The Impact of Advanced Syngas Conversion Technologies on the Cost of Electricity from Gasification-based Power Generation Platforms

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Summary

Virtually pollution-free, fuel cells have the potential to reshape the future of power generation. By harnessing the chemical energy of fuels – much like a battery – they generate power quietly at high efficiencies with few moving parts. Fuel cells are also capable of generating power from a variety of carbon and/or hydrogen-rich fuels. To date, most electric power fuel cells have operated using natural gas, but future fuel cells could use gas made from coal.

The greatest hurdle for widespread fuel cell application has been that their cost per kilowatt is well above the cost of conventional power generating technologies. The Department of Energy's Clean Coal Program is sponsoring research to develop solid state solid oxide fuel cells that are an order of magnitude lower in capital cost, yet capable of achieving very high efficiencies with coal as the feedstock. DOE believes that this target is achievable primarily because advances in solid-state components and manufacturing techniques continue to be made at a remarkable rate. Ceramic-based technology continues to show great promise for achieving the dramatic cost reductions needed to make fuel cells widely competitive in tomorrow's energy market.

The technology target for the Fuel Cells R&D program is to ultimately develop fuel cells that when integrated with coal gasification achieve 60 percent efficiency (on a higher heating value basis). With a dramatic cost reduction in the fuel cell system, these gasification based fuel cell plants have the potential to generate electricity quiet competitively.

This analysis provides cost estimates of several coal-based power plants, including cases in which a fuel cell system in integrated with gasification. Starting with performance and cost estimates for integrated gasification combined cycles (IGCC) and supercritical pulverized coal (SCPC) plants as a benchmark from the 2007 NETL report, "Cost and Performance Baseline for Fossil Energy Plants," the costs of more advanced systems with integrated fuel cell systems were scaled based on parameters such as efficiency and net power output. The performance of the fuel cell plants used to scale the costs was determined by separate systems analysis conducted on behalf of NETL.

The levelized cost of electricity was determined for each case, with and without carbon capture, revealing that highly efficient coal-based power generation using fuel cells have the potential to generate power with virtually no greenhouse gas emissions at a cost lower than pulverized coal (PC) and IGCC plants either equipped with carbon capture and sequestration or willing to pay a tax on uncontrolled carbon emissions.

Introduction

This analysis projects the capital cost of advanced gasification-based power generation platforms based on heat and material balances and the relative size of the different unit operations compared to state-of-the-art IGCC systems that are fully designed and costed in the 2007 NETL report, "Cost and Performance Baseline for Fossil Energy Plants."

Table 1 presents the following five power platforms under both a “no CO_2 capture” and a “with CO_2 capture” configuration.

1. Supercritical pulverized coal (SCPC, state-of-the-art)
2. Integrated gasification combined cycle (IGCC, state-of-the-art, GE 7FA-type gas turbine)
3. Advanced IGCC configuration that incorporates a dry feed pump, warm gas sulfur removal, membrane-based oxygen supply, and a GE 7FB-type gas turbine. Balance of plant is state-of-the-art.
4. Atmospheric pressure integrated gasification fuel cell (IGFC)
5. Pressurized IGFC

Each case contains data on efficiency, percent of CO_2 capture, capital, fixed and variables costs, and a calculated levelized cost of electricity (LCOE). Consistent with the DOE program goals, the atmospheric IGFC is based on a fuel cell cost of $400 per kW AC (2002 dollars) and 0.8 V. The pressurized fuel cell maintains the $400/kW cost goal and achieves a higher conversion efficiency. In the “with CO_2 capture” cases, the pressurized fuel cell has the benefit of a higher CO_2 discharge pressure and reduced compression load. A CO_2 cost of $30/mt was assessed to all cases.

