Online Supporting Material for

Techno-Economic Analysis of a Novel Indirect Coal-Biomass to Liquids Plant Integrated with a Combined Cycle Plant and CO_2 Capture and Storage

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Appendix A: Lists of major equipment in the indirect CBTL plant with CCS

Appendix B: Validation of the APEA model for the capital investment

Appendix A. Lists of major equipment in the indirect CBTL plant with CCS

Table S1 Detailed equipment list for the syngas production section and water treatment units

Equipment	# Req	# Spares	Model in APEA	Cost source	Material
Biomass handling and drying	1	0	C*	Baliban et al.[1]	N/A
Coal handling and drying	1	0	C*	Baliban et al.[1]	N/A
Air separation unit	1	0	C*	Baliban et al.[1]	N/A
Gasifier (with steam generator)	1	0	C*	Baliban et al.[1]	N/A
Slag separator	1	0	VT CYLINDER	Aspen Icarus	SS304
Scrubber	1	0	VT CYLINDER	Aspen Icarus	CS
Sour water gas shift reactor	1	0	C*	Baliban et al.[1]	N/A
COS hydrolysis	1	0	C*	Baliban et al.[1]	N/A
Medium pressure steam generator	1	0	HE WASTE HEAT	Icarus	CS
Low pressure steam generator	2	0	HE WASTE HEAT	Icarus	CS
Hydrocarbons preheater	1	0	HE FLOAT HEAD	Icarus	A285C, A214
Boiler feed water heater	1	0	HE FLOAT HEAD	Icarus	A285C, A214
K.O. drum	5	0	VT CYLINDER	Icarus	A516
Fuel gas preheater	1	0	HE FLOAT HEAD	Icarus	A285C, A214
Syngas cooler	2	0	HE FLOAT HEAD	Icarus	A285C, A214
Makeup water heater	1	0	HE FLOAT HEAD	Icarus	A285C, A214
Black water treatment	1	0	VT CYLINDER	Icarus	A516
Black water pump	1	1	CP CENTRIF	Icarus	CS casing
Makeup water pump	1	1	CP CENTRIF	Icarus	CS casing
Multi-stage O_2 compressor	1	0	GC CENTRIF	Icarus	CS casing
Slurry tank	1	1	AT MIXER	Icarus	A285C
Slurry water pump	1	1	CP CENTRIF	Icarus	CS casing
SWS - condenser	1	0	HE FIXED T S	Icarus	A285C, A214
SWS - drum	1	0	HT HORIZ DRUM	Icarus	A516
SWS - reboiler	1	0	RB U TUBE	Icarus	A285C, A214
SWS - reflux pump	1	1	CP CENTRIF	Icarus	CS casing
SWS - tower	1	0	TW TRAYED	Icarus	A516, A285C
SWS bottom pump	1	1	CP CENTRIF	Icarus	CS casing
Claus unit	1	0	C*	Baliban et al.[1]	N/A
Scrubber water pump	1	1	CP CENTRIF	Aspen Icarus	CS casing

*Quoted equipment
SWS=sour water stripper

Table S2 Detailed equipment list for the Selexol unit and the CO_2 compression unit

Description	# Req	# Spares	Model in APEA	Cost source	Material
Tail gas compressor	1	1	GC RECIP MOTR	Icarus	CS casing

