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# HYDROGEN PRODUCTION AND CARBON DIOXIDE RECOVERY FROM KRW OXYGEN-BLOWN GASIFICATION*

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## ABSTRACT

An oxygen-blown KRW integrated gasification combined-cycle 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 was chosen 160-km from Old Ben #26 mine which ships 3,866 tonnes/day of Illinois #6 coal by diesel locomotive. Three parallel gasifier trains, each capable of providing 42% of the plant's 413.5 MW nominal capacity use a combined total of 3,488 tonnes/day of 1/4" prepared coal. The plant produces a net 52 MW of power and $3.71 \times 10^6$ $nm^3$/day of 99.999% purity hydrogen which is sent 100 km by pipeline at 34 bars. The plant also produces $3.18 \times 10^6$ $nm^3$/day of supercritical $CO_2$ at 143 bars, which is sequestered in enhanced oil recovery operations 500 km away. A $CO_2$ emission rate of 1 kg$CO_2$/kWh was assumed for power purchases outside the fence of the IGCC plant.

## INTRODUCTION

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.

## 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.

## INTEGRATED GASIFICATION COMBINED CYCLE 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 plantís 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. The designed plant availability is 95%. This is largely reflected in higher projected maintenance costs.

## $H_2$ PIPELINE

A 100-km pipeline design was prepared and costs were estimated for a high purity hydrogen flow of $3.71 \times 10^6$ $nm^3$/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 an availability of 95% and capital recovery of 12% to yield transmission costs of 0.171 \$/Mscf; 0.564 \$/GJ. It is very important to observe that the high costs of a dedicated pipeline dictate the high availabilities.

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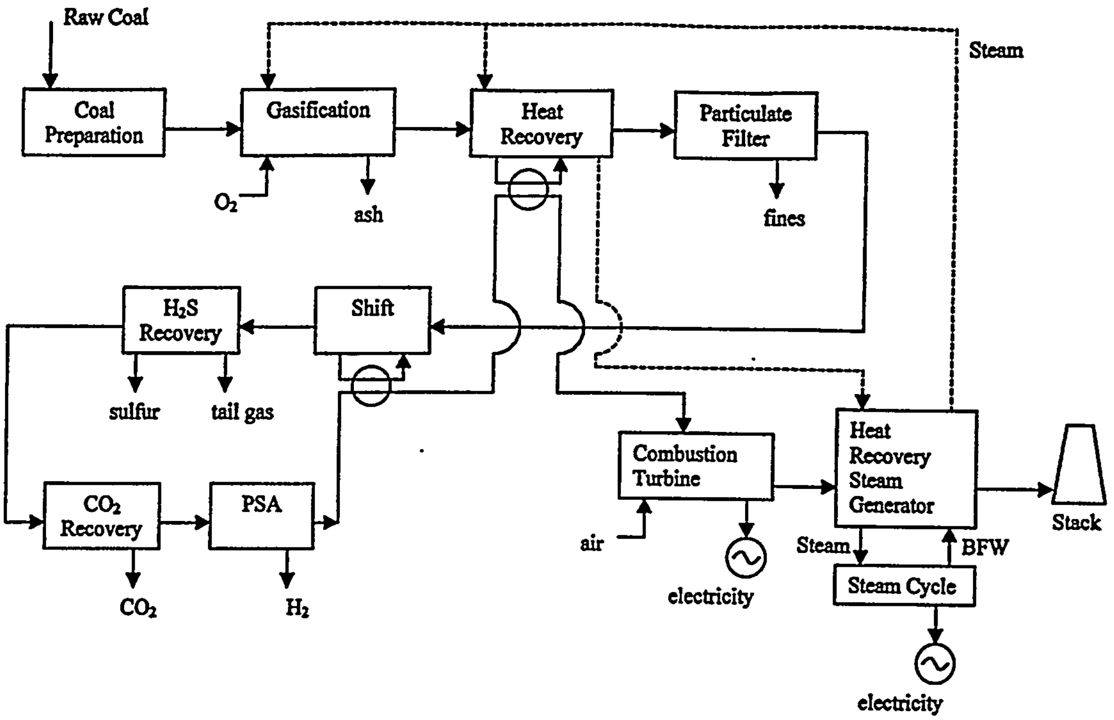

Fig. 1. Integrated Gasification Combined-Cycle Producing Electricity, $CO_2$ and $H_2$

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

| metric units | Electricity kWh/tonne | Diesel Fuel #2 tonne-km/liter | $CO_2$ Emissions kg/tonne coal | Electricity MW | Losses % | Coal kg/h | $CO_2$ 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 – resulting in economies of scale – 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 kg$CO_2$/kWh. There is a derating with $CO_2$ recovery. Delivered power becomes 366-MW full-cycle at 0.20 kg$CO_2$/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 kg$CO_2$/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 |
| **a. 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** | | | |
| **b. NET Power** | | | | **413.50** | | | |
| **c. $CO_2$ PIPELINE AND SEQUESTERING** | | | | 0.00 | 0 | | |
| **d. $H_2$ PIPELINE** | | | | 0.00 | 0 | | |
| **e. TRANSMISSION LOSS-3.5%** | | | | **-14.47** | 0 | | |
| **f. NET ENERGY CYCLE -Base Case*** | **0.833** | **kg $CO_2$/kWh** | | **396.20** | **330,060** | **566** | **0.66267** |

