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APPENDICES

Appendix A CO_2 Conversion Process Flowsheet and Steam Tables Implemented by Aspen Plus 8.6

A.1 Hydrogenation of CO_2 into Methanol

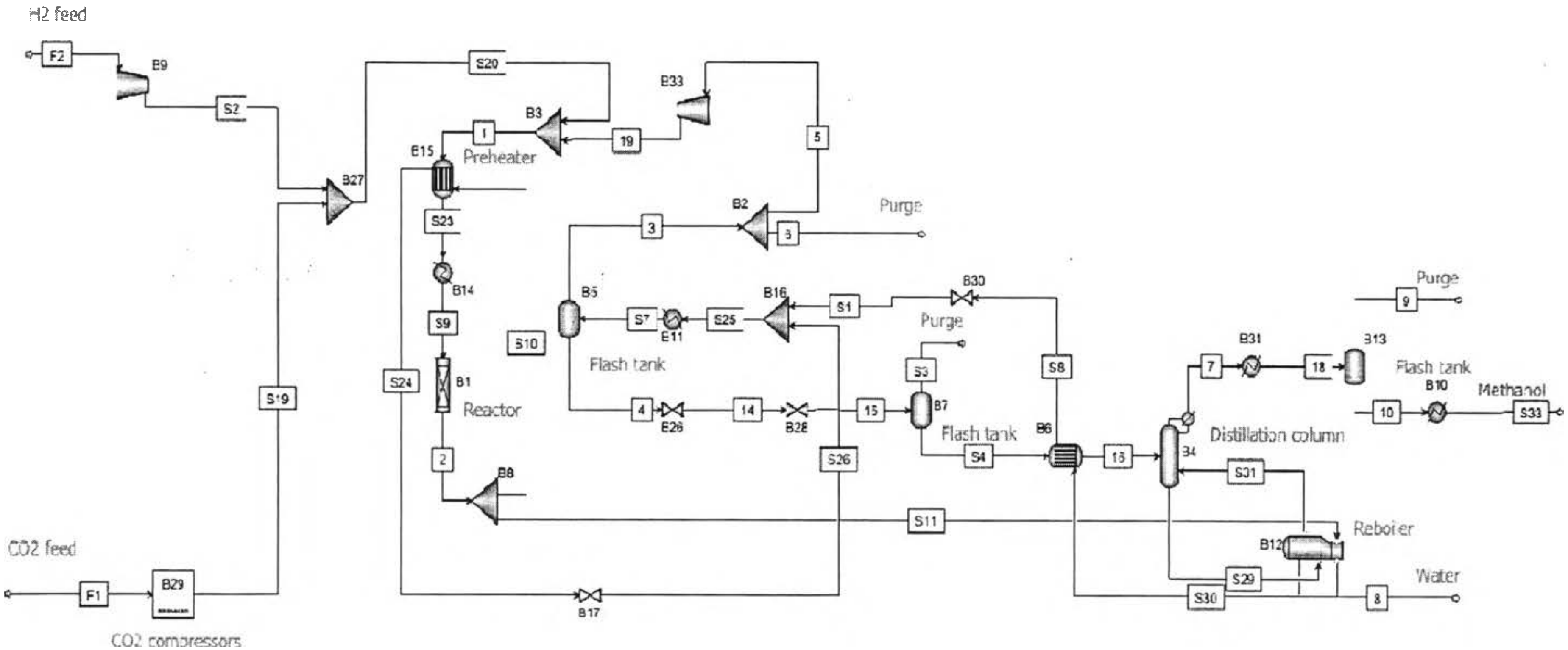

Figure A1.1 Flowsheet of the hydrogenation of CO_2 into methanol for the base case design.

Table A1.1 Stream table of the hydrogenation of CO_2 into methanol for the base case design

	1	2	3	4	5	6	7	8	9	10	14	15
Temperature, °C	58.3	284.5	40	40	40	40	64.3	102.3	50	50	30.2	27.5
Pressure, bar	76	74.36	73	73	73	73	1	1.1	1	1	10	1.2
Vapor Frac	1	1	1	0	1	1	1	0	1	0	0.03	0.041
Mole Flow, kmol/hr	17741.2	16476.1	15157.3	1318.74	15081.5	75.787	631.45	632.573	1.341	630.109	1318.74	1318.74
Mass Flow, kg/hr	122488	122488	89665.8	32822.7	89217.5	448.329	20216.5	11396	46.592	20169.9	32822.7	32822.7
Volume Flow, cum/hr	6596.32	10513.6	5557.47	51.195	5529.68	27.787	17406.9	16.12	35.654	34.871	148.913	1185.86
Enthalpy, Gcal/hr	-174.7	-153.84	-115.26	-81.761	-114.68	-0.576	-30.153	-42.315	-0.084	-35.788	-81.761	-81.761
Mass Flow, kg/hr												
CO_2	76156.7	48164.9	47143.4	1021.83	46907.7	235.717	71.818	0	22.437	49.381	1021.83	1021.83
H_2	31194.3	27361.8	27309.1	52:701	27172.5	136.545	0.183	0	0.164	0.019	52.701	52.701
WATER	221.184	11679.5	222.295	11457.2	221.184	1.111	42.764	11395.9	0.019	42.745	11457.2	11457.2
CO	13059.5	13157.4	13125.1	32.373	13059.5	65.626	0.125	0	0.109	0.016	32.373	32.373
METHANOL	1856.62	22124.5	1865.95	20258.6	1856.62	9.33	20101.6	0.138	23.863	20077.7	20258.6	20258.6

Table A1.1 Stream table of the hydrogenation of CO_2 into methanol for the base case design (con't.)

