Engineering Assessment of CO_2 Recovery, Transport, and Utilization*

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Introduction

The need to establish benchmarks for available power-generating cycles having reduced atmospheric emissions of CO_2 served as the basis for this study. Innovative process technologies need this benchmark so they can be appreciated in their proper perspective. An oxygen-blown KRW coal-gasification plant producing hydrogen, electricity, and supercritical-CO_2, was studied in a full-energy cycle analysis extending from the coal mine to the final destination of the gaseous product streams. A location in the mid-western United States 100 mi from Old Ben #26 mine was chosen. Three parallel gasifier trains, each capable of providing 42% of the plant's 413.5 MW nominal capacity use 3,845 tons/day of Illinois #6 coal from this mine. The plant produces a net 52 MW of power and 131 MMscf/day of 99.999% purity hydrogen which is sent 62 mi by pipeline at 34 bars. The plant also produces 112 MMscf/day of supercritical-CO_2 at 143 bars, which is sequestered in enhanced oil recovery operations 310 mi away.

Objective

This project emphasizes CO_2-capture technologies combined with integrated gasification combined-cycle (IGCC) power systems that produce both merchant hydrogen and electricity. Comparisons of energy penalties, capital investment, and CO_2 emission reductions are based on the full-energy cycle including mining, coal transportation, coal preparation, gasification, gas treatment, power generation, infrastructure to transfer power or hydrogen to end users, and pipeline transport of CO_2 to enhanced-oil recovery. Technical and economic aspects of H_2 pipelines and supercritical CO_2 pipelines, as well as issues relating to CO_2 sequestering in EOR are considered so that process conditions and energy use are accounted for by the study.

Approach

Oxygen-blown gasification is used to convert Illinois #6 coal to synthesis gas [Fig. 1]. After particulate removal, a shift reactor uses steam to convert the CO component of the gas to CO_2 and hydrogen (H_2). Next, H_2S is removed from the stream and processed to produce marketable sulfur. Carbon dioxide is then recovered in a glycol-based process and transported by pipeline for enhanced oil recovery. The gas stream after CO_2 recovery is processed using pressure-swing adsorption (PSA) to recover H_2 at a purity suitable for fuel cells, although there is no restriction on the actual hydrogen end-use. The H_2 stream is transported to end users via pipeline, while the residual gas from PSA - a combination of hydrogen, methane, and light hydrocarbons - is used to generate electricity by combustion turbine combined cycle. Part of the electricity generated supplies the internal needs of the plant, and the excess is sent to the grid.

