Advanced Coal Power Systems

Competing in Multiple Market Scenarios

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Kristin Gerdes
Senior Analyst, Office of Program Planning & Analysis

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Overview

- OBJECTIVE
  - How can R&D help maintain a balanced energy supply for our nation's energy and economic security through use of its abundant domestic coal resources?
  - Determine cost and performance requirements for new coal power plants to deploy in the 2030-2035 timeframe
    - With and without CO_2 utilization for enhanced oil recovery

- METHODOLOGY
  - DOE/EIA's National Energy Modeling System (NEMS) Annual Energy Outlook (AEO) 2011 used to examine competitiveness of new power generation capacity under different scenarios
  - NEMS competes the full array of power generation options, including coal, NGCC, nuclear and renewables
  - Deployment largely driven by levelized cost of electricity (LCOE)

Advanced Coal Power Systems

with and without CO_2 capture

State-of-the-Art	2nd Generation	Transformational
Today's IGCC	*Advanced IGCC + Advanced Pre-combustion Capture*	*Integrated Gasification Fuel Cells (IGFC)*
		IGFC + Catalytic Gasification
		X-Class IGCC
		Pulse Combustion
Today's Supercritical PC	*Advanced Ultra-supercritical (AUSC) PC + Advanced Post-combustion Capture*	*Direct Power Extraction*
		Coal Chemical Looping
	AUSC Oxycombustion	*Supercritical CO_2 Cycles*

Market Uncertainties Impacting Competiveness of Coal Power Systems

- Natural gas (NG) prices
- Macroeconomic growth and its impact on electricity demand
- Cost and performance of competing baseload technologies
- Enhanced Oil Recovery (EOR) CO_2 prices and opportunities
- Regulations limiting emissions for coal plants
- Regulation-based cost for CO_2 emissions (i.e. CO_2 tax)

AEO 2011 Scenarios Evaluated

CO_2-EOR Revenues Available	No	Yes
Reference	X	X
Low Shale Gas Recovery (i.e. high NG prices)	X	X
High Shale Gas Recovery (i.e. low NG prices)	X	X
High Macro-economic Growth (i.e. high electricity demand)	X	X

- **Reference Case**: Baseline economic growth (2.7 percent per year from 2009 through 2035), world oil price, and technology assumptions
- **Low Shale EUR:** Estimated Ultimate Recovery (EUR) per shale gas well is assumed to be 50 percent lower than in Reference case
- **High Shale EUR:** EUR per shale gas well is assumed to be 50 percent higher than in Reference case
- **High Macroeconomic Growth**: Real GDP grows at an average annual rate of 3.2 percent from 2009 to 2035; other energy market assumptions are the same as in the Reference case
- *In all scenarios without GHG regulations, EIA applies a 3 %-pt increase in the cost of capital for GHG intensive technologies without CCUS (including coal)*

Key Findings

Market Competiveness of Coal Power Systems in 2030

<table>
<tr><th></th><th colspan="3">No CO_2 Capture</th><th colspan="3">With CO_2 Capture</th></tr>
<tr><td>Generation</td><td>No R&D</td><td>2nd Gen</td><td>Transf.</td><td>No R&D</td><td>2nd Gen</td><td>Transf.</td></tr>
<tr><td>Higher NG Prices</td><td colspan="3" rowspan="2">Competitive</td><td colspan="2" rowspan="2">Competitive with CO_2 sales</td><td rowspan="2">CO_2 sales may not be required</td></tr>
<tr><td>Greater Electricity Demand</td></tr>
<tr><td>Reference AEO 2011 Case</td><td colspan="2" rowspan="3">Not competitive</td><td rowspan="3">Possible</td><td>Higher CO_2 sales price</td><td rowspan="2">Higher CO_2 sales price</td><td rowspan="3">With CO_2 sales</td></tr>
<tr><td>Lower NG Prices</td><td colspan="2">Not competitive</td></tr>
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ADVANCED POWER SYSTEMS

2nd-Gen Technology Pathways

- Advanced USC PC Pathway
  - Advanced ultra-supercritical steam conditions (5000 psig/1350F/1400F)
  - Advanced post-combustion capture such as CO_2 separation membranes or CO_2 sorbents
  - Advanced CO_2 compression

- Oxycombustion PC Pathway
  - Advanced ultra-supercritical steam conditions
  - Compact oxy-fuel boiler
  - Advanced oxygen separation
  - Advanced CO_2 compression
  - Co-sequestration of CO_2/SO_2

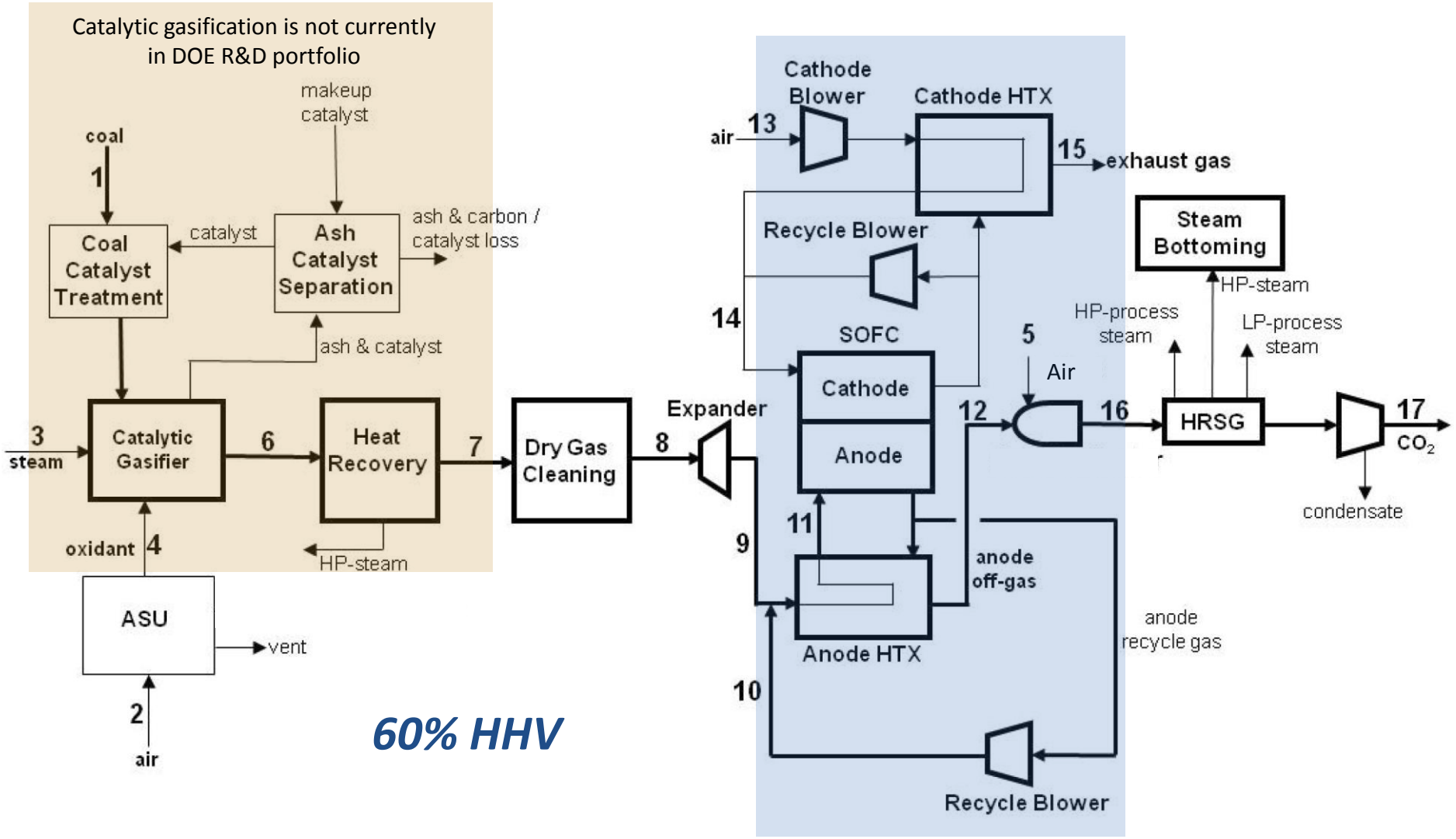
- Advanced IGCC Pathway
  - Advanced hydrogen or syngas turbine (>2600F TIT)
  - Warm gas clean up
  - Advanced H_2-CO_2 separation (i.e. high temperature hydrogen membrane)
  - Ion transport membrane for oxygen separation
  - Dry coal feed pump

