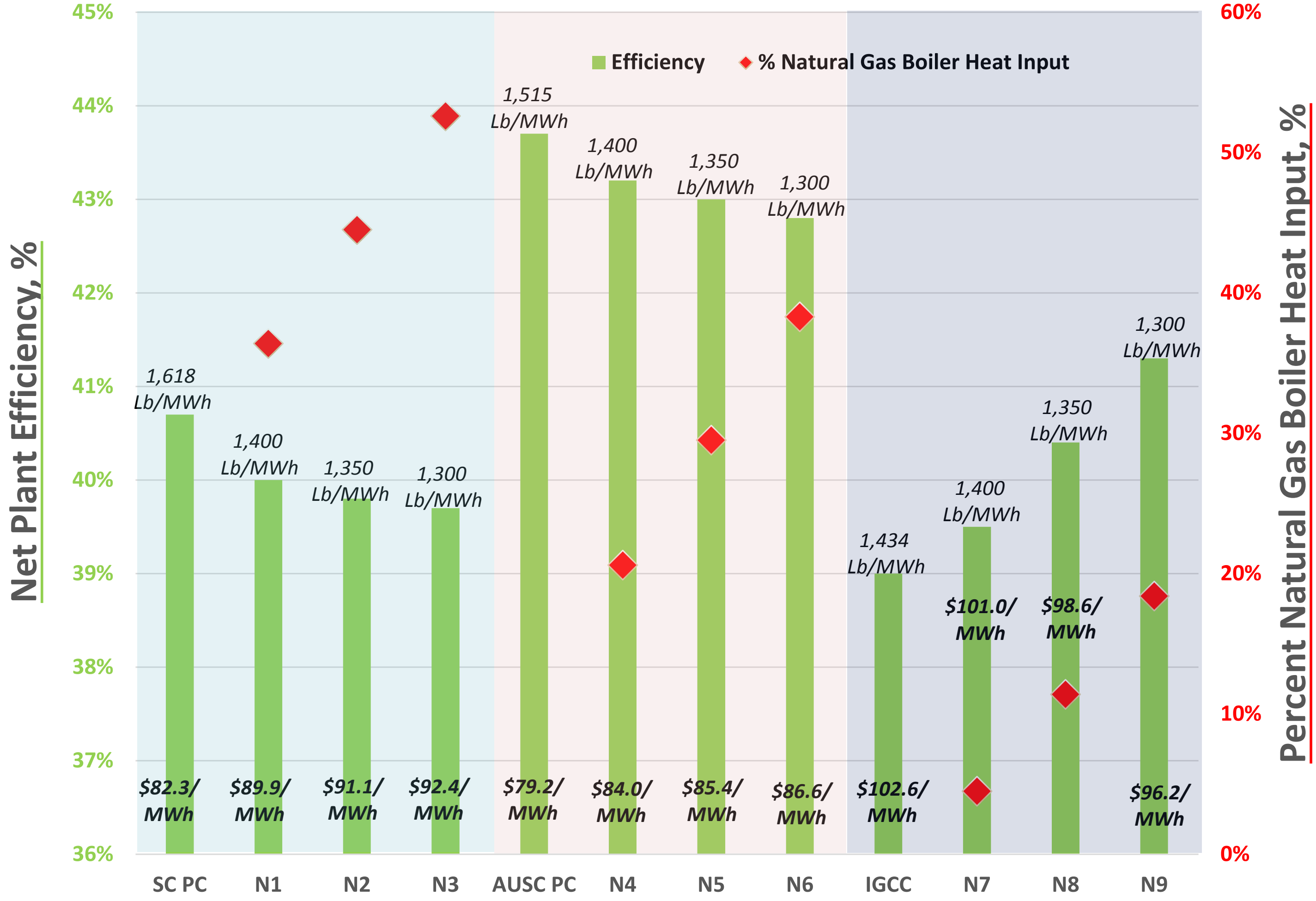
NETL Non-CCS Compliance Study

- **Recently completed NETL study evaluated cost, performance of non-CCS compliance options for Carbon Pollution Standard**

