EXECUTIVE SUMMARY

BACKGROUND

In 1999, both Parsons Infrastructure & Technology Group (Parsons) and the National Renewable Energy Laboratory (NREL) prepared conceptual plant designs and cost estimates for producing hydrogen from coal gasification. Parsons' approach to producing hydrogen focused on integrating high-temperature ceramic membranes with coal gasification to both shift and separate hydrogen from the syngas.[1] Parsons also prepared a base case design for hydrogen from coal gasification utilizing conventional technology. The NREL approach to plant design focused on advanced and conventional technology for hydrogen production with high-temperature gas cleanup, shift, and PSA purification, augmented with various concepts to sequester CO_2 and increase hydrogen production.[2] These concepts consisted of a base case design for production of hydrogen from coal gasification accompanied by CO_2 sequestration in coal seams, reforming extracted methane, and producing power from extracted coal seam methane. The base case cost for producing hydrogen from coal gasification was reported by Parsons to be $5.57/MMBtu, while NREL reported the base case cost for hydrogen from coal gasification to be $18.97/MMBtu.

The primary differences in the cost of hydrogen from the Parsons and NREL plants can be realized from the Total Plant Investment (TPI). The TPI for the NREL plant per unit of hydrogen production is 2.3 times that of the Parsons plant.

Due to the wide differences in reported costs for capital and the need to provide a baseline cost for hydrogen production, NETL has tasked Parsons to review its prior plant design and cost estimate for producing hydrogen from coal gasification utilizing commercial technology. The key benefit of utilizing commercial technology is the obtaining of credible cost estimates for the plant, with a minimum of process contingency. The results of this effort are intended to prepare a basis from which to utilize individualized financial parameters in the U.S. Department of Energy (DOE) Integrated Gasification Combined Cycle (IGCC) Cost Estimating Model to arrive at a selling price for hydrogen.

Focus of the plant design will be from a common thermal gasifier throughput. Two coals will be reviewed, Pittsburgh No. 8 and PRB Wyodak. Hydrogen costs from these coals will be prepared to quantify the differing plant characteristics associated with bituminous coal or sub-bituminous coal.

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[1] "Decarbonized Fuel Production Facilities/Base Case Comparisons," Letter Report, U.S. DOE, June 1999.

[2] Spath, Pamela and Amos, Wade, "Technoeconomic Analysis of Hydrogen Production from Low-Btu Western Coal Augmented with CO_2 Sequestration and Coalbed Methane Recovery Including Delivered Hydrogen Costs," NREL, September 1999.

INTRODUCTION

The objective of this task was to prepare capital and operating cost data to be used to arrive at a plant gate cost for hydrogen produced from coal gasification. The two coals used in this study are Pittsburgh No. 8 bituminous and Wyodak Powder River Basin (PRB) sub-bituminous. Hydrogen cost was determined by first preparing two plant designs for hydrogen production, based on currently available process technology, and meeting current permitting regulations for environmental compliance. These baseline plants will not capture CO_2.

To arrive at a cost estimate for hydrogen, the design included commercially available process technology obtained from verifiable sources. The plants utilized commercially available technology including a Wabash River-scale Destec (E-Gas™) gasifier, conventional gas cooling, commercial shift conversion and acid gas cleanup, commercial sulfuric acid technology, and commercial pressure swing adsorption (PSA). The E-Gas™ gasifier is the gasifier of choice for this study since it has been operated on both bituminous and sub-bituminous coals. Figure ES-1 is the block flow diagram for the plant.

Based on financial assumptions typically used by Parsons for IGCC, the cost of hydrogen was estimated for Pittsburgh No. 8 coal and for Wyodak PRB coal at the plant gate. The results of these two cases were imported into the DOE IGCC financial model. Using the financial model, sensitivities of the effect of financial parameters can easily be determined. When different financial parameters are defined, the impact can be quantified.