	16	**18**	**19**	**F1**	**F2**	**S1**	**S2**	**S3**	**S4**	**S7**	**S8**	**S9**
Temperature, °C	80	50	44.5	25	25	84.6	139.2	27.5	27.5	40	84.8	215
Pressure, bar	1.1	1	76	1	30	73	76	1.2	1.2	73	74.36	75.7
Vapor Frac	0.501	0.002	1	1	1	0.943	1	1	0	0.92	0.943	1
Mole Flow, kmol/hr	1264.02	631.45	15081.5	664.602	1995.03	6590.44	1995.03	54.715	1264.02	16476.1	6590.44	17741.2
Mass Flow, kg/hr	31612.5	20216.5	89217.5	29249	4021.74	48995.3	4021.74	1210.17	31612.5	122489	48995.3	122488
Volume Flow, cum/hr	16676.1	70.525	5395.87	16393.3	1679.54	2610.58	934.313	1137.05	48.812	5608.66	2565.54	9780.52
Enthalpy, Gcal/hr	-72.313	-35.872	-114.19	-62.471	0.012	-75.127	1.631	-2.353	-79.408	-197.02	-75.127	-153.84
Mass Flow, kg/hr												
CO_2	71.817	71.818	46907.7	29249	0	19266	0	950.007	71.817	48165.2	19266	76156.7
H_2	0.183	0.183	27172.5	0	4021.74	10944.7	4021.74	52.518	0.183	27361.8	10944.7	31194.3
WATER	11438.7	42.764	221.184	0	0	4671.81	0	18.574	11438.7	11679.5	4671.81	221.184
CO	0.125	0.125	13059.5	0	0	5262.98	0	32.248	0.125	13157.5	5262.98	13059.5
METHANOL	20101.8	20101.6	1856.62	0	0	8849.81	0	156.818	20101.8	22124.5	8849.81	1856.62

Table A1.1 Stream table of the hydrogenation of CO_2 into methanol for the base case design (con't.)

	S10	S11	S19	S20	S23	S24	S25	S26	S29	S30	S31	S33
Temperature, °C	284.5	284.5	127	129.9	215	81.7	82.7	81.5	102.3	159.9	102.3	40
Pressure, bar	74.36	74.36	76	76	75.7	74.36	73	73	1.1	74.36	1.1	1
Vapor Frac	1	1	1	1	1	0.94	0.941	0.94	0	1	1	0
Mole Flow, kmol/hr	9885.64	6590.44	664.602	2659.63	17741.2	9885.64	16476.1	9885.64	1299.23	6590.44	666.656	630.109
Mass Flow, kg/hr	73493.1	48995.3	29249	33270.8	122488	73493.1	122489	73493.1	23406.5	48995.3	12010.5	20169.9
Volume Flow, cum/hr	6308.2	4205.46	258.219	1187.74	9780.52	3806.9	6484.51	3873.78	33.109	3253.8	18747.8	34.436
Enthalpy, Gcal/hr	-92.305	-61.537	-62.137	-60.506	-153.84	-113.16	-188.29	-113.16	-86.91	-68.032	-38.1	-35.928
Mass Flow, kg/hr												
CO_2	28899.1	19266	29249	29249	76156.7	28899.1	48165.2	28899.1	0	19266	0	49.381
H_2	16417.1	10944.7	0	4021.74	31194.3	16417.1	27361.8	16417.1	0	10944.7	0	0.019
WATER	7007.72	4671.81	0	0	221.184	7007.72	11679.5	7007.72	23405.3	4671.81	12009.4	42.745
CO	7894.49	5262.98	0	0	13059.5	7894.49	13157.5	7894.49	0	5262.98	0	0.016
METHANOL	13274.7	8849.81	0	0	1856.62	13274.7	22124.5	13274.7	1.217	8849.81	1.08	20077.7

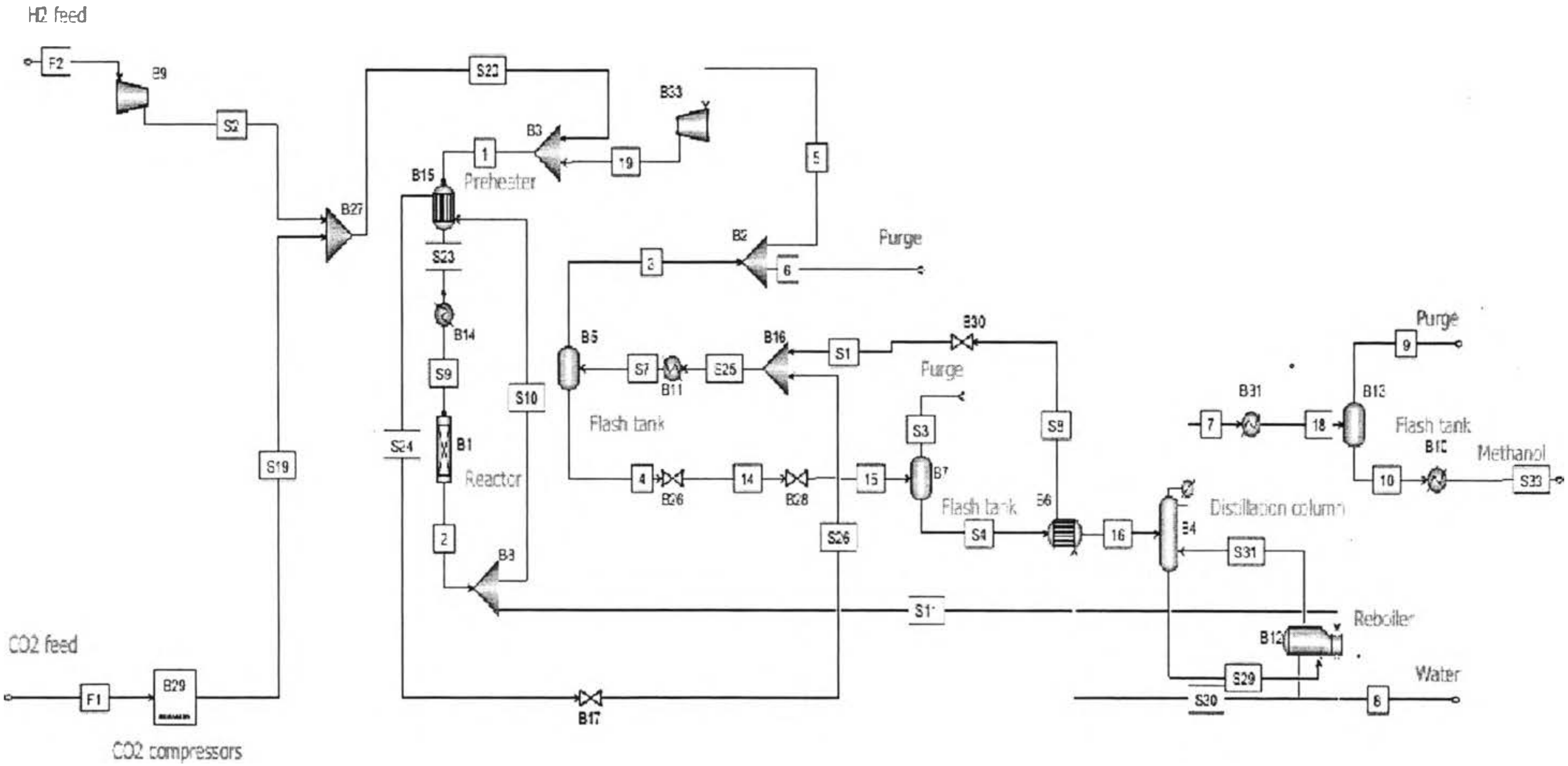

Figure A1.2 Flowsheet of the hydrogenation of CO_2 into methanol for the optimized case design.

