CO_2 CONTROL TECHNOLOGY EFFECTS ON IGCC PLANT PERFORMANCE AND COST

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ABSTRACT

As part of the USDOE's Carbon Sequestration Program, we have developed an integrated modeling framework to evaluate the performance and cost of alternative carbon capture and storage (CCS) technologies for fossil-fueled power plants in the context of multi-pollutant control requirements. The model (called IECM, for Integrated Environmental Control Model) also allows for explicit characterization of the uncertainty or variability in any or all input parameters. Power plant options currently include pulverized coal (PC) combustion plants, natural gas combined cycle (NGCC) plants, and integrated gasification combined cycle (IGCC) plants. This paper uses the IECM to analyze the effects of adding CCS to an IGCC system employing a GE quench gasifier with a water gas shift reactor and Selexol system for CO_2 capture. Parameters of interest include the effects of varying the CO_2 removal efficiency, the quality and cost of coal, and selected other factors affecting overall plant performance and cost. The stochastic simulation capability of the model also is used to illustrate the effect of uncertainties or variability in key parameters. The potential for advanced oxygen production and gas turbine technologies to reduce the cost and environmental impacts of IGCC with CCS also is analyzed.

INTRODUCTION

As an emerging coal-based technology for electric power generation, IGCC systems are becoming an increasingly attractive option to limit emissions of CO_2 as well as conventional pollutants. CO_2 emissions can be prevented in a gasification-based power plant by transferring almost all carbon compounds to CO_2 through the water gas shift reaction, then removing the CO_2 before it is diluted in the combustion stage. CO_2 removal from IGCC requires considerably smaller and simpler process equipment than the post-combustion CO_2 removal [1].

IGCC power plants with CO_2 capture have been the subject of previous studies over the past 15 years [2]. These studies included conceptual designs, flowsheet modeling and cost estimation based on different technology selections and assumptions [3-8]. However, there are no generally available process models that can be easily used or modified to study the performance and cost of CO_2 removal options from IGCC systems for different user-defined assumptions and technology selections. Reported cost data also are relatively limited and often incomplete, and uncertainties in performance and cost are seldom considered.

As part of the USDOE's Carbon Sequestration Program, we have developed a general integrated modeling framework to evaluate the performance and cost of alternative carbon capture and storage (CCS) technologies for PC, NGCC and IGCC power plants [9-11]. The model (called IECM, for Integrated Environmental Control Model) combines plant-level mass and energy balances with empirical data and process economics. It also allows for explicit characterization of the uncertainty or variability in any or all input parameters. This paper briefly introduces the models developed for IGCC systems with and without CCS. Then, the IECM is used to assess a range of options for Selexol-based CO_2 capture for an IGCC plant.

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IGCC POWER PLANT MODEL

In the IECM framework, engineering-economic models are developed to simulate the performance and cost of an IGCC system with and without CCS for different design assumptions. As the first step, a detailed engineering model of an IGCC system without CCS was developed in the Aspen Plus software environment. This involved updating IGCC process and cost models developed in previous research [12,13]. The nominal system design employed a GE (formerly Texaco) gasifier with a water quench, followed by an acid gas removal system with byproduct sulfur recovery, plus a combined cycle plant based on a GE-7FA gas turbine and a 3-stage heat recovery steam generator (HRSG). To incorporate CO_2 capture, new performance and cost models of a two-stage water gas shift (WGS) reactor system and a Selexol unit for CO_2 capture were derived using detailed chemical simulations, theoretical analysis, and regression analysis of published performance and cost data [14]. The CO_2 capture system (WGS plus Selexol) was incorporated into the IGCC model in Aspen Plus with a re-design of the plant heat integration. All cost models for IGCC components (with or without CO_2 capture) were directly coupled to plant performance models, so that any process design changes directly affect plant costs (capital cost, operating costs and maintenance costs). Response surface models based on Aspen Plus simulation results also were developed for selected plant components to provide computationally more efficient performance models that were integrated into the IECM. The probabilistic capability of the IECM also facilitates risk and uncertainty analysis. Thus, the overall modeling set (IECM, supported by more detailed Aspen Plus performance models) provides the analytic environment and tools for technical and economic assessments of gasification-based energy conversion systems with various CO_2 capture options on a systematic and consistent basis.

SENSITIVITY STUDIES FOR CURRENT PLANT DESIGNS

The newly developed IGCC process models are used here to explore several factors influencing the performance and cost of IGCC power plants with and without CO_2 capture and storage. First, the effects of coal quality are studied. Then, effects of CO_2 capture efficiency are studied. The general technical design assumptions are given in Table 1 and the economic and financial assumptions are given in Table 2.