Figure ES-1
Block Flow Diagram
Conventional Hydrogen Plant

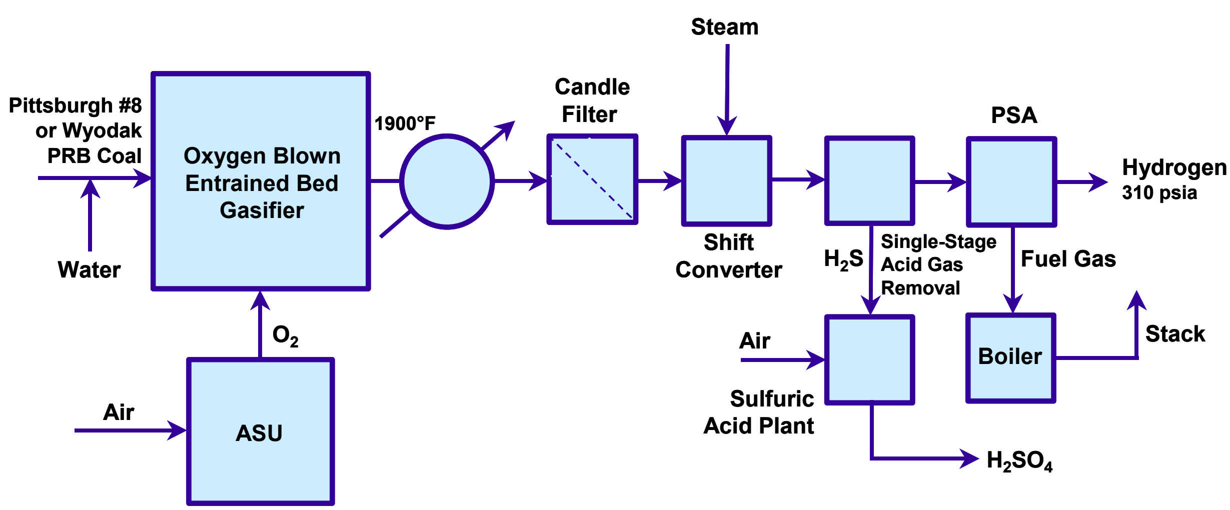

Table ES-1 lists the plant design criteria and site conditions.

Table ES-1
Design Criteria for Conventional Hydrogen Production Plant

Hydrogen Production Plant Parameter	Hydrogen Production Plant Design Basis
Ambient Conditions	14.7 psia, 60°F, river water access
Coal Feed	Pittsburgh No. 8/PRB Wyodak
Gasifier	Oxygen-blown E-Gas™ with second stage adjusted for 1900°F output
Coal Feed Rate	2,500 tpd dry basis
Hot Gas Temperature	~1900°F
Gasifier Outlet Pressure	450 psia
Gas Quench/Cooling	625°F
Metallic Candle Filter	Following quench/cooling
CO-Shift	Single-stage high-temperature, sulfur-tolerant
Desulfurization	Proprietary amine
Sulfur Recovery	Sulfuric acid byproduct
CO_2 Recovery	None
Hydrogen Purification	Pressure swing adsorption (PSA)
PSA Retinate Gas	Fired in auxiliary boiler
CO_2 Product Pressure	N/A
Hydrogen Utilization	315 psia at plant gate
Auxiliary Power Block	Steam turbine generator
Plant Size	Maximum hydrogen production from 2,500 tpd dry coal feed
Plant Capacity Factor	90 percent

Process Selection

Gasifier. The E-Gas™ gasifier is selected for these plants because of the wide differences in the coals to be compared. The E-Gas™ two-stage design has resulted in successful operation on both bituminous and sub-bituminous coals. By comparison, the Texaco gasifier with its single-stage entrained slurry feed reaches operational limitations with high-moisture coals, e.g., sub-bituminous and lignite.

Shift Reactor Catalyst. For this plant design the CO converter was located upstream of the acid gas removal (AGR) unit. The CO shift catalyst selected for these plants is the Haldor-Topsoe SSK Sulfur Tolerant CO Conversion Catalyst. The plant will utilize a single-stage high-temperature shift, resulting in a CO conversion of greater than 80 percent. The SSK catalyst also promotes COS hydrolysis, thereby resulting in an acid gas consisting of all H_2S.

Acid Gas Removal. The traditional approach to acid gas removal is with regenerable amines. Other methods include removal of H_2S with membranes systems or with molecular sieves. Regenerable amines are by far the most popular means of removal of acid gas from all types of gaseous streams. Therefore, the AGR process selected for these plants is a proprietary amine with an H_2S concentrator on the regenerated acid gas. The gas from the AGR process, concentrated in H_2S, will be used as a feed for a Monsanto H_2S-fired sulfuric acid plant.