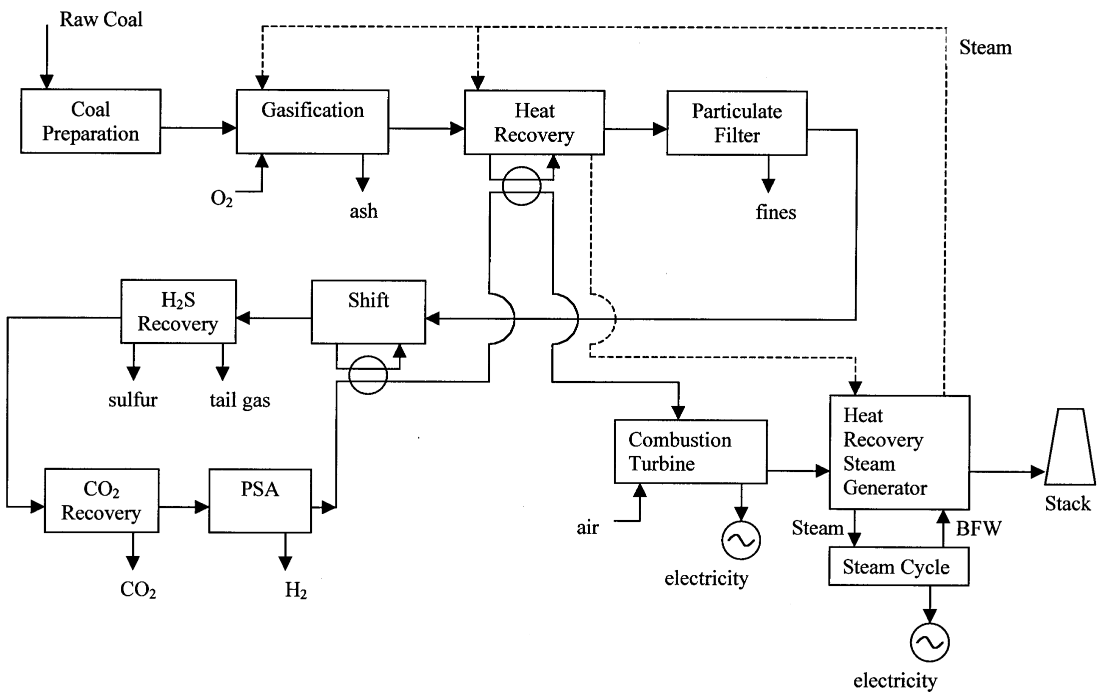

Fig. 1. Integrated Gasification Combined-Cycle Producing Electricity, CO_2 and H_2

Description

Mining: The assumed power plant location is 100 mi (160 km) by diesel-rail transport from the Old Ben #26 underground mine in Sesser, Illinois. The plant receives 4,112 tons/day (155.4 metric tonnes/h) of 2 x 4-in. coal, which is prepared to 0 x 1/4-in. with 3.5% weight loss. A summary of this portion of the power cycle appears in Table 1.

Conversion: Previous process design studies to characterize integrated gasification combined-cycle (IGCC) power systems with CO_2-capture technologies were modified using ASPEN© modeling to evaluate a configuration producing both merchant hydrogen and electricity [1,2,3,4,5]. The power plant configuration employs three parallel gasifier trains, each capable of providing 42% of the plant's 413.5 MW nominal capacity (for the base case with no CO_2 recovery.) After modification, the plant produces 131 MMscf/day (3.71 million standard cubic m/day) of 99.999% purity hydrogen at 287.7 Btu/scf; 119.9 KJ/g (LHV) which is sent 100 km by pipeline at 34 bars.

At 100% efficiency, this could yield 460 MW of power. The plant also produces 112 MMscf/day (3.18 million standard cubic m/day) of supercritical-CO_2 at 143 bars, which is sent 500-km for sequestering in enhanced oil recovery. PSA reject gas goes to a turbine cycle to produce 118 MW. After supplying 66 MW for internal power use this yields 52 MW Net power.

H_2 pipeline: A 100-km pipeline design was prepared and costs were estimated for a high purity hydrogen flow of 131 MMscf/day through a 343 mm pipe at 30 bar. There appears to be no economic justification for going to higher pipeline pressures and an internal study of the costs for delivering energy as methane vs. energy as H_2 showed a 13% advantage for methane at 500 psi rising to a 46% advantage at 800 psi. Economic assumptions were for a capacity factor of 95% and capital recovery of 12% to yield transmission costs of 0.171 \$/Mscf; 0.564 \$/GJ.

Table 1. Energy Use in Coal Mining, Preparation, and Transportation

	Electricity	Diesel Fuel #2	CO_2 Emissions	Electricity	Losses	Coal	CO_2
metric units	kWh/tonne	tonne-km/liter	kg/tonne coal	MW	%	kg/h	kg/h
MINING (a)							
Methane emissions (b)			9.63		0.0%	178,981	1,724
Hoisting	6.12		6.12				
Drilling	2.03		2.03				
Ventilation	2.20		2.20				
Dewatering	2.67		2.67				
Break and convey	0.73		0.73				
Ancillary	0.46		0.46				
subtotal	14.21		14.21	2.54	0.0%	178,981	2,543
PREPARATION 2x4-in.	0.44		0.44	0.07	10.0%	161,083	71
TRANSPORT - 161 km							
Mine to IGCC by rail		135	3.27				
General service	0.98		0.98	0.15			
Return to mine		50	1.22				
General service	0.36		0.36	0.06			
subtotal			5.83	0.21	3.5%	155,445	905
PREPARATION 1/4-in. (c)	5.85				6.5%	145,341	

(a) Operations of 250 days/yr at 13 hr/day
(b) Methane emissions of 175 scf/ton counted only as conversion to CO_2 within a 14-yr life
(c) Accounted for in IGCC plant balance

CO_2 pipeline: Design and economic assumptions for a supercritical-CO_2 pipeline were compared against current plans for Dakota Gasification Company, Beulah, ND [6] and Shell estimates of CO_2 purchase costs at $3.25/bbl of oil recovered [7] with a reasonable CO_2 utilization of 5.6 Mscf/bbl oil [8], which would come to a purchase price of about $0.60/Mscf. Since, the 30-in. Shell Cortez line is unusually large Ð resulting in economies of scale Ð previously determined pipeline costs of $0.77/Mscf CO_2 still appear reasonable.