Table 1. Technical design assumptions for the IGCC power plant

Parameter	Value
Design ambient temperature	59°F
Design ambient pressure	14.7 psia
ASU oxygen purity	95%
Gasifier	GE quench
Gasifier operation conditions	615 psia, 2450°F
No. of gasifiers	2 operating plus 1 spare
Gas turbines	2 GE 7FA
Steam cycle	1400 psi/1000°F/1000°F
Condenser pressure	0.67 psia
Syngas sulfur removal efficiency	99%
NO_x control	fuel gas moisturization
CO_2 capture efficiency	90%
CO_2 product final pressure	2100 psia
Reference fuel type	Pittsburgh #8 coal
Plant capacity factor	75%

Table 2. Economic and financial assumption for the IGCC power plant

Parameter	Value
Fixed charge factor	14.8%
Cost year	2002
Construction period	4 years
Plant lifetime	30 years
Fuel price	1.26 $/MBtu
CO_2 transport and storage cost	10 $/tonne CO_2

Effects of Coal Quality on Plant Performance

Although an entrained flow gasifier, like the GE gasifier, can process many varieties of coal regardless of rank, caking characteristics, or amount of coal fines, it is the coal rank that most influences the performance of gasifiers and the overall IGCC system. Here, four coals are used to investigate this influence, representing bituminous, sub-bituminous and lignite coals. The composition of each coal is given in Table 3.

Table 3. Composition of the case study coals and total water content of slurry feed

Dry Basis (wt%)				
Coal name	Pittsburgh #8	Illinois #6	Wyoming PRB	ND Lignite
Coal rank	Bituminous	Bituminous	Sub-bituminous	Lignite
HHV (Btu/lb)	13,965	12,529	11,955	8,989
Ash	7.63	12.64	7.63	23.77
Carbon	77.74	70.34	69.07	52.32
Hydrogen	5.14	4.83	4.74	4.00
Nitrogen	1.50	1.33	1.00	1.15
Chlorine	0.06	0.20	0.01	0.13
Sulfur	2.24	3.74	0.53	1.73
Oxygen	5.70	6.92	17.02	16.89
Wet Basis (wt %)				
	Pittsburgh #8	Illinois #6	Wyoming PRB	ND Lignite
HHV (Btu/lb)	13,260	10,900	8,340	6,020
LHV (Btu/lb)	12,761	10,381	7,722	5,431
Moisture	5.05	13.00	30.24	33.03
Ash	7.24	11.00	5.32	15.92
Carbon	73.81	61.20	48.18	35.04
Hydrogen	4.88	4.20	3.31	2.68
Nitrogen	1.42	1.16	0.70	0.77
Chlorine	0.06	0.17	0.01	0.09
Sulfur	2.13	3.25	0.37	1.16
Oxygen	5.41	6.02	11.87	11.31
Total water content of slurry (wt%)				
Water	34	37	44	55

For the GE gasifier, each type of coal has a minimum requirement for water needed to pump the slurry feed into the gasifier. When added to the inherent moisture content of the coal, the total water content in the slurry feed for the Pittsburgh #8, Illinois #6, Wyoming PRB and ND lignite coals must be no less than 34%, 37%, 44% and 50%, respectively [15], as shown in Table 3.

Figure 1 compares the gasification efficiency, net plant thermal efficiency and net plant heat rate (the reciprocal of net efficiency) using the four types of coal. Pittsburgh #8 coal is used as the reference case. From this figure, it is clear that the coal rank significantly influences the overall plant performance. The heat rate of the IGCC power plant using ND lignite coal is about 33% higher than the plant using Pittsburgh #8 bituminous coal.