NH_3 compressor	1	0	GC CENTRIF	Icarus	SS304
CO_2 absorber	1	0	TW TRAYED	Icarus	A516, A285C
Solvent chilling	2	0	HE FLOAT HEAT	Icarus	A285C, A214
Solvent pre-cooler	1	0	HE FLOAT HEAT	Icarus	A285C, A214
Solvent recycle pump	1	1	CP CENTRIF	Icarus	CS casing
H_2 recovery drum	1	0	VT CYLINDER	Icarus	A516
H_2 recovery compressor	1	0	GC CENTRIF	Icarus	SS316 casing
H_2 recovery cooler	1	0	HE FLOAT HEAT	Icarus	A285C, A214
High pressure flash	1	0	VT CYLINDER	Icarus	A516
Medium pressure flash	1	0	VT CYLINDER	Icarus	A516
Low pressure flash	1	0	VT CYLINDER	Icarus	A516
Rich solvent pump	1	1	CP CENTRIF	Icarus	CS casing
H_2S absorber solvent chilling	1	0	HE FLOAT HEAT	Icarus	A285C, A214
H_2S absorber	1	0	TW TRAYED	Icarus	A516, A285C
Lean solvent pre-cooler	1	0	HE FLOAT HEAT	Icarus	A285C, A214
H_2S concentrator	1	0	TW TRAYED	Icarus	A516, A285C
H_2S concentrator cooler	1	0	HE FLOAT HEAT	Icarus	A285C, A214
Acid gas K.O. drum	1	0	VT CYLINDER	Icarus	A516
Strippered gas compressor	1	0	GC CENTRIF	Icarus	CS casing
Selexol stripper - top product pump	1	1	CP CENTRIF	Icarus	CS casing
Selexol stripper - condenser	1	0	HE FIXED T S	Icarus	A285C, A214
Selexol stripper - drum	1	0	HT HORIZ DRUM	Icarus	A516
Selexol stripper - reboiler	1	0	RB U TUBE	Icarus	A516
Selexol stripper - reflux pump	1	1	CP CENTRIF	Icarus	CS casing
Selexol stripper - tower	1	0	TW TRAYED	Icarus	A516, A285C
Lean solvent pump	1	1	CP CENTRIF	Icarus	CS casing
Lean solvent vessel	1	0	VT CYLINDER	Icarus	A516
Makeup solvent pump	1	1	CP CENTRIF	Icarus	CS casing
CO_2 compressor	1	0	C*	NETL[2,3]	N/A

*Quoted equipment

Table S3 Detailed equipment list for the synfuel production and upgrading units

Description	# Req	# Spares	Model in APEA	Cost source	Material
Fischer-Tropsch synthesis	1	0	C*	Bechtel[4,5]	N/A
Autothermal reformer	1	0	C*	Baliban et al.[1]	N/A
Syncrude pump	1	1	CP CENTRIF	Icarus	CS casing
Hydrotreating feed furnace	1	0	FU BOX	Icarus	A213F
Feed/product heat exchanger	1	0	HE FLOAT HEAD	Icarus	A285C, A214
Hydrotreating reactor	1	0	VT MULTI WALL	Icarus	SS347
Product cooler	1	0	HE FLOAT HEAD	Icarus	A285C, A214
High pressure flash	1	0	VT CYLINDER	Icarus	A516
H_2 recycle compressor	1	0	GC CENTRIF	Icarus	SS316

Low pressure flash	1	0	VT CYLINDER	Icarus	A516
Heavy naphtha pumparoud	1	0	HE FLOAT HEAD	Icarus	A285C, A214
Diesel pumparoud	1	0	HE FLOAT HEAD	Icarus	A285C, A214
Heavy naphtha heat exchanger	1	0	HE FLOAT HEAD	Icarus	A285C, A214
Diesel heat exchanger	1	0	HE FLOAT HEAD	Icarus	A285C, A214
Wax heat exchanger	1	0	HE FLOAT HEAD	Icarus	A285C, A214
Main column - condenser	1	0	HE FIXED T S	Icarus	A285C, A214
Main column - drum	1	0	HT HORIZ DRUM	Icarus	A516
Main column - reflux pump	1	1	CP CENTRIF	Icarus	CS casing
Main column - tower	1	0	TW TRAYED	Icarus	A516, A285C
Main column - feed furnace	1	0	FU BOX	Icarus	A213C
Side stripper - heavy naphtha	1	0	TW TRAYED	Icarus	A516, A285C
Side stripper - diesel	1	0	TW TRAYED	Icarus	A516, A285C
Pump to the stabilizer	1	1	CP CENTRIF	Icarus	CS casing
Stabilizer - condenser	1	0	HE FIXED T S	Icarus	A285C, A214
Stabilizer - drum	1	0	HT HORIZ DRUM	Icarus	A516
Stabilizer - reboiler	1	0	RB U TUBE	Icarus	A285C, A214
stabilizer - reflux pump	1	1	CP CENTRIF	Icarus	CS casing
Stabilizer - tower	1	0	TW TRAYED	Icarus	A516, A285C
Hydrocracking	1	0	C*	Shah et al.[6]	N/A
Isomerization	1	0	C*	Bechtel[4,5]	N/A
Catalytic reformer	1	0	C*	Bechtel[4,5]	N/A
H_2 recovery (PSA)	1	0	C*	Bechtel[4,5]	N/A
Diesel storage tank (30 days)	1	0	VT STORAGE	Icarus	A285C
Gasoline storage tank (30 days)	1	0	VT STORAGE	Icarus	A285C