RESULTS: Full-Energy Cycle Balances

The energy costs of delivering electricity 100-km from the IGCC plant are presented for three cases; the IGCC base case with no CO_2 recovery (Table 2); the IGCC system with CO_2 recovery (Table 3); the IGCC system developed for this study with H_2 production and CO_2 recovery (Table 4). For the Base-case with no CO_2 recovery; delivered power was 396-MW full-cycle with emissions of 0.83 $kgCO_2$/kWh.

There is a derating with CO_2 recovery. Delivered power becomes 366-MW full-cycle at 0.20 $kgCO_2$/kWh. An additional derating takes place in the present case with both H_2 production and CO_2 recovery where the hydrogen goes to 3-stage solid-oxide fuel cells. The delivered power now becomes 344-MW full-cycle at 0.22 $kgCO_2$/kWh. This is the combination of 52-MW busbar at the plant and 298-MW from fuel cells and a steam generator topping cycle.

Table 2. KRW O_2-blown IGCC - Base Case

Basis: Electric power delivery 100 km from station

	nm^3/d	tons/d	kg/h	Power MW	CO_2 kg/h	CH_4 kg/h	N_2O kg/h
MINING AND TRANSPORT							
Coal methane emissions						566	
Mining operations & preparation				-2.61	2,614		0.00003
Transport by rail - 161 km				-0.21	905		0.66265
Subtotal				**-2.82**	**3,520**	**566**	**0.66267**
POWER PLANT							
Coal preparation (0-in. x 1/4-in.)		3,845	145,341	-0.85			
O_2 by cryogenic separation	8,937,000	2,347	88,717	-29.29			
Steam from heat recovery generator			17,254				
Gasifier island				-2.90			
Solid waste		492	18,598				
Sulfur		78	2,948	-4.64			
SO_2 (gasifier only)		6.92	262		6,157		unknown
Power island				-7.02	320,383		
Miscellaneous (5%)				-2.24			
Subtotal				**-44.70**	**326,540**		
Power - gas turbine				627.40			
Power - air compressor and losses				-328.60			
Power - steam turbine				159.40			
GROSS Power Subtotal				458.20			
NET Power				**413.50**			

CO_2 PIPELINE AND SEQUESTERING			0.00	0		
H_2 PIPELINE			0.00	0		
TRANSMISSION LOSS-3.5%			**-14.47**	0		
NET ENERGY CYCLE -Base Case	**0.833**	**kg CO_2/kWh**	**396.20**	**330,060**	**566**	**0.66267**

Table 3. O_2-blown IGCC with CO_2

Glycol CO_2 and H_2S recovery; turbine topping
Basis: Electric power delivery 100 km from station

	nm^3/d	tons/d	kg/h	Power MW	CO_2 kg/h	CH_4 kg/h	N_2O kg/h
MINING AND TRANSPORT							
Coal methane emissions						566	
Mining operations & preparation				-2.61	2,614		0.00003
Transport by rail - 161 km				-0.21	905		0.66265
Subtotal				**-2.82**	**3,520**	**566**	**0.66267**
POWER PLANT							
Coal preparation (0-in. x 1/4-in.)		3,845	145,341	-0.85			
O_2 by cryogenic separation	8,937,000	2,347	88,717	-29.29			
Steam from heat recovery generator			17,254				
Gasifier island				-2.90			
Solid waste		492	18,598				
Sulfur		78	2,948				
SO_2 (gasifier only)		6.92	262		6,157		unknown
Glycol circulation				-5.80	320,383		
Glycol refrigeration				-4.50			
Power recovery turbines				3.40			
CO_2 compression to pipeline (143 bar)	3,178,000			-17.30	-260,055		
Power island				-6.90			
Miscellaneous (5%)				-2.86			
Subtotal				**-67.01**	**66,485**	**0**	unknown
Power - gas turbine				580.78			
Power - air compressor and losses				-325.51			
Power - steam turbine				195.30			
GROSS Power Subtotal				**450.57**			
NET Power				**383.56**			
CO_2 PIPELINE AND SEQUESTERING	3,178,000				260,055		
Pipeline booster stations				-1.64	1,637		0.00002
Geological reservoir (1% loss)					-257,454		
Subtotal				**-1.64**	**4,238**	**0**	**0.00002**
H_2 PIPELINE				0.00			