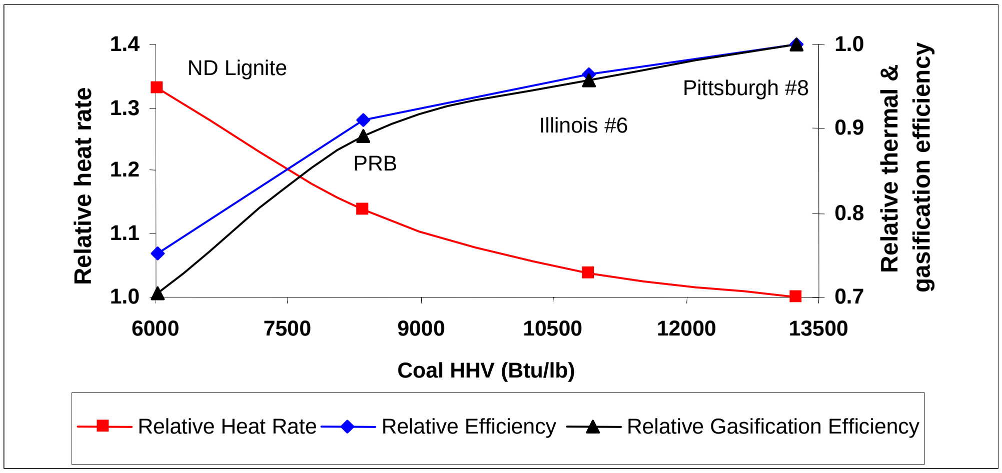

Figure 1. Effects of coal rank on IGCC plant efficiency

The coal rank also influences the economics of IGCC power plants. Figure 2 shows that low rank coals significantly increase the unit capital cost of the plant. For instance, the total capital requirement (TCR) ($/kW) of the plant using ND lignite coal is about 68% higher than the plant using Pittsburgh #8 coal. On the other hand, the lower rank coals typically have a lower fuel price, which partially offsets the effect of coal quality on the cost of electricity. Thus, the cost of electricity (COE) of the IGCC plant using the Wyoming PRB coal is only 8.6% higher than the plant using Pittsburgh #8 coal.

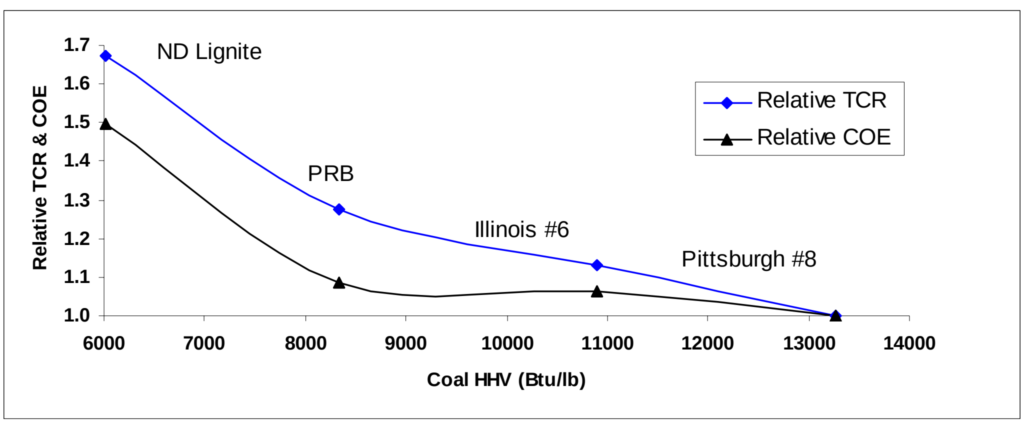

Figure 2. The effect of coal rank on TCR and COE. (For the COE calculation, the coal price ratios based on mine month coal price are: Pittsburgh #8: Illinois #6: PRB: ND: Lignite = 1.00: 0.667: 0.200: 0.265. The net plant capacity varies across cases but is approximately 500 MW.)

Effects of CO_2 Capture Efficiency on Plant Performance

Studies of CO_2 capture from IGCC power plants typically assume a constant CO_2 capture efficiency whose value in the range of 75% to 92%. There is usually no explanation for the choice of CO_2 capture efficiency and no analysis of the effect of different capture efficiencies on the performance and cost of IGCC power plants. In this section, the performance of IGCC power plants, including the CO_2 avoidance cost, energy penalty, capital cost and cost of electricity are studied for different CO_2 capture efficiencies. An objective is to determine the least-cost CO_2 capture efficiency for a given IGCC power plant. Here, the total CO_2 removal efficiency is defined as:

$$CO_2 \text{ removal efficiency} = \frac{CO_2 \text{ captured (moles)}}{\text{Total carbon in syngas from gasifier (moles)}} \quad (1)$$

For the CO_2 captured, this study considers three situations: (1) CO_2 captured in the Selexol process without further compression; (2) CO_2 captured and compressed to 2100 psia; and (3) CO_2 captured and compressed to 2100 psia, then transported via pipeline and sequestered in a geological formation at a cost of \$10/tonne CO_2. The plant modeled is again based on the assumptions shown earlier in Tables 1 and 2, except that the IGCC plant assumed here has one operating gasifier plus one spare (yielding a net plant capacity of approximately 250 MW), to illustrate that the IECM can simulate IGCC plants of different sizes. For this study the conversion of CO to CO_2 in the WGS reactor was approximately 99%, with some CO_2 also removed by the sulfur capture system and subsequently vented. All flowsheet details for this case are provided in Ref. 14.