Hydrogen Purification. The three main processes for hydrogen purification are the pressure swing adsorption, the selective permeation process using polymer membranes, and the cryogenic separation process. Each of these processes is based on a different separation principle, and the process characteristics differ significantly. The PSA system was selected based on the ability to produce high purity (99.9 percent) hydrogen, low amounts of CO and CO_2, ease of operation, and a single system.

PITTSBURGH NO. 8 COAL

This section is dedicated to the design and cost estimate for a hydrogen plant fed with Pittsburgh No. 8 bituminous coal. This coal is characterized having high volatility, low ash and moisture content, and high as-received heating value. The high sulfur content results in a significant value-added from the sulfuric acid byproduct.

Heat and Material Balance

The heat and material balance for the IGCC plant is based on the maximum hydrogen production from 2,500 tons per day of dry coal. Ambient operating conditions are indicated in the plant design basis. The pressurized entrained flow E-Gas™ two-stage gasifier uses a coal/water slurry and oxygen to produce a medium heating value fuel gas. The syngas produced in the gasifier first stage at about 2450°F (1343°C) is quenched to 1900°F (1038°C) by reacting with slurry injected into the second stage. The syngas passes through a fire tube boiler syngas cooler and leaves at 1300°F (704°C). A second gas cooler in series cools the gas further to 645°F (341°C). High-pressure saturated steam is generated in the syngas coolers and is joined with the main steam supply.

The gas goes through a series of additional gas coolers and cleanup processes including a scrubber. Slag captured by the syngas scrubber is recovered in a slag recovery unit.

The syngas stream from the syngas scrubber enters the high-temperature shift converter, which contains a bed of sulfided shift catalyst. The shift reaction converts over 80 percent of the CO to hydrogen and CO_2 and hydrolyzes COS to H_2S. Following the shift converter, the cooled gas stream passes through a proprietary amine acid gas removal process, which removes H_2S and some of the CO_2. The clean gas stream then passes through the PSA for final purification of the hydrogen. Regeneration gas from the PSA contains fuel value, and is fed to the heat recovery steam generator (HRSG). Regeneration gas from the AGR plant is fed to a sulfuric acid plant.

The cryogenic oxygen plant supplies 99 percent purity oxygen to the gasifiers at the rated pressure. A dedicated air compressor provides air supply for the oxygen plants.

The steam cycle is based on maximizing heat recovery from the gasifier cooler and HRSG, as well as utilizing steam generation opportunities in the shift process.

Overall performance for the entire plant is summarized in Table ES-2, which includes auxiliary power requirements. The net plant output power, after plant auxiliary power requirements are deducted, is nominally 38 MW_e. The overall plant thermal effective efficiency (thermal value of hydrogen and power produced) is 62.3 percent, on an HHV basis.

Table ES-2
Performance Summary
Hydrogen Production from Pittsburgh No. 8 Coal

Plant Size, tons H_2/day (MMscfd) @ 346 psia	312.6 (112.2)
Coal Feed (dry basis)	2,500 tpd
Plant Availability	90%
Cold Gas Efficiency	57.7%
Equivalent Thermal Efficiency, HHV	62.3%
Gross Power Production	78.5 MW
Auxiliary Power	40.9 MW
Net Power	37.6 MW

Capital Cost

The total plant cost for the plant producing 313 tons of hydrogen per day from Pittsburgh No. 8 coal is $376.1 million in 2001 dollars. The capital cost summary is included in Table ES-3.

Consumables

Shift Catalyst:

- Change-out every 3 years
- 0.0045 pound of catalyst per 1,000 standard cubic feet of hydrogen
- 250 tons initial charge
- 85 tons per year annual cost

Proprietary Amine:

- 12 pounds per hour
- 100,000 pounds per year

Table ES-3
Capital Cost Summary – Hydrogen Production from Pittsburgh No. 8 Coal

Client: DEPARTMENT OF ENERGY **Report Date:** 03-Jun-2002 01:19 PM
Project: NETL H_2 Production Facility

TOTAL PLANT COST SUMMARY

Case: Bituminous H_2 Plant w/o CO_2 Capture
Plant Size: 312.6 H_2 TPD **Estimate Type:** Conceptual Cost Base (Dec) 2001 ($X1000 & $X1000/TPD)