*Quoted equipment

Table S4 Detailed equipment list for the post-FT CO_2 capture unit

Description	# Req	# Spares	Model in APEA	Cost source	MOC
Treated gas K.O. drum*	1	0	VT CYLINDER	Icarus	A516
Feed gas K.O. drum*	1	0	VT CYLINDER	Icarus	SS304
Activated carbon drum*	1	0	VT CYLINDER	Icarus	A516
Rich amine flash drum*	1	0	HT HORIZ DRUM	Icarus	A516
Absorber	1	0	TW PACKED	Icarus	A516**, M107YC
Absorber intercooling	1	0	HE FLOAT HEAD	Icarus	A285C, A214
Lean/rich heat exchanger	4	0	HE PLAT FRAM	Icarus	SS316
Solvent regeneration - condenser	2	0	HE FIXED T S	Icarus	T150A, SS316
Solvent regeneration - drum	2	0	HT HORIZ DRUM	Icarus	A516
Solvent regeneration - reboiler	8	0	RB U TUBE	Icarus	316LW, SS316
Solvent regeneration - reflux pump	2	2	CP CENTRIF	Icarus	SS316
Solvent regeneration - tower	2	0	TW PACKED	Icarus	304L, M107YC
Solvent cooling	1	0	HE FLOAT HEAD	Icarus	A285C, A214

Solvent recycle pump	1	1	CP CENTRIF	Icarus	SS316
Amine storage tank *	1	0	VT STORAGE	Icarus	A285C

*sizing information available in Bechtel's report[18]

**With 1/8 inch SS304 cladding

Table S5 Detailed equipment list for the combined cycle power plant*

Description	# Req	# Spares	Model in APEA	Cost source	Material
Clean fuel gas heater	1	0	HE FLOAT HEAD	Icarus	A258C, A214
Fuel gas compressor	1	0	GC CENTRIF	Icarus	CS Casing
Gas turbine	1	0	C*	NETL[2,3]	N/A
Boiler feed water pump	1	1	CP CENTRIF	Icarus	CS Casing
Medium pressure steam reheater	1	0	HE AIR COOLER	Icarus	A214
High pressure steam superheater	1	0	HE AIR COOLER	Icarus	A214
High pressure steam generator	1	0	HE WASTE HEAT	Icarus	CS
High pressure BFW economizer	1	0	HE AIR COOLER	Icarus	A214
High pressure steam blowdown	1	0	VT CYLINDER	Icarus	CS
Low pressure steam generator	1	0	HE WASTE HEAT	Icarus	CS
Low pressure BFW economizer	1	0	HE AIR COOLER	Icarus	A214
High pressure BFW pre-economizer	1	0	HE AIR COOLER	Icarus	A214
Pre-deaerator heater	1	0	HE AIR COOLER	Icarus	A214
Deaerator	1	0	TW TRAYED	Icarus	A516, A285C
Steam packing exhauster	1	0	HE FLOAT HEAD	Icarus	A516, A285C
Air ejector	1	0	HE FLOAT HEAD	Icarus	A516, A285C
Condenser pump	1	1	VP MECH BOOST	Icarus	CS Casing
Surface condenser	1	0	C BAROMETRIC	Icarus	N/A
Steam turbine	1	0	EG TURBO GEN	Icarus	CS Casing
High pressure BFW pump	1	1	CP CENTRIF	Icarus	CS Casing
Medium pressure BFW pump	1	1	CP CENTRIF	Icarus	CS Casing
Low pressure BFW pump	1	1	CP CENTRIF	Icarus	CS Casing

*Quoted equipment

BFW= boiler feed water

Reference (for Appendix A)

(1) Baliban, R.C.; Elia, J.A.; Floudas, C.A. Optimization framework for the simultaneous process synthesis, heat and power integration of a thermochemical hybrid biomass, coal and natural gas facility. *Compt. Chem. Eng.* **2011**, *35*, 1647-1690.