An energy efficiency penalty (EP) is defined to characterize the influence of the CO_2 capture system on the energy performance of an IGCC power plant. It is defined for this study as follows:

$$EP = \frac{\text{Reference plant efficiency} - \text{Capture plant efficiency}}{\text{Reference plant efficiency}} \quad (2)$$

Figure 3 shows the calculated energy penalty of an IGCC power plant as a function of the total CO_2 removal efficiency. Without CO_2 compression, the energy penalty is about 8% when the total CO_2 removal efficiency is 0.7; it rises to 10% when the CO_2 removal efficiency increases to 0.9. CO_2 compression further increases the energy penalty. For instance, when the total CO_2 removal efficiency is 0.9 the energy penalty including compression is 15%. According to Equation (2), this means that 15% more coal (as well as oxygen and other plant inputs) must be supplied relative to a similar plant without CCS.

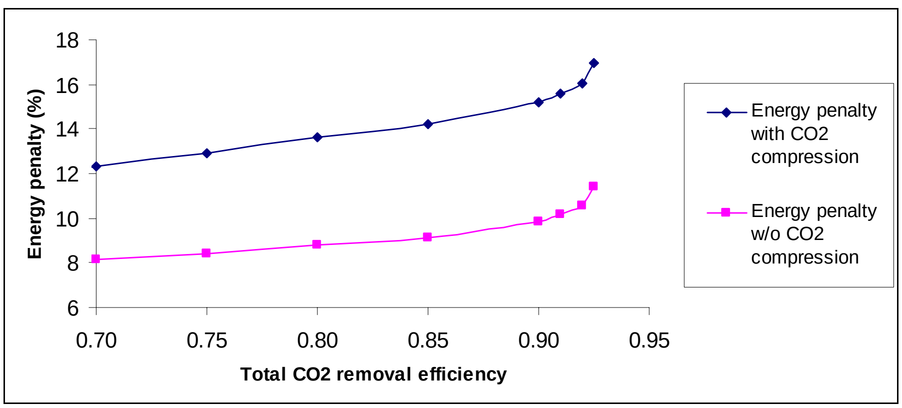

Figure 3. Energy penalty for CO_2 removal (thermal efficiency of IGCC reference plant is 0.371)

The capital cost of the IGCC plant also is influenced significantly by the CO_2 capture system. Figure 4 gives the total capital requirement (TCR) of the plant with CCS. When the total CO_2 removal efficiency exceeds 0.9 (or 90%), the TCR begins to increase more rapidly. For a 90% CO_2 removal efficiency, the TCR without CO_2 compression is about 1800 \$/kW; when CO_2 compression is added the TCR is approximately 11% higher (2000 \$/kW). Note that while the cost of CO_2 compression is commonly attributed to the capture system, it could just as readily be considered as a cost of CO_2 transport and storage, since those are the CCS components that require the higher pressure for their operation.

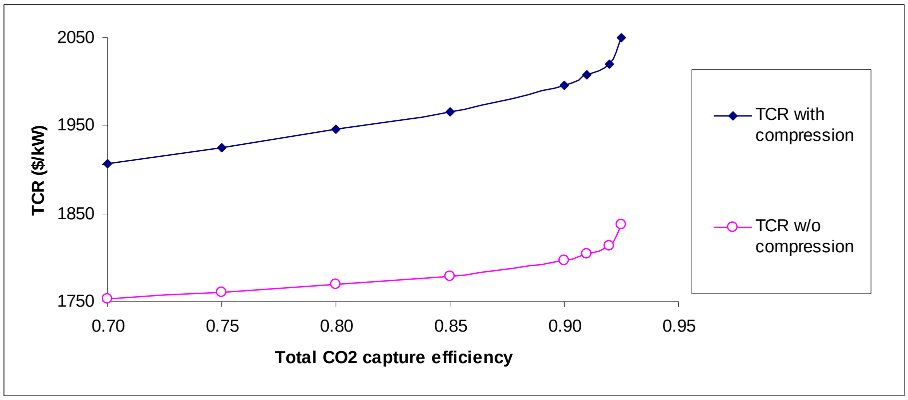

Figure 4: Total capital requirement of an IGCC power plant as a function of total CO_2 capture efficiency. (Net capacity is approximately 250 MW. All costs in 2002 dollars.)

