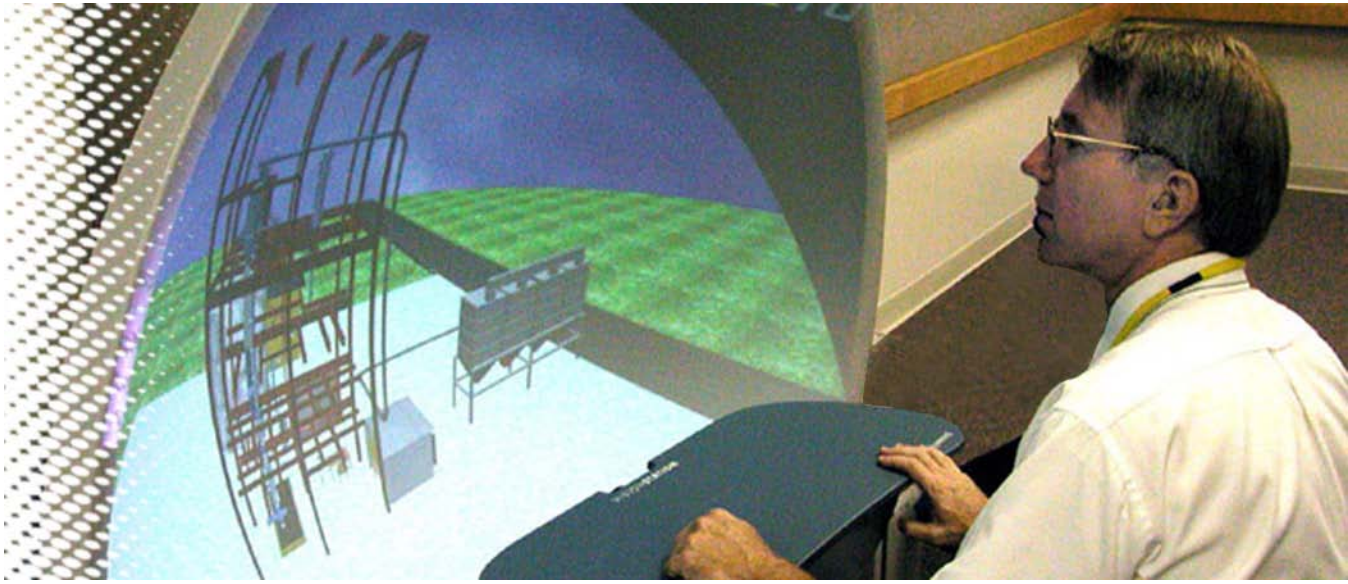
NATIONAL ENERGY TECHNOLOGY LABORATORY



A Pathway of Advanced Technologies for IGCC Carbon Capture

Walter Shelton

U.S. DEPARTMENT OF ENERGY

Acknowledgements

- **Noblis, Inc. (modeling and analysis)**
  - Charles White
  - David Gray
  - John Plunkett
  - Sal Salerno
- **DOE/NETL**
  - Kristin Gerdes
  - Richard Dennis, Turbines Technology Manager
  - Jenny Tennant, Gasification Technology Manager

Overview

- **Objectives and Use of Study**
- **Approach and Design Basis**
- **Advanced Hydrogen Turbine Features**
- **Advanced Technology Pathway**
  - Case Matrix and Results
- **Summary**
- **Questions**

Objectives and Use of Study Results

- **Objectives:**
  - Evaluate improved performance and cost resulting from DOE-funded R&D
  - Identify enabling technologies within DOE's portfolio
  - Show relative contribution of different R&D efforts
  - Create clear and quantitative linkage between R&D portfolio and DOE's program goals

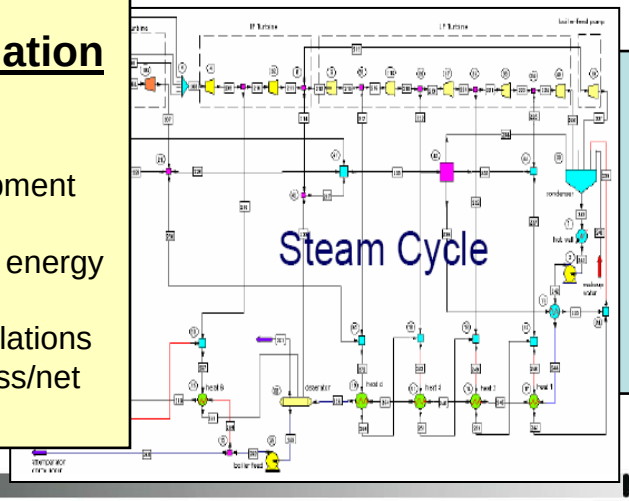
- **Use of study results:**
  - Identify R&D opportunities/gaps within DOE portfolio
  - Roadmap for program defense
  - Validation of program goals
  - Input to benefits and deployment assessments

IGCC Pathway Studies: Approach

- **Begin with established cost and performance of conventional IGCC – NETL Cost and Performance Baseline series**
- **Substitute conventional technologies with advanced technologies in a cumulative fashion assuming successful R&D**
  - Turbines, gas cleanup, oxygen production, pre-combustion CO_2 capture, coal feed systems, availability improvements
- **Evaluate cost and performance in a manner consistent with baseline studies**

1. **Extensive Process Simulation (ASPEN)**

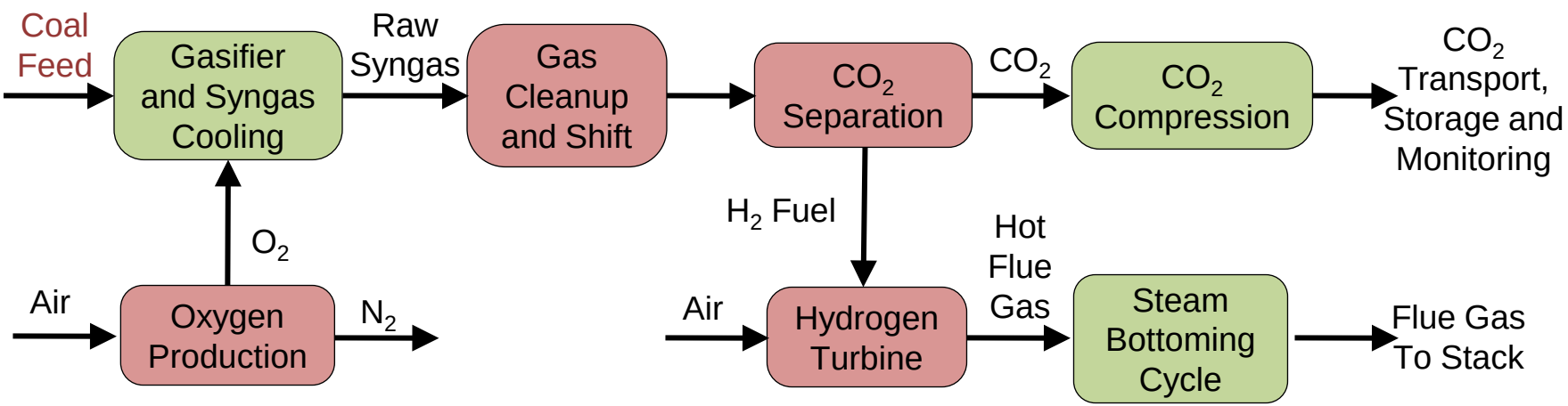
- All major chemical processes and equipment are simulated
- Detailed mass and energy balances
- Performance calculations (auxiliary power, gross/net power output)



2. Cost Estimation

- **Inputs from process simulation** (Flow Rates/Gas Composition/Pressure/Temp.)
- **Sources for cost estimation**
  - Baseline – WorleyParsons & vendor sources
  - Advanced cases – Scaled from Baseline study, vendor sources, R&D targets
- **Follow DOE Analysis Guidelines**