TRANSMISSION LOSS-3.5%			**-13.42**			
NET ENERGY CYCLE	**0.203**	**kg CO_2/kWh**	**365.67**	**74,242**	**566**	**0.66269**
NET ENERGY CYCLE -Base Case	**0.833**	**kg CO_2/kWh**	**396.20**	**330,060**	**566**	**0.66267**

Table 4. KRW O_2-blown IGCC

Glycol CO_2 and H_2S recovery; PSA H_2 recovery; turbine topping; 3-stage solid oxide fuel cell

	nm^3/d	tons/d	kg/h	Power MW	CO_2 kg/h	CH_4 kg/h	N_2O kg/h
MINING AND TRANSPORT							
Coal methane emissions						566	
Mining operations & preparation				-2.61	2,614		0.00003
Transport by rail - 161 km				-0.21	905		0.66265
Subtotal				**-2.82**	**3,520**	**566**	**0.66267**
POWER PLANT							
Coal preparation (0-in. x 1/4-in.)		3,845	145,341	-0.85			
O_2 by cryogenic separation	8,937,000	2,347	88,717	-29.29			
Steam from heat recovery generator			17,254				
Gasifier island				-2.90			
Solid waste		492	18,598				
Sulfur		78	2,948				
SO_2 (gasifier only)		6.92	262		6,157		unknown
Glycol circulation				-5.80	320,383		
Glycol refrigeration				-4.50			
Power recovery turbines				3.40			
CO_2 compression to 143 bar	3,178,000			-17.30	-260,055		
H_2 PSA purification to 31 bar	3,710,000			-3.18			
H_2 cryo-storage for pipeline				-0.92			
Power island				-1.81			
Miscellaneous (5%)				-3.07			
Subtotal				**-66.22**	**66,485**	**0**	unknown
Power - gas turbine				244.53			
Power - air compressor and losses				-169.48			
Power - steam turbine				42.93			
GROSS Power Subtotal				**117.98**			
NET Power				**51.76**			
CO_2 PIPELINE & SEQUESTERING	3,178,000				260,055		
Pipeline booster stations				-1.64	1,637		0.00002
Geological reservoir (1% loss)					-257,454		
Subtotal				**-1.64**	**4,238**	**0**	**0.00002**

H_2 PIPELINE OUTLET (21 bar)	3,710,000					
H_2 3-stage SOFC (58% of 460.0 MW)			266.80			
Steam Generator (85% of 36.8 MW)			31.28			
Subtotal			**298.08**	**0**	**0**	**0.00000**
TRANSMISSION LOSS-3.5%			**-1.81**			
NET ENERGY CYCLE	**0.216**	**kg CO_2/kWh**	**343.56**	**74,242**	**566**	**0.66269**
NET ENERGY CYCLE -Base	**0.833**	**kg CO_2/kWh**	**396.20**	**330,060**	**566**	**0.66267**

Applications

Carbon dioxide as a supercritical product (143 bar) can be recovered from coal gasification and power production. Where there is an enhanced oil recovery market, this actually is profitable.

The need for high-pipeline utilization is critical. Hydrogen can be recovered at high purity (99.999%) for sale from coal gasification, however the need for high pipeline-utilization is

critical. Pressures of 35 bar are optimal. Fuel-cell conversion efficiencies need to approach 77% to match the base-case output. At present, solid-oxide fuel cell efficiencies are 53-58%; while alkaline fuel cell efficiencies are near 70%.

Future Work

Costs for the current study have been prepared for the pipelines, but changes to the IGCC plant itself must be reviewed and finalized to yield the comparative costs of electricity.

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