***f = a+b+c+d+e.**

## 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%.

## 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 |
| **a. 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** | | | |
| **b. 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 | | |
| **c. Subtotal** | | | | **-1.64** | **4,238** | **0** | **0.00002** |
| **d. $H_2$ PIPELINE** | | | | 0.00 | | | |
| **e. TRANSMISSION LOSS-3.5%** | | | | **-13.42** | | | |
| **f. NET ENERGY CYCLE*** | **0.203** | **kg $CO_2$/kWh** | | **365.67** | **74,242** | **566** | **0.66269** |

***f = a+b+c+d+e.**

## 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 |
| **a. 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** | | | |
| **b. 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 | | |
| **c. 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 | | | |
| **d. Subtotal** | | | | **298.08** | **0** | **0** | **0.00000** |
| **e. TRANSMISSION LOSS-3.5%** | | | | **-1.81** | | | |
| **f. NET ENERGY CYCLE*** | **0.216** | **kg $CO_2$/kWh** | | **343.56** | **74,242** | **566** | **0.66269** |

***f = a+b+c+d+e**

## FULL ENERGY CYCLE ANALYSIS OF GREENHOUSE GAS FORCING

Recent consideration of full-energy cycle analysis for power production (9) have emphasized the importance of greenhouse gases such as methane and $N_2O$ in addition to other than carbon dioxide. Modeling results suggest that a molecule of methane is equivalent to 56 molecules of $CO_2$ in its climate-forcing impact, while each $N_2O$ molecule is equivalent to 280 molecules of carbon dioxide (10). These "equivalent $CO_2$ impacts" were used as the basis for Fig. 2 which shows the equivalent $CO_2$ emissions to provide 396-MW of electricity 100-km from the IGCC system.

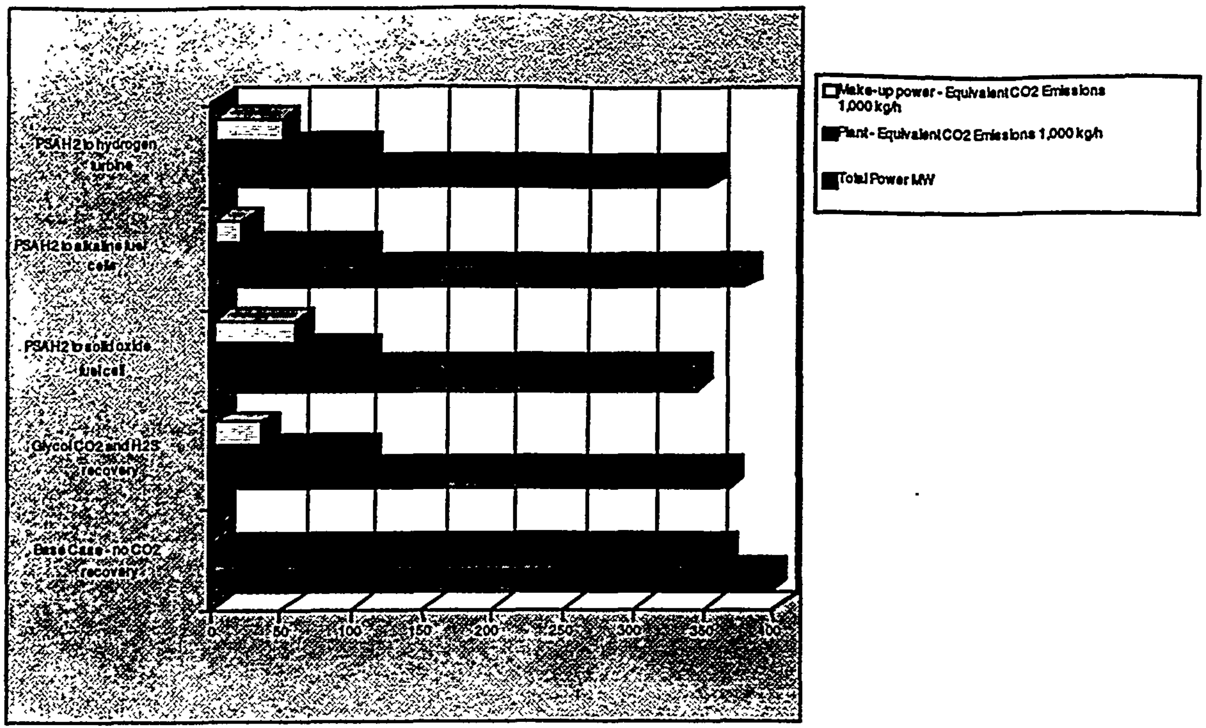

Fig. 2. Equivalent $CO_2$ Greenhouse Emissions 396 MW Net-Cycle.

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