This analysis highlights that as systems for converting syngas into AC power become more efficient, the related equipment (e.g., coal handling, gasifier, sulfur capture, CO_2 compression) shrinks in size per kWh of net generation. Thus improvements in efficiency cause cascading improvements in capital cost ($/kW) and the levelized cost of electricity (LCOE) ($/kWh). A state-of-the art IGCC system, without CO_2 capture and storage, has an efficiency of 39% (AC power per Btu coal HHV). Systems analyses of a gasification-based power plant using a pressurized solid oxide fuel cell show an efficiency of 62%. As a result, the fuel cell-based power plant will use 37% less coal per kWh generated; the coal handling system, gasifier, and a number of other unit operations will be 37% smaller as well. The end result with the assumptions stated below is that the cost of electricity to produce GHG-free power using coal-based fuel cells can be more competitive than the other options.

Levelized COE Information and Sources

The text below describes the information sources and calculation methods for the numbers set forth in Table 1. Table 2 shows a number of key inputs used in the LCOE calculations. Note that the fuel cell and fuel cell stack replacement costs in this table are adjusted to 2007 dollars. Table 3 shows the information sources for the information in Tables 1 and 2.

Table 1. Levelized Cost of Electricity from advanced PC, IGCC, and IGFC power plants, with and without CO_2 capture and storage

	Baseline power systems (no CO_2 capture)						Systems with CO_2 capture, compression, and storage				
	SCPC	GEE IGCC	Adv IGCC	Atm IGFC	Press IGFC		SCPC	GEE IGCC	Adv IGCC	Atm IGFC	Press IGFC
Information source	1	1	2	3	4		1	1	2	3	4
Operating Parameters											
Efficiency	39.1%	38.2%	45.0%	49.0%	62.0%		27.2%	32.5%	40.2%	42.3%	57.0%
Capacity factor (hr/yr/8760hrs)	85%	80%	90%	90%	90%		85%	80%	90%	90%	90%
% of power from steam cycle	100%	39%	39%	26%	0%		100%	37%	37%	26%	0%
O_2 requirement (lbO_2/lbdry coal))	0.00	0.89	0.89	0.80	0.52		0.00	0.89	0.89	0.80	0.52
% CO_2 capture	0%	0%	0%	0%	0%		90%	90%	90%	100%	100%
Total CO_2, $kgCO_2$/kWh	0.83	0.85	0.72	0.66	0.52		1.20	1.00	0.81	0.77	0.57
CO_2 compression % inerts							0%	0%	0%	6%	6%
Parasitic load due to CO_2 capture							11.9%	5.7%	4.8%	6.7%	5.0%
Cost Data						*Scaling Factors*					
Capital cost, $/kW net											
Coal handling	97	141	123	114	93	0.85	122	166	139	133	103
ASU		287	250	212	120	0.85		342	286	250	134
Gasifier		426	383	362	311	0.65		498	434	420	346
Gas clean up	229	203	177	164	134	0.85	302	239	199	191	148
Combustion turbine/fuel cell		187	188	407	550	0.85		238	238	472	598
Boiler	510	0	0	0	0	0.65	660	0	0	0	0
HRSG	65	89	89	65	0	0.80	70	99	99	75	0
Steam turbine	204	105	105	75	0	0.85	232	116	116	86	0
CO_2 capture	0	0	0	0	0	0.65	752	175	153	0	0
CO_2 compression	0	0	0	0	0	0.85	85	68	57	59	46
Other	470	375	375	375	375	n/a	647	449	449	449	449
Total capital cost, $/kW net	1,575	1,813	1,688	1,774	1,584		2,870	2,390	2,169	2,135	1,824
Variable O&M, cents/kWH	0.49	0.65	0.55	0.51	0.56		0.94	0.81	0.53	0.50	0.55
Fixed O&M, $/kW/yr	25.2	35.3	35.3	53.0	60.4		37.4	43.7	43.7	60.6	68.0
Fuel cost, cents/kWh	1.57	1.61	1.36	1.25	0.99		2.26	1.89	1.53	1.45	1.08
CO_2 cost, cents/kWh	2.49	2.55	2.17	1.99	1.57		0.75	0.63	0.51	0.31	0.23
LCOE	**8.8**	**10.4**	**8.7**	**8.8**	**7.8**		**11.6**	**10.6**	**8.5**	**8.3**	**7.2**

Table 2. Key inputs to the LCOE calculation for advanced PC, IGCC, and IGFC power plants