(2) *Baseline Technical and Economic Assessment of a Commercial Scale Fischer-Tropsch Liquids Facility*; DOE/NETL-2007/1260; National Energy Technology Laboratory, 2007; http://www.netl.doe.gov.

(3) *Technical and Economic Assessment of Small-Scale Fischer-Tropsch Liquids Facilities*; DOE/NETL-2007/1253; National Energy Technology Laboratory, 2007; http://www.netl.doe.gov.

(4) *Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Final Report*; DE-AC22-91PC90027; Bechtel Corp., April 1998; http://www.fischer-tropsch.org.

(5) *Aspen Process Flowsheet Simulation Model for a Battelle Biomass-Based Gasification, Fischer-Tropsch Liquefaction and Combined-Cycle Power Plant*, Topical Report; DE-AC22-93PC91029; Bechtel Corp., May 1998; http://www.fischer-tropsch.org.

(6) Shah, P.P; Sturtevant, G.C.; Gregor, J. H.; Humbach, M.J.; Padtra, F.G.; Steigleder, K.Z. *Fischer-Tropsch Wax Characterization and Upgrading, Final Report*; DE-AC22-85PC80017; UOP Inc., June 1988; http://www.fischer-tropsch.org.

Appendix B. Validation of the APEA model for the capital investment

Table S6 Comparison with Bechtel studies[1]

		Bechtel*	Model	Difference	Notes
		(MM$, 2014)		%	
ISBL cost of each unit					(1)
Unit 100	Syngas production and treatment	2056.6	2280.4	-10.88	
	Pre-processing & gasificaiton	1355.7	1266.8	6.56	
	Syngas treating & cooling	60.8	63.4	-4.26	
	Sour water stripper	5.1	4.9	5.33	
	Acid gas removal	29.9	299.6		(2)
	Sulfur recovery	69.5	70.0	-0.77	
	Syngas wet scrubbing	12.1	13.3	-9.75	
	Air separation unit	523.5	422.3	19.34	
	Ash handling		140.1		(3)
Unit 200	Fischer-Tropsch synthesis loop	800.2	437.3	45.35	(4)
	Fischer-Tropsch synthesis	352.8	326.0	7.61	
	Carbon dioxide removal	226.7	60.6	-6.93**	(5)
	Dehydration and hydrocarbon recovery	114.5	3.0		
	Autothermal reformer	35.1	35.0	-0.35	
	Hydrogen recovery	71.1	15.8		(6)
Unit 300	Product upgrading and refining	243.7	190.5	21.83	(7)
	Wax hydrocracking	69.8	65.9	5.63	
	Hydrotreating	33.0	30.6	7.3	
	Catalytic reforming	50.2	46.4	7.66	
	C_5/C_6 isomerization	11.7	13.4	-14.63	
	C_4 isomerization and alkylation	70.2			
	Others	8.9			(8)
Total ISBL cost		3100.5	2883.0	5.91	
Total project cost***		4748.5	4905.6	-3.31	(9)

*Original data reported in 1998 is escalated to 2014 pricing basis using CEPCI.

**Difference in capital investment for same amount of CO_2 capture

*** TPC includes OSBL, engineering cost, contingency cost.

(1) HRSG section with steam turbine is included in OSBL section in Bechtel's analysis.

(2) In Bechtel's baseline design, CCS is not considered; amine solvent is used in the acid gas removal unit for removing H_2S only in Unit 100.

(3) Ash handling system is considered as OSBL facility in Bechtel's baseline design.

(4) Dehydration unit was considered in Bechtel's design but not in this project. More complicated hydrocarbon recovery unit is considered in Bechtel's design

(5) In Bechtel's baseline design, CCS is not considered. Hence, most of the CO_2 is captured by the post FT CO_2 capture unit in Unit 200. However, in the base case of this study, WGS reactor is used to increase the H_2/CO ratio in the FT inlet. As a result, significant amount of CO_2 is captured in the acid gas removal unit instead of the post-FT CO_2 removal unit.

(6) The capital cost estimate is consistent with the recent data released by NETL for hydrogen production plant.[4]

(7) C_4 isomerization & C_3-C_5 alkylation units are considered in Bechtel's design for upgrading light hydrocarbons to gasoline but these units are not considered in this project.

(8) Saturated gas plant considered by Bechtel is not considered in this project because light gases are used in furnace and gas turbine in this project instead of upgraded into gasoline in Bechtel's design.