IGCC Advanced Technology Assessments



	2003 Reference	R&D Progress-to-Date	2nd Gen IGCC
Turbine	7FA-based H_2 Turbine →	Adv F H_2 Turbine →	Adv H_2 Turbine
Coal Feed System	Slurry Feed	→	Coal Feed Pump
Oxygen Production	Cryogenic Air Separation	→	Ion Transport Membrane
Gas Cleanup	Selexol	→	Warm Gas Cleanup
CO_2 Separation	Selexol	→	H_2 Membrane
RAM Improvements	Capacity Factor = 75%→	CF = 80% →	CF = 85%

RAM = Reliability, Availability and Maintainability

2003 Reference Plants & Economic Basis

Gasifier	GE Slurry-fed, entrained, radiant only; 815 psia
Coal Type/Price	Bituminous, Illinois #6; $1.64/MMBtu
Site Info	Greenfield, midwestern USA, ISO conditions
Oxidant Source	Cryogenic, Elevated Pressure ASU
Acid Gas Removal	Selexol
Gas Turbine	7FA-based turbine (2003 vintage)
Steam Cycle	1800 psig/994°F/994°F
Carbon Capture	90%
Capacity Factor	Equal to availability at 75-80%
Year Dollars	June 2007
Capital Cost Basis (for Baseline Case)	WorleyParsons and other vendor estimates; "Next-of-a-kind" application, contingencies assigned as appropriate; EPCM contracting strategy; owner's costs included; +30/-15% accuracy
Construction Period	5 years
Operational Period	30 years
Cost of Electricity Basis	Required sales price to meet 12% ROE; Assumes a 3% escalation per year consistent with the assumed inflation rate
Financial Structure	D/E = 45/55; Debt rate = 5.5%; Debt term = 30 years; IRROE = 12%; resulting capital charge factor = 12.4%
CO_2 Transport, Storage and Monitoring Costs	Costs added to COE; based on 50-mile pipeline transport to favorable saline aquifer formation

Advanced Hydrogen Turbine

- **DOE program goals for its hydrogen turbine program include a 3-5 percentage point net plant efficiency increase over 2003-era IGCC with a 7FA-based turbine**

- **Advanced hydrogen turbine (AHT) modeled features:**
  - Firing temperature increase from ~2250F to 2600°F+
  - 77% increase in turbine output from 192 to 340 MW per turbine
  - 85°F increase in turbine exhaust temperature
  - Improvements in turbine efficiency, cooling air bleeds, combustor operation to reduce NOx, etc.
  - Allows air integration with ASU

AHT versus 7FA (2003 Reference)

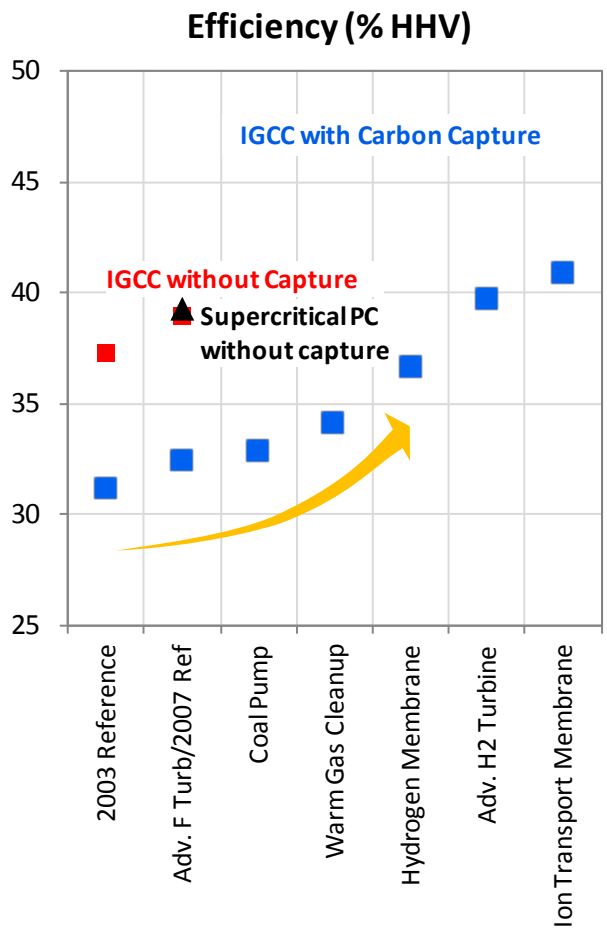
- **Plant performance**
  - 63% increase in coal feed
  - 50 MW (30%) increase in auxiliary load
    - ASU integration provides benefit
  - 128 MW (59%) increase in steam turbine output
    - Turbine exhaust temperature
    - Heat recovery from gas turbine air to ASU
  - 375 MW (50%) increase in total net power to 815 MW
  - 4.3 point improvement in net plant efficiency

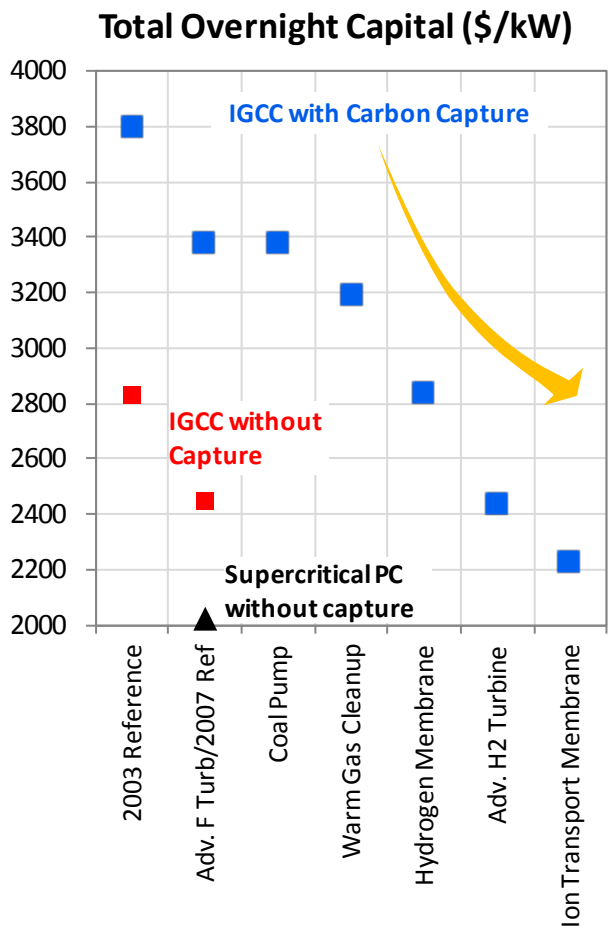
- **IGCC cost and cost of electricity (COE)**
  - AHT provides >25% capital cost and COE savings versus 7FA-based reference IGCC