A final measure of cost is the CO_2 avoidance cost, which is defined as:

$$\text{Cost of CO}_2\text{ Avoided} = \frac{\text{COE of capture plant} - \text{COE of reference plant}}{\text{Reference plant CO}_2\text{/kWh} - \text{Capture plant CO}_2\text{/kWh}} \qquad (3)$$

Figure 5 shows the CO_2 avoidance cost disaggregated into the three cases shown earlier. When the total CO_2 removal efficiency is 0.9, the CO_2 avoidance cost including CO_2 compression is 1.7 times greater than the cost without CO_2 compression. When CO_2 transport and storage costs are included, the CO_2 avoidance cost is 2.7 times greater than without compression, transport and storage. Also notice that in all cases the avoidance cost is minimized when the total CO_2 removal efficiency is in the range of 85% to 90%.

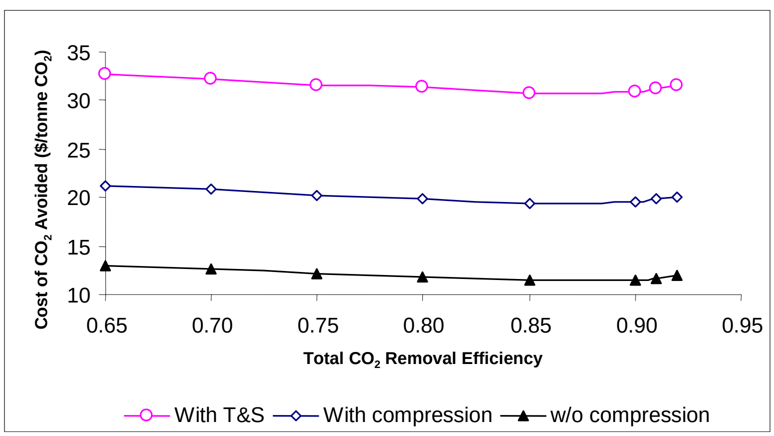

Figure 5: CO_2 avoidance cost of an IGCC plant as a function of total CO_2 removal efficiency

Effects of Uncertainty

An IGCC plant is a complex chemical processing and energy conversion system. Large-scale commercial experience with IGCC power plants and systems for CO_2 capture is still limited. Consequently, there are substantial uncertainties associated with using the limited performance and cost data available to predict the commercial-scale performance and cost of a new IGCC plant. Uncertainties may apply to different aspects of the process, including performance variables, equipment sizing parameters, process area capital costs, requirements for initial catalysts and chemicals, indirect capital costs, process area maintenance costs, requirements for consumables during plant operation, and the unit costs of consumables, byproducts, wastes, and fuel [13]. Model parameters in any or all of these areas may be uncertain or variable, depending on the state of technology development, the level of detail of performance and cost estimates, assumptions about future markets and prices for chemicals, catalysts, byproducts and wastes, plus a host of other factors. The following simulation results are based on an IGCC plant with CCS, but with two GE 7FA gas turbines and two operating gasifiers plus one spare (roughly 500 MW net capacity), as in Table 1.

Figure 7 shows the uncertainties associated with the total capital requirement of the IGCC capture plant based on the parameter uncertainties summarized in Tables 4 and 5 [14]. The deterministic value of TCR in this case is 1714 $/kW. The overall range varies from 1650 to 1800 $/kW, with a 90% confidence interval of 1687 to1760 $/kW. The separate contributions of the reference plant and CCS system also are shown in Figure 7. From this figure, it is clear that most of the uncertainty in total capital cost comes from the IGCC process rather than from the capture system.

Table 4. Distribution functions assigned to parameters of the IGCC system

Parameter	Unit	Nominal Value	Distribution Function
Facility cost parameters			
Fixed charged factor	%	14.8	Triangular(7.1, 14.8, 17.4)
Engineering and home office fee	% TPC	10	Triangular(7,10,12)
Indirect construction cost factor	% TPC	20	Triangular(15,20,20)
Project uncertainty	% TPC	12.5	Uniform(10,15)
General facilities	% TPC	15	Triangular(10,15,25)
Process contingency factors			
Oxidant feed	% PFC	5	Uniform(0,10)
Gasification	% PFC	10	Triangular(0,10,15)
Selexol process	% PFC	10	Triangular(0,10,20)
Low temperature gas cleanup	% PFC	0	Triangular(-5,0,5)
Claus plant	% PFC	5	Triangular(0,5,10)
Beavon-Stretford	% PFC	10	Triangular(0,10,20)
Process condensate treatment	% PFC	30	Triangular(0,30,30)
Gas turbine	% PFC	12.5	Triangular(0,12.5,25)
Heat recovery steam generator	% PFC	2.5	Triangular(0,2.5,5)
Steam turbine	% PFC	2.5	Triangular(0,2.5,5)
General facilities	% PFC	5	Triangular(0,5,10)
Maintenance cost factors			
Gasification	% TPC	4.5	Triangular(3,4.5,6)
Selexol for sulfur removal	% TPC	2	Triangular(1.5,2,4)
Low temperature gas cleanup	% TPC	3	Triangular(2,3,4)
Claus plant	% TPC	2	Triangular(1.5,2,2.5)
Boiler feed water	% TPC	2	Triangular (1.5, 2, 4)
Process condensate treatment	% TPC	2	Triangular(1.5,2,4)
Gas turbine	% TPC	1.5	Triangular(1.5,1.5,2.5)
Heat recovery steam generator	% TPC	2	Triangular (1.5, 2, 4)
Steam turbine	% TPC	2	Triangular(1.5,2,2.5)
Other fixed operating cost parameters			
Labor rate	$/hr	25	Triangular(17,25,32)
Variable operating cost parameters			
Ash disposal	$/ton	10	Triangular(10,10,25)
Sulfur byproduct	$/ton	75	Triangular(60,75,125)