Table A1.2 Stream table of the hydrogenation of CO_2 into methanol for the optimized case design

	1	2	3	4	5	6	7	8	9	10	14	15
Temperature, °C	53.1	264.9	40	40	40	40	64.3	102.3	50	50	30.2	27.8
Pressure, bar	55.3	52.925	52.3	52.3	52.3	52.3	1	1.1	1	1	10	1.2
Vapor Frac	1	1	1	0	1	1	1	0	1	0	0.022	0.033
Mole Flow, kmol/hr	18740.2	17472.1	16161.4	1310.68	16080.6	80.807	633.702	634.122	1.665	632.038	1310.68	1310.68
Mass Flow, kg/hr	135943	135943	103189	32755	102673	515.943	20296.4	11423.9	58.953	20237.5	32755	32755
Volume Flow, cum/hr	9334.1	15009.2	8182.16	51.006	8141.24	40.911	17467.4	16.159	44.258	34.99	120.558	940.035
Enthalpy, Gcal/hr	-201.18	-180.55	-141.32	-81.682	-140.61	-0.707	-30.266	-42.419	-0.106	-35.896	-81.682	-81.682
Mass Flow, kg/hr												
CO_2	88004.3	59968.4	59050.6	918.023	58755.3	295.253	80.742	0	29.045	51.697	918.023	918.023
H_2	32658	28817.4	28780.2	37.201	28636.3	143.901	0.166	0	0.151	0.014	37.201	37.201
WATER	308.377	11784.8	309.927	11474.9	308.377	1.55	36.299	11423.8	0.02	36.279	11474.9	11474.9
CO	12425.2	12508.5	12487.7	20.884	12425.2	62.438	0.103	0	0.093	0.011	20.884	20.884
METHANOL	2547.52	22864.4	2560.32	20304	2547.52	12.802	20179.1	0.149	29.643	20149.5	20304	20304

Table A1.2 Stream table of the hydrogenation of CO_2 into methanol for the optimized case design (con't.)

	16	**18**	**19**	**F1**	**F2**	**S1**	**S2**	**S3**	**S4**	**S7**	**S8**	**S9**
Temperature, °C	80	50	46.2	25	25	76.8	96.8	27.8	27.8	40	76.9	200
Pressure, bar	1.1	1	55.3	1	30	52.3	55.3	1.2	1.2	52.3	52.925	55
Vapor Frac	0.503	0.003	1	1	1	0.946	1	1	0	0.925	0.946	1
Mole Flow, kmol/hr	1267.83	633.702	16080.6	664.602	1995.03	6988.84	1995.03	42.853	1267.83	17472.1	6988.84	18740.2
Mass Flow, kg/hr	31720.4	20296.4	102673	29249	4021.74	54377.4	4021.74	1034.64	31720.4	135944	54377.4	135943
Volume Flow, cum/hr	16795.4	79.248	7864.03	16393.3	1679.54	3749.45	1143.24	891.044	48.991	8233.16	3707.27	13673.1
Enthalpy, Gcal/hr	-72.509	-36.002	-139.9	-62.471	0.012	-85.846	1.024	-2.041	-79.64	-223	-85.846	-180.55
Mass Flow, kg/hr												
CO_2	80.742	80.742	58755.3	29249	0	23987.3	0	837.281	80.742	59968.6	23987.3	88004.3
H_2	0.166	0.166	28636.3	0	4021.74	11527	4021.74	37.035	0.166	28817.4	11527	32658
WATER	11460.1	36.299	308.377	0	0	4713.93	0	14.785	11460.1	11784.8	4713.93	308.377
CO	0.103	0.103	12425.2	0	0	5003.41	0	20.781	0.103	12508.6	5003.41	12425.2
METHANOL	20179.3	20179.1	2547.52	0	0	9145.75	0	124.76	20179.3	22864.3	9145.75	2547.52

Table A1.2 Stream table of the hydrogenation of CO_2 into methanol for the optimized case design (con't.)

	S10	S11	S19	S20	S23	S24	S25	S26	S29	S30	S31	S33
Temperature, °C	264.9	264.9	95.1	91.7	200	75.8	76.1	75.7	102.3	146.6	102.3	40
Pressure, bar	52.925	52.925	55.3	55.3	55	52.925	52.3	52.3	1.1	52.925	1.1	1
Vapor Frac	1	1	1	1	1	0.945	0.945	0.945	0	1	1	0
Mole Flow, kmol/hr	10483.2	6988.84	664.602	2659.63	18740.2	10483.2	17472.1	10483.2	1300.78	6988.84	666.655	632.038
Mass Flow, kg/hr	81566.1	54377.4	29249	33270.8	135943	81566.1	135944	81566.1	23434.4	54377.4	12010.5	20237.5
Volume Flow, cum/hr	9005.52	6003.68	321.186	1462.83	13673.1	5537.87	9350.39	5600.9	33.149	4664.51	18747.8	34.552
Enthalpy, Gcal/hr	-108.33	-72.219	-62.307	-61.283	-180.55	-128.96	-214.81	-128.96	-87.014	-78.714	-38.1	-36.036
Mass Flow, kg/hr												
CO_2	35981.1	23987.3	29249	29249	88004.3	35981.1	59968.6	35981.1	0	23987.3	0	51.697
H_2	17290.4	11527	0	4021.74	32658	17290.4	28817.4	17290.4	0	11527	0	0.014
WATER	7070.89	4713.93	0	0	308.377	7070.89	11784.8	7070.89	23433.1	4713.93	12009.3	36.279
CO	7505.14	5003.41	0	0	12425.2	7505.14	12508.6	7505.14	0	5003.41	0	0.011
METHANOL	13718.6	9145.75	0	0	2547.52	13718.6	22864.3	13718.6	1.314	9145.75	1.165	20149.5

