APPENDIX K: INPUT-OUTPUT DATA FOR HYDROGEN FROM COAL AND HYDROGEN FROM BIOMASS CONVERSION PROCESSES

An Appendix to the Report "A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials"

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Table 1. Overview of literature on hydrogen production process via coal gasification

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
R. H. Williams, 2001			
	Coal input rate(MW_{th})	1550	1554
	CO_2 emission rate(kgC/GJ_{H2})	36.33	2.62
	CO_2 disposal rate(t CO_2/h)	-	445.9
	Electric power balance(*MWe*)		
	Gas turbine output	-	58.9
	Steam turbine output	143.5	107.1
	Syngas expander output	-	-
	Air separation	-41.8	-41.9
	Extra O_2 compressor	-25.5	-25.6
	Gasification auxiliaries	-14.7	-14.7
	CO_2 compressor(→*150 bar*)	-	-37.0
	Purge compressor for PSA unit	-	-8.6
	Other auxiliaries	-6.4	-5.2
	Net power output(*MWe*)	55.1	33.0
	1^{st} law efficiency (η_{1st}), HHV basis (%)	68.07	66.47
	Effective efficiency (η_{eff}) of H_2 production, HHV basis (%)	70.30	67.68
	Plant capacity factor (%)	80	80
	Notes: 1) For this case, H_2 and electricity is co-produced. The main outputs are H_2, electricity, sulfur, N_2, and CO_2. 2) η_{1st} = (electricity + H_2 output) / (coal input); η_{eff} = (H_2 output) / (coal input – coal saved), where the coal saved is the amount of coal that would otherwise have to be consumed in a stand-alone facility to produce the amount of electricity generated as a co-product of H_2. 3) t = metric tonne. 4) CO_2 recovery case involves CO_2 compression to 150 bars for pipeline transport to a sequestration site. 5) 92.7% of coal C is recovered as CO_2 for disposal.		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
Bechtel Corporation et al.,2003			
	Configuration		
	Plant location	Midwest	
	# of air separation units	1	
	# of gas turbines	0	
	# of gasification trains	1	
	# of gasification vessels	2	
	# of syngas processing trains	1	
	# of 50% H_2 trains	2	
	Design Feed Rates		
	Feedstock type	Illinois NO. 6 coal	
	Coal, TPD as received	3,517	
	Coal, TPD dry	3,007	
	Feed, MMBtu HHV/hr	3,195	
	Feed, MMBtu LHV/hr	3,076	
	Flux, TPD	0	
	Water, gpm	2,457	
	Oxygen, TPD of 95% O_2	2,522 (99.5%)	
	Oxygen, TPD of O_2	2,507	
	Design Product Rates		
	Electric power, MW	-18.4	
	Steam (750 °F/700 psig), Mlb/hr	-	
	Hydrogen, MMscfd	141.2	
	Sulfur, TPD	76	
	Slag (@15% water), TPD	474	
	Fuel gas, MMBtu HHV/hr	-	
	Solid waste to disposal, TPD	-	
	Gas Turbine		
	Cold gas efficiency (HHV), %	76.5	
	Steam turbine power, MW	70.6	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Internal power use, MW	89.0	
	Emissions		
	SO_x as SO_2, lb/hr	191	
	NO_x as NO_2, lb/hr	27	
	CO, lb/hr	1,840	
	CO_2, Mlb/hr	638.0	
	Sulfur removal, %	98.5	
	Performance parameters—emissions		
	SO_x (SO_2) as lb/MMBtu(H_2, HHV)	0.060	
	NO_x (NO_2) as lb/MMBtu(H_2, HHV)	0.008	
	CO, lb/MMBtu(H_2, HHV)	0.576	
	CO_2, lb/MMBtu(H_2, HHV)	200	
	Notes: 1) For this case, there is no CO_2 capture and no electricity co-produced for export. 2) The gasifier is Global Energy's two-stage gasifier which employs full slurry quench to control the second stage outlet temperature. 3) From 3,007 TPD of dry Illinois NO. 6 coal and 18.4 MW of import power, the coal-to-H_2 plant produces 141.2 MMscfd of hydrogen, 76 TPD of sulfur and 474 TPD of slag (15% water). 4) All the carbon in the feed eventually is converted to CO_2 except for the small amounts that are contained in the slag and leave as CO. 5) Heavy metals are very low in the gasification facility because they are encapsulated in the slag. Other metals such as mercury and selenium are volatile and are detected in the syngas; however, metals removal should be easier compared to a conventional combustion plant. Mercury removal was not considered in the plant design. 6) Slag, the major solid byproduct of the gasification process, can be marketed as construction material. There are no solid wastes from the coal gasification process—no scrubber sludge, fly ash or bottom ash. Small amounts of used catalysts or adsorbents still require disposal. 7) TPD = ton per day. 8) CO_2 capture involves energy requirements to transport CO_2 to the sequestration site.		
G. Rizeq et al., 2002			
	Plant size, MW		400
	Coal capacity, TPD		2,800

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Capacity factor, %		75
	CO_2 capture, %		99
	Efficiency, %(HHV)		57.4
	Fuel flexibility		Coal, biomass planned
	Notes: 1) This process is called AGC (Advanced Gasification Combustion; it is a novel concept addressed by Vision 21 program), which is different from IGCC. 2) For this case, H_2 and electricity is co-produced. The main outputs are high-purity H_2, electricity, sequestration-ready CO_2 and SO_2. 3) Process efficiency = (electricity + H_2 output) / (coal input), which could be as high as 67% on a HHV basis. 4) No NO_x formation. 5) Hg concentrated in Reactor 1 product stream for AGC, whereas Hg concentrated in syngas stream for IGCC. 6) CO_2 capture involves energy requirements to transport CO_2 to the sequestration site.		
R. H. Williams et al., 2003			
	<u>Comparison of process efficiency</u>		
	Electricity, % HHV	η_e = 100*(elec out)/(coal in)	
	Quench	40.8	34.9
	Syncooler	44.3	37.1
	H_2, % HHV	η_h = 100*(H_2 out)/[coal in – (elec out / η_e)]	
	Quench	69.7	67.0
	Syncooler	72.9	69.6
	<u>Case 1: Conventional Tech.</u>		
	Size (H_2), MWh	1,265	1,265
	Power coproduct, MWe	78	39
	η_h, % HHV	69.7	67.0
	<u>Case 2: Conventional Tech.</u>		
	Size (H_2), MWh		268
	Power coproduct, MWe		349
	<u>Case 3: Co-storage of CO_2 and SO_2</u>		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Size (H_2), MWh		1,000
	Power coproduct, MWe		18
	η_h, % HHV		69.1
	Notes: 1) These cases correspond to 70 bar coal gasifier, conventional technology, i.e., IGCC. 2) Gasifier at 70 bar with (i) quench or (ii) radiative + convective syngas cooler. 3) Co-capture and co-storage of SO_2 and CO_2 would probably be cost-effective, though viability of co-storage option requires clarification. 4) Increasing gasifier pressure (70→120 bar) raises system efficiency and offers potentially lower H_2 cost, if electricity coproduct has high value. 5) But efficiency gains often are not cost-effective (coal prices are low). 6) CO_2 capture cases involve energy requirements for CO_2 capture and storage.		
J. Ogden et al., 2003			
	Notes: 1) To make enough H_2 for all Columbus cars in a coal→ H_2 plant with 65% energy conv. Efficiency, would need to use ~12-22% of present of coal flow at General Gavin. 2) General Gavin power plant is operated at only ~74% capacity factor today (because it follows electricity load). If this plant is "repowered" with a coal IGCC, with CO_2 capture, and run at a higher capacity factor, then it might be possible to supply electric and needs and make enough H_2 during off-peak electric demand hours for light duty vehicles.		
P. Chiesa et al., 2003			
	Capacity factor, %	80	80
	<u>Quench: % of coal LHV input</u>		
	Gas turbine	4.23	4.23
	Steam turbine	7.49	7.49
	Syngas expander	0.00	0.00
	ASU and gas compression	-5.37	-5.37
	Auxiliaries	-1.32	-1.36
	CO_2 removal and compression	-0.82	-2.91
	Net electric output	4.21	2.09