IGFC Pathway

Parameter	Base	Improved
SOFC Degradation (%/1000 hrs)	1.5	0.2
Cell Overpotential (mv)	140	70
Gasifier CH_4 (conventional)	5.9%	10.2%
Gasifier CH_4 (catalytic)	30%	NA
SOFC Stack Cost (Atm.) ($/kW)	296	268
SOFC Stack Cost (Pressure) ($/kW)	442	414
Inverter Efficiency	97%	98%

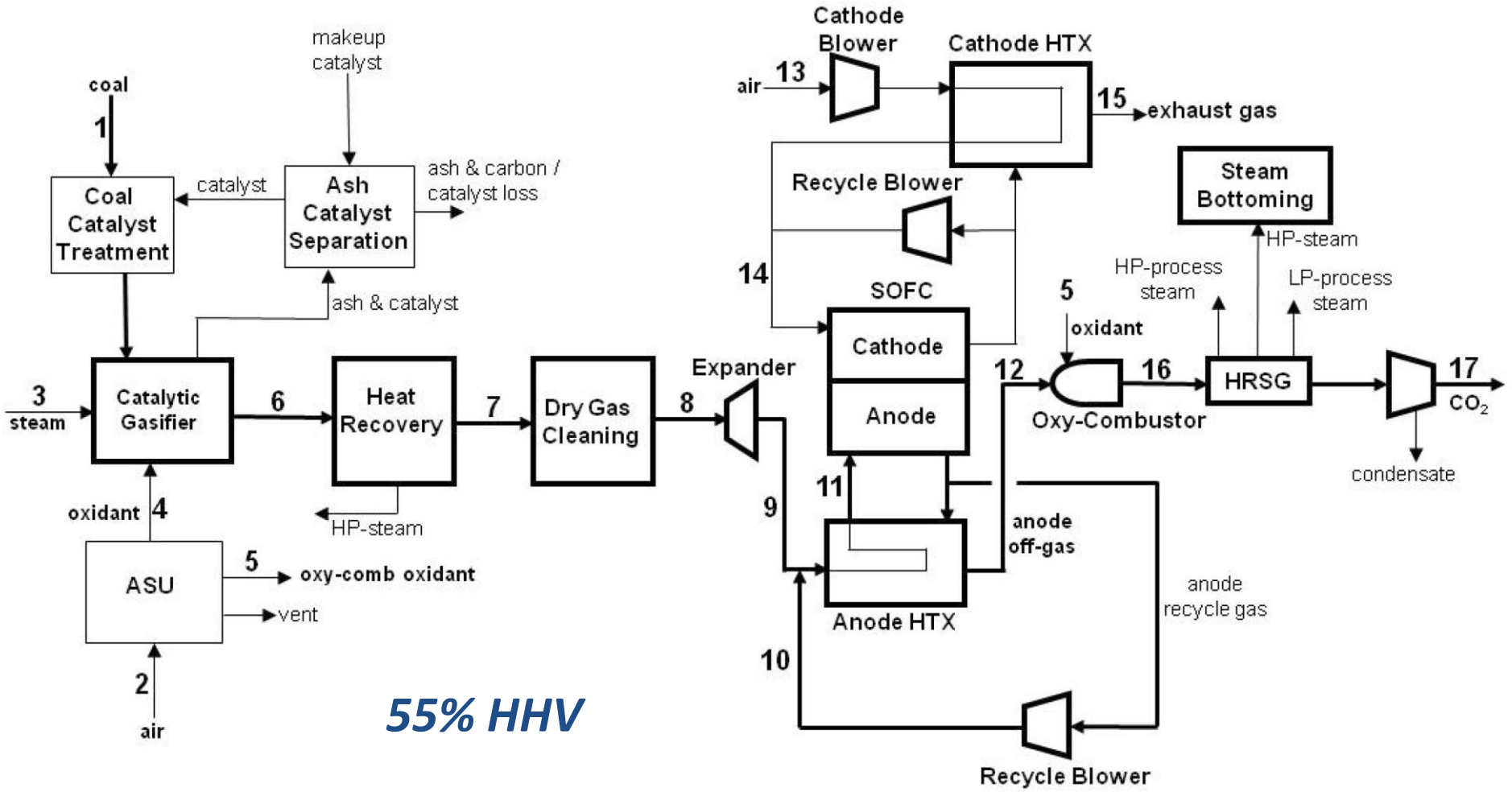
IGFC

Catalytic Gasification and Atmospheric SOFC



IGFC with CO_2 Capture

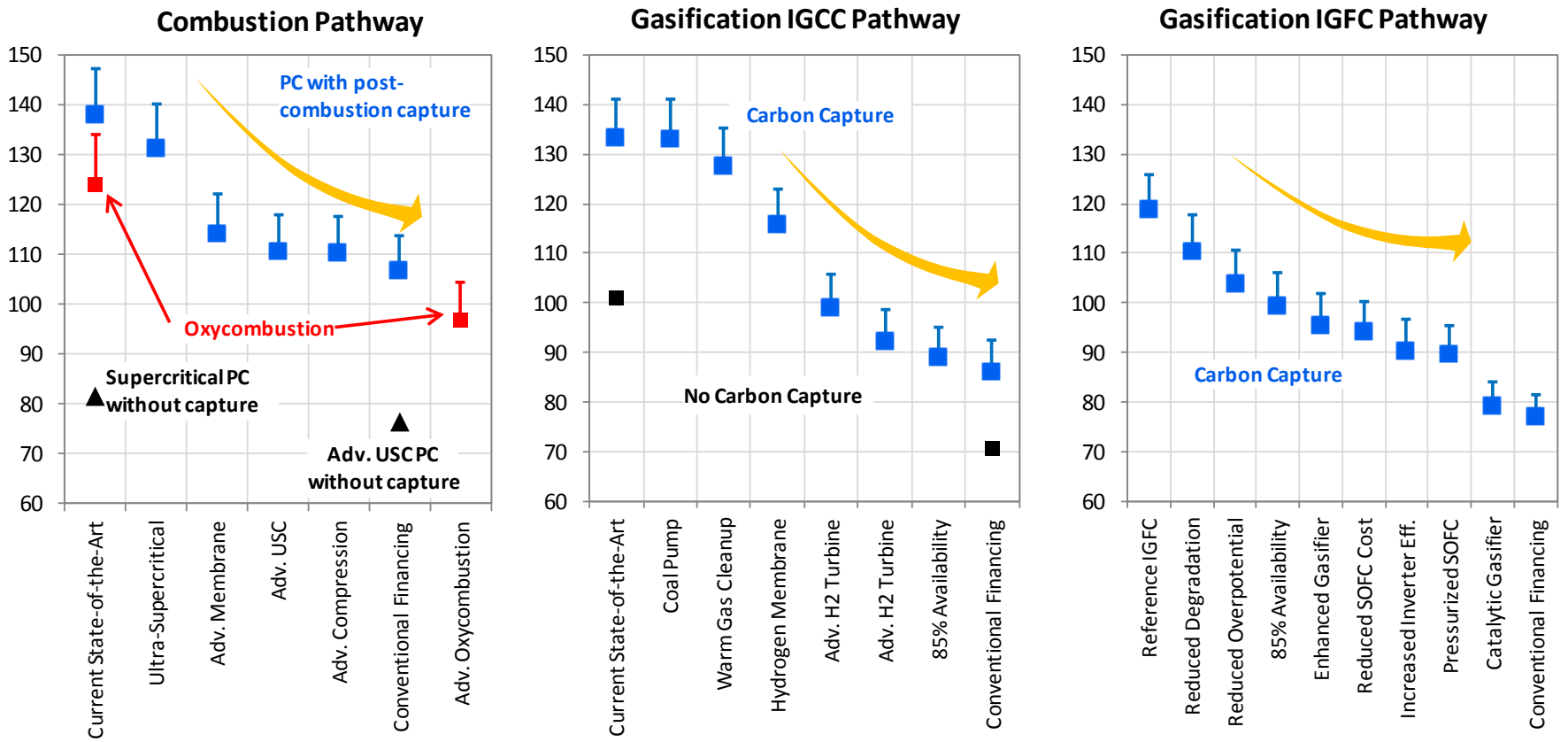
Catalytic Gasification and Atmospheric SOFC