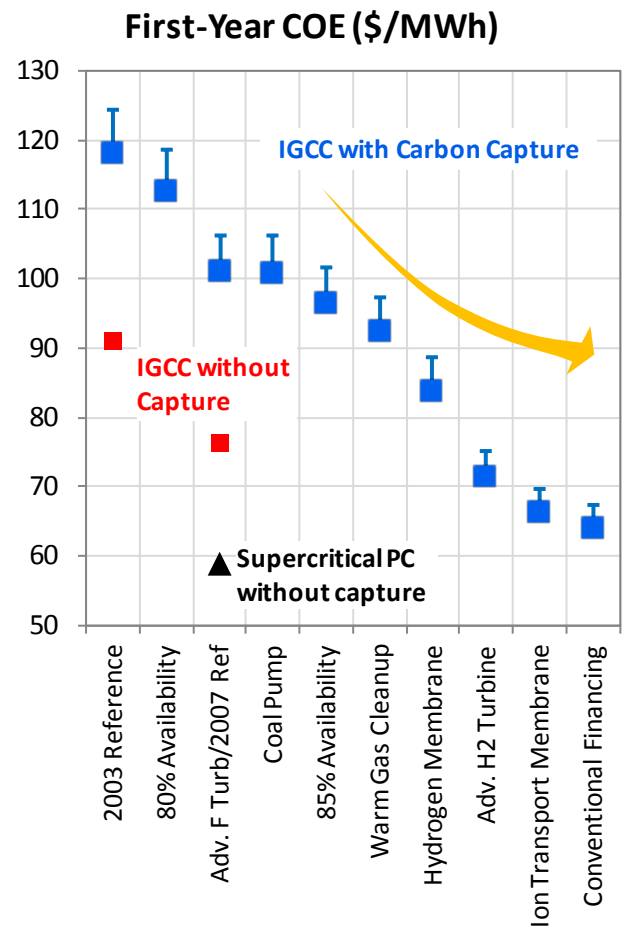
IGCC Pathway Case Metric

Case Number	Case Title	Gas Turbine	Coal Feed System	Avail-ability	Gas Clean Up	CO_2 Separation	Oxygen Production	Finance Structure
1	2003 Reference IGCC	7FA-based H_2 Turbine	Slurry	75%	2-Stage Selexol		Cryogenic	High Risk
2	Adv. F H_2Turbine / R&D Progress-to-Date	Advanced	Feed	80%			Air	
3	Coal Feed Pump	F-frame	Coal				Separation	
4	85% Availability	H_2Turbine	Feed	85%			Unit	
5	Warm Gas Cleanup (WGCU)/Selexol		Pump		WGCU	Selexol	(ASU)	
6	WGCU/H_2 Membrane					Hydrogen		
7	Adv. H_2 Turbine (AHT)	AHT				Membrane		
8	Ion Transport Membrane (ITM)						ITM	
9	Conventional Financing							Conventional

IGCC Pathway Study Results





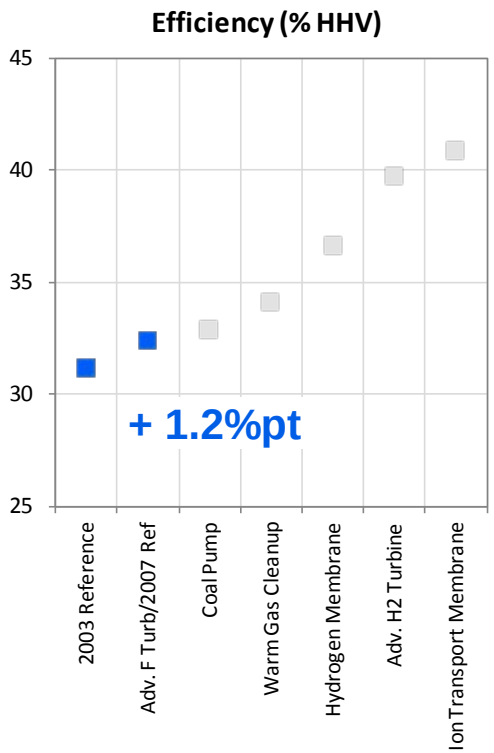


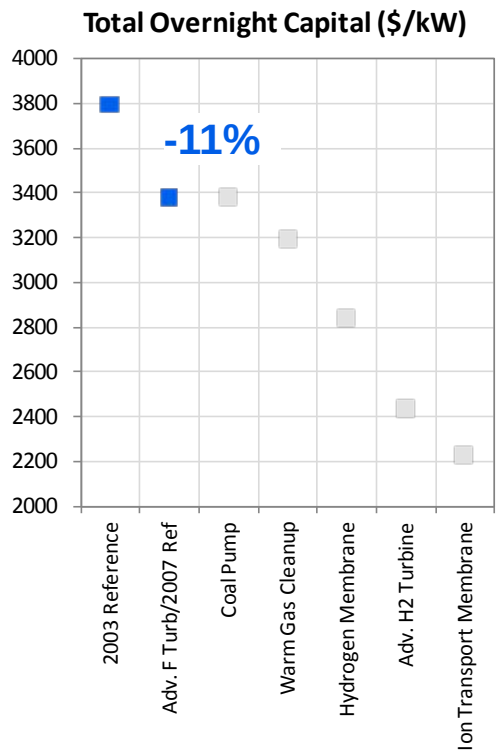
June 2007 Dollars

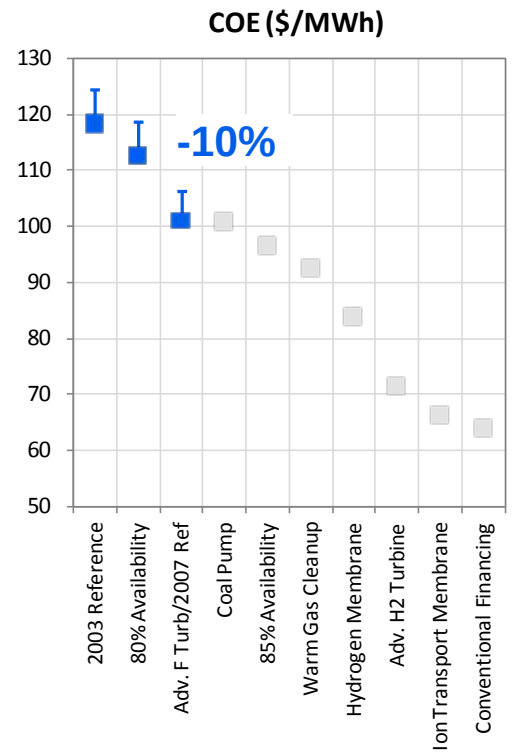
CO_2 transport, storage and monitoring cost

Advanced F vs. 7FA-based Hydrogen Turbine

- **Represents R&D progress-to-date, consistent with Case 2 from NETL Bituminous Baseline Study**
- **Higher firing temperature, pressure ratio, efficiency than 7FA**
- **Increase in turbine power output from 192 MW to 232 MW per turbine**
- **Capital cost increases due to greater coal feed, turbine power output, but decreases on $/kW basis with net power increase**
- **Net plant efficiency increases by 1.2 points, COE decreases by 10%**