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Net H_2 output	57.46	57.46
	Note: The above info is based on 70 bar, S removal, 99+ purity, and max H_2.		
	<u>Syncooler: % of coal LHV input</u>		
	Gas turbine	4.51	4.51
	Steam turbine	9.38	9.38
	Syngas expander	0.00	0.00
	ASU and gas compression	-5.39	-5.39
	Auxiliaries	-1.49	-1.49
	CO_2 removal and compression	-0.82	-2.89
	Net electric output	6.18	4.11
	Net H_2 output	57.45	57.45
	Note: The above info is based on 70 bar, S removal, 99+ purity, and max H_2.		
	<u>Quench: % of coal LHV input. Gasifier at 120 bar</u>		
	Gas turbine		4.33
	Steam turbine		6.62
	Syngas expander		1.71
	ASU and gas compression		-5.56
	Auxiliaries		-1.40
	CO_2 removal and compression		-2.90
	Net electric output		2.80
	Net H_2 output		57.28
	<u>Quench: % of coal LHV input. Co-capture of H_2S and CO_2</u>		
	Gas turbine		4.23
	Steam turbine		7.49
	Syngas expander		0.00
	ASU and gas compression		-5.37
	Auxiliaries		-1.36

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	CO_2 removal and compression		-2.91
	Net electric output		2.09
	Net H_2 output		57.46
	Quench: % of coal LHV input. **Fuel grade purity**		
	Gas turbine		3.91
	Steam turbine		7.25
	Syngas expander		0.18
	ASU and gas compression		-4.98
	Auxiliaries		-1.40
	CO_2 removal and compression		-2.91
	Net electric output		2.06
	Net H_2 output		58.17
	Quench: % of coal LHV input. **Increase E/H_2 by reducing flow to PSA**		
	Gas turbine		22.31
	Steam turbine		15.03
	Syngas expander		0.73
	ASU and gas compression		-6.97
	Auxiliaries		-1.64
	CO_2 removal and compression		-2.91
	Net electric output		26.56
	Net H_2 output		17.25

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Notes: 1) Such plant can operate with Electricity/ H_2 ratios spanning the whole range from about zero to infinity. 2) In configurations with syngas cooler, efficiencies ~70% can be achieved at the expense of higher CO_2 emissions. 3) Co-capture of CO_2 and H_2S appears to have the same cost of sulfur removal alone. If that is confirmed, co-capture allows capturing CO_2 at almost zero cost. 4) Increasing gasification pressure from 70 to 120 bar does not seem to give significant advantages. 5) "Fuel-grade"(~93% pure by volume) H_2 VS pure H_2 increases electric efficiency by ~1% and decreases H_2 cost by ~4%. 6) Final delivery pressure of CO_2 (after compression) is 150 bars. 7) CO_2 capture includes energy requirements to transport CO_2 to the sequestration site.		
T. Kreutz et al., 2002			
	Plant scale, GW_{th} H_2	1	1
	Capacity factor, %	80	80
	Plant lifetime, yr	25	25
	Construction time, yr	4	4
	Conventional Tech., efficiency, % HHV		
	Base case	71.6	69.4
	Fuel-grade H_2	75.5	74.7
	HSMR-Based System, efficiency, % HHV		
	Base case	75	69.1
	Cooled raf. Turbine	66	57.8
	High perm HSMR	76	69.9

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Notes: 1) HSMR refers to Hydrogen Separation Membrane Reactor. 2) Sequestration lowers efficiency and increases costs. 3) Co-sequestration has potential to lower costs. 4) H_2 purity comes at a significant cost. Fuel grade (~94% H_2) can be produced at a significantly lower cost in a system with significantly lower capital cost. 5) CO_2 capture cases involve the capture, compression, dehydration, and pipeline transport of CO_2.		
D. Gray et al., 2002			
	Case 1		
	Carbon sequestration, %	0	
	H_2, MMscfd	131	
	Coal, TPD (AR)	3,000	
	Efficiency, %HHV	63.7	
	Excess electric power, MW	20.4	
	Case 2		
	Carbon sequestration, %		87%
	H_2, MMscfd		119
	Coal, TPD (AR)		3,000
	Efficiency, %HHV		59
	Excess electric power, MW		26.9
	Note: For Cases 1 and 2, applied is a Texaco quench gasification system with conventional acid gas removal and PSA for hydrogen recovery. They are a single train 3,000 tons per day plant.		
	Case 3		
	Carbon sequestration, %		100
	H_2, MMscfd		158
	Coal, TPD (AR)		3,000
	Efficiency, %HHV		75.5
	Excess electric power, MW		25

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Note: The configuration for Case 3 uses advanced E-gas gasification with hot gas cleanup in combination with a ceramic membrane system operating at about 600 °C.		
	Case 4		
	Carbon sequestration, %	0	
	H_2, MMscfd	149	
	Coal, TPD (AR)	6,000	
	Efficiency, %HHV	62.4	
	Total power generated, MW	592	
	Parasitic power required, MW	117	
	Excess electric power, MW	475	
	Case 5		
	Carbon sequestration, %		95
	H_2, MMscfd		153
	Coal, TPD (AR)		6,000
	Efficiency, %HHV		56.5
	Total power generated, MW		484
	Parasitic power required, MW		126
	Excess electric power, MW		358
	Note: In Cases 4 and 5, two trains of advanced entrained gasification are used and the coal feed is 6,000 TPD. One train makes synthesis gas to feed the PSA unit for hydrogen production and the other train makes synthesis gas to feed a combined cycle power plant.		
	Case 6		
	Carbon sequestration, %		100
	H_2, MMscfd		153
	Coal, TPD (AR)		6,000
	Efficiency, %HHV		59
	Total power generated, MW		619
	Parasitic power required, MW		202
	Excess electric power, MW		417

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Note: Case 6 is similar to Case 3 except that two trains of gasification are used.		
	Case 7		
	Carbon sequestration, %	0	
	H_2, MMscfd	0	
	Coal, TPD (AR)	3,000	
	Efficiency, %HHV	65.7	
	Total power generated, MW	624	
	Parasitic power required, MW	57	
	Excess electric power, MW	567	
	Case 8		
	Carbon sequestration, %		98
	H_2, MMscfd		0
	Coal, TPD (AR)		3,000
	Efficiency, %HHV		61.3
	Total power generated, MW		590
	Parasitic power required, MW		61
	Excess electric power, MW		529
	Case 9		
	Carbon sequestration, %		90
	H_2, MMscfd		149
	Coal, TPD (AR)		6,000
	Efficiency, %HHV		64.5
	Total power generated, MW		629
	Parasitic power required, MW		120
	Excess electric power, MW		509
	Case 10		
	Carbon sequestration, %		95
	H_2, MMscfd		150
	Coal, TPD (AR)		6,000
	Efficiency, %HHV		65.2