Fossil Energy R&D Program

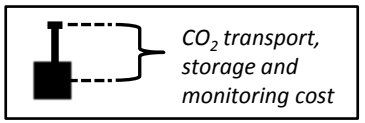
Driving Down the Cost of Electricity for Coal Power with Capture

First-year cost of electricity ($/MWh)



Integrated Gasification Combined Cycle (IGCC), Integrated Gasification Fuel Cell (IGFC), Pulverized Coal (PC)

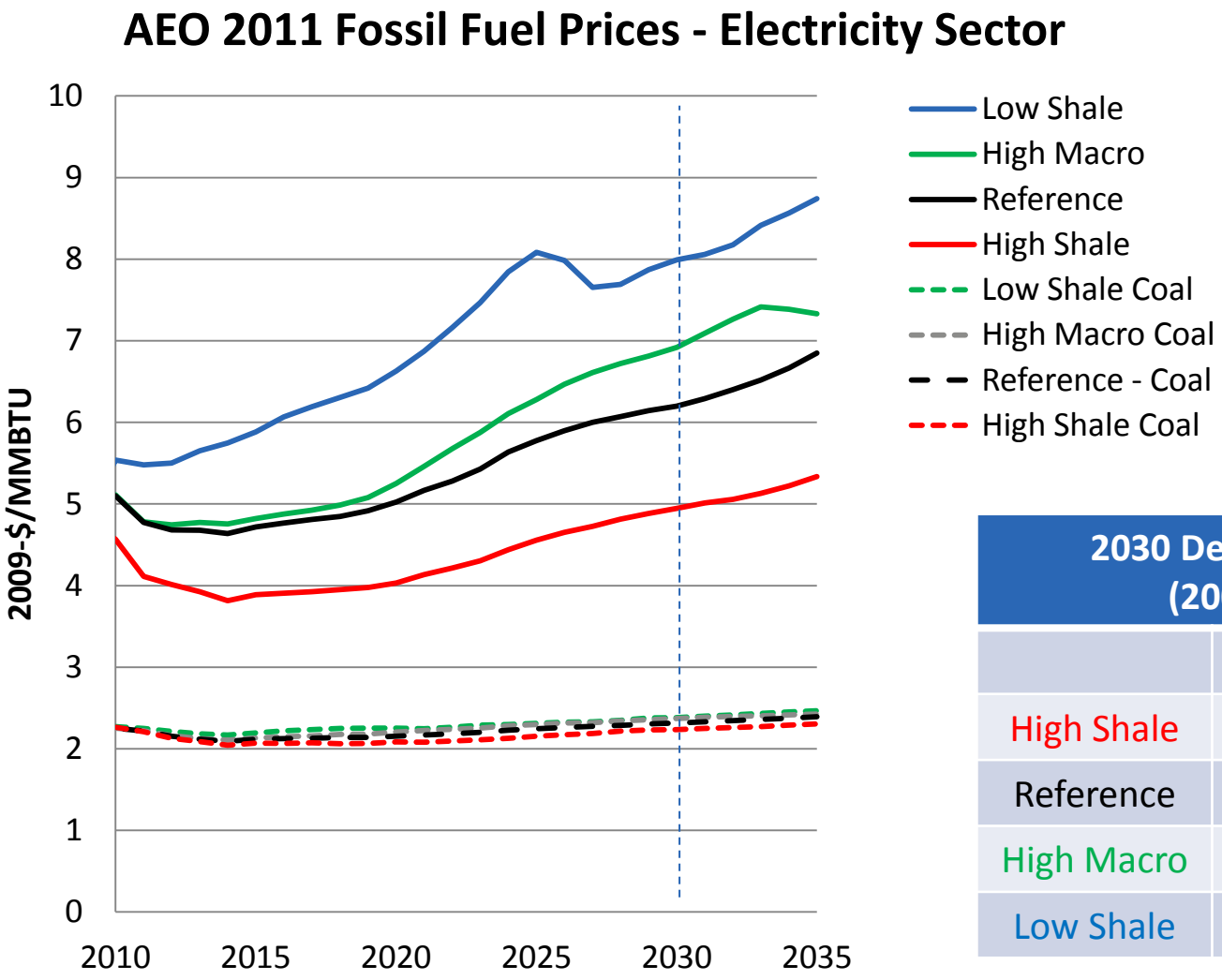
COE is reported in June 2011 dollars on a first-year (non-levelized) basis, and is assumed to escalate at a nominal annual rate of 3%.