Key Inputs	Value	Source
Coal cost	1.80 $/Mmmbtu	1. page 30
PC capital factor	0.186 $/yr/$	goal seek to give LCOE of 6.33 for no CO_2 capture or cost shown on exhibit ES-7, ref 1
Gasification capital factor	0.195 $/yr/$	goal seek to give LCOE of 7.80 for no CO_2 capture or cost shown on exhibit ES-7, ref 1
Fuel cell system cost	550 $/kW AC	program goal adjusted to 2007 dollars
Cost for emitted CO_2 (w/ capture cases)	30 $/mtCO2	5. midrange allowance price under McCain/Leiberman (S.280)
Cost for emitted CO_2 (no capture cases)	30 $/mtCO2	5. midrange allowance price under McCain/Leiberman (S.280)
Cost for CO_2 transport and injection	4 $/mtCO2	1. consistent with 4mils/kWh estimate on page 13
Coal CO_2 emissions factor	95.3 MMmtCO2/qbtu	6. Table 6-1, coal for electric utility, 25.98 * (44/12)
CO_2 compression load for SCPC	0.0826 kWh/kg CO2	1. case 12, $SCPCwCO_2$, 46,900 kW / 1,252,440 $lbCO_2$/hr *0.454 kg/lb
% of IGCC FO&M for comb turbine	10%	engineering estimate
Fuel cell stack replacement cost	175 $/kW	program goal adjusted to 2007 dollars
Stack life	5 years	program goal
Discount rate for stack O&M	10%	1. page 52, exhibit 2-15
Catalytic gasifer, cat. make-up cost	30 cents/mmbtu coal	7.

Table 3. Information sources for LCOE calculation for advanced PC, IGCC, and IGFC power plants

Information Sources
1 Cost and Performance Baseline for Fossil Energy Plants, August 2007, DOE/NETL-2007/1281
2 Systems analysis conducted by Noblis
3 Systems analysis conducted by Eric Grol of NETL
4 Systems analyses conducted by Dale Keairns of SAIC
5 Energy Market and Economic Impacts of S. 280, the Climate Stewardship and Innovation Act of 2007,SR/OIAF/2007-04, July 2007
6 Emissions of Greenhouse Gases in the United States 2002, EIA, Table 6-1
7 Exxon Catalytic Coal Gasification Process Predevelopment Program. Final Project Report. Exxon Research and Engineering Co., Baytown, TX, FE236924, December 1978

Operating parameters

All operating parameters for the SCPC and GEE (GE Energy) IGCC cases came from the 2007 NETL Baseline report. The bases for the operating parameters for the advanced IGCC and the fuel cell platforms are as follows:

- **No CO_2 capture:**
  - Efficiency, percent of power from the steam cycle, and oxygen consumption per ton of coal are taken from process simulations for advanced IGCC, atmospheric IGFC and pressurized IGFC performed by Noblis, NETL, and SAIC, respectively.
  - Capacity factors for the PC and GEE IGCC cases are based on the NETL Baseline report assumptions of 85% and 80%, respectively. Due to use of advanced instrumentation and controls and additional experience with IGCC, the capacity factors assumed for the advanced IGCC and the fuel cell cases is 90%.
  - Total CO_2 per kWh is calculated utilizing the coal CO_2 emissions factor show in Table 2.

- **With CO_2 capture:**
  - Efficiencies from the "no capture" cases must be reduced by the parasitic load associated with the CO_2 capture and compression. For each case this load was calculated as follows:
    - For the advanced IGCC case, the parasitic load due to CO_2 capture is calculated by scaling back the parasitic load for the GEE IGCC case based on the improved base efficiency of the advanced platform relative to the GEE case as shown in {1}.

$$CO2\_parasitic\_load_{AdvIGCC} = CO2\_parasitic\_load_{GEE} * no\_capt\_eff_{GEE} / no\_capt\_eff_{AdvIGCC} \qquad \{1\}$$

    - For the fuel cell platforms, the parasitic load is calculated by increasing the CO_2 compression load for the supercritical PC case in the baseline study (Table 2) to account for inerts present in the fuel cell platform CO_2 as shown in {2}. Based on stream data from the process simulations, the compression load should be increased by 6% to account for these inerts. Fully optimized fuel cell systems likely will exhaust CO_2 at some pressure to reduce parasitic load.