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Total power generated, MW		879
	Parasitic power required, MW		359 (Air Separation Unit [ASU], 109; CO_2 compr., 68; H_2 compr., 8; and SOFC air compression, 175)
	Excess electric power, MW		519
	Notes: 1) Cases 7 and 8 are baseline SOFC (Solid Oxide Fuel Cell) configurations that only produce electric power. 2) Case 9 is a two-gasification train carbon sequestered co-production case where a SOFC topping cycle configuration is used in combination with a PSA system for hydrogen separation. 3) Case 10 is a two gasification train co-production case where a SOFC topping cycle configuration is used in combination with a ceramic membrane system for hydrogen separation.		
	Notes: 1) In the above Cases 1 to 10, efficiency = (electricity + H_2 output) / (coal input) on a HHV basis. 2) Excess electric power refers to net power output; e.g., for Case 6, total power production is 619 MW and parasitic power needed is 202 MW leaving net power for sales of 417 MW. 3) TPD = ton per day. 4) For CO_2 capture cases, the performance and economics of these technologies are analyzed including configurations for carbon sequestration; that is, they include energy requirements to transport CO_2 to the sequestration site. 5) For cases with sequestration it is assumed that $10 per ton of carbon is added for sequestration after the concentrated carbon dioxide stream has been isolated, and the carbon dioxide stream is compressed to 200 bars.		
P. Chiesa et al., 2005			
	Specifications of Illinois #6 coal: (as the feedstock for all cases below)		
	C (% by weight)	61.27	
	H (% by weight)	4.69	
	O (% by weight)	8.83	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	N (% by weight)	1.10	
	S (% by weight)	3.41	
	Moisture (% by weight)	12.00	
	Ash (% by weight)	8.70	
	HHV (MJ/kg)	26.143	
	LHV (MJ/kg)	24.826	
	<u>Case 1: Quench</u>		
	Gasification pressure, bar	70	
	Hydrogen purity, %	99.999	
	Net power output, MW	78.4	
	CO_2 captured, % of input	0	
	CO_2 emissions, g/kWh	751.8	
	CO_2 emissions, kg/GJ (H_2, LHV)	140.7	
	Fuel input, MW (LHV)	1862.7	
	H_2 output, MW (LHV)	1070.3	
	η_E, % (LHV)	4.21	
	η_H, % (LHV)	57.46	
	<u>Case 2: Quench</u>		
	Gasification pressure, bar		70
	Hydrogen purity, %		99.999
	Net power output, MW		38.9
	CO_2 captured, % of input		91.28
	CO_2 emissions, g/kWh		70.1
	CO_2 emissions, kg/GJ (H_2, LHV)		11.8
	Fuel input, MW (LHV)		1862.7
	H_2 output, MW (LHV)		1070.3
	η_E, % (LHV)		2.09
	η_H, % (LHV)		57.46
	<u>Case 3: Syngas Cooler</u>		
	Gasification pressure, bar	70	
	Hydrogen purity, %	99.999	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Net power output, MW	111.0	
	CO_2 captured, % of input	0	
	CO_2 emissions, g/kWh	692.6	
	CO_2 emissions, kg/GJ (H_2, LHV)	135.2	
	Fuel input, MW (LHV)	1795.6	
	H_2 output, MW (LHV)	1031.5	
	η_E, % (LHV)	6.18	
	η_H, % (LHV)	57.45	
	Case 4: Syngas Cooler		
	Gasification pressure, bar		70
	Hydrogen purity, %		99.999
	Net power output, MW		73.82
	CO_2 captured, % of input		90.43
	CO_2 emissions, g/kWh		73.4
	CO_2 emissions, kg/GJ (H_2, LHV)		12.3
	Fuel input, MW (LHV)		1795.6
	H_2 output, MW (LHV)		1031.5
	η_E, % (LHV)		4.11
	η_H, % (LHV)		57.45
	Case 5: Syngas Cooler		
	Gasification pressure, bar		70
	Hydrogen purity, %		99.999
	Net power output, MW		89.49
	CO_2 captured, % of input		90.65
	CO_2 emissions, g/kWh		73.4
	CO_2 emissions, kg/GJ (H_2, LHV)		12.0
	Fuel input, MW (LHV)		1069.2
	H_2 output, MW (LHV)		535.6
	η_E, % (LHV)		8.37
	η_H, % (LHV)		50.10
	Case 6: Syngas Cooler		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Gasification pressure, bar		70
	Hydrogen purity, %		99.999
	Net power output, MW		100.3
	CO_2 captured, % of input		73.53
	CO_2 emissions, g/kWh		73.4
	CO_2 emissions, kg/GJ (H_2, LHV)		42.1
	Fuel input, MW (LHV)		972.0
	H_2 output, MW (LHV)		486.9
	η_E, % (LHV)		10.32
	η_H, % (LHV)		50.10
	Case 7: Quench		
	Gasification pressure, bar		70
	Hydrogen purity, %		~93
	Net power output, MW		38.34
	CO_2 captured, % of input		91.28
	CO_2 emissions, g/kWh		70.1
	CO_2 emissions, kg/GJ (H_2, LHV)		11.6
	Fuel input, MW (LHV)		1862.7
	H_2 output, MW (LHV)		1083.6
	η_E, % (LHV)		2.06
	η_H, % (LHV)		58.17
	Case 8: Quench		
	Gasification pressure, bar		120
	Hydrogen purity, %		99.999
	Net power output, MW		51.42
	CO_2 captured, % of input		91.11
	CO_2 emissions, g/kWh		70.1
	CO_2 emissions, kg/GJ (H_2, LHV)		11.8
	Fuel input, MW (LHV)		1837.1
	H_2 output, MW (LHV)		1052.4
	η_E, % (LHV)		2.80

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	η_H, % (LHV)		57.28
	Case 9: Syngas cooler		
	Gasification pressure, bar		120
	Hydrogen purity, %		99.999
	Net power output, MW		66.03
	CO_2 captured, % of input		90.12
	CO_2 emissions, g/kWh		73.4
	CO_2 emissions, kg/GJ (H_2, LHV)		13.0
	Fuel input, MW (LHV)		1760.1
	H_2 output, MW (LHV)		1006.9
	η_E, % (LHV)		3.75
	η_H, % (LHV)		57.21
	Case 10: Quench Co-capture of CO_2 and H_2S		
	CO_2 captured, % of input		94.93
	CO_2 emissions, g/kWh		38.0
	CO_2 emissions, kg/GJ (H_2, LHV)		6.4
	H_2S + CO_2 compr., MW		-3.9
	η_E, % (LHV)		1.88
	η_H, % (LHV)		57.47
	Case 11: Syngas Cooler Co-capture of CO_2 and H_2S		
	CO_2 captured, % of input		94.08
	CO_2 emissions, g/kWh		43.3
	CO_2 emissions, kg/GJ (H_2, LHV)		7.2
	H_2S + CO_2 compr., MW		-3.7
	η_E, % (LHV)		3.90
	η_H, % (LHV)		57.46
	Case 12: Syngas Cooler Co-capture of CO_2 and H_2S		
	CO_2 captured, % of input		94.29

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	CO_2 emissions, g/kWh		43.3
	CO_2 emissions, kg/GJ (H_2, LHV)		6.9
	H_2S + CO_2 compr., MW		-2.2
	η_E, % (LHV)		8.16
	η_H, % (LHV)		50.11
	Case 13: Syngas Cooler **Co-capture of CO_2 and H_2S**		
	CO_2 captured, % of input		77.18
	CO_2 emissions, g/kWh		43.3
	CO_2 emissions, kg/GJ (H_2, LHV)		37.3
	H_2S + CO_2 compr., MW		-2.0
	η_E, % (LHV)		10.11
	η_H, % (LHV)		50.11
	Case 14: Quench **Co-capture of CO_2 and H_2S**		
	CO_2 captured, % of input		94.93
	CO_2 emissions, g/kWh		38.0
	CO_2 emissions, kg/GJ (H_2, LHV)		6.3
	H_2S + CO_2 compr., MW		-3.9
	η_E, % (LHV)		1.85
	η_H, % (LHV)		58.17
	Case 15: Quench **Co-capture of CO_2 and H_2S**		
	Gasification pressure, bar		120
	CO_2 captured, % of input		94.76
	CO_2 emissions, g/kWh		38.0
	CO_2 emissions, kg/GJ (H_2, LHV)		6.5
	H_2S + CO_2 compr., MW		-3.8
	η_E, % (LHV)		2.59
	η_H, % (LHV)		57.30