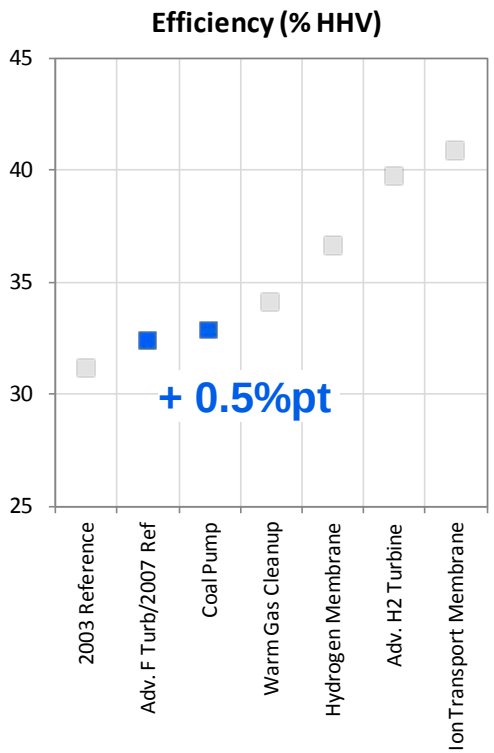


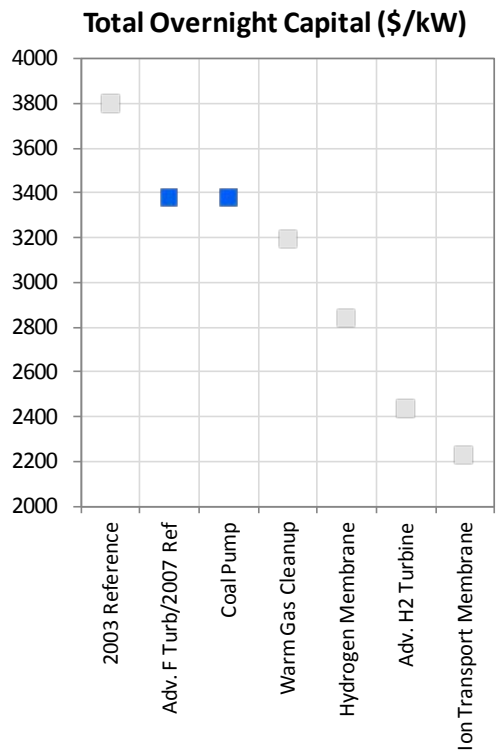
June 2007 Dollars

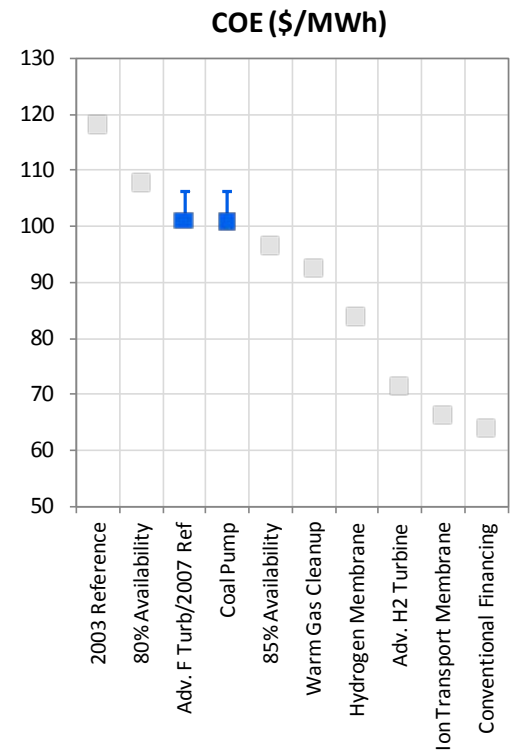
CO_2 transport, storage and monitoring cost

Coal Feed Pump

- **Coal fed as-received, eliminating slurry water addition**
- **Increased gasifier cold gas efficiency**
- **Reduction in steam turbine power generation due to additional steam required for water gas shift with the loss of slurry water**
- **Minimal cost benefit under this configuration**
  - Alternative configurations: Non-carbon capture, replacement of lock-hoppers for dry feed gasifiers, enabling gasifiers for low rank coal







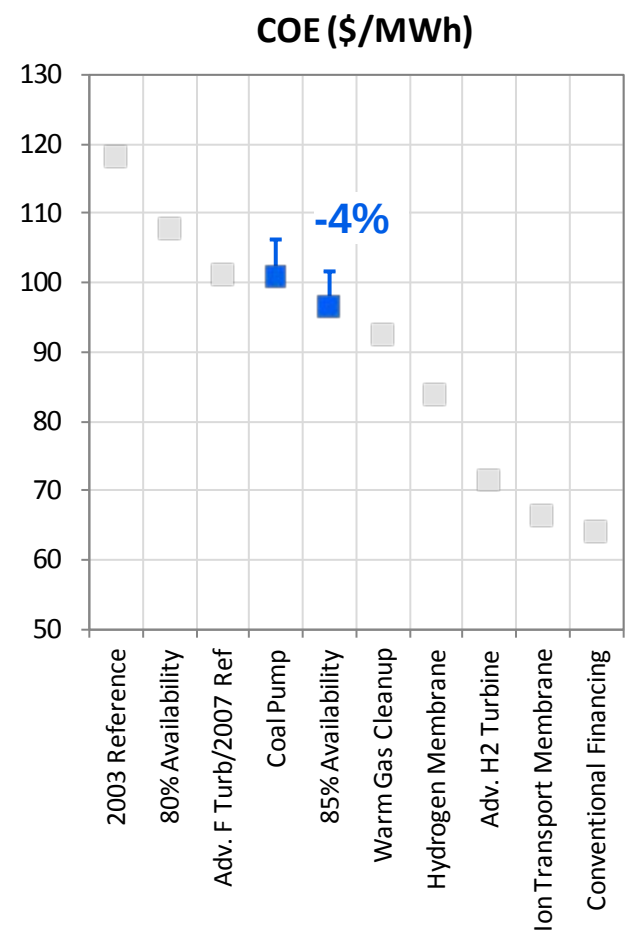
June 2007 Dollars

CO_2 transport, storage and monitoring cost

Reliability, Availability and Maintainability

- **Current materials and instrumentation limited life in harsh environment**
- **Specific R&D not identified; example improvements include:**
  - Advanced materials
  - Advanced sensors and controls
  - Syngas cooler design/maintenance
- **Demonstration and operating experience**
- **Assumes minimal effect on process efficiency or plant cost**
- **5% availability improvement to 85% provides 4% COE reduction**
  - Encompasses planned and unplanned outages and reduced output
  - Analysis assumes plant is always dispatched when available, i.e. availability = capacity factor

- **Challenge: Ensure subsequent advanced technologies meet or exceed availability of conventional technologies**

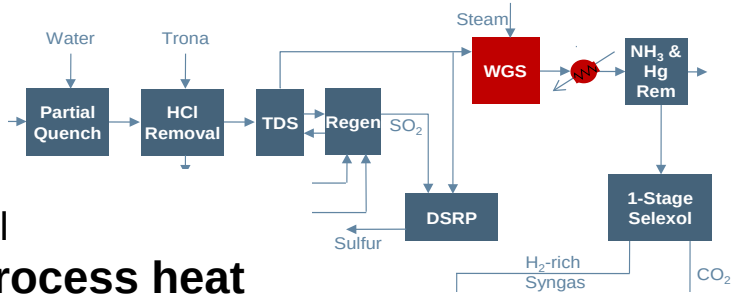


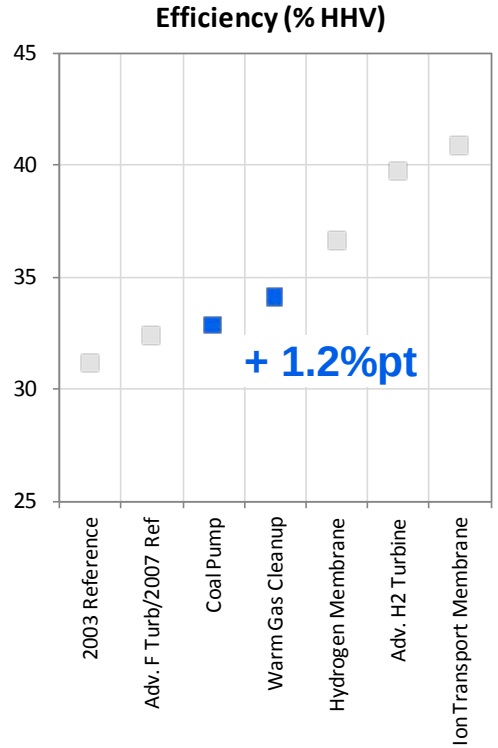
June 2007 Dollars

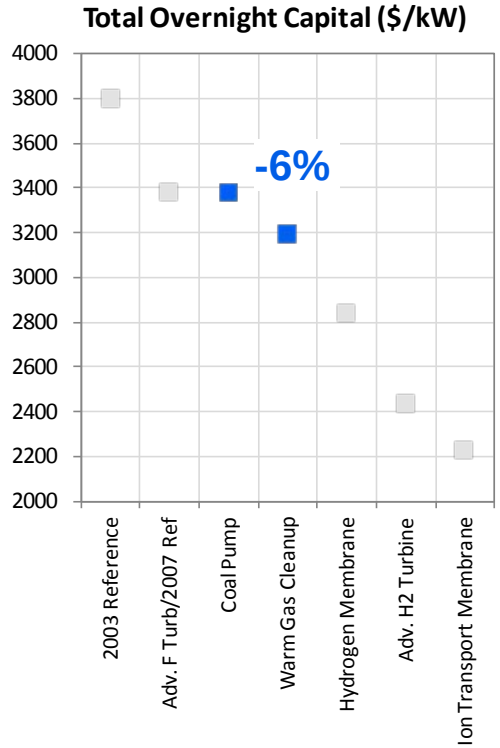
CO_2 transport, storage and monitoring cost