Table 5. Distribution functions assigned to parameters of the CO_2 capture system

Parameter	Unit	Nominal Value	Distribution function
Selexol system parameters			
Mole weight of Selexol	lb/mole	280	Triangular(265,280,285)
Pressure at flash tank 1	psia	60	Uniform(40,75)
Pressure at flash tank 2	psia	20	Uniform(14.7,25)
Pressure at flash tank 3	psia	7	Uniform(4,11)
Power recovery turbine efficiency	%	75	Uniform(70,80)
Selexol pump efficiency	%	75	Uniform(70,80)
Recycle gas compressor efficiency	%	75	Uniform(70,80)
CO_2 compressor efficiency	%	79	Triangular(75,79,85)
Cost parameters			
WGS catalyst cost	$/ft^3	250	Triangular(220,250,290)
Selexol solvent cost	$/lb	1.96	Triangular(1.32,1.96,2.9)
WGS process contingency cost	% PFC	5	Triangular(2,5,10)
Selexol process contingency cost	% PFC	10	Triangular(5,10,20)
Maintenance cost of WGS system	% PFC	2	Triangular (1, 2, 5)
Maintenance cost of Selexol system	% PFC	5	Triangular(2,5,10)

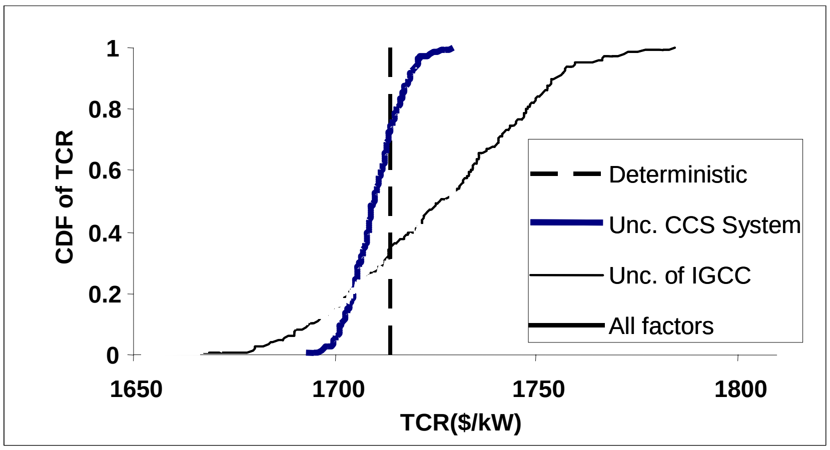

Figure 7. Cumulative probability distributions of IGCC total capital requirement (based on parameter distributions from Tables 4 and 5)

ADVANCED IGCC SYSTEM DESIGNS

As a developing technology, there is room for significant improvement in the future performance and cost of IGCC plants. There are substantial R&D programs in the U.S. and elsewhere directed at improving the efficiency and cost-effectiveness of IGCC technology. Over the next decade or so, IGCC technology is expected to make significant improvements in the following five areas [16,17]:

- Advanced gasifier concepts with higher efficiency, reliability and higher operating pressure for more economic CO_2 capture
- Advanced air separation units with better thermal integration with IGCC systems
- Syngas cleanup processes with less expensive particulate removal systems or hot gas filtration
- Advanced gas turbines with higher energy efficiency and the ability to burn syngas and hydrogen-rich fuels
- Optimal system integration with new technologies and components.

This section of the paper discusses two novel technologies that will likely influence the development and application of IGCC systems in the near future: (1) advanced air separation units based on ion transport membrane (ITM) technology, and (2) advanced gas turbines based on the GE H-frame system.