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Case 16: Syngas Cooler Co-capture of CO_2 and H_2S		
	Gasification pressure, bar		120
	CO_2 captured, % of input		93.77
	CO_2 emissions, g/kWh		43.3
	CO_2 emissions, kg/GJ (H_2, LHV)		7.8
	H_2S + CO_2 compr., MW		-3.7
	η_E, % (LHV)		3.54
	η_H, % (LHV)		57.22
	Notes: 1) In the above Cases 1 to 16, η_E = (net electric power) / (coal input LHV), and η_H = (H_2 LHV) / (coal input LHV). 2) "CO_2 captured" refers to the percentage of the carbon in the input coal that is captured and stored as CO_2. 3) Results show that state-of-the-art commercial technology allows transferring to de-carbonized hydrogen 57-58% of coal LHV, while exporting to the grid de-carbonized electricity amounting to 2-6% of coal LHV. 4) The specific CO_2 emissions (g/kWh) charged to electricity are assumed to equal those from the electricity-only plant that is most similar in design; the remaining CO_2 emissions are charged to H_2. 5) CO_2 capture includes energy requirements to transport CO_2 to the sequestration site.		
$(S\&T)^2$ Consultants Inc., 2003			
	Case 1 Cited by the study		
	Coal consumed, TPD (ton/day)	3,000	
	Coal description	Pittsburgh #8 coal	
	Coal quality, HHV	12,450 BTU/lb	
	Hydrogen produced, MMscfd	131	
	Excess power produced, MW	20.4	
	Coal consumed per MMBTU hydrogen	135.5 lb	
	Excess electricity produced per MMBTU hydrogen	11 kWh	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Cold gas efficiency	59.3%	
	Overall efficiency	63.0%	
	Note: 1) This case should be the same one as Case 1 in the study by Gray et al. (2002).		
	<u>Case 2 Cited by the study</u>		
	Coal consumed, TPD (ton/day)	2,500	
	Coal description	Pittsburgh #8 coal	
	Coal quality, HHV	12,450 BTU/lb	
	Hydrogen produced, MMscfd	112	
	Excess power produced, MW	38	
	Coal consumed per MMBTU hydrogen	132 lb	
	Excess electricity produced per MMBTU hydrogen	24 kWh	
	Cold gas efficiency	59.9%	
	Overall efficiency	64.4%	
	Note: 1) This case should be the same one as Case 1 in the US DOE (2002) study.		
	<u>Emissions Factors for Hydrogen Production Plants:</u> (Grams/million BTU consumed [HHV])		
	Aldehydes (as HCHO) exhaust	n.e.	
	Fuel evaporation or leakage	4.5	
	NMOC exhaust	88.2	
	Evaporation + NMOC exhaust	92.8	
	Carbon in evap. + NMOC exh.	54.6	
	Ozone-weighted total NMOC	58.1	
	CH_4 (exhaust)	9.3	
	CO	7.6	
	N_2O	1.4	
	NO_x (NO_2)	29.4	
	SO_x (SO_2)	29.4	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	PM	5.9	
	PM_{10}	4.4	
	$PM_{2.5}$	n.e.	
	Note: 1) The emissions factors for the coal to hydrogen process have been set the same as the coal to methanol process. These were originally derived from EPA AP-42 and other sources by the literature authors.		
US DOE, 2002			
	Specifications of Pittsburgh #8 coal: (as the feedstock for all cases below)		
	C (% by weight)	69.36	
	H (% by weight)	5.18	
	N (% by weight)	1.22	
	S (% by weight)	2.89	
	O (% by weight)	11.41	
	Ash (% by weight)	9.94	
	Total (% by weight)	100	
	Moisture (% by weight)	6.00	
	Ash (% by weight)	9.94	
	Volatile matter (% by weight)	35.91	
	Fixed carbon (% by weight)	48.15	
	Total (% by weight)	100	
	Higher heating value (HHV)	12,450 Btu/lb	
	Case 1		
	Plant size, tons H_2/day (MMscfd) @346 psia	312.6 (112)	
	H_2 output purity	>99.5%	
	Coal feed (dry basis), tpd	2,500	
	Feedstock description	Pittsburgh #8 coal, <10% ash	
	Plant availability	80%	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Cold gas efficiency, HHV	57.7%	
	Equivalent thermal efficiency, HHV	62.3%	
	Steam export?	No	
	CO_2 recovered, tpd (percent)	0	
	Net power	38 MW	
	H_2SO_4 output, tpd	230	
	<u>Case 2</u>		
	Plant size, tons H_2/day (MMscfd) @346 psia		317.8 (114)
	H_2 output purity		>99.5%
	Coal feed (dry basis), tpd		2,500
	Feedstock description		Pittsburgh #8 coal, <10% ash
	Plant availability		80%
	Cold gas efficiency, HHV		58.6%
	Equivalent thermal efficiency, HHV		60.1%
	Steam export?		No
	CO_2 recovered, tpd (percent, pressure)		6,233 (92%, 30 psia)
	Net power		12 MW
	H_2SO_4 output, tpd		230
	Note: 1) For the above Cases 1 to 2, they are conventional hydrogen plants.		
	<u>Case 3</u>		
	Plant size, tons H_2/day (MMscfd) @346 psia		430.8 (147)
	H_2 output purity		>99.5%
	Coal feed (dry basis), tpd		2,500
	Feedstock description		Pittsburgh #8 coal, <10% ash
	Plant availability		80%
	Cold gas efficiency, HHV		79.5%

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Equivalent thermal efficiency, HHV		80.4%
	Steam export?		No
	CO_2 recovered, tpd (percent, pressure)		6,362 (94%, 20 psia)
	Net power		7 MW
	H_2SO_4 output, tpd		230
	Notes: 1) For the above Case 3, it is an advanced hydrogen plant with HSD operation at 1112°F (600°C), and maximum H_2 production from 2,500 tpd dry gasifier is persued. 2) Case 3 is using E-Gas (Destec two-stage entrained) oxygen-blown gasifiers. 3) Case 3 utilizes a hydrogen separation device (HSD) being developed by Oak Ridge National Laboratory (ORNL). The HSD is based on a high-temperature membrane separation concept that can be designed to selectively separate hydrogen from other gases. By utilizing the HSD, it should be possible to separate hydrogen from CO_2 passively and economically.		
	Notes to the above Cases 1 to 3: 1) Cold gas efficiency equals HHV of the product gas divided by the HHV of the feed x 100. 2) Effective thermal efficiency (ETE) is defined as follows. ETE= (Hydrogen heating value + Electrical Btu Equivalent) / (Fuel hearting Value), based on HHV. 3) Coal quality is 12,450 Btu/lb (HHV). 4) For cases 2 and 3, A low-pressure H_2S stream is sent to the sulfuric acid plant and a low-pressure CO_2 stream is sent offsite for sequestration. Thus, it seems that the CO_2 capture here doesn't involve the energy requirements to compress and pipeline CO_2 to a storage site. 5) tpd = ton per day.		

Table 2. Summary of literature data on hydrogen production process via biomass gasification