A.2 Bi-reforming of CO_2 into Methanol

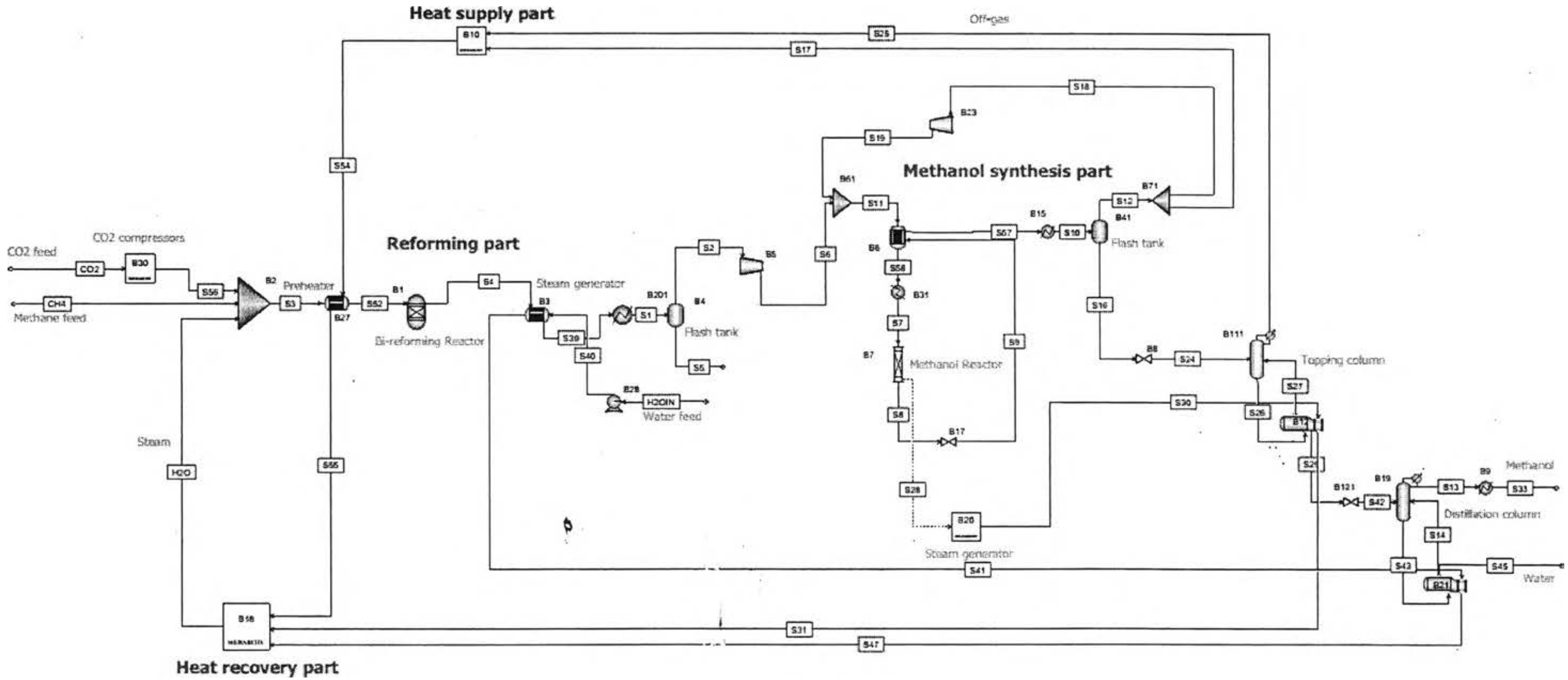

Figure A2.1 Flowsheet of the bi-reforming of CO_2 into methanol for the base case design.

Table A2.1 Stream table of bi-reforming of CO_2 into methanol for the base case design

	CH_4	CO_2	H_2O	H_2OIN	S1	S2	S3	S4	S5	S6	S7	S8
Temperature, °C	25	50	227	25	55	55	199.4	920	55	173.5	220	246
Pressure, bar	25	1	25	1	25	25	25	25	25	63.3	63	61.376
Vapor Frac	1	1	1	0	0.729	1	0.938	1	0	1	1	1
Mole Flow, kmol/hr	589.66	152.722	1474.1	2000	3270.96	2383.76	2216.48	3270.96	887.2	2383.76	12001.8	10725
Mass Flow, kg/hr	9459.78	6721.27	26556.3	36030.6	42737.4	26753	42737.4	42737.4	15984.4	26753	108523	108523
Volume Flow, cum/hr	560.782	4087.81	2145.93	36.137	2649.36	2632.79	3065.72	13044.1	16.572	1440.61	7992.71	7665.15
Enthalpy, Gcal/hr	-10.554	-14.321	-83.527	-136.62	-93.476	-32.787	-108.29	-60.678	-60.689	-30.689	-118.23	-129.25
Mass Flow, kg/hr												
CO_2	0	6721.27	0	0	8775.92	8773.67	6721.27	8775.92	2.253	8773.67	35695.5	28387.7
CH_4	9459.78	0	0	0	1001.4	1001.39	9459.78	1001.4	0.014	1001.39	32652.4	32652.1
CO	0	0	0	0	13460.5	13460.5	0	13460.5	0.019	13460.5	21473.5	8243.49
H_2	0	0	0	0	3282.67	3282.66	0	3282.67	0.008	3282.66	16774.8	13866.2
WATER	0	0	26556.3	36030.6	16216.9	234.774	26556.3	16216.9	15982.1	234.774	301.82	3293.22
O_2	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	0	0	0	0	0	0	0	0	0	0	1625.02	22079.9
N_2	0	0	0	0	0	0	0	0	0	0	0	0

Table A2.1 Stream table of bi-reforming of CO_2 into methanol for the base case design (con't.)

	S9	S10	S11	S12	S13	S14	S16	S17	S18	S19	S24	S25
Temperature, °C	246	35	66.1	35	63.9	99.5	35	35	35	40.1	34.8	51.7
Pressure, bar	60.3	60.3	63.3	60.3	1	1.1	60.3	60.3	60.3	63.3	17.5	17
Vapor Frac	1	0.92	1	1	0	1	0	1	1	1	0.025	1
Mole Flow, kmol/hr	10725	10725.1	12001.8	9864.68	635.286	792.714	860.387	246.617	9618.06	9618.06	860.387	46.103
Mass Flow, kg/hr	108523	108523	108523	83866.8	20316.2	15474.2	24656.1	2096.67	81770.1	81770.1	24656.1	1074.24
Volume Flow, cum/hr	7799.23	4259.62	5427.82	4219.18	35.823	22108.7	40.436	105.48	4113.7	3990.89	71.442	71.692
Enthalpy, Gcal/hr	-129.25	-155.82	-132.96	-105.27	-35.845	-44.474	-50.556	-2.632	-102.63	-102.27	-50.556	-1.966
Mass Flow, kg/hr												
CO_2	28387.7	28387.8	35695.5	27612.1	1.734	0	775.616	690.303	26921.8	26921.8	775.616	773.882
CH_4	32652.1	32652.3	32652.4	32462.6	0.006	0	189.694	811.564	31651	31651	189.694	189.688
CO	8243.49	8243.5	21473.5	8218.54	0	0	24.962	205.464	8013.08	8013.08	24.962	24.962
H_2	13866.2	13866.3	16774.8	13838.1	0	0	28.202	345.952	13492.1	13492.1	28.202	28.202
WATER	3293.22	3293.22	301.82	68.765	51.677	12748.4	3224.46	1.719	67.046	67.046	3224.46	0.8
O_2	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	22079.9	22079.9	1625.02	1666.69	20262.8	2725.81	20413.2	41.667	1625.02	1625.02	20413.2	56.701
N_2	0	0	0	0	0	0	0	0	0	0	0	0

Table A2.1 Stream table of bi-reforming of CO_2 into methanol for the base case design (con't.)