MARKET ASSESSMENT IN 2030

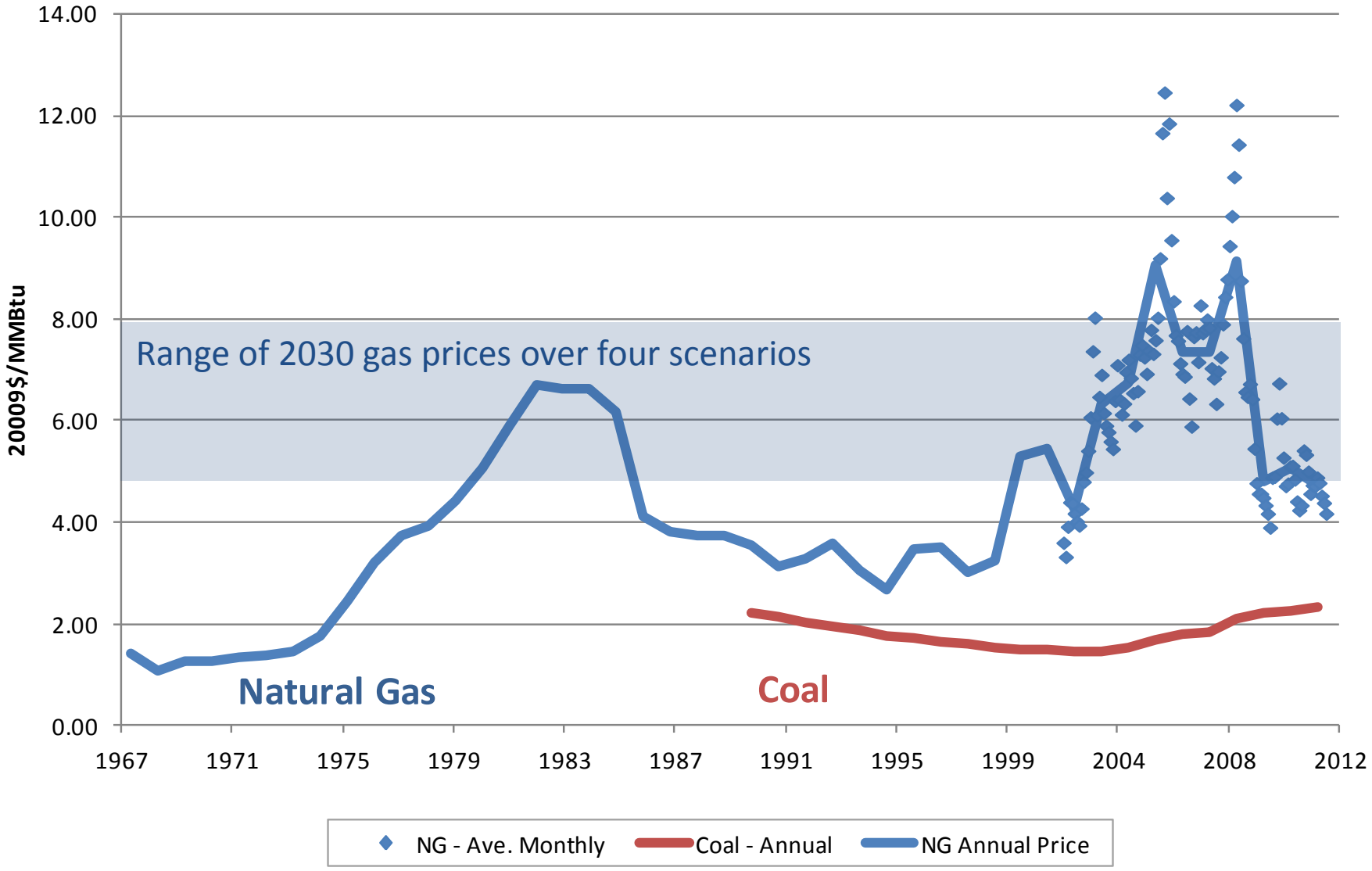
Forecasted Gas Price is Key Variable Across Scenarios

Coal Price is Stable Across Scenarios

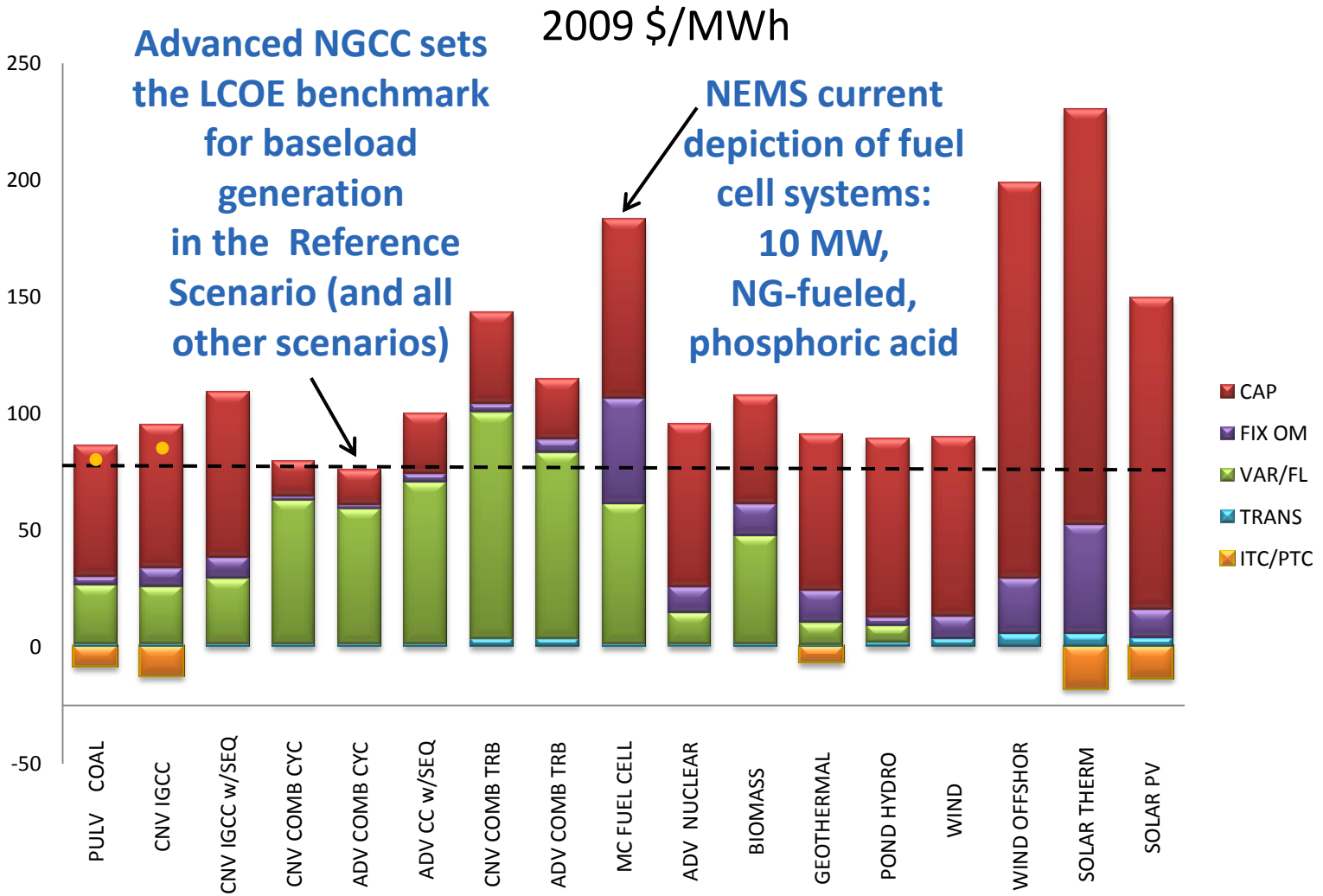


2030 Delivered Fuel Prices (2009 $/MMBtu)			
	Gas	Coal	Delta
High Shale	4.95	2.23	2.7
Reference	6.20	2.31	3.9
High Macro	6.92	2.37	4.6
Low Shale	7.99	2.38	5.6