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
C. Hamelinck et al., 2002			
	Case 1		
	Biomass input (dry tonne/h)	80.0	
	Biomass input (MW_{th} HHV)	428.4	
	Load (h/year)	8,000	
	Biomass input (PJ/year, HHV)	12.3	
	Fuel output, MW (HHV)	175.5	
	Net electricity, MW (Gross - Internal)	72.7 (93-21)	
	Efficiency fuel, % HHV	41.0	
	Efficiency power, % HHV	17.0	
	(Fuel + E) efficiency, % HHV	57.9	
	(Fuel only) efficiency, % HHV	66	
	Note: 1) For Case 1: IGT, hot gas cleaning, dual shift, pressure swing adsorption, combined cycle.		
	Case 2		
	Biomass input (dry tonne/h)	80.0	
	Biomass input (MW_{th} HHV)	428.4	
	Load (h/year)	8,000	
	Biomass input (PJ/year, HHV)	12.3	
	Fuel output, MW (HHV)	259.2	
	Net electricity, MW (Gross - Internal)	-0.7 (25-26)	
	Efficiency fuel, % HHV	60.5	
	Efficiency power, % HHV	-0.2	
	(Fuel + E) efficiency, % HHV	60.3	
	(Fuel only) efficiency, % HHV	60	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Note: 1) For Case 2: IGT, max H_2, high temperature dust filter, ceramic membrane (internal shift), expansion turbine.		
	<u>Case 3</u>		
	Biomass input (dry tonne/h)	80.0	
	Biomass input (MW_{th} HHV)	428.4	
	Load (h/year)	8,000	
	Biomass input (PJ/year, HHV)	12.3	
	Fuel output, MW (HHV)	177.1	
	Net electricity, MW (Gross - Internal)	84.4 (103-19)	
	Efficiency fuel, % HHV	41.3	
	Efficiency power, % HHV	19.7	
	(Fuel + E) efficiency, % HHV	61.0	
	(Fuel only) efficiency, % HHV	74	
	Note: 1) For Case 3: IGT, hot gas cleaning, ceramic membrane (internal shift), combined cycle.		
	<u>Case 4</u>		
	Biomass input (dry tonne/h)	80.0	
	Biomass input (MW_{th} HHV)	428.4	
	Load (h/year)	8,000	
	Biomass input (PJ/year, HHV)	12.3	
	Fuel output, MW (HHV)	303.0	
	Net electricity, MW (Gross - Internal)	-22.4 (0-22)	
	Efficiency fuel, % HHV	70.7	
	Efficiency power, % HHV	-5.2	
	(Fuel + E) efficiency, % HHV	65.5	
	(Fuel only) efficiency, % HHV	63	
	Note: 1) For Case 4: BCL, scrubber, steam reformer, dual shift, pressure swing adsorption.		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	<u>Case 5</u>		
	Biomass input (dry tonne/h)	80.0	
	Biomass input (MW_{th} HHV)	428.4	
	Load (h/year)	8,000	
	Biomass input (PJ/year, HHV)	12.3	
	Fuel output, MW (HHV)	149.0	
	Net electricity, MW (Gross - Internal)	72.2 (97-25)	
	Efficiency fuel, % HHV	34.8	
	Efficiency power, % HHV	16.9	
	(Fuel + E) efficiency, % HHV	51.6	
	(Fuel only) efficiency, % HHV	56	
	Note: 1) For Case 5: BCL, scrubber, dual shift, pressure swing adsorption, combined cycle.		
	Notes to above Cases 1 to 5: 1) These are results of the Aspen+ performance calculations, for 430 MW_{th} input HHV systems (equivalent to 380 MW_{th} LHV for biomass with 30% moisture). 2) Net electrical output is gross output minus internal use. 3) The fuel only efficiency is calculated by η = fuel / ($MW_{th,in}$ – electricity / η_e). The electricity part is assumed to be produced from biomass at η_e = 45% HHV efficiency.		
F. S. Lau et al., 2002			
	<u>Case 1: Bagasse</u>		
	Ultimate analysis		
	C	46.46	
	H	5.4	
	N	0.18	
	S	0.06	
	Ash	8.5	
	O (by difference)	39.36	
	Cl	0.04	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Proximate analysis		
	Ash	6.99	
	Volatile	80.06	
	Fixed C	12.95	
	HHV (MJ/kg)	17.77	
	Biomass fed, tonnes/day (moisture content)	500 (20%)	
	Heat Used in Reformer [GJ/h]	24.8	
	Heat Used in Dryer [GJ/h]	45.8	
	Heat Recovered from PSA Reject [GJ/h]	60.0	
	Heat Recovered from Reformer Stream [GJ/h]	19.1	
	Net Heat from the system [GJ/h]	8.5	
	Power Used in PSA Compressor [GJ/h]	6.97	
	Power Used for Air Separation [GJ/h]	5.90	
	H_2 Product Heating Value [GJ/h], HHV	186	
	Dry Biomass Feed Heating Value [GJ/h], HHV	297	
	Cold Efficiency, HHV	0.628	
	Effective Thermal Efficiency, HHV	0.583	
	H_2 / Dry Biomass [g/kg]	78.1	
	Case 2: Switchgrass		
	Ultimate analysis		
	C	47.73	
	H	5.56	
	N	0.67	
	S	0.12	
	Ash	5.24	
	O (by difference)	40.57	
	Cl	0.11	
	Proximate analysis		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Ash	5.24	
	Volatile	80.09	
	Fixed C	14.67	
	HHV (MJ/kg)	18.62	
	Biomass fed, tonnes/day (moisture content)	500 (12%)	
	Heat Used in Reformer [GJ/h]	25.7	
	Heat Used in Dryer [GJ/h]	0	
	Heat Recovered from PSA Reject [GJ/h]	80.5	
	Heat Recovered from Reformer Stream [GJ/h]	8.1	
	Net Heat from the system [GJ/h]	62.9	
	Power Used in PSA Compressor [GJ/h]	8.20	
	Power Used for Air Separation [GJ/h]	5.10	
	H_2 Product Heating Value [GJ/h], HHV	220	
	Dry Biomass Feed Heating Value [GJ/h], HHV	342	
	Cold Efficiency, HHV	0.644	
	Effective Thermal Efficiency, HHV	0.744	
	H_2 / Dry Biomass [g/kg]	84.1	
	Case 3: Nutshell Mix		
	Ultimate analysis		
	C	48.51	
	H	5.65	
	N	0.77	
	S	0.01	
	Ash	3.07	
	O (by difference)	41.98	
	Cl	0.01	
	Proximate analysis		
	Ash	2.38	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Volatile	76.28	
	Fixed C	21.34	
	HHV (MJ/kg)	19.80	
	Biomass fed, tonnes/day (moisture content)	500 (12.5%)	
	Heat Used in Reformer [GJ/h]	24.2	
	Heat Used in Dryer [GJ/h]	0	
	Heat Recovered from PSA Reject [GJ/h]	89.0	
	Heat Recovered from Reformer Stream [GJ/h]	5.3	
	Net Heat from the system [GJ/h]	70.1	
	Power Used in PSA Compressor [GJ/h]	8.45	
	Power Used for Air Separation [GJ/h]	4.10	
	H_2 Product Heating Value [GJ/h], HHV	230	
	Dry Biomass Feed Heating Value [GJ/h], HHV	361	
	Cold Efficiency, HHV	0.637	
	Effective Thermal Efficiency, HHV	0.756	
	H_2 / Dry Biomass [g/kg]	88.3	
	Notes: 1) The process flow designs for the three cases were developed using a GTI proprietary gasifier model and the Hysys process design and simulation program. The gasifier model utilizes GTI's data bank that has been assembled for a large number of feeds and operating experiences. 2) Cold Efficiency = {Hydrogen Heating Value in the Product (HHV)} / {Biomass Heating Value in the Feed (HHV)}. 3) Effective Thermal Efficiency = {Hydrogen Heating Value in Product (HHV) + Net Heat from System} / {Biomass Heating Value in Feed (HHV) + (Electricity Use / 0.35)}. 4) Net Heat from the System = Heat Recovered from Reformer Effluent + Heat Recovered from PSA Reject – Heat Used in Reformer – Heat Used in Biomass Dryer.		
H. L. Chum et al., 2001			
	Efficiency (HHV), from gasification	60%	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
R. H. Williams et al., 1995			
	Case 1: IGT gasifier		
	Feedstock characteristics:		
	Dry, ash free composition	$CH_{1.52}O_{0.68}$	
	HHV (GJ/dry tonne)	19.28	
	Initial moisture (%)	45	
	Moisture after drying (%)	15	
	Energy inputs from:		
	Feedstock (GJ/GJ hydrogen product), HHV	1.50	
	Electricity (kWh/GJ hydrogen product [HHV])		
	Pumps	0.99	
	Compressors	7.77	
	Lockhopper	1.30	
	Oxygen	11.17	
	PSA	11.88	
	Total	33.11	
	Steam (kg/kg dry feed)	1.0	
	Energy ratio (ER), HHV	0.669	
	Fraction of electricity input from:		
	Waste heat	0.109	
	Purge gases	0.000	
	External sources	0.891	
	Thermal efficiency (TE), HHV	0.564	
	Case 2: MTCI gasifier		
	Feedstock characteristics:		
	Dry, ash free composition	$CH_{1.63}O_{0.66}$	
	HHV (GJ/dry tonne)	19.40	
	Initial moisture (%)	45	
	Moisture after drying (%)	20	
	Energy inputs from:		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Feedstock (GJ/GJ hydrogen product), HHV	1.32	
	Electricity (kWh/GJ hydrogen product [HHV])		
	Pumps	0.01	
	Compressors	26.21	
	Lockhopper	0.00	
	Oxygen	0.00	
	PSA	9.23	
	Total	35.45	
	Steam (kg/kg dry feed)	1.37	
	Energy ratio (ER), HHV	0.759	
	Fraction of electricity input from:		
	Waste heat	0.033	
	Purge gases	0.000	
	External sources	0.967	
	Thermal efficiency (TE), HHV basis	0.611	
	Case 3: BCL gasifier		
	Feedstock characteristics:		
	Dry, ash free composition	$CH_{1.54}O_{0.65}$	
	HHV (GJ/dry tonne)	19.46	
	Initial moisture (%)	45	
	Moisture after drying (%)	10	
	Energy inputs from:		
	Feedstock (GJ/GJ hydrogen product), HHV	1.37	
	Electricity (kWh/GJ hydrogen product [HHV])		
	Pumps	0.04	
	Compressors	22.84	
	Lockhopper	0.00	
	Oxygen	0.00	
	PSA	8.90	
	Total	31.79	
	Steam (kg/kg dry feed)	0.95	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Energy ratio (ER), HHV	0.732	
	Fraction of electricity input from:		
	Waste heat	0.317	
	Purge gases	0.000	
	External sources	0.683	
	Thermal efficiency (TE), HHV	0.636	
	Case 4: Shell gasifier		
	Feedstock characteristics:		
	Dry, ash free composition	$CH_{1.52}O_{0.68}$	
	HHV (GJ/dry tonne)	19.28	
	Initial moisture (%)	45	
	Moisture after drying (%)	11	
	Energy inputs from:		
	Feedstock (GJ/GJ hydrogen product), HHV	1.27	
	Electricity (kWh/GJ hydrogen product [HHV])		
	Pumps	0.29	
	Compressors	6.21	
	Lockhopper	0.88	
	Oxygen	14.22	
	PSA	11.62	
	Total	33.23	
	Steam (kg/kg dry feed)	1.65	
	Energy ratio (ER), HHV	0.788	
	Fraction of electricity input from:		
	Waste heat	0.032	
	Purge gases	0.151	
	External sources	0.817	
	Thermal efficiency (TE), HHV	0.645	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Notes: 1) In all cases the production facility is designed to produce gaseous H_2 at a pressure of 75 bars. 2) For PSA, electricity use is assumed to be 4.46 kWh/kmole of CO_2. 3) For the Steam item in the above cases, this is the total amount of steam generated for the process, excluding steam that is used for electricity production. 4) The energy ratio (ER) is defined as the energy content of the product fuel divided by the energy in the input feedstock (HHV basis), which takes no account of the energy required to provide electricity or heat from external sources. 5) The thermal efficiency (TE) is defined as the energy content of the product fuel divided by the energy content of all energy inputs to the process, including the feedstock and additional amounts of feedstock used to generate the electricity and heat requirements not provided from byproduct process heat or purge gases.		
L. Basye et al., 1997			
	Conversion efficiency, based on HHV	57.8%	
	Capacity	1.31 million Nm^3/day for biomass gasifier (46 million SCF/day)	
	Plant operating factor	328 day/year	
	Annual production, GJ (HHV)	5,486,000 (4.9×10^6 MBtu, 429 million Nm^3, 38.6 million kg)	
	Life of plant in years	20	
G. Brinkman, 2003			
	Efficiency (Source: Williams)	73%	
	Efficiency (Source: Bowen)	66%	
	Efficiency (Source: Spath)	57%	
	Efficiency (Source: Hamelinck)	61%	
	Statistics:		
	Mean	65%	
	Standard Deviation	8%	
	Note: 1) For this report, all energy content values are expressed in terms of higher heating value (HHV).		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
P. L. Spath et al., 2000			
	Case 1: Battelle/FERCO		
	H_2 production rate @ 100% capacity (kg/day)	22,737	
	Biomass feed rate for each technology (bone dry Mg/day)	314	
	Case 2: Battelle/FERCO		
	H_2 production rate @ 100% capacity (kg/day)	75,790	
	Biomass feed rate for each technology (bone dry Mg/day)	1,046	
	Case 3: Battelle/FERCO		
	H_2 production rate @ 100% capacity (kg/day)	113,685	
	Biomass feed rate for each technology (bone dry Mg/day)	1,569	
	Case 4: IGT		
	H_2 production rate @ 100% capacity (kg/day)	22,737	
	Biomass feed rate for each technology (bone dry Mg/day)	311	
	Case 5: IGT		
	H_2 production rate @ 100% capacity (kg/day)	75,790	
	Biomass feed rate for each technology (bone dry Mg/day)	1,035	
	Case 6: IGT		
	H_2 production rate @ 100% capacity (kg/day)	113,685	
	Biomass feed rate for each technology (bone dry Mg/day)	1,553	
	Case 7: Pyrolysis		
	H_2 production rate @ 100% capacity (kg/day)	22,737	
	Biomass feed rate for each technology (bone dry Mg/day)	542	
	Case 8: Pyrolysis		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	H_2 production rate @ 100% capacity (kg/day)	75,790	
	Biomass feed rate for each technology (bone dry Mg/day)	1,806	
	Case 9: Pyrolysis		
	H_2 production rate @ 100% capacity (kg/day)	113,685	
	Biomass feed rate for each technology (bone dry Mg/day)	N/A	
	Notes: 1) For both of the gasification technologies studied in this analysis, three plant sizes were examined. 2) Only two plant sizes were studied for hydrogen via pyrolysis. The largest plant size was not considered to be feasible for pyrolysis due to the large quantity of biomass that would be required since a portion of the oil that is produced from the biomass goes to the coproduct rather than to hydrogen.		
$(S\&T)^2$ Consultants Inc., 2003			
	Investigated plant performance		
	Hydrogen produced, MW_{th} [HHV]	259	
	Biomass input, MW_{th} [HHV]	430	
	Electricity required, MW	1	
	Model inputs by GHGenius		
	Hydrogen produced, million BTU [HHV]	1	
	Biomass input, lbs	198.9	
	Electricity required, kWh	1.13	
	Notes: 1) For the base modeling case, the work of Hamelinck is used. 2) The electrical requirements are the net requirements after the electricity produced by the process and the total process demands are considered. The wood required as the input must have a moisture content of less than 30% in this case. 3) The thermal efficiency for this case is about 60% which is comparable to that reported in several of the other studies.		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Emissions Factors: Mann's Case (Grams/million BTU [HHV] feed INPUT)		
	Aldehydes (as HCHO) exhaust		
	Fuel evaporation or leakage		
	NMOC exhaust	150	
	CH_4 (exhaust)	0.08	
	CO	0.25	
	N_2O		
	NO_x (NO_2)	140	
	SO_x (SO_2)	74	
	PM	1.1	
	PM_{10}		
	$PM_{2.5}$		
	Emissions Factors: EREN's Case (Grams/million BTU [HHV] feed INPUT)		
	Aldehydes (as HCHO) exhaust		
	Fuel evaporation or leakage		
	NMOC exhaust	10.0	
	CH_4 (exhaust)		
	CO	21.8	
	N_2O		
	NO_x (NO_2)	68.2	
	SO_x (SO_2)	85.6	
	PM		
	PM_{10}		
	$PM_{2.5}$		
	Emissions Factors: AP-42's Case (Grams/million BTU [HHV] feed INPUT)		
	Aldehydes (as HCHO) exhaust	2.4	
	Fuel evaporation or leakage		
	NMOC exhaust	6	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	CH_4 (exhaust)	9.5	
	CO	270	
	N_2O	6	
	NO_x (NO_2)	100-225	
	SO_x (SO_2)	11	
	PM		
	PM_{10}	18-227	
	$PM_{2.5}$	16-195	
	<u>**Emissions Factors: GHGenius's Case**</u> (Grams/million BTU [HHV] feed INPUT)		
	Aldehydes (as HCHO) exhaust	0.5	
	Fuel evaporation or leakage	0.0	
	NMOC exhaust	10.0	
	CH_4 (exhaust)	2.0	
	CO	50	
	N_2O	4	
	NO_x (NO_2)	75	
	SO_x (SO_2)	Calc.	
	PM		
	PM_{10}	25	
	$PM_{2.5}$	25	
	Notes: 1) Two reports (Mann and Spath, 1997, and US DOE EREN) on biomass gasification used for power generation were found with information on emissions. 2) The AP-42 results were for wood combustion. 3) The values chosen by GHGenius are based on the other researchers' values as well as considering the values in the model for wood fired boilers. These factors are an estimate and are not based on any test data.		
H. Audus et al.			
	Ultimate analysis for SRC feed		
	Acacia		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	C	50.7	
	H	5.7	
	O	41.9	
	N	0.6	
	S	0.01	
	Ash	1.0	
	Eucalyptus		
	C	48.3	
	H	5.9	
	O	45.1	
	N	0.15	
	S	0.01	
	Ash	0.5	
	Case 1: Biomass Gasi. Power plant		
	Power plant efficiency (Maniatis reports)	30.6%	
	Power plant efficiency (Ciferno et al.)	33%	
	Future efficiency assumed (LHV)	40%	
	Biomass fed (t/yr, dry)	121,000 (2.0 million GJ/yr [LHV])	
	Biomass type	Mixture of acacia and eucalyptus	
	Electricity output (MWh/yr)	225,000 (0.8 million GJ/yr)	
	CO_2 storage (t CO_2/yr)	0	
	CO_2 emissions (t CO_2/yr)	216,000	
	SO_2 (t/yr)	26	
	PM (t/yr)	8	
	Case 2: Biomass Gasi. Power plant		
	Future efficiency assumed (LHV)		32%