	S26	S27	S29	S30	S31	S33	S39	S40	S41	S42	S43	S45
Temperature, °C	162.9	164.5	164.5	253.3	253.3	40	150	26.1	286.7	70.9	91.1	99.5
Pressure, bar	17.5	17.5	17.5	42	42	1	25	42	42	1.1	1.1	1.1
Vapor Frac	0	1	0	1	0.54	0	0.898	0	1	0.276	0	0
Mole Flow, kmol/hr	1253.43	439.15	814.284	938.117	938.117	635.286	3270.96	2000	2000	814.284	971.711	178.998
Mass Flow, kg/hr	36831.7	13249.8	23581.9	16900.4	16900.4	20316.2	42737.4	36030.6	36030.6	23581.9	18740	3265.74
Volume Flow, cum/hr	76.675	780.373	48.893	799.841	441.324	34.715	4149.36	36.081	1926.35	5766.83	27.288	4.643
Enthalpy, Gcal/hr	-70.151	-21.186	-45.808	-53.206	-56.362	-36.186	-84.776	-136.55	-112.45	-45.808	-64.194	-11.949
Mass Flow, kg/hr												
CO_2	32.891	31.158	1.734	0	0	1.734	8775.92	0	0	1.734	0	0
CH_4	0.321	0.315	0.006	0	0	0.006	1001.4	0	0	0.006	0	0
CO	0.012	0.012	0	0	0	0	13460.5	0	0	0	0	0
H_2	0.011	0.01	0	0	0	0	3282.67	0	0	0	0	0
WATER	4289.07	1065.41	3223.66	16900.4	16900.4	51.677	16216.9	36030.6	36030.6	3223.66	15920.4	3171.98
O_2	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	32509.4	12152.9	20356.5	0	0	20262.8	0	0	0	20356.5	2819.57	93.758
N_2	0	0	0	0	0	0	0	0	0	0	0	0

Table A2.1 Stream table of bi-reforming of CO_2 into methanol for the base case design (con't.)

	S47	S52	S54	S55	S56	S57	S58
Temperature, °C	253.3	650	1000	659.4	137.7	101.6	220
Pressure, bar	42	25	1	1	25	60.3	63
Vapor Frac	0.535	1	1	1	1	0.986	1
Mole Flow, kmol/hr	2000	2216.48	3979.29	3979.29	152.722	10725	12001.8
Mass Flow, kg/hr	36030.6	42737.4	109395	109395	6721.27	108523	108523
Volume Flow, cum/hr	933.871	6796.17	421326	308633	200.92	5491.19	7992.71
Enthalpy, Gcal/hr	-120.22	-96.333	-44.43	-56.389	-14.211	-143.98	-118.23
Mass Flow, kg/hr							
CO_2	0	6721.27	14808.4	14808.4	6721.27	28387.7	35695.5
CH_4	0	9459.78	0	0	0	32652.1	32652.4
CO	0	0	0.006	0.006	0	8243.49	21473.5
H_2	0	0	0.001	0.001	0	13866.2	16774.8
WATER	36030.6	26556.3	13934.1	13934.1	0	3293.22	301.82
O_2	0	0	2185.84	2185.84	0	0	0
C	0	0	0	0	0	0	0
METHANOL	0	0	0	0	0	22079.9	1625.02
N_2	0	0	78466.9	78466.9	0	0	0