Delivered Fuel Costs to U.S. Electric Utilities



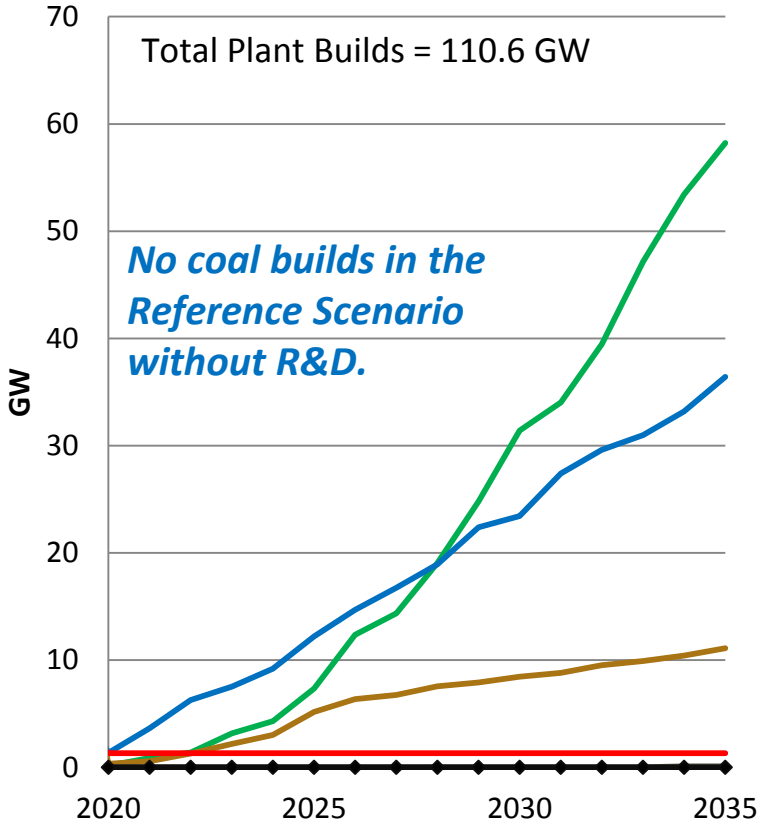
LCOE's of New Power Generation Options in 2030 Reference Scenario (No Coal R&D)



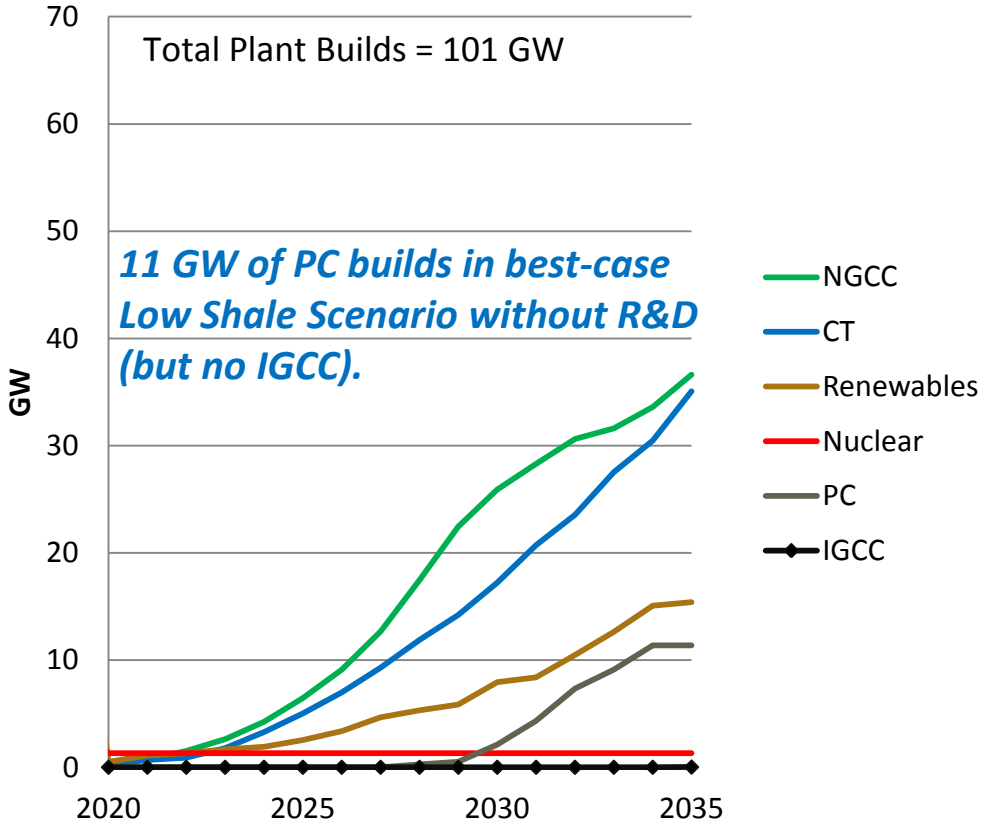
Advanced NGCC: 400 MW-net H-Class, 53% HHV