$$CO2\_parasitic\_load_{IGFC} = CO2\_comp\_load_{SPC}*(1+\%inerts_{IGFC})*CO2\_captured\_per\_kWh_{IGFC} \quad \{2\}$$

  - For all cases, capacity factors for the respective "no capture" cases are used.
  - Percent of power from the steam cycle for each case is as follows:
    - For the advanced IGCC, the GEE IGCC "with capture" values are used.
    - For the fuel cell cases, their respective "no capture" values are used.
  - Oxygen consumption per ton of coal matches the "no capture" values for all cases. Both the lower temperature E-Gas gasifier used in the atmospheric fuel cell case and the catalytic gasifier used in the pressurized fuel cell case use less oxygen per ton of CO_2 than does the high temperature GEE gasifier used in the state-of-the-art IGCC. The oxygen factors for the fuel cell systems include oxygen used in the anode gas oxy-combustors.
  - As the fuel cell platforms oxycombust residual fuel in the anode off gas, they sequester nearly 100% of the carbon contained in the coal feedstock, compared to the 90% carbon capture capability for a PC or IGCC.
  - Total CO_2 per kWh is calculated utilizing the coal CO_2 emissions factor shown in Table 2.

Cost Data

All cost data for the SCPC and GEE IGCC cases came from the 2007 NETL Baseline report with the exception of the CO_2 costs. The bases for the cost data for the advanced IGCC and the fuel cell platforms are as follows:

- The costs for most of the cost categories in the advanced IGCC and fuel cell platforms are derived by scaling the cost using the appropriate GEE IGCC operating parameter. The "no CO_2 capture" and "with CO_2 capture" are scaled to their respective GEE IGCC baseline parameter.

- **Capital costs:**
  - Each capital cost category uses a distinct scaling factor based on engineering expertise.
  - Capital costs associated with coal handling, gasifier, gas clean-up and CO_2 capture are scaled using efficiency and the scaling factor as shown in {3}.

    $$Cost_{adv} = Cost_{base} * (eff_{base}/eff_{adv})^{\wedge scaling\ factor} \qquad \{3\}$$

  - The cost of the air separation unit (ASU) is scaled both on the efficiency and the oxygen use per ton of coal as shown in {4}.

    $$Cost_{adv} = Cost_{base} * \{(eff_{base}/eff_{adv})*(oxygen_{adv}/oxygen_{base})\}^{\wedge scaling\ factor} \qquad \{4\}$$

  - The steam turbine and HRSG cost are scaled on the percent of power from steam cycle as shown in {5}.

    $$Cost_{adv} = cost_{base} * (power\_from\_steam_{adv}/power\_from\_steam_{base})^{\wedge scaling\ factor} \qquad \{5\}$$

  - The combustion turbine/fuel cell capital cost line item is calculated differently for each case. Table 4 shows the equipment that was included in the cost estimation for the combustion turbine or fuel cell for each case.

    - For the advanced IGCC case, the cost item "combustion turbine/fuel cell" scales to "one minus the percent of power from steam" as shown in {6}. The cost is not scaled for efficiency based on the assumption that the reduced costs due to efficiency will be offset by increased material costs. The result is a value very similar to the GEE IGCC case.

      $$Cost_{adv} = cost_{base} * \{(1 - power\_from\_steam_{adv})/(1 - power\_from\_steam_{base})\}^{\wedge scaling\ fctr} \qquad \{6\}$$

    - For the fuel cell cases, the cost is equal to the program goal, \$400/kW (2002\$) AC, scaled to "one minus the percent of power from steam" as shown in {7}.

      $$Cost_{adv} = program\_goal * \{(1 - power\_from\_steam_{adv})/(1 - power\_from\_steam_{base})\} \qquad \{7\}$$