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Biomass fed (t/yr, dry)		121,000 (2.0 million GJ/yr [LHV])
	Biomass type		Mixture of acacia and eucalyptus
	Electricity output (MWh/yr)		178,000 (0.64 million GJ/yr)
	CO_2 storage (t CO_2/yr)		184,000 (85%)
	CO_2 emissions (t CO_2/yr)		32,000
	Notes: 1) Compared with coal IGCC, combining biomass gasification with gas turbine combustion in an integrated cycle is referred to as BIGCC here. 2) The recent work on coal IGCC reported by Bressan et al. indicate that the adoption of CO_2 capture and compression incurs an energy penalty of about 8% points. The penalty would not be less for BIGCC, and we have therefore assumed that the BIGCC plant with CO_2 capture has an efficiency of 32% (c.f. the 40% assumed originally for a future commercial unit). 3) t = metric tonne. 4) All the analysis in this study is based on LHV. 5) The CO_2 capture case includes the energy requirements to capture, compress, and transport CO_2 to a storage site.		
W. Iwasaki, 2003			
	Wood biomass composition:		
	Moisture (% wet base)	4.8	
	Combustible (% wet base)	95.0	
	Ash (% wet base)	0.2	
	C (% dry base)	49.0	
	H (% dry base)	6.7	
	O (% dry base)	44.1	
	N (% dry base)	0.0	
	S (% dry base)	0.0	
	Cl (% dry base)	0.0	
	HHV (MJ/kg), wet base	17.6	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	LHV (MJ/kg), wet base	16.1	
	Wood biomass feed, t/d	100	
	Product H_2, m^3/h (NTP)	2,740 (5.9 t/d)	
	H_2 purity	99.99%	
	Conversion efficiency (HHV)	47.9%	
	Note: 1) t/d = metric tonne per day. 2) Hydrogen is produced by biomass gasification with pyrolysis process.		
S. P. Babu			
	Demonstration Power Plant		
	Feed capacity, kW	8,000	
	Electrical output, kW	2,000	
	Thermal output, kW (HHV)	4,500	
	Electrical efficiency, %	25.0	
	Thermal efficiency, % (HHV)	56.3	
	Total efficiency, %	81.3	
	Note: 1) Following the initial development of the Fast Internal Circulation Fluidized Bed (FICFB) Process in a laboratory test unit at Technical University of Vienna (TUV), a demonstration plant was erected. This plant is situated in Burgenland and went into operation in Autumn 2001. Those data above are for this demonstration plant.		
EERE, 2005			
	BGCC Power Plant (For the base year 1997)		
	Annual capacity factor	80%	
	Net kJ/kWh (HHV)	10,000	
	Thermal Efficiency	36.0% (HHV)	
	Annual energy delivery	526 GWh/yr	
	Plant size	75 MW_e	
	Energy: Biomass	2.26 PJ/yr (HHV)	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Feedstock: Biomass (dry)	0.267 Tg/yr	
	Emissions from a High-pressure, Direct Gasification System		
	PM10, g/Nm^3	0.007	
	NOx @ 15% O_2, g/GJ of feed input	64.5	
	CO, g/GJ of feed input	20.6	
	Non-CH4 Hydrocarbons, g/GJ of feed input	9.6	
	SO_2, g/GJ of feed input	81.8	
	Ash, Mg/yr	2,912	
	Boiler blowdown, Mg/yr	6,989	
	Notes: 1) This case is electricity production from biomass using a biomass gasification combined cycle (BGCC) system. 2) The emissions data shown are taken from DeLong and are based on alfalfa feed. 3) Those emissions are from a high-pressure, direct gasification system.		
J. P. Ciferno et al., 2002			
	Case 1: MTCI Technology		
	Feedstock type	Pulp sludge	
	Throughput (tonne/day)	7	
	Emissions		
	Liquid waste (tar/oil) (kg/kg feed)	-	
	Solid waste (char/ash) (kg/kg feed)	0.091	
	Product tar content	-	
	CO	-	
	NO_x	25 ppm	
	SO_2	9 ppm	
	Organic carbon	-	
	NH_3	-	
	H_2S	-	
	Case 2: GTI Technology		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Feedstock type	Wood	
	Throughput (tonne/day)	12	
	Emissions		
	Liquid waste (tar/oil) (kg/kg feed)	0.03	
	Solid waste (char/ash) (kg/kg feed)	0.03	
	Product tar content	2-3%	
	CO	-	
	NO_x	-	
	SO_2	-	
	Organic carbon	-	
	NH_3	-	
	H_2S	-	
	<u>Case 3: Lurgi Technology</u>		
	Feedstock type	Bark	
	Throughput (tonne/day)	84-108	
	Emissions		
	Liquid waste (tar/oil) (kg/kg feed)	Low	
	Solid waste (char/ash) (kg/kg feed)	0.01-0.04	
	Product tar content	1 g/m^3	
	CO	250 mg/m^3	
	NO_x	250 mg/m^3	
	SO_2	100 mg/m^3	
	Organic carbon	150 mg/m^3	
	NH_3	5 mg/m^3	
	H_2S	5 mg/m^3	
	<u>Case 4: Aerimpianti Technology</u>		
	Feedstock type	RDF	
	Throughput (tonne/day)	45-100	
	Emissions		
	Liquid waste (tar/oil) (kg/kg feed)	-	
	Solid waste (char/ash) (kg/kg feed)	250-630 kg/h	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Product tar content	25-40 kg/h	
	CO	-	
	NO_x	-	
	SO_2	<300 ppm	
	Organic carbon	-	
	NH_3	-	
	H_2S	-	
	Case 5: SEI Technology		
	Feedstock type	Wood	
	Throughput (tonne/day)	181	
	Emissions		
	Liquid waste (tar/oil) (kg/kg feed)	592	
	Solid waste (char/ash) (kg/kg feed)	-	
	Product tar content	Burned	
	CO	-	
	NO_x	-	
	SO_2	-	
	Organic carbon	-	
	NH_3	-	
	H_2S	-	
	Case 6: TPS Technology		
	Feedstock type	Wood	
	Throughput (tonne/day)	9	
	Emissions		
	Liquid waste (tar/oil) (kg/kg feed)	<100	
	Solid waste (char/ash) (kg/kg feed)	-	
	Product tar content	100 g/m^3	
	CO	-	
	NO_x	-	
	SO_2	-	
	Organic carbon	-	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	NH_3	-	
	H_2S	-	
	Case 7: Sofresid Technology		
	Feedstock type	MSW	
	Throughput (tonne/day)	195	
	Emissions		
	Liquid waste (tar/oil) (kg/kg feed)	0	
	Solid waste (char/ash) (kg/kg feed)	10	
	Product tar content	Burned	
	CO	-	
	NO_x	120 ppm	
	SO_2	79 ppm	
	Organic carbon	<10 ppm	
	NH_3	-	
	H_2S	-	
	Notes: 1) RDF -- Refuse Derived Fuel; MSW—Municipal Solid Waste. 2) Emissions are highly variable and depend on gasifier type, feedstock, process conditions (temperature and pressure) and gas conditioning systems. 3) Gasification of municipal solid waste and sewage sludge results in ash containing heavy metals.		
M. M. DeLong, 1995			
	Alfalfa Stems Analysis		
	Feedstock analysis (as fed to gasifier):		
	C (wt%)	42.8	
	H (wt%)	5.3	
	N (wt%)	1.9	
	Cl (wt%)	0	
	S (wt%)	0.07	
	O (wt%)	35.8	
	Moisture (wt%)	9.4	