Little or No New Coal Capacity is Deployed In Scenarios without Coal R&D

New Plant Builds by Technology
Reference Scenario Baseline

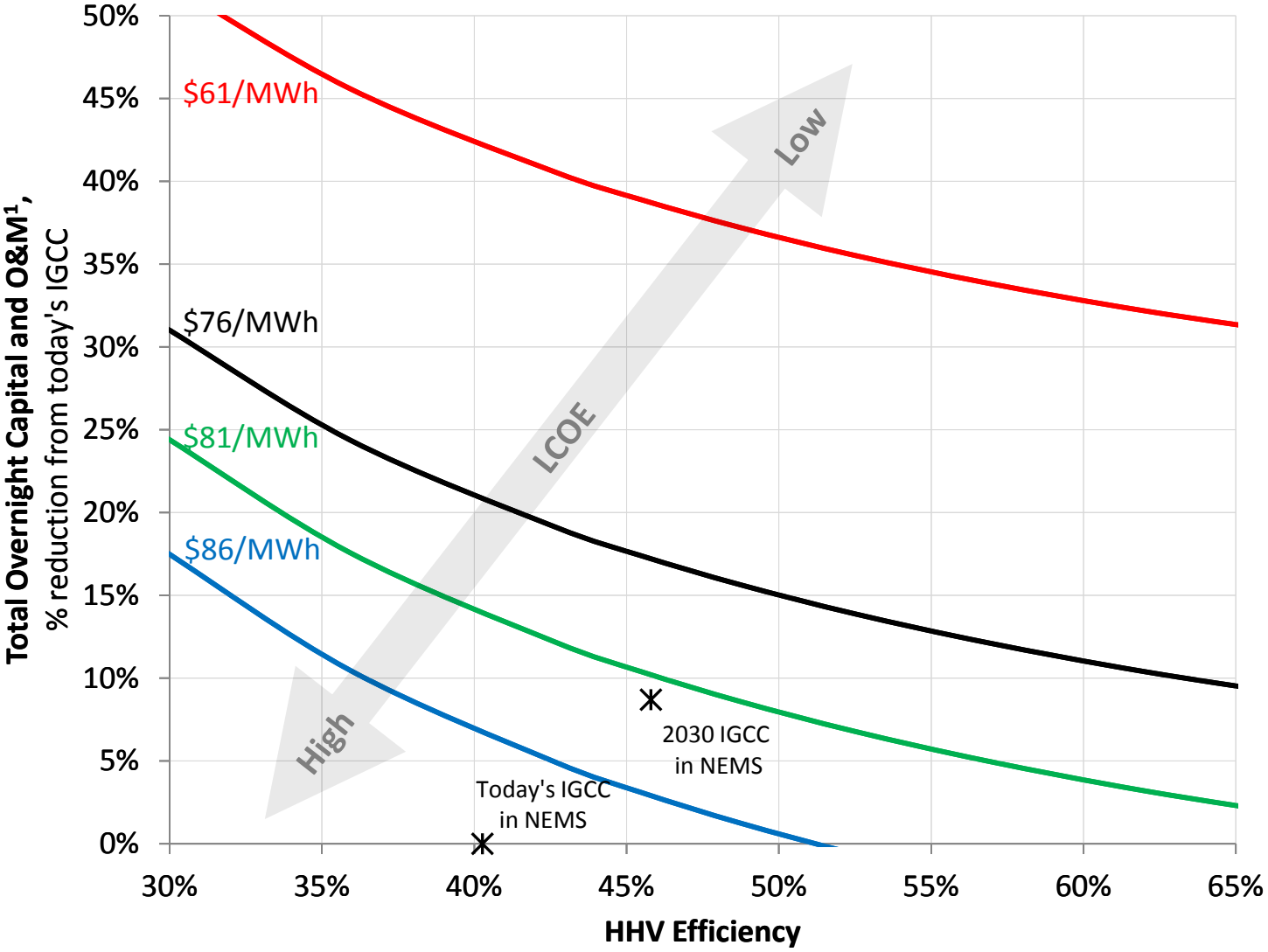


New Plant Builds by Technology
Low Shale Scenario Baseline



Competitiveness of Non-Capture Coal Plants in 2030

Impact of Improvements in Capital Cost and/or Efficiency

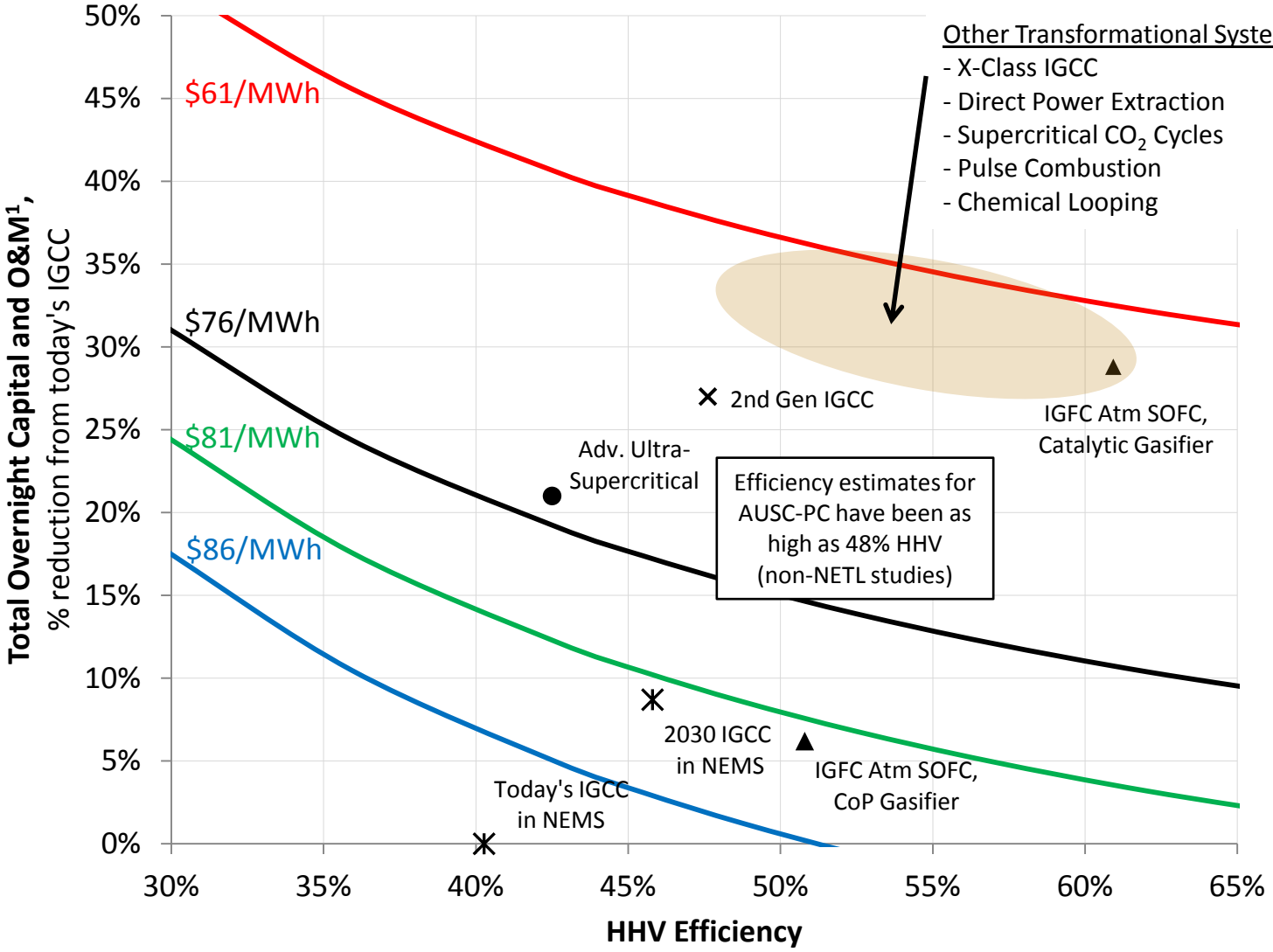


AEO 2011 Case	NG Price in 2030 (2009$/MMBtu)	NGCC LCOE in 2030 (2009$/MWh)
High Shale	$5.0	$61
Refer-ence	$6.2	$76
High Macro	$6.9	$81
Low Shale	$8.0	$86

[1]Cost reductions calculated on a $/MWh basis and thus also benefits from efficiency improvements

How R&D Can Enable Coal Plants to Compete in 2030

Improvements in Capital Cost and/or Efficiency



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Preliminary Deployment Assessment of Non-Capture Advanced Coal (with R&D) in NEMS

- Baseline IGCC parameters in NEMS replaced with select advanced coal cases
  - 2020-2030 transition period with advanced system cost and performance fully met in 2030

- Transformational Coal (i.e. IGFC with Catalytic Gasification)
  - >10 GW deployment 2020-2035 in AEO 2011 Reference case
    - Compare to no deployment without R&D
  - >25 GW deployment 2020-2035 in Low Shale case (i.e. high NG price)
    - Compare to 11 GW without R&D
  - *Target cost and performance not likely fully in place in 2030 timeframe (i.e. 2030 readiness requires completion of R&D, commercial demonstration, and initial deployments, and plants built and ready to produce power)*

CO_2 CAPTURE, UTILIZATION AND STORAGE (CCUS)

Incentivizing CO_2 Capture

- Most coal-based power systems would require some level of CO_2 capture to meet 1,000 lb CO_2/MWh-gross
  - IGFC with atmospheric SOFC and catalytic gasification comes closest with ~1,020 lb CO_2/MWh-gross
  - Adding capture to coal systems further hampers competiveness