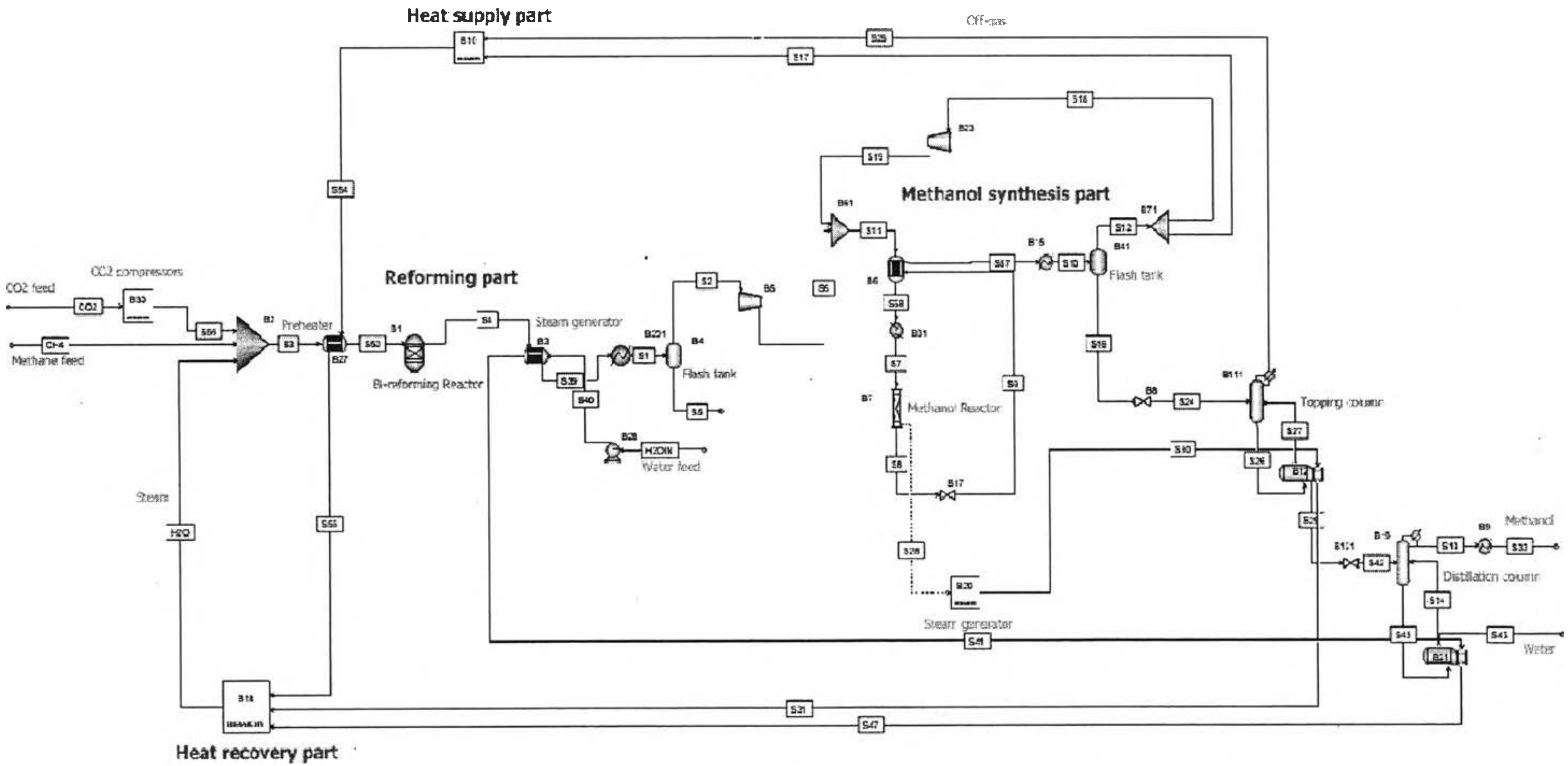

Figure A2.2 Flowsheet of the bi-reforming of CO_2 into methanol for the optimized case design.

Table A2.2 Stream table of bi-reforming of CO_2 into methanol for the optimized case design

	CH_4	CO_2	H_2O	H_2OIN	S1	S2	S3	S4	S5	S6	S7	S8
Temperature, °C	25	50	227	25	55	55	199.3	915	55	168.8	215	241.3
Pressure, bar	25	1	25	1	25	25	25	25	25	61.3	61	59.28
Vapor Frac	1	1	1	0	0.728	1	0.938	1	0	1	1	1
Mole Flow, kmol/hr	589.66	152.722	1469.95	2000	3257.71	2371.55	2212.34	3257.71	886.162	2371.55	12105.7	10839.1
Mass Flow, kg/hr	9459.78	6721.27	26481.6	36030.6	42662.7	26696.9	42662.7	42662.7	15965.7	26696.9	112149	112149
Volume Flow, cum/hr	560.782	4087.81	2139.89	36.137	2635.68	2619.13	3059.7	12937.1	16.553	1463.24	8233.92	7941.43
Enthalpy, Gcal/hr	-10.554	-14.321	-83.292	-136.62	-93.466	-32.849	-108.06	-60.876	-60.618	-30.844	-124.15	-134.96
Mass Flow, kg/hr												
CO_2	0	6721.27	0	0	8842.06	8839.78	6721.27	8842.06	2.279	8839.78	37027.4	29685.2
CH_4	9459.78	0	0	0	1074.42	1074.41	9459.78	1074.42	0.015	1074.41	35355.3	35355
CO	0	0	0	0	13290.9	13290.9	0	13290.9	0.019	13290.9	21173.7	8108.25
H_2	0	0	0	0	3258.17	3258.16	0	3258.17	0.008	3258.16	16600.9	13711.3
WATER	0	0	26481.6	36030.6	16197.1	233.699	26481.6	16197.1	15963.4	233.699	304.036	3309.52
O_2	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	0	0	0	0	0	0	0	0	0	0	1687.75	21979.4
N_2	0	0	0	0	0	0	0	0	0	0	0	0

Table A2.2 Stream table of bi-reforming of CO_2 into methanol for the optimized case design (con't.)

	S9	S10	S11	S12	S13	S14	S16	S17	S18	S19	S24	S25
Temperature, °C	241.3	35	64.8	35	63.9	102.3	35	35	35	40.2	34.8	70.6
Pressure, bar	58.3	58.3	61.3	58.3	1	1.1	58.3	58.3	58.3	61.3	17.5	17
Vapor Frac	1	0.921	1	1	0	1	0	1	1	1	0.025	1
Mole Flow, kmol/hr	10839.1	10839.1	12105.7	9983.74	633.401	797.549	855.391	249.593	9734.15	9734.15	855.391	47.666
Mass Flow, kg/hr	112149	112149	112149	87643.2	20222.2	14368.1	24505.7	2191.08	85452.1	85452.1	24505.7	1143.1
Volume Flow, cum/hr	8072.33	4447.19	5622.36	4407.03	35.64	22428.9	40.164	110.176	4296.86	4163.89	70.052	78.174
Enthalpy, Gcal/hr	-134.96	-161.35	-138.72	-111.03	-35.764	-45.581	-50.317	-2.776	-108.25	-107.88	-50.317	-2.064
Mass Flow, kg/hr												
CO_2	29685.2	29685.2	37027.4	28910.3	1.625	0	774.857	722.759	28187.6	28187.6	774.857	773.231
CH_4	35355	35355.2	35355.3	35159.9	0.006	0	195.327	878.997	34280.9	34280.9	195.327	195.321
CO	8108.25	8108.27	21173.7	8084.95	0	0	23.326	202.124	7882.82	7882.82	23.326	23.325
H_2	13711.3	13711.4	16600.9	13684.9	0	0	26.501	342.121	13342.7	13342.7	26.501	26.5
WATER	3309.52	3309.52	304.036	72.14	94.816	14368	3237.38	1.804	70.337	70.337	3237.38	2.086
O_2	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	21979.4	21979.4	1687.75	1731.02	20125.7	0.132	20248.3	43.276	1687.75	1687.75	20248.3	122.639
N_2	0	0	0	0	0	0	0	0	0	0	0	0

Table A2.2 Stream table of bi-reforming of CO_2 into methanol for the optimized case design (con't.)