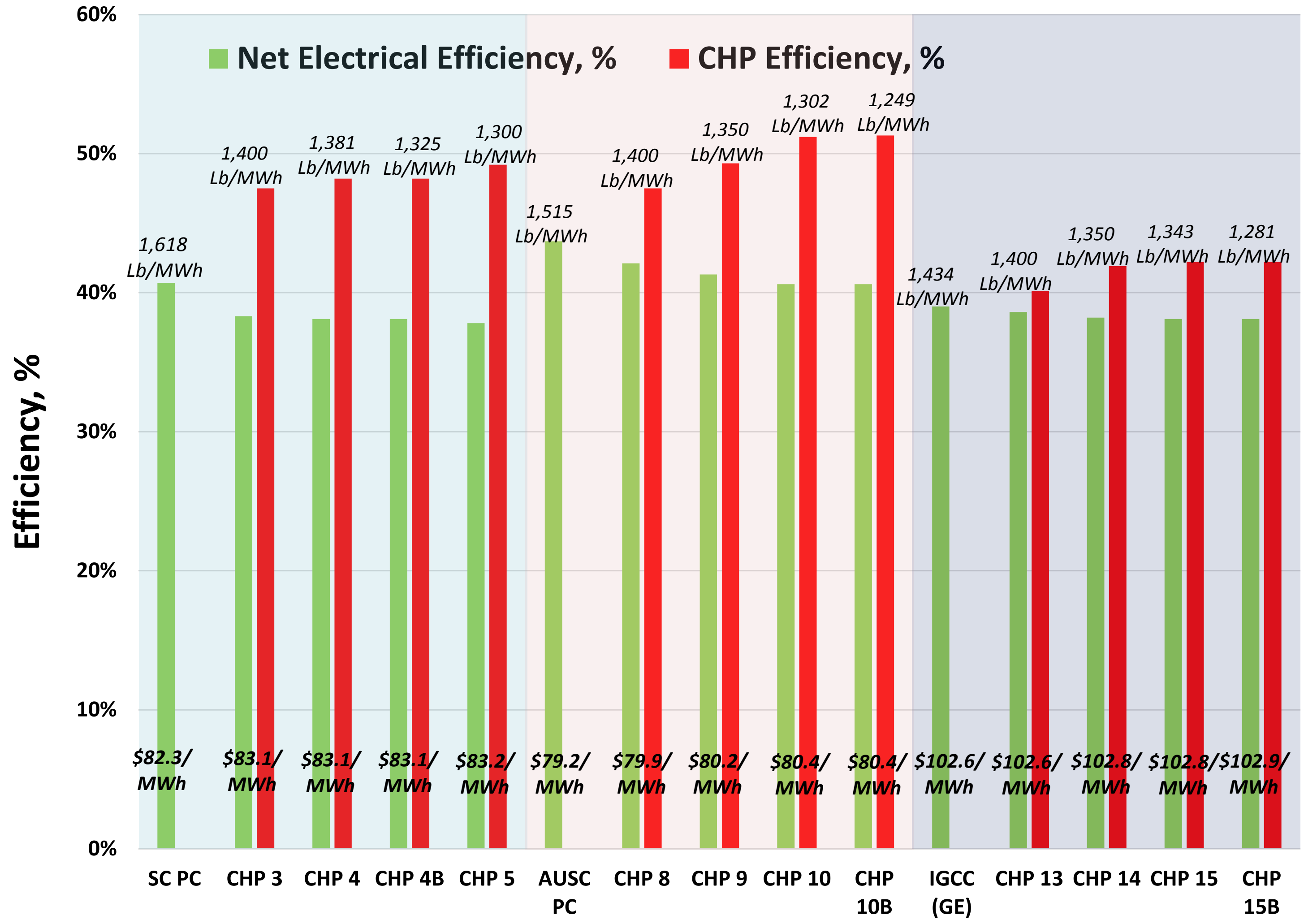
- **Supercritical and advanced ultrasupercritical pulverized coal, IGCC gas co-firing, combined heat and power cases**