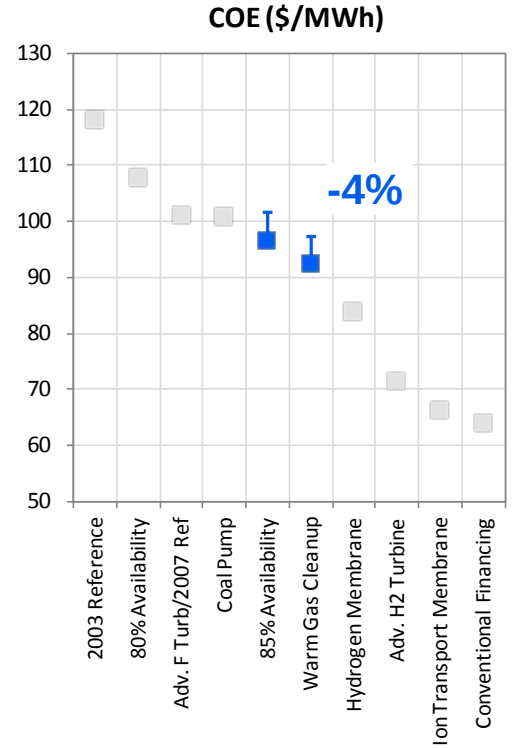
Warm Gas Cleanup (WGCU)

- **Process modifications**
  - Partial quench to 900°F, warm HCL removal
  - Transport desulfurizer (TDS) + direct sulfur reduction process (DSRP) replaces 1st-Stage Selexol + Claus
  - Sweet water gas shift, novel warm NH_3 and Hg removal
- **Steam turbine power increase due to improved process heat recovery and elimination of sour water stripper reboiler**
- **6% TOC, 4% COE decreases driven by increase in net power**







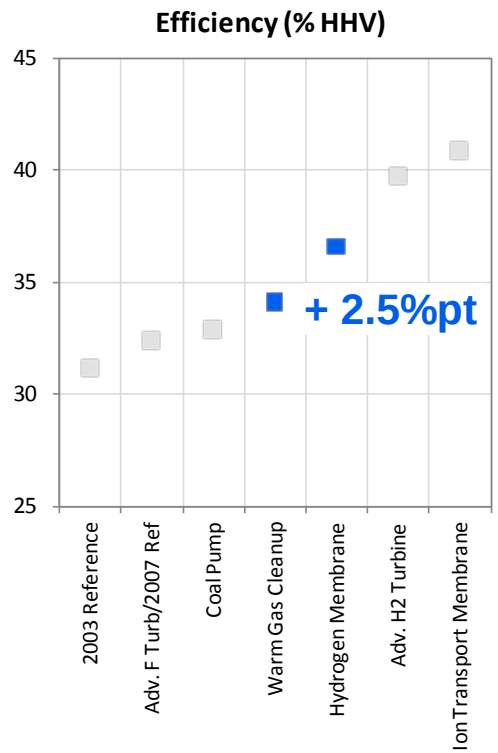


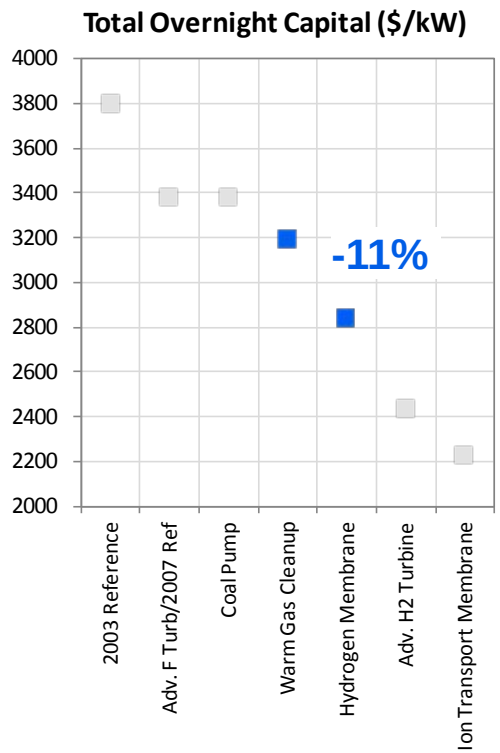
June 2007 Dollars

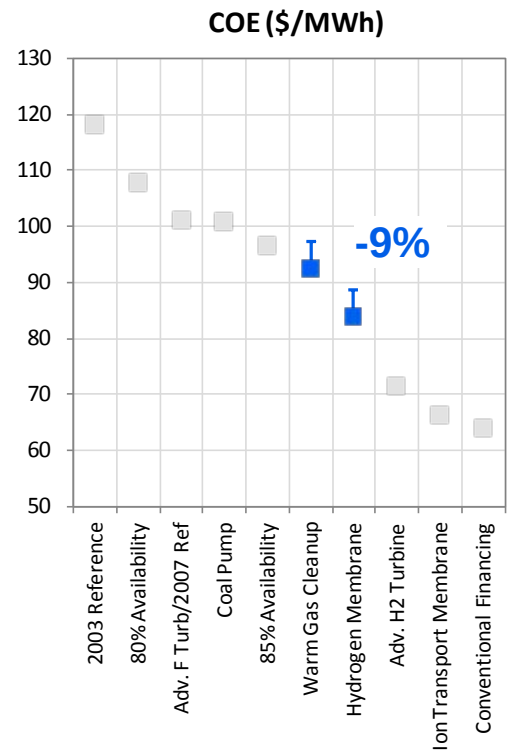
CO_2 transport, storage and monitoring cost

Hydrogen Membrane

- **100% hydrogen selectivity; nitrogen diluent provides sweep gas to membrane**
- **CO_2-rich non-permeate provides CO_2 at elevated pressure, requires purification to 95%+ by refrigeration**
  - Selexol auxiliaries eliminated, CO_2 compression load decreased
- **2.5 percentage point net efficiency benefit**
  - Dependent on pairing with WGCU due to high temperature operation of membrane
- **Membrane flux, cost and lifetime based on meeting DOE targets**
- **11% TOC (in $/kW) and 9% COE decrease driven by low membrane cost relative to Selexol and increase in net power**