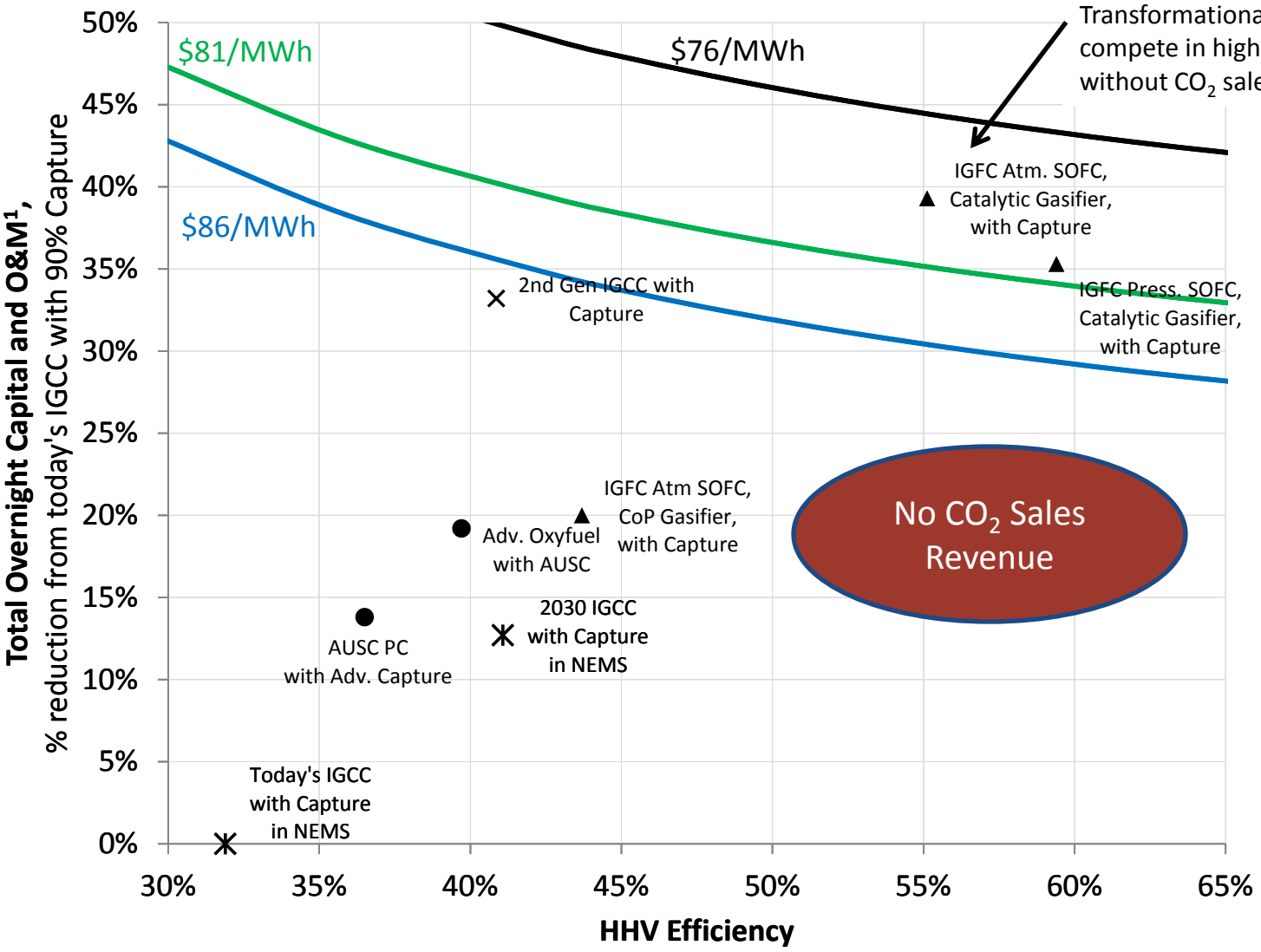
- For advanced coal with capture, objective shifts to assess competitiveness if CO_2 can be sold for EOR
  - Utilization of CO_2 for EOR provides market incentive for coal with CCUS and will speed deployment

- LCOEs of capture systems adjusted to include CO_2 plant gate sales price
  - NEMS currently has limited functionality to sell CO_2 for use in EOR
  - NETL CO_2 Transport, Utilization and Storage (CTUS) model integration into NEMS in final stages of development

- NGCC continues to set LCOE benchmark in 2030
  - NGCC with CCUS not incentivized until CO_2 plant gate sales prices reach ~$70/tonne

Competitiveness of Coal Plants **with Capture** in 2030

Adding Carbon Capture to Coal Plants



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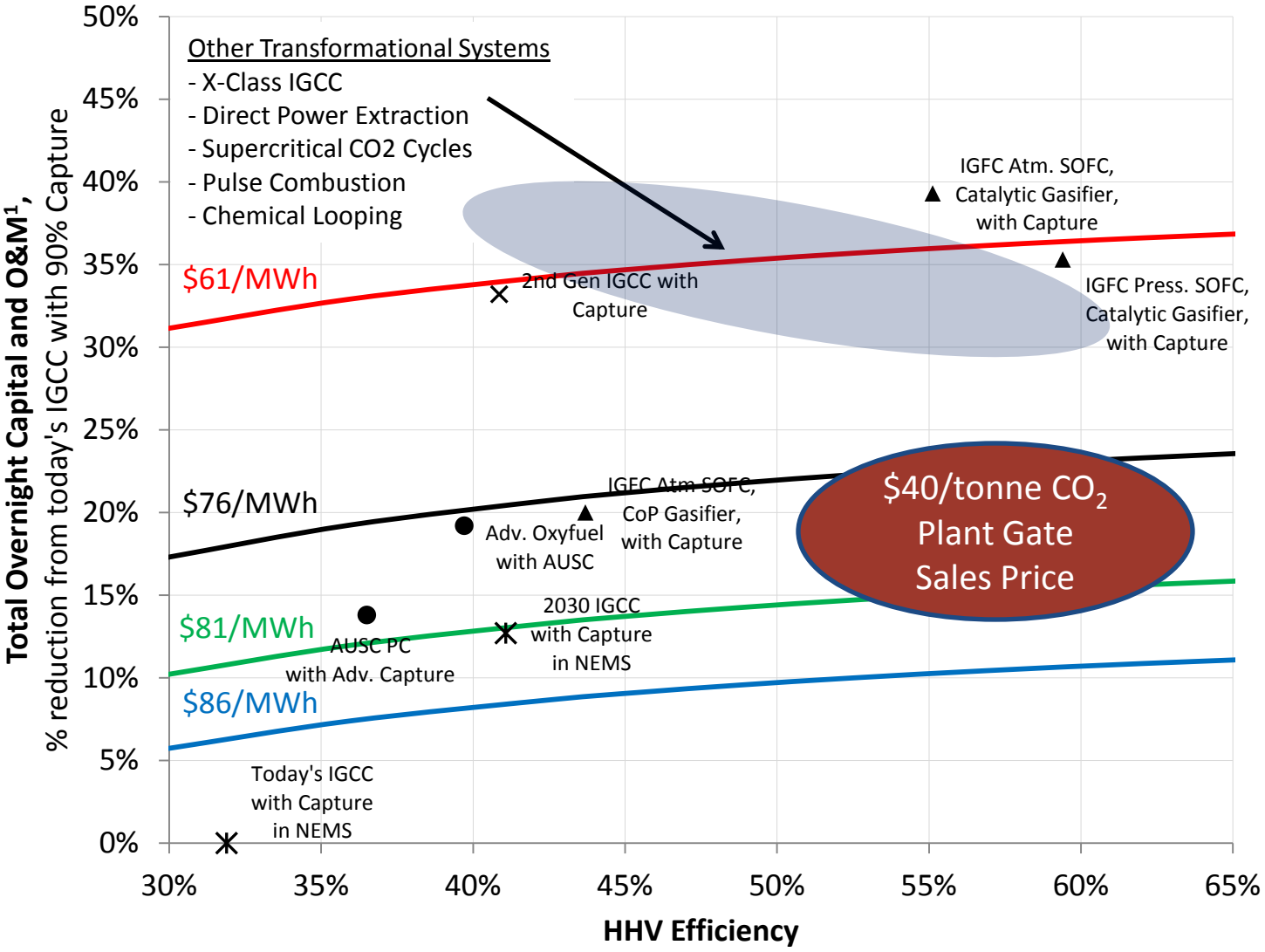
Competitiveness of Coal Plants **with CCUS** in 2030