(9) The OSBL cost is expected to be higher in this project because more electricity produced.

Table S7 Comparison with NETL's study on large scale CTL plant[2]

		NETL*	Model	Difference	Notes
		(MM$, 2014)		%	
Bare erected cost of each unit					
Unit 100	Syngas production and treatment	1562.7	1543.6	1.22	
	Preprocessing	295.2	316.3	-7.13	
	Gasifier & accessories	936.7	857.8	8.42	
	Air separation unit	330.7	369.5	-11.72	
Unit 200	Gas cleanup	420.1	420.9	-0.19	(1)
Unit 300	Fuel production and upgrading	480.9	561.4	-13.91	
	without naphtha upgrading	480.9	466.9	2.91	(2)
Unit 400	OSBL facilities	383.8	441.4	15.03	
	Gas turbine & accessories	84.1	86.3	-2.56	
	HRSG & steam turbine	117.7	87.5	25.68	(3)
	Cooling water system	42.0	75.2		(4)
	Slag disposal	139.9	192.5		
Total bare erected cost		2847.4	2970.8	-4.33	
Total project cost**		5214.3	5137.6	1.47	(5)

*Original data reported in 2007 is escalated to 2014 pricing basis using CEPCI.

**TPC includes OSBL, engineering cost, contingency cost.

(1) Dual-stage Selexol unit is used for pre-FT CO_2 removal in NETL's design, which is the same as the base case of this project.

(2) Catalytic reforming & C_5/C_6 isomerization units for naphtha upgrading are not considered in NETL's study but these units are considered in this study.

(3) Difference in power output

(4) Cost of the cooling water distribution system is included in APEA model but not in NETL's case study. Relative error is 12.59% if the cooling water distribution is not considered in this case.

(5) Additional 25% of process contingency is considered for FTS in NETL's study.

Table S8 Comparison with NETL's study on small scale CTL plant[3]

		NETL*	Model	Difference	Notes
		(MM$, 2014)		%	
Bare erected cost of each unit					
Unit 100	Syngas production and treatment	372.5	377.7	-1.38	
	Preprocessing	60.0	52.4	12.7	
	Gasifier & accessories	234.3	221.0	5.68	
	Air separation unit	78.1	104.2		

Unit 200	Gas cleanup	84.9	173.6		(1)
Unit 300	Fuel production and upgrading	89.4	151.1		(2)
Unit 400	OSBL facilities	79.5	82.4	3.73	
	Gas turbine & accessories	16.7	20.4		(3)
	HRSG & steam turbine	25.7	21.9		
	Cooling water system	8.4	14.8		(4)
	Slag disposal	28.6	25.4	11.38	
Total bare erected cost		658.0	784.7	-24.96	
Total project cost**		1124.1	1185.2	-5.44	(5)

*Original data reported in 2007 is escalated to 2014 pricing basis using CEPCI.

** TPC includes OSBL, engineering cost, contingency cost.

(1) CCS is not considered in NETL's design; Area 200 is only for H_2S removal in NETL's study on the small-scale plant.

(2) CCS, catalytic reforming and C_5/C_6 isomerization units are not considered in NETL's study but these units are considered in this study.

(3) Difference in power output

(4) Cost of the cooling water distribution system is included in APEA model but not included in NETL's case study.

(5) Additional 25% process contingency is considered for FTS in NETL's study.

Reference (for Appendix B)

(1) *Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Final Report*; DE-AC22-91PC90027; Bechtel Corp., April 1998; http://www.fischer-tropsch.org.

(2) *Baseline Technical and Economic Assessment of a Commercial Scale Fischer-Tropsch Liquids Facility*; DOE/NETL-2007/1260; National Energy Technology Laboratory, 2007; http://www.netl.doe.gov.

(3) *Technical and Economic Assessment of Small-Scale Fischer-Tropsch Liquids Facilities*; DOE/NETL-2007/1253; National Energy Technology Laboratory, 2007; http://www.netl.doe.gov.

(4) *Production of High Purity Hydrogen from Domestic Coal: Assessing the Techno-Economic Impact of Emerging Technologies*; DOE/NETL-2010/1432; National Energy Technology Laboratory, 2010; http://www.netl.doe.gov.