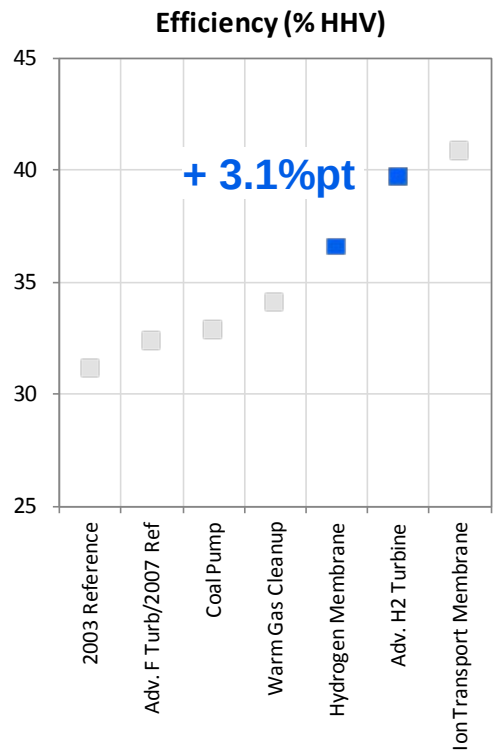


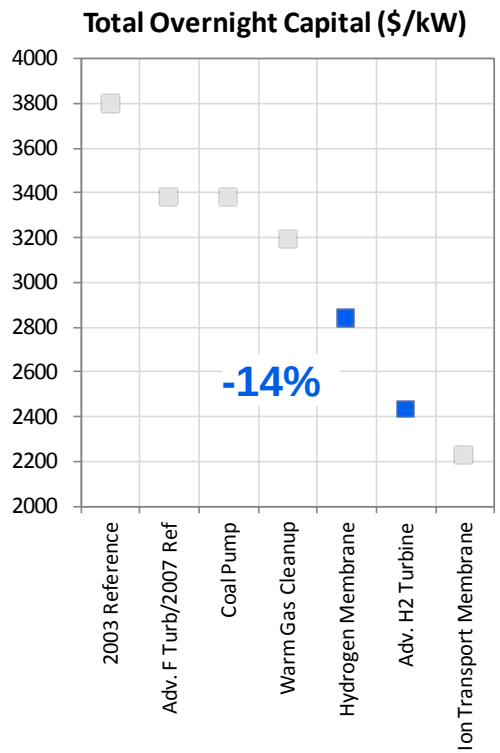
June 2007 Dollars

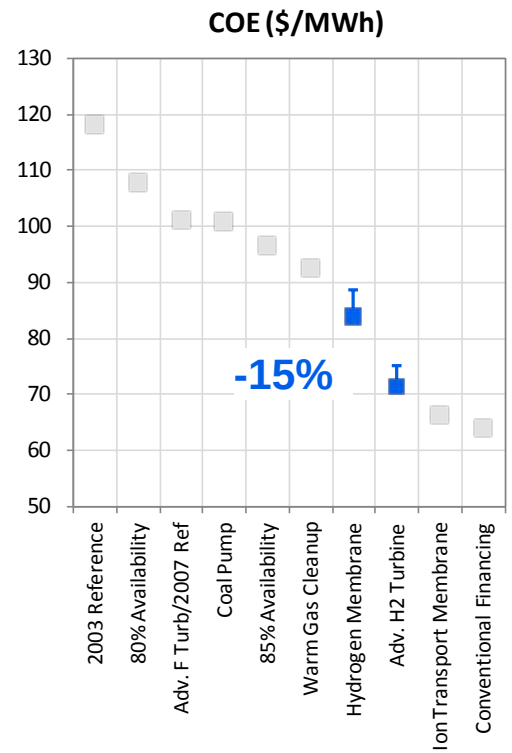
CO_2 transport, storage and monitoring cost

AHT vs. Advanced F

- Incorporates AHT features including higher firing temperature, increase in turbine power output (47% increase from 232 to 340 MW vs. Advanced F)
- Increase in turbine exhaust temperature increases steam cycle temperature and steam turbine output
- Allows air integration (12% of air extracted provides 47% of ASU air) providing savings in auxiliary load
- 38% increase in coal feed, coupled with 50% net power increase results in 3.1 point net efficiency benefit
- 14% TOC (in $/kW) and 15% COE decreases driven by improved power block efficiency and economies of scale provided by net power increase to 800+ MW





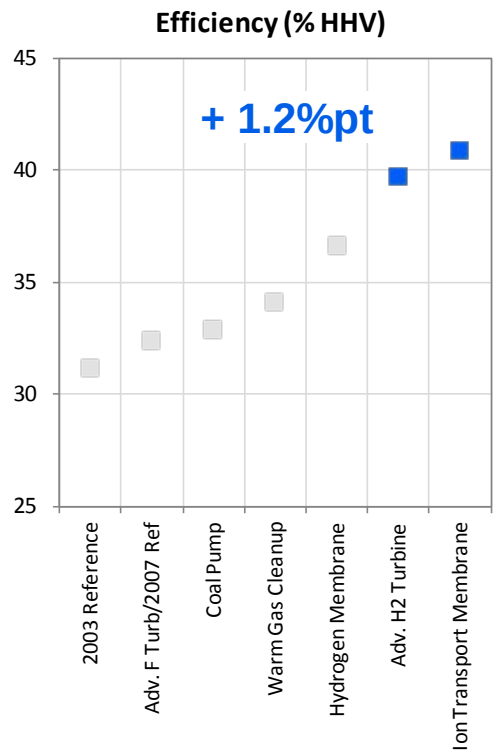


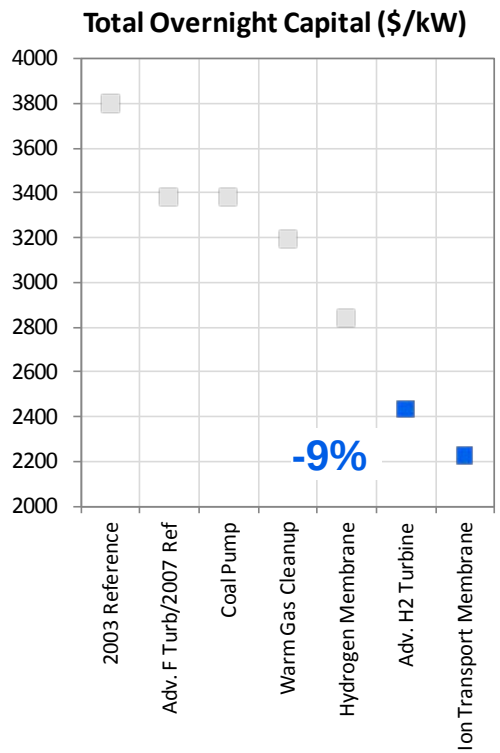
June 2007 Dollars

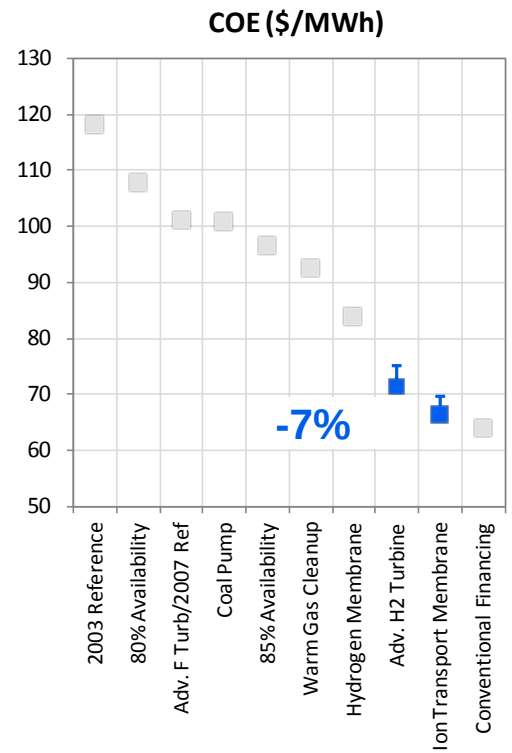
CO_2 transport, storage and monitoring cost

Ion Transport Membrane

- **High temperature operation consumes H_2 fuel for heating of feed air, but provides increase in steam turbine output due to ITM heat recovery**
- **Oxygen diffuses through ITM, leaving an elevated pressure nitrogen-rich non-permeate**
  - Oxygen compression loads increase
- **Key considerations to maximizing benefit include air integration with turbine and matching nitrogen-rich non-permeate production with turbine diluent needs**
- **Air separation target development cost savings, coupled with net power increase results in reductions of 9% and 7% for TOC in $/kW and COE, respectively**