Acct No.	Item/Description	Equipment Cost	Material Cost	Labor		Sales Tax	Bare Erected Cost $	Eng'g CM H.O.& Fee	Contingencies		TOTAL PLANT COST	
				Direct	Indirect				Process	Project	$	$/TPD
1	COAL & SORBENT HANDLING	5,354	1,099	3,955	277		$10,686	855		1,154	$12,694	41
2	COAL & SORBENT PREP & FEED	8,987	1,307	4,905	343		$15,542	1,733		1,728	$19,003	61
3	FEEDWATER & MISC. BOP SYSTEMS	4,506	1,339	2,679	187		$8,711	697		941	$10,348	33
4	GASIFIER & ACCESSORIES											
4.1	Gasifier, Syngas Cooler & Auxiliaries (E	51,616		21,976	1,538		$75,130	9,016		8,415	$92,560	296
4.2	Syngas Cooling	w/4.1		w/ 4.1	w/ 4.1			w/ 4.1		w/ 4.1		
4.3	ASU/Oxidant Compression	29,284		w/equip.			$29,284	2,343		3,163	$34,789	111
4.4-4.9	Other Gasification Equipment	6,881	5,691	4,811	337		$17,720	1,447		1,917	$21,084	67
	SUBTOTAL 4	*87,781*	*5,691*	*26,787*	*1,875*		*$122,134*	*12,805*		*13,494*	*$148,433*	*475*
5	HYDROGEN SEPARATION/GAS CLEAN	59,135	4,205	21,176	1,482		$85,999	10,111		9,611	$105,721	338
6	COMBUSTION TURBINE/ACCESSORIES											
6.1	Expander Turbine/Generator											
6.2-6.9	Combustion Turbine Accessories											
	SUBTOTAL 6											
7	HRSG, DUCTING & STACK											
7.1	Heat Recovery Steam Generator	4,533		551	39		$5,123	410		553	$6,086	19
7.2-7.9	HRSG Accessories, Ductwork and Stack	561	209	335	23		$1,129	90		122	$1,341	4
	SUBTOTAL 7	*5,094*	*209*	*886*	*62*		*$6,251*	*500*		*675*	*$7,427*	*24*
8	STEAM TURBINE GENERATOR											
8.1	Steam TG & Accessories	7,612		1,061	74		$8,747	700		945	$10,392	33
8.2-8.9	Turbine Plant Auxiliaries and Steam Pip	3,470	106	1,611	113		$5,300	424		572	$6,296	20
	SUBTOTAL 8	*11,082*	*106*	*2,672*	*187*		*$14,047*	*1,124*		*1,517*	*$16,688*	*53*
9	COOLING WATER SYSTEM	2,375	1,163	1,901	133		$5,572	446		602	$6,619	21
10	ASH/SPENT SORBENT HANDLING SYS	5,147	653	2,196	154		$8,150	888		904	$9,941	32
11	ACCESSORY ELECTRIC PLANT	5,029	2,077	4,075	285		$11,467	917		1,238	$13,623	44
12	INSTRUMENTATION & CONTROL	5,292	1,257	3,903	273		$10,725	858		1,158	$12,741	41
13	IMPROVEMENTS TO SITE	1,566	900	2,593	182		$5,241	419		566	$6,226	20
14	BUILDINGS & STRUCTURES		2,663	2,711	190		$5,564	445		601	$6,610	21
	TOTAL COST	**$201,347**	**$22,671**	**$80,439**	**$5,631**		**$310,088**	**$31,798**		**$34,189**	**$376,074**	**1203**

PSA Sorbent:

- Periodic change-out with scheduled maintenance

SO_2 Conversion Catalyst:

- Periodic change-out with scheduled maintenance

Byproduct Credits

The production of 229 tons of sulfuric acid per day is taken as a byproduct credit at $75 per ton.

WYODAK PRB COAL

This section is dedicated to the design and cost estimate for a hydrogen plant fed with Wyodak PRB sub-bituminous coal. This coal is characterized having low volatility, high ash and moisture content, and a lower as-received heating value. The low sulfur content results in a lesser value-added from the sulfuric acid byproduct.