Advanced Oxygen Production

Figure 8 represents a schematic of an IGCC system with ITM oxygen production. In this design, the air fed into the ITM unit comes from a stand-alone compressor. While this design requires a new air compressor, it also offers more flexible operation. The IGCC model with an ITM system is based on a simple performance model for the ITM that assumes an operating temperature of 1500°F, an air feed pressure of 200 psia, and a theoretical recovery of 50% [18-22]. Models of the WGS reactor and Selexol process for CO_2 capture also are integrated into this design to study the effect of adopting ITM technology on the performance and cost of the plant with CCS.

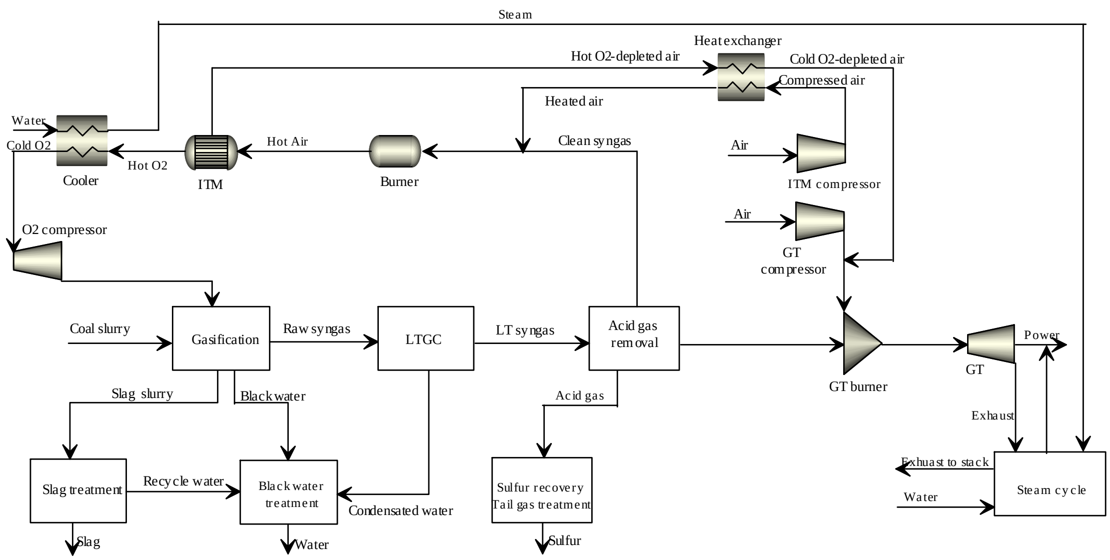

Figure 8. A schematic of an IGCC system integrated with ITM oxygen production

Advanced Gas Turbine

For IGCC plants using a GE H-frame gas turbine, the steam cycle can operate at higher pressure and temperatures to achieve higher energy efficiency. The parameters of the three-pressure reheat steam cycle used in the simulation model are given in Table 6. Other technical and economic parameters for these case studies are the same as those given earlier in Tables 1 and 2.

Table 6. Steam cycle parameters of the IGCC using GE H-frame turbine

Parameter	HP throttle	Hot reheat	LP admission
Pressure (psig/bar)	2400/165	345/23.8	31/2.2
Temperature (°F/°C)	1050/565	1050/565	530/277

Case Study Results

From Figure 9, the future IGCC systems modeled here are projected to achieve a thermal efficiency as high as 42.3% (HHV basis). With CO_2 capture and storage, the HHV efficiency is approximately 38.2%, which is higher than the current IGCC reference system without CCS modeled earlier.

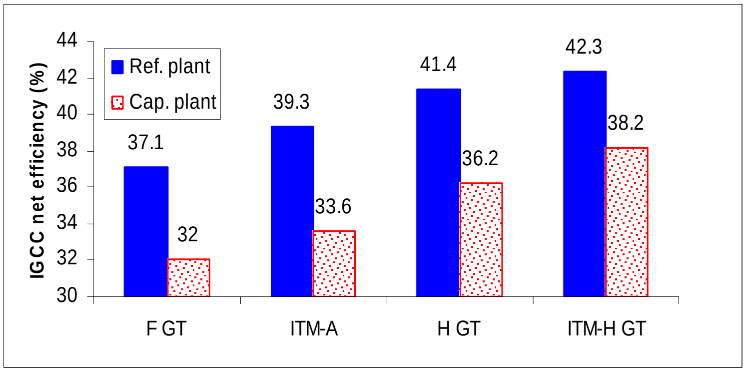

Figure 8. Thermal efficiency of IGCC plants based on advanced technologies

Figure 10 shows that the estimated total capital requirement of the advanced IGCC plant without CCS is 1184 $/kW, compared to 1714 $/kW for today's reference plant. With CO_2 capture, the capital cost of the advanced IGCC system is estimated at 1470 $/kW, which is only about 10% higher than the cost of a current IGCC system without capture. Due to the lower capital cost and higher plant efficiency, the cost of electricity for the advanced IGCC plant is projected to be substantially lower than current costs, as shown in Figure 11. Of course, there are also significant uncertainties associated with advanced IGCC designs. These remain to be quantified and modeled in future work, similar to the uncertainty analysis shown earlier for current technologies.