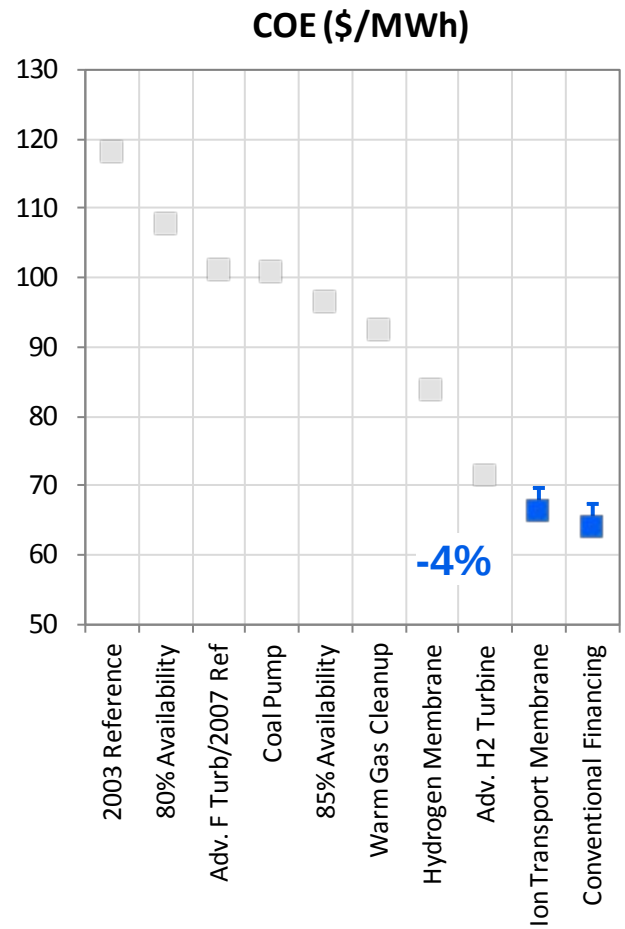
June 2007 Dollars

CO_2 transport, storage and monitoring cost

Elimination of High Risk Finance Structure

- **Financing parameters (Debt/Equity ratio, debt rate) for all IGCC cases adjusted to include a premium to capture effect of risk**

- **Eliminating this premium– consistent with nth-of-a-kind operation post-demonstration– provides 4% reduction in COE**



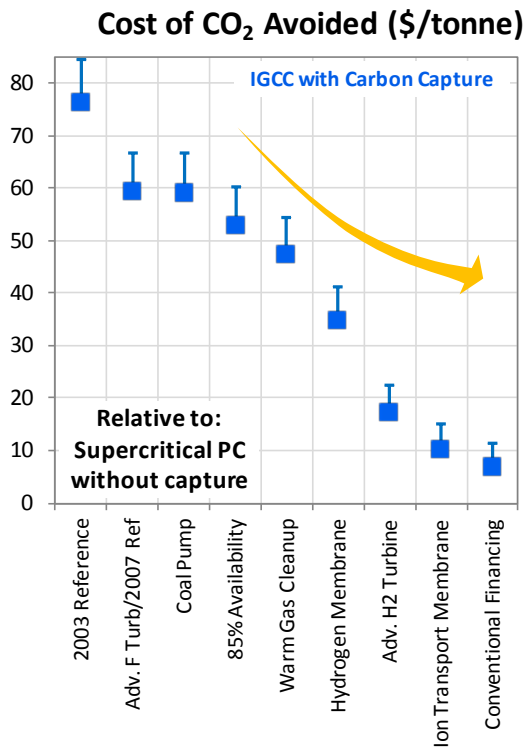
June 2007 Dollars

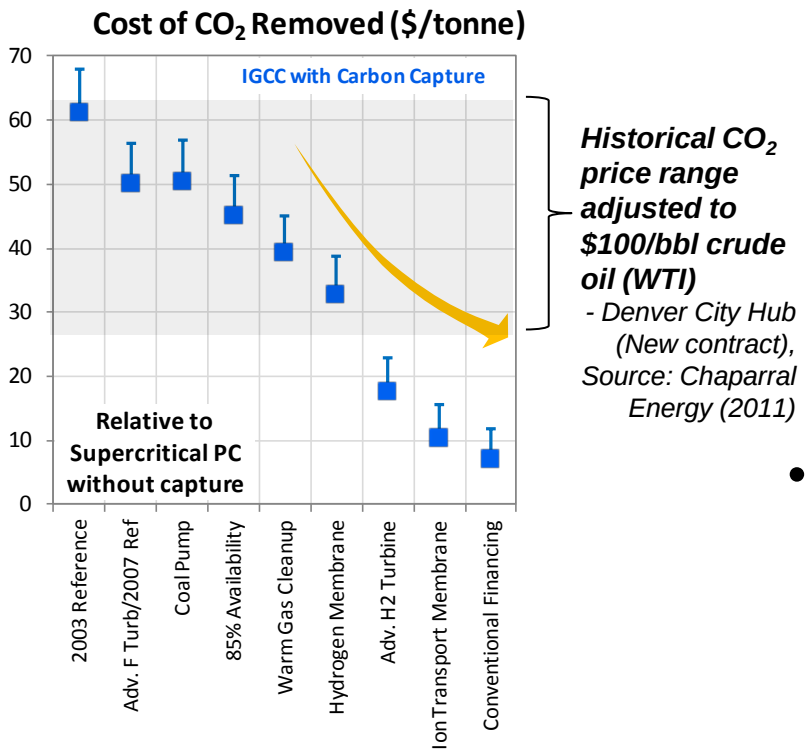
CO_2 transport, storage and monitoring cost

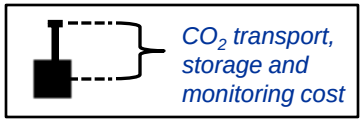
Key Performance and Cost Assumptions

- **Hydrogen turbines**
  - Business-sensitive nature of technology developer data impact modeling and costing capability
  - Plant economics highly sensitive to turbine power rating
  - Turbine cost is scaled to power rating assuming no additional premium due to higher firing temperature, improved materials, etc.
- **Warm gas cleanup and hydrogen membrane**
  - Performance is mix of demonstration data and targets
  - New data from WGCU demonstration design and H_2 membrane testing on syngas to be incorporated in future analyses as available
  - Cost results sensitive to projected/targeted costs that are significantly lower than 2-stage Selexol
- **Ion Transport Membrane is 1/3 less costly than cryogenic ASU**
- **Availability is assumed to increase to 85% without significant change in total plant cost or efficiency; availability is maintained as advanced technologies replace conventional technologies**