Heat and Material Balance

The heat and material balance for the IGCC plant is based on the maximum hydrogen production from 2,500 tons per day of dry coal. Ambient operating conditions are indicated in the plant design basis. The pressurized entrained flow E-Gas™ two-stage gasifier uses a coal/water slurry and oxygen to produce a medium heating value fuel gas. The syngas produced in the gasifier first stage at about 2450°F (1343°C) is quenched to 1900°F (1038°C) by reacting with slurry injected into the second stage. The syngas passes through a fire tube boiler syngas cooler and leaves at 1300°F (704°C). A second gas cooler in series cools the gas further to 645°F (341°C). High-pressure saturated steam is generated in the syngas coolers and is joined with the main steam supply.

The gas goes through a series of additional gas coolers and cleanup processes including a scrubber. Slag captured by the syngas scrubber is recovered in a slag recovery unit.

The syngas stream from the syngas scrubber enters the high-temperature shift converter, which contains a bed of sulfided shift catalyst. The shift reaction converts over 80 percent of the CO to hydrogen and CO_2 and hydrolyzes COS to H_2S. Following the shift converter, the cooled gas stream passes through a proprietary amine acid gas removal process, which removes H_2S and some of the CO_2. The clean gas stream then passes through the PSA for final purification of the hydrogen. Regeneration gas from the PSA contains fuel value, and is fed to the HRSG. Regeneration gas from the AGR plant is fed to a sulfuric acid plant.

The cryogenic oxygen plant supplies 99 percent pure oxygen to the gasifiers at the rated pressure. A dedicated air compressor provides air supply for the oxygen plants.

The steam cycle is based on maximizing heat recovery from the gasifier cooler and HRSG, as well as utilizing steam generation opportunities in the shift process.

Overall performance for the entire plant is summarized in Table ES-4, which includes auxiliary power requirements. The net plant output power, after plant auxiliary power requirements are deducted, is nominally 42 MW_e. The overall plant thermal effective efficiency (thermal value of hydrogen and power produced) is 59.7 percent, on an HHV basis.

Table ES-4
Performance Summary
Hydrogen Production from Wyodak Coal

Plant Size, tons H_2/day (MMscfd) @ 346 psia	259.2 (93.1)
Coal Feed (dry basis)	2,500 tpd
Plant Availability	90%
Cold Gas Efficiency	54.2%
Equivalent Thermal Efficiency, HHV	59.7%
Gross Power Production	81.5 MW
Auxiliary Power	39.6 MW
Net Power	41.9 MW

Capital Cost

The total plant cost for the plant producing 313 tons of hydrogen per day from Wyodak PRB coal is $364.6 million in 2001 dollars. The capital cost summary is included in Table ES-5.

Table ES-5
Capital Cost Summary – Hydrogen Production from Wyodak Coal

Client: DEPARTMENT OF ENERGY
Project: NETL H_2 Production Facility
Report Date: 03-Jun-2002 03:16 PM

TOTAL PLANT COST SUMMARY

Case: Sub-Bituminous H_2 Plant w/o CO_2 Capture
Plant Size: 259.2 H_2 TPD **Estimate Type:** Conceptual Cost Base (Dec) 2001 ($X1000 & $X1000/TPD)