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	Ash (wt%)	4.8	
	HHV (dry basis), Btu/lb	8,083	
	HHV (as fed to gasifier), Btu/lb	7,326	
	IGCC Biomass Gasi. Power Plant: Overall Plant Performance		
	Dried biomass feed rate, lb/h (9.4% moisture)	91,300	
	Gasifier heat input (HHV), MMBtu/h	669	
	Combustion turbine firing rate (HHV), MMBtu/h	614	
	Heat export to leaf processing plant		
	- Steam @ 4,100 lb/h, MMBtu/h	5	
	- Flue gas @ 310,000 lb/h, MMBtu/h	20	
	Combustion turbine gross power, kW	50,100	
	Steam turbine gross power, kW	29,300	
	Gross plant output, kW	79,400	
	Auxiliary power, kW	4,310	
	Net plant output, kW	75,090	
	Net plant heat rate (HHV), Btu/kWh	8,910	
	Net plant efficiency (HHV), %	38.3	
	Combustion Turbine Performance		
	Fuel consumption (HHV), MMBtu/h	614	
	Combustion turbine gross power, kW	50,100	
	Exhaust flow, lb/h	1,397,500	
	Exhaust temperature, ^{o}F	973	
	Exhaust composition, % vol.		
	Oxygen	12.8	
	Water vapor	7.5	
	Carbon dioxide	6.2	
	Nitrogen and Argon	73.5	
	Estimated Emissions (at Gas Turbine Exhaust)		