CO_2 Avoided and Captured Costs





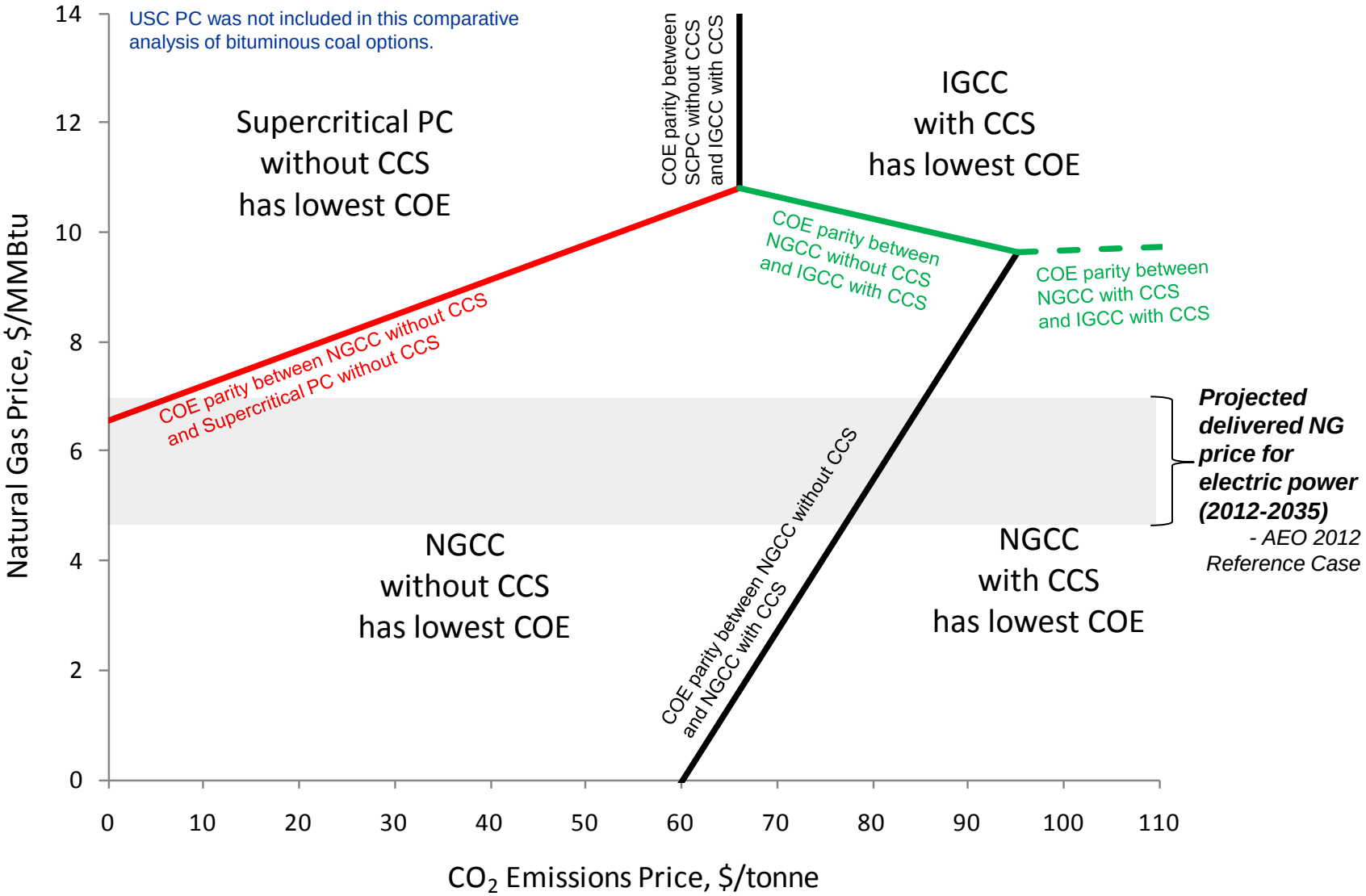


- **CO_2 emissions value to incentivize CCS drops from $67 to $12/tonne with successful R&D**
  - *Measured by cost of CO_2 avoided with CO_2 TS&M*
- **CO_2 power plant gate sales price for CO_2-EOR to incentivize CCUS drops from $50 to $7/tonne with successful R&D**
  - *Measured by cost of CO_2 removed excluding CO_2 TS&M*

June 2007 Dollars

Lowest Cost Power Generation Options

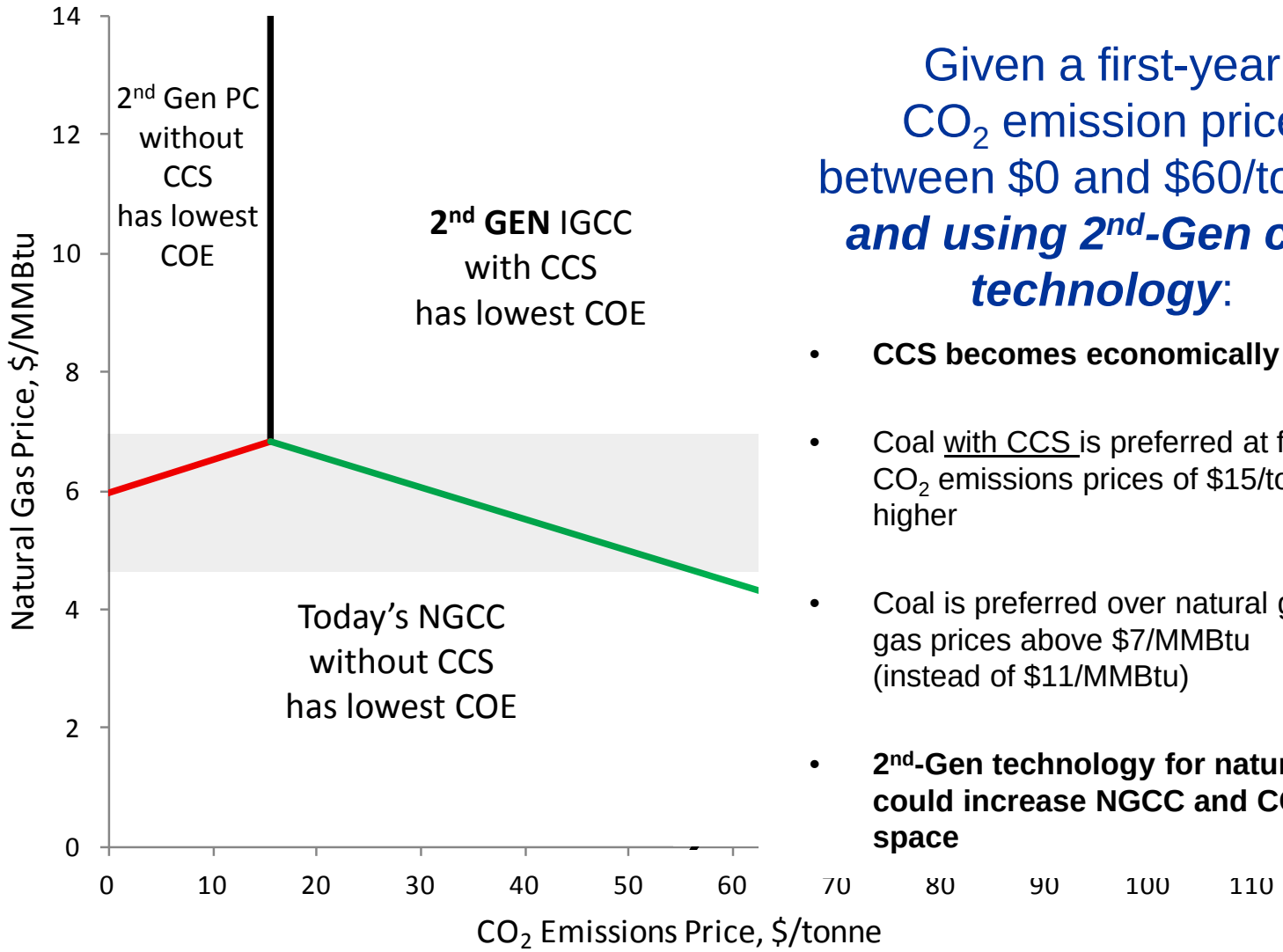
TODAY's NGCC versus Today's Coal



Assumes capacity factor = availability (i.e. all plants including NGCC are base load).
Assumes June 2007 dollars; bituminous coal at delivered price of $1.64/MMBtu

Lowest Cost Power Generation Options

Today's NGCC versus 2nd Generation Coal



Given a first-year CO_2 emission price between $0 and $60/tonne, ***and using 2nd-Gen coal technology***:

- **CCS becomes economically viable**
- Coal <u>with CCS</u> is preferred at first-year CO_2 emissions prices of $15/tonne or higher
- Coal is preferred over natural gas at gas prices above $7/MMBtu (instead of $11/MMBtu)
- **2nd-Gen technology for natural gas could increase NGCC and CCS market space**

Assumes capacity factor = availability (i.e. all plants including NGCC are base load).
Assumes June 2007 dollars; coal price of $1.64/MMBtu

Summary of IGCC Pathway Potential

Technology Addition	Impact	Efficiency Δ (% points, HHV)	TOC Δ ($/kW)	COE Δ ($/MWh)
R&D Progress-to-Date: Advanced F Turbine (SOA vs. 2003 reference)		*1.2*	*415*	*-12*
Coal feed pump	Increases cold gas efficiency	0.5	-	-
Materials/instrumentation/ advanced controls/ demonstration	Increases planned & unplanned availability to 85%		-	-5
Warm gas cleanup and hydrogen membrane	Low cost cleanup and CO_2 separation at temp and pressure	3.7	-540	-13
Advanced turbine	Increases firing temp, efficiency, power output; allows air integration	3.1	-405	-13
Ion transport membrane	Reduces capital cost	1.2	-205	-5
Conventional financing	Reduced capital charge			-3
2nd Gen IGCC with CCS vs. State-of-the-Art (SOA)		**+8.5% pts**	**-$1,150/kW -34%**	**-$39/MWh -37%**

June 2007 Dollars

QUESTIONS