	S26	**S27**	**S29**	**S30**	**S31**	**S33**	**S39**	**S40**	**S41**	**S42**	**S43**	**S45**
Temperature, °C	163	164.6	164.6	253.3	253.3	40	150	26.1	280.3	71	102.3	102.3
Pressure, bar	17.5	17.5	17.5	42	42	1	25	42	42	1.1	1.1	1.1
Vapor Frac	0	1	0	1	0.525	0	0.897	0	1	0.276	0	0
Mole Flow, kmol/hr	1246.92	439.199	807.724	909.122	909.122	633.401	3257.71	2000	2000	807.724	971.873	174.323
Mass Flow, kg/hr	36603.9	13241.3	23362.6	16378.1	16378.1	20222.2	42662.7	36030.6	36030.6	23362.6	17508.6	3140.48
Volume Flow, cum/hr	76.174	780.69	48.408	775.119	416.603	34.535	4128.11	36.081	1886.81	5716.99	24.766	4.442
Enthalpy, Gcal/hr	-69.813	-21.194	-45.463	-51.561	-54.718	-36.105	-84.801	-136.55	-112.63	-45.463	-65.013	-11.661
Mass Flow, kg/hr												
CO_2	31.205	29.58	1.625	0	0	1.625	8842.06	0	0	1.625	0	0
CH_4	0.317	0.311	0.006	0	0	0.006	1074.42	0	0	0.006	0	0
CO	0.011	0.011	0	0	0	0	13290.9	0	0	0	0	0
H_2	0.01	0.009	0	0	0	0	3258.17	0	0	0	0	0
WATER	4313.11	1077.82	3235.3	16378.1	16378.1	94.816	16197.1	36030.6	36030.6	3235.3	17508.5	3140.48
O_2	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	32259.2	12133.5	20125.7	0	0	20125.7	0	0	0	20125.7	0.136	0.004
N_2	0	0	0	0	0	0	0	0	0	0	0	0

Table A2.2 Stream table of bi-reforming of CO_2 into methanol for the optimized case design (con't.)

	S47	S52	S54	S55	S56	S57	S58
Temperature, °C	253.3	650	1000	656	137.7	100.4	215
Pressure, bar	42	25	1	1	25	58.3	61
Vapor Frac	0.523	1	1	1	1	0.986	1
Mole Flow, kmol/hr	2000	2212.34	3934.36	3934.36	152.722	10839.1	12105.7
Mass Flow, kg/hr	36030.6	42662.7	108180	108180	6721.27	112149	112149
Volume Flow, cum/hr	914.155	6783.54	416568	304034	200.92	5717.45	8233.92
Enthalpy, Gcal/hr	-120.4	-96.115	-44.086	-56.028	-14.211	-149.53	-124.15
Mass Flow, kg/hr							
CO_2	0	6721.27	14707.4	14707.4	6721.27	29685.2	37027.4
CH_4	0	9459.78	0	0	0	35355	35355.3
CO	0	0	0.006	0.006	0	8108.25	21173.7
H_2	0	0	0.001	0.001	0	13711.3	16600.9
WATER	36030.6	26481.6	13784.2	13784.2	0	3309.52	304.036
O_2	0	0	2159.7	2159.7	0	0	0
C	0	0	0	0	0	0	0
METHANOL	0	0	0	0	0	21979.4	1687.75
N_2	0	0	77528.5	77528.5	0	0	0

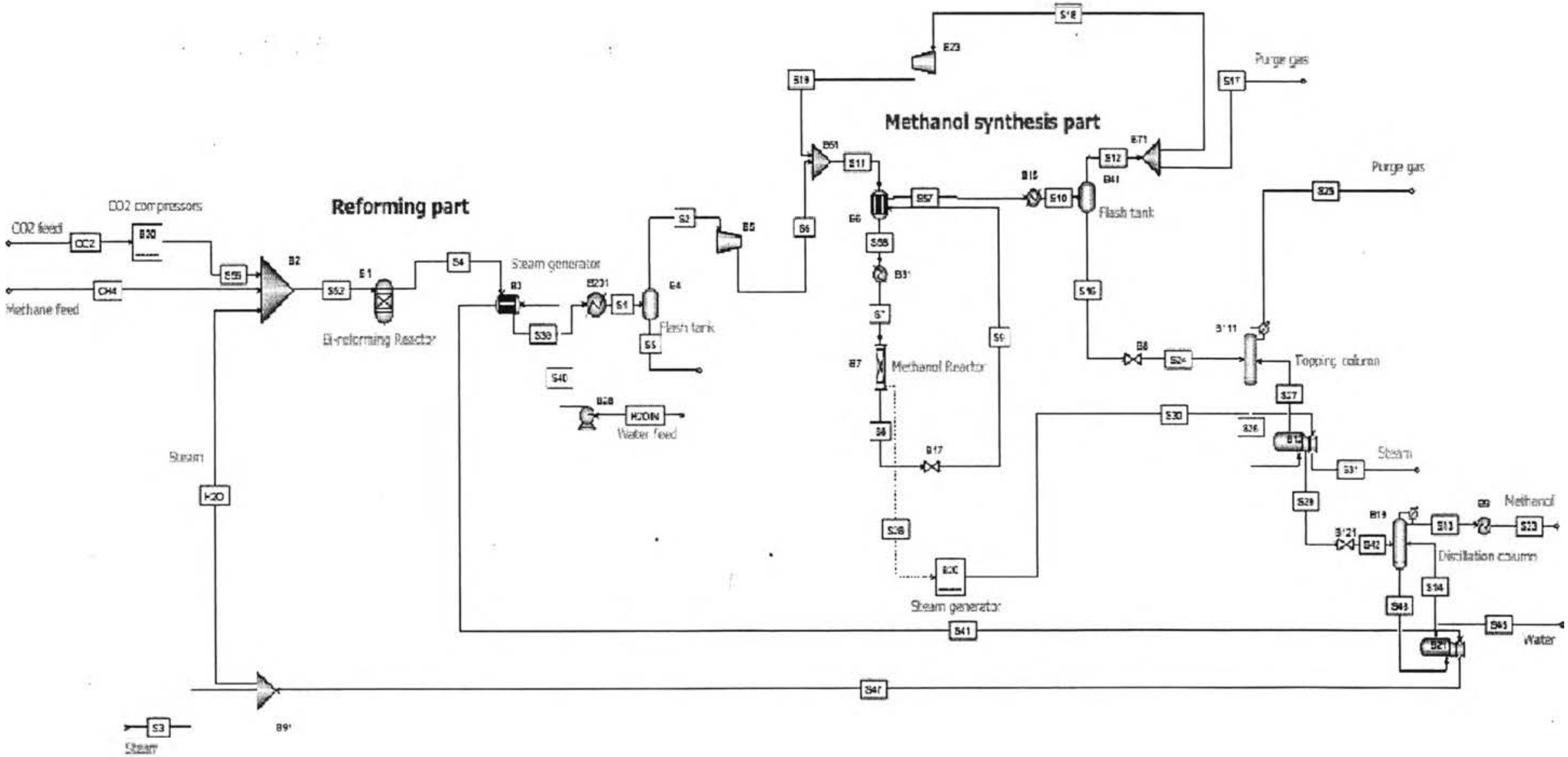

Figure A2.3 Flowsheet of the bi-reforming of CO_2 into methanol for the alternative case design.