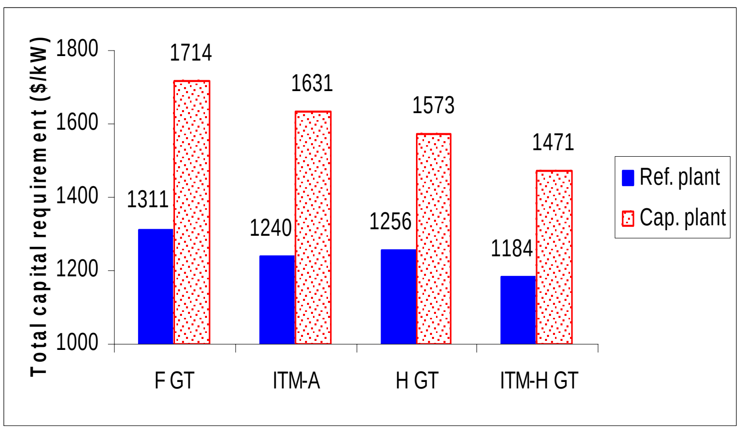

Figure 10. Total capital requirement of IGCC plants based on advanced technologies

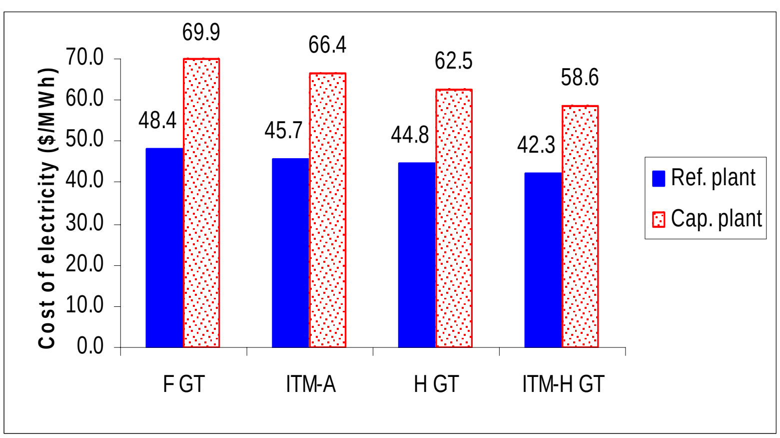

Figure 11. Cost of electricity of IGCC plants based on advanced technologies

CONCLUSION

Using the IECM, a general integrated modeling framework for power plant analysis, several factors influencing the performance and cost of IGCC plants with CO_2 capture were investigated. Four coals, including selections of bituminous, sub-bituminous and lignite coals, were used to investigate the effects of coal quality on the performance and cost of IGCC systems employing a GE quench gasifier. Although this gasifier is able to process all four coals, the coal rank significantly influences the gasification efficiency, thermal efficiency and capital cost of the power plant. In particular, an IGCC system using a slurry feeding mechanism is not an ideal technology for utilizing low-rank coals like lignite since the total water input substantially exceeds the requirements of an optimal design.

The effect of different CO_2 capture efficiencies on auxiliary power requirements, thermal efficiency, capital cost, cost of electricity and CO_2 avoidance cost also was studied. For the case study plant, the avoidance cost was lowest when the total CO_2 removal efficiency was in the range of 85%–90%, which indicates that the optimal CO_2 capture efficiency is also in this same range.

A preliminary uncertainty analysis focused on total capital cost also was conducted using the probabilistic capabilities of the IECM. Case study results showed that most of the uncertainty in total capital cost arose from uncertainty or variability in parameters for the basic IGCC process rather then the CO_2 capture system.

Finally, a preliminary performance and cost analysis of advanced IGCC systems showed that incorporation of advanced oxygen production and gas turbine technologies is expected to greatly improve the performance and reduce the cost of future IGCC systems with and without CCS. For plants with CCS, simulation results showed that the benefit of these two advanced technologies eliminates nearly all of the performance and cost penalties currently associated with CO_2 capture and storage for IGCC plants. An analysis of the uncertainties associated with advanced IGCC designs remains for future research.

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