Literature sources	Configuration or Other Items	With CO_2 Venting	With CO_2 capture
	NO_x (as NO_2 at 15% O_2), ppmvd	40	
	CO, ppmvd	25	
	SO_x (as SO_2), ppmvw	40	
	Total IGCC Emissions at Full Load		
	Gaseous emissions		
	SO_x (as SO_2)	127 lb/h (40 ppmvw)	
	NO_x (as NO_2)	99 lb/h (40 ppmvd @ 15% O_2)	
	CO	32 lb/h (25 ppmvd)	
	PM_{10}	6 lb/h (4 ppm weight)	
	UHC	15 lb/h (20 ppmvd)	
	Solids emissions		
	Bottom ash, lb/h	4,700	
	Fly ash, lb/h	1,800	
	Aqueous emissions		
	Boiler blowdown, lb/h	2,200	
	Notes: 1) ppmvw = parts per million by volume on wet gas basis; ppmvd = parts per million by volume on dry gas basis; and ppm weight = parts per million on weight basis. 2) The gaseous emissions are mainly from combustion turbine. 3) The alfalfa stem feedstock is used here as the biomass source. 4) UHC = unburned hydrocarbons. 5) For SO_x, NO_x, and CO, total IGCC emissions at full load are the same as emissions at gas turbine exhaust. 6) NO_x is controlled to 40 ppmvd (parts per million by volume on a dry gas basis) at 15% O_2 by a combination of fuel-bound nitrogen-to-ammonia reduction by the gasifier system and by the use of special low-Btu fuel combustion turbine combustors.		

REFERENCES

R. H. Williams, "Toward Zero Emissions for Transportation Using Fossil Fuels," *Transportation, Energy, and Environmental Policy*: 63-103, September (2001).

Bechtel Corporation, Global Energy Inc, and Nexant Inc., *Gasification Plant Cost and Performance Optimization*, Final Report, DOE Contract No. DE-AC26-99FT40342, U.S. Department of Energy, National Energy Technology Laboratory (NETL), September (2003).

G. Rizeq, J. West, et al, *Fuel-Flexible Gasification-Combustion Technology for Production of H_2 and Sequestration-Ready CO_2*, annual technical progress report, DOE Award No. DE0FC26-00FT40974, GE Energy and Environmental Research Corporation (GE EER), October (2002).

R. H. Williams, Robert H. Socolow et al., "Co-Production of Hydrogen and Electricity from Fossil Fuels with CO_2 Capture", Presentation at Second Annual conference on Carbon Sequestration, Washington, May 5-8 (2003).

J. Ogden and E. Kaijuka, "Conceptual Design of Optimized Fossil H_2 Energy Systems with Capture and Sequestration of CO_2", Presentation at the National Carbon Sequestration Conference Alexandria, VA, May 7 (2003).

P. Chiesa, S. Consonni et al., "Co-production of Hydrogen, Electricity and CO_2 from Coal using Commercially-Ready Technology", Presentation at Second Annual conference on Carbon Sequestration, Washington, May 5-8 (2003).

T. Kreutz, B. Williams et al., "Production of Hydrogen and Electricity from Coal with CO_2 Capture", Presentation at the 6th International Conference on Greenhouse Gas Control Technologies (GHGT-6), Kyoto Japan, September 30-October 4 (2002).

D. Gray, and G. Tomlinson, "Hydrogen from Coal," Mitretek Technical Paper, MTR 2002-31, July (2002).

P. Chiesa, S. Consonni, T. Kreutz, and R. Williams, "Co-production of hydrogen, electricity and CO_2 from coal with commercially ready technology. Part A: Performance and emissions," *International Journal of Hydrogen Energy* **30**: 747 – 767 (2005).

$(S\&T)^2$ Consultants Inc., "The Addition of Coal and Biomass to Hydrogen Pathways to GHGenius," Prepared for Office of Energy Efficiency of Natural Resources Canada, August 25 (2003)**.**

US DOE, *Hydrogen Production Facilities Plant Performance and Cost Comparisons,* Final report, Parsons Infrastructure and Technology Group Inc., March (2002).

C. Hamelinck and A. Faaij, “Future prospects for production of methanol and hydrogen from biomass,” *Journal of Power Sources* **111**: 1–22 (2002).

F. S. Lau, D. A. Bowen et al, *Techno-Economic Analysis of Hydrogen Production by Gasification of Biomass*, Final Technical Report, DOE Contract Number: DE-FC36-01GO11089, prepared for the Period September 15, 2001 to September 14, 2002, Gas Technology Institute, Dec (2002).

H. L. Chum and R. P. Overend, “Biomass and renewable fuels,” *Fuel Processing Technology* **71**: 187–195 (2001).

R. H. Williams, E. D. Larson et al., “Methanol and hydrogen from biomass for transportation,” *Energy for Sustainable Development*, Volume I No. 5, January (1995).

L. Basye and S. Swaminathan, "Hydrogen Production Costs --A Survey", Sentech Inc., Dec 4 (1997).

G. Brinkman, "Economics and Environmental Effects of Hydrogen Production Methods," Fall (2003).

P. L. Spath, J. M. Lane et al, "Update of Hydrogen from Biomass -Determination of the Delivered Cost of Hydrogen," Report, prepared for the U.S. Department of Energy’s Hydrogen Program, National Renewable Energy Laboratory, April (2000).

H. Audus and P. Freund, “Climate Change Mitigation by Biomass Gasification Combined with CO_2 Capture and Storage,” IEA Greenhouse Gas R&D Programme, Cheltenham, U.K.

W. Iwasaki, “A consideration of the economic efficiency of hydrogen production from biomass,” *International Journal of Hydrogen Energy* **28**: 939– 944 (2003).

S. P. Babu, “Biomass Gasification for Hydrogen Production – Process Description and Research Needs,” Gas Technology Institute, IEA Thermal Gasification Task.

EERE, “Gasification-based Biomass“, **http://www.eere.energy.gov/consumerinfo/pdfs/bio_gasification.pdf,** accessed Apr 20 (2005).

J. P. Ciferno and J. J. Marano, "Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production," Prepared for U.S. Department of Energy National Energy Technology Laboratory, June (2002).

M. M. DeLong, *Economic development through biomass system integration: Summary report*, Report Number: NREL/TP--430-20517, DOE Contract Number: AC36-83CH10093, Gas Technology Northern States Power Company, Oct (1995).