Impact of CO_2 Plant Gate Sales



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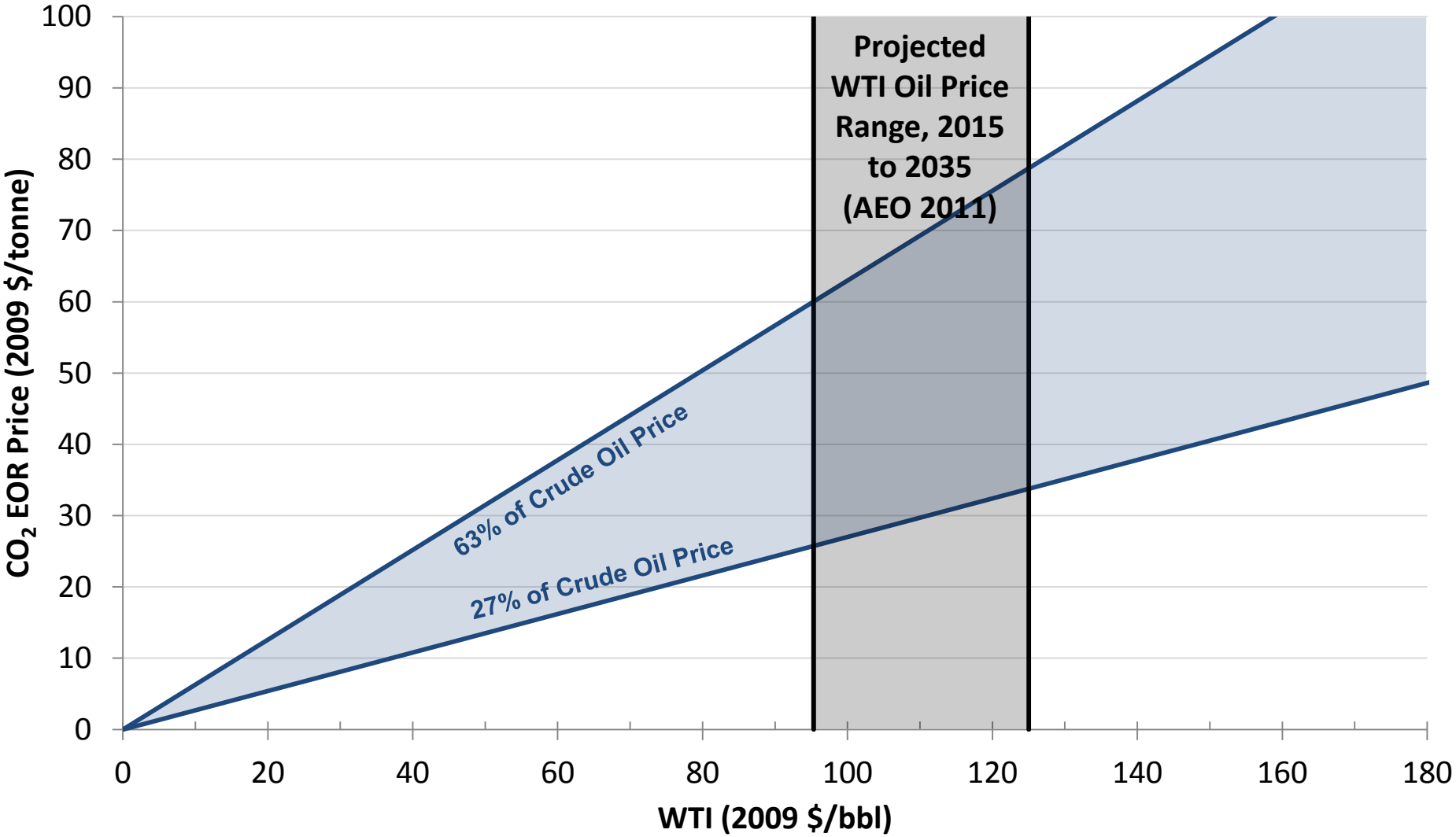
Future Oil Prices May Support CO_2 Prices for EOR that are Equal to or Above CO_2 Capture Costs



From 2008 to 2011, the market price of CO_2 (expressed in $/MCF) for EOR, quoted at the Denver City, TX "hub", varied between 1.4% and 3.3% of the WTI Crude oil price (expressed in $/bbl). Restating this correlation, the market price of CO_2 (expressed in $ per metric tonne) would be 27% to 63% of the crude oil price ($/bbl). Source: Chaparral Energy "US CO_2 & CO_2 EOR Developments" Panel Discussion at CO_2 Carbon Management Workshop December 06, 2011

Primary Findings

- Advanced NGCC (H-class; 53% HHV) sets the LCOE benchmark for deployment in all scenarios
  - More advanced turbines could be available by 2030 (J-class and beyond) that enable HHV efficiencies of 56-59% for NGCC
- Scenarios without Coal R&D
  - Little or no new coal capacity is added under any scenario except with the highest natural gas price
    - At high natural gas price, 11 GW is deployed from 2020 to 2035 (~10% of all new capacity)
  - CO_2 plant gate sales price of >$50/tonne would be required in 2030 for NEMS coal with CCUS to deploy in Reference case

Primary Findings

- Scenarios with Coal R&D
  - "2nd-Gen" non-capture coal systems can compete in all scenarios but lowest natural gas price case
  - "Transformational" non-capture coal systems add potential to compete in scenario with the lowest natural gas price
  - "2nd-Gen" coal systems with CO_2 capture can compete in most scenarios with CO_2 plant gate sales prices of $20-50/tonne
    - $20-50/tonne within range of historical CO_2:crude oil price ratio
  - "Transformational" coal systems with CO_2 capture:
    - Compete in the higher natural gas price cases even without CO_2 sales
    - Compete in the lower natural gas price cases with CO_2 plant gate sales prices of $10-$40/tonne

Conclusions

- 2nd Gen technologies competitive in all but lowest natural gas price scenario
  - For capture systems, CO_2 sales revenue provides a key market incentive
- Transformational R&D provides promising prospect and is a key next step for future competitiveness of coal-based power
  - Competes in nearly all scenarios
  - High risk-high reward
  - Longer development time period

Future Work & Additional Considerations

- Examine deployment (i.e. total GWs built) for 2nd Gen and Transformational coal power systems
  - Detailed modeling of Enhanced Oil Recovery as a revenue source with new NETL CTUS model
- Assess impact of CO_2 tax
  - Expand beyond CO_2-EOR opportunities
  - Transformational coal plants with capture competitive at lower natural gas prices
- Consider coal program technology impacts on advancement of natural gas-fueled systems
  - Advanced turbines
  - SOFC

Questions?