Table 4. Equipment assumption for combustion turbine/fuel cell capital costs

Equipment Included in the Turbine/Fuel Cell Capital Cost Line Item					
	SCPC	GEE IGCC	Adv IGCC	Atm IGFC	Press IGFC
Combustion turbine	NA	x	x		
Generator	NA	x	x		
Accessories	NA	x	x		
Syngas expander	NA			x	x
Fuel cell stack	NA			x	x
Rectifier	NA			x	x
Cathode blower	NA			x	
Oxycombustor	NA			x	x
Anodegas expander	NA				x

- The CO_2 compression capital costs are scaled on the percent of CO_2 capture and the efficiency as shown in {8}.

$$Cost_{adv} = Cost_{base} * \{(eff_{base}/eff_{adv})*(pct\_CO2\_capture_{adv}/pct\_CO2\_capture_{base})\}\text{^}^{scaling\ factor} \quad \{8\}$$

- The cost items in the "other" category were assumed not to change in scale with efficiency or other factors and were held equal to the GEE IGCC case.

- **Variable O&M costs:**
  - For the advanced IGCC and atmospheric IGFC, the costs are scaled using efficiency as shown in {9}.

$$Cost_{adv} = Cost_{base} * (eff_{base}/eff_{adv}) \quad \{9\}$$

  - For the pressurized IGFC, the costs are scaled using efficiency as shown in {9}, but with the addition of catalyst make-up costs for the catalytic gasifier based on the catalyst cost shown in Table 2.

- **Fixed O&M costs:**
  - For the advanced IGCC case, the fixed O&M costs from the GEE IGCC case are used.
  - For the fuel cell cases, the GEE IGCC case is adjusted as follows:
    - A factor for periodic stack replacements is added utilizing assumptions shown in Table 2 and described here. The stack replacement is assumed to cost $175/kW (adjusted to 2007 dollars from the NETL program goal of $100/kW in 2002 dollars) and occur once every 5 years. A 10% discount factor is used to first move the payment to year zero and then spread it out into annual payments over the stack life. This value is consistent with the cost of capital used in the NETL baseline study. This works out to $16/yr per kW from the fuel cell stack. The stack replacement cost scales to "one minus the percent of power from the steam cycle."
    - 10% of the GEE IGCC fixed O&M costs are subtracted to account for fixed costs associated with the combustion turbine.
    - The resulting equation is as shown in {10}.

$$Cost_{base} = Cost_{adv} * (1–10\%) + (1–power\_from\_steam_{adv}) * annualized\_stack\_cost\_perkWh \quad \{10\}$$

- **Fuel cost:**
  - The fuel cost equals the heat rate (3412/efficiency) multiplied by the cost of coal, $1.8 per million Btu, as shown in Table 2.

- **CO_2 cost:**
  - CO_2 cost consists of two components, cost of transport and injection and cost of emitted CO_2, and is calculated as shown in {11}.
    - Cost of transport and injection is assumed to be $4/mt CO_2 consistent with the NETL 2007 baseline study.
    - The cost of emitted CO_2 is assumed to be $30/mt$CO_2$, the midpoint projected in EIA's assessment of the McCain Lieberman bill. The fuel cell systems are able to sequester nearly 100% of the carbon contained in the coal feedstock. By representing allowance prices for un-captured CO_2, the analysis accurately characterizes a policy scenario wherein such assets would be deployed.

CO2_cost = CO2/kWh * (%capture * trans&inj._cost + (1-%capture) * CO2emitted_price) {11}

- **Levelized cost of electricity:**
  - The levelized cost of electricity (cents/kWh) is calculated as shown in {12}.
  - Capital and fixed costs are adjusted using the capacity factor.
  - Capital costs are adjusted using a capital factor.
    - The GEE IGCC capital factor from the 2007 baseline study is applied to the advanced IGCC and fuel cell cases, both with and without CO_2 capture. The baseline study uses a slightly lower cost of capital for PC without capture versus IGCC. As shown in Table 2, capital factors of 0.186 for PC and 0.195 for IGCC were determined using goal seek to match the "no capture" LCOEs reported in the NETL baseline study.

LCOE = (Cap_cost * capital_factor + fixed_O&M) / (capacity_factor * 8760)
+ var_O&M + CO2_cost + fuel_cost {12}