Acct No.	Item/Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Sales Tax	Bare Erected Cost $	Eng'g CM H.O.& Fee	Contingencies Process	Contingencies Project	TOTAL PLANT COST $	TOTAL PLANT COST $/TPD
1	COAL & SORBENT HANDLING	6,242	1,282	4,611	323		**$12,457**	997		1,345	**$14,799**	57
2	COAL & SORBENT PREP & FEED	10,581	1,539	5,776	404		**$18,299**	2,040		2,034	**$22,373**	86
3	FEEDWATER & MISC. BOP SYSTEMS	4,259	1,253	2,561	179		**$8,253**	660		891	**$9,804**	38
4	GASIFIER & ACCESSORIES											
4.1	Gasifier, Syngas Cooler & Auxiliaries (E	54,709		23,270	1,629		**$79,607**	9,553		8,916	**$98,076**	378
4.2	Syngas Cooling	w/4.1		w/ 4.1	w/ 4.1			w/ 4.1		w/ 4.1		
4.3	ASU/Oxidant Compression	29,814		w/equip.			**$29,814**	2,385		3,220	**$35,419**	137
4.4-4.9	Other Gasification Equipment	7,665	5,742	5,067	355		**$18,829**	1,538		2,037	**$22,404**	86
	SUBTOTAL 4	*92,188*	*5,742*	*28,336*	*1,984*		*$128,250*	*13,476*		*14,173*	*$155,899*	*602*
5	HYDROGEN SEPARATION/GAS CLEAN	46,572	3,701	16,976	1,188		**$68,437**	8,005		7,644	**$84,086**	324
6	COMBUSTION TURBINE/ACCESSORIES											
6.1	Expander Turbine/Generator											
6.2-6.9	Combustion Turbine Accessories											
	SUBTOTAL 6											
7	HRSG, DUCTING & STACK											
7.1	Heat Recovery Steam Generator	4,533		551	39		**$5,123**	410		553	**$6,086**	23
7.2-7.9	HRSG Accessories, Ductwork and Stack	496	185	296	21		**$997**	80		108	**$1,185**	5
	SUBTOTAL 7	*5,029*	*185*	*847*	*59*		*$6,120*	*490*		*661*	*$7,271*	*28*
8	STEAM TURBINE GENERATOR											
8.1	Steam TG & Accessories	7,843		1,094	77		**$9,013**	721		973	**$10,707**	41
8.2-8.9	Turbine Plant Auxiliaries and Steam Pip	3,567	109	1,656	116		**$5,447**	436		588	**$6,471**	25
	SUBTOTAL 8	*11,409*	*109*	*2,749*	*192*		*$14,460*	*1,157*		*1,562*	*$17,178*	*66*
9	COOLING WATER SYSTEM	2,438	1,193	1,951	137		**$5,719**	458		618	**$6,795**	26
10	ASH/SPENT SORBENT HANDLING SYS	4,322	559	1,845	129		**$6,855**	745		760	**$8,360**	32
11	ACCESSORY ELECTRIC PLANT	4,974	2,052	4,028	282		**$11,335**	907		1,224	**$13,466**	52
12	INSTRUMENTATION & CONTROL	5,045	1,199	3,720	260		**$10,224**	818		1,104	**$12,146**	47
13	IMPROVEMENTS TO SITE	1,465	842	2,425	170		**$4,902**	392		529	**$5,824**	22
14	BUILDINGS & STRUCTURES		2,630	2,702	189		**$5,521**	442		596	**$6,559**	25
	TOTAL COST	**$194,524**	**$22,285**	**$78,527**	**$5,497**		**$300,832**	**$30,586**		**$33,142**	**$364,560**	**1407**

Consumables

Shift Catalyst:

- Change-out every 3 years
- 0.0045 pound of catalyst per 1,000 standard cubic feet of hydrogen
- 210 tons initial charge
- 70 tons per year annual cost

Proprietary Amine:

- 12 pounds per hour
- 100,000 pounds per year

PSA Sorbent:

- Periodic change-out with scheduled maintenance

SO_2 Conversion Catalyst:

- Periodic change-out with scheduled maintenance

Byproduct Credits

The production of 61 tons of sulfuric acid per day is taken as a byproduct credit at $75 per ton.

BASIS OF COST OF HYDROGEN COMPARISONS FOR VARIOUS FINANCIAL ASSUMPTIONS

Based on financial assumptions typically used by Parsons for IGCC (see Table ES-6), the cost of hydrogen was estimated to be $6.01/MMBtu ($2.06/Mcf) for Pittsburgh No. 8 and $6.44/MMBtu ($2.20/Mcf) for Wyodak PRB coal at plant gate.

The results of these two cases were imputed into the DOE IGCC financial model. Using the financial model, sensitivities of the effect of financial parameters can easily be determined. When different financial parameters are defined, the impact can be quantified. Figure ES-2 shows one such variation, the internal rate of return (IRR) versus the cost of hydrogen.

Table ES-6
Financial Parameters

Levelized capacity factor	90%
Design/construction period	4 years
Plant startup date	January 2005
Land area/Unit cost	100 acres @ 41,500/acre
Project book life	20 years
Project tax life	20 years
Tax depreciation method	Accelerated based on ACRS class
Property tax rate	1.0% per year
Insurance tax rate	1.0% per year
Federal income tax rate	34.0%
State income tax rate	4.2%
Capital structure	
Common equity	20% @ 16.50% annum
Debt	80% @ 6.30% annum
Weighted cost of capital (after tax)	6.49%
Sulfur credit	$75/ton
Power sales	$30.00/MWh

Figure ES-2
Sensitivity of IRR to Hydrogen Costs