- **How much does it cost to comply with CPS without the use of CO_2 capture?**

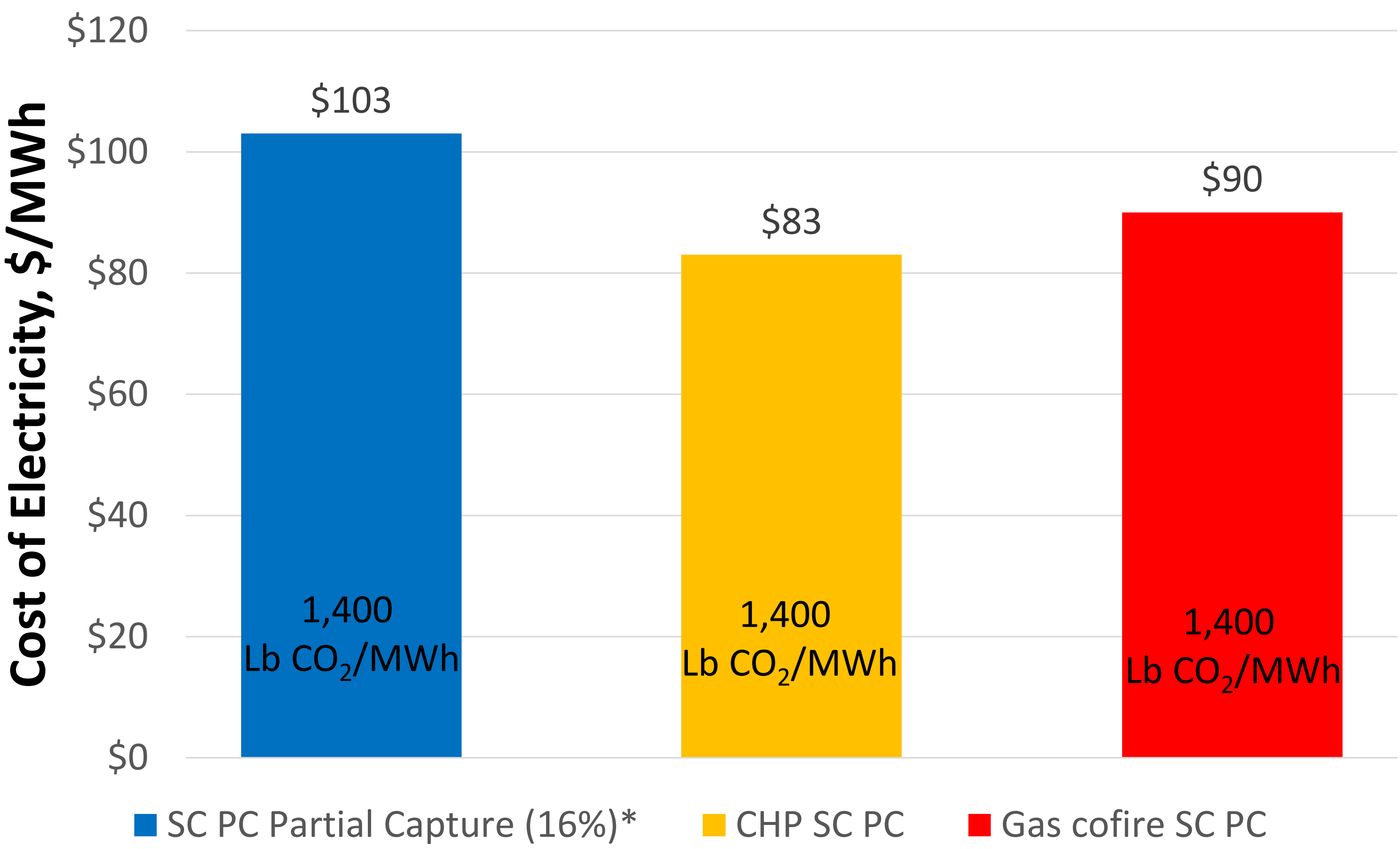
Natural gas co-firing cost and performance



Combined Heat and Power Cost and Performance



Cost of CCS and non-CCS compliant cases



"Cost and Performance Baseline for Fossil Energy Plants Supplement: Sensitivity to CO_2 Capture Rate in Coal-Fired Power Plants," NETL, June 22, 2015

Importance of Continued CCS Research

Continued development of CCS still critical to meeting our energy goals!!!

Evolution of New Source Performance Standards

- **New Source Performance Standards (CPS) reviewed every 8 years**

- *"The Administrator shall, at least every 8 years, review and, if appropriate, revise such standards following the procedure required by this subsection…" "When implementation and enforcement of any requirement of this chapter indicate that emission limitations and percent reductions beyond those required by the standards…are achieved in practice, the Administrator shall…consider the emission limitations and percent reductions achieved in practice."**

- **CPS finalized in 2015…where will CCS be in 2023?**

**Standards of Performance for new stationary sources, https://www.law.cornell.edu/uscode/text/42/7411*

Future of CO_2 Capture?

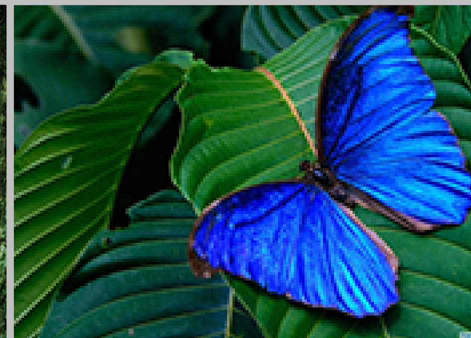
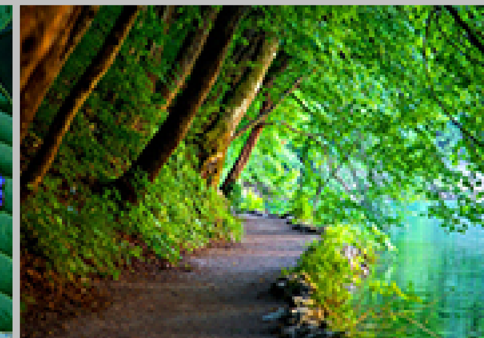
- **Deeper emission reductions required from coal (over time, emission limit may become more stringent)**

- **CO_2 capture may be required on gas someday**

- **Future fuel prices (coal, gas), emission limits, U.S. generation mix could all require cost-effective, dependable CCS**

It's All About a Clean, Affordable Energy Future



For More Information, Contact NETL

the ENERGY lab

Delivering Yesterday and Preparing for Tomorrow