Table A2.3 Stream table of bi-reforming of CO_2 into methanol for the alternative case design

	CH_4	CO_2	H_2O	H_2OIN	S1	S2	S3	S4	S5	S6	S7	S8
Temperature, °C	25	50	252	25	55	55	252	915	55	168.8	215	241.3
Pressure, bar	25	1	42	1	25	25	42	25	25	61.3	61	59.28
Vapor Frac	1	1	0.5	0	0.728	1	0.5	1	0	1	1	1
Mole Flow, kmol/hr	589.66	152.722	1470	2000	3257.77	2371.57	530	3257.77	886.199	2371.57	12105.2	10838.6
Mass Flow, kg/hr	9459.78	6721.27	26482.5	36030.6	42663.5	26697.1	9548.1	42663.5	15966.4	26697.1	112141	112141
Volume Flow, cum/hr	560.782	4087.81	669.909	36.137	2635.7	2619.15	241.532	12937.3	16.553	1463.25	8233.6	7941.04
Enthalpy, Gcal/hr	-10.554	-14.321	-88.49	-136.62	-93.469	-32.849	-31.905	-60.879	-60.62	-30.844	-124.14	-134.95
Mass Flow, kg/hr												
CO_2	0	6721.27	0	0	8842.3	8840.02	0	8842.3	2.279	8840.02	37026.6	29684.2
CH_4	9459.78	0	0	0	1074.37	1074.35	0	1074.37	0.015	1074.35	35349.1	35348.8
CO	0	0	0	0	13290.8	13290.8	0	13290.8	0.019	13290.8	21173.1	8107.65
H_2	0	0	0	0	3258.2	3258.2	0	3258.2	0.008	3258.2	16600.8	13711.2
WATER	0	0	26482.5	36030.6	16197.8	233.701	9548.1	16197.8	15964.1	233.701	304.035	3309.61
O_2	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	0	0	0	0	0	0	0	0	0	0	1687.64	21979.3
N_2	0	0	0	0	0	0	0	0	0	0	0	0

Table A2.3 Stream table of bi-reforming of CO_2 into methanol for the alternative case design (con't.)

	S9	S10	S11	S12	S13	S14	S16	S17	S18	S19	S24	S25
Temperature, °C	241.3	35	64.8	35	63.9	102.3	35	35	35	40.2	34.8	70.5
Pressure, bar	58.3	58.3	61.3	58.3	1	1.1	58.3	58.3	58.3	61.3	17.5	17
Vapor Frac	1	0.921	1	1	0	1	0	1	1	1	0.025	1
Mole Flow, kmol/hr	10838.6	10838.6	12105.2	9983.23	633.403	797.549	855.398	249.581	9733.65	9733.65	855.398	47.664
Mass Flow, kg/hr	112141	112141	112141	87635.1	20222.3	14368.1	24505.9	2190.88	85444.2	85444.2	24505.9	1143.03
Volume Flow, cum/hr	8071.96	4446.97	5622.17	4406.82	35.64	22428.9	40.164	110.17	4296.64	4163.68	70.051	78.166
Enthalpy, Gcal/hr	-134.95	-161.34	-138.76	-111.02	-35.765	-45.581	-50.317	-2.775	-108.24	-107.87	-50.317	-2.064
Mass Flow, kg/hr												
CO_2	29684.2	29684.2	37026.6	28909.3	1.626	0	774.875	722.733	28186.6	28186.6	774.875	773.25
CH_4	35348.8	35348.8	35349.1	35153.6	0.006	0	195.303	878.841	34274.8	34274.8	195.303	195.297
CO	8107.65	8107.65	21173.1	8084.34	0	0	23.325	202.109	7882.23	7882.23	23.325	23.325
H_2	13711.2	13711.2	16600.8	13684.7	0	0	26.502	342.118	13342.6	13342.6	26.502	26.502
WATER	3309.61	3309.61	304.035	72.137	94.757	14368	3237.47	1.803	70.334	70.334	3237.47	2.085
O_2	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	21979.3	21979.3	1687.64	1730.91	20125.9	0.132	20248.4	43.273	1687.64	1687.64	20248.4	122.569
N_2	0	0	0	0	0	0	0	0	0	0	0	0

Table A2.3 Stream table of bi-reforming of CO_2 into methanol for the alternative case design (con't.)

	S26	S27	S29	S30	S31	S33	S39	S40	S41	S42	S43	S45
Temperature, °C	163	164.6	164.6	253.3	253.3	40	150	26.1	280.3	71	102.3	102.3
Pressure, bar	17.5	17.5	17.5	42	42	1	25	42	42	1.1	1.1	1.1
Vapor Frac	0	1	0	1	0.525	0	0.897	0	1	0.276	0	0
Mole Flow, kmol/hr	1246.93	439.198	807.735	909.15	909.15	633.403	3257.77	2000	2000	807.735	971.881	174.332
Mass Flow, kg/hr	36604.1	13241.2	23362.9	16378.6	16378.6	20222.3	42663.5	36030.6	36030.6	23362.9	17508.8	3140.64
Volume Flow, cum/hr	76.174	780.689	48.408	775.143	416.627	34.535	4128.13	36.081	1886.96	5717.06	24.766	4.442
Enthalpy, Gcal/hr	-69.814	-21.193	-45.464	-51.563	-54.719	-36.105	-84.804	-136.55	-112.62	-45.464	-65.013	-11.662
Mass Flow, kg/hr												
CO_2	31.209	29.583	1.626	0	0	1.626	8842.3	0	0	1.626	0	0
CH_4	0.317	0.311	0.006	0	0	0.006	1074.37	0	0	0.006	0	0
CO	0.011	0.011	0	0	0	0	13290.8	0	0	0	0	0
H_2	0.01	0.009	0	0	0	0	3258.2	0	0	0	0	0
WATER	4313.22	1077.83	3235.39	16378.6	16378.6	94.757	16197.8	36030.6	36030.6	3235.39	17508.6	3140.63
O_2	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	32259.4	12133.5	20125.9	0	0	20125.9	0	0	0	20125.9	0.136	0.004
N_2	0	0	0	0	0	0	0	0	0	0	0	0

Table A2.3 Stream table of bi-reforming of CO_2 into methanol for the alternative case design (con't.)

	S47	S52	S56	S57	S58
Temperature, °C	253.3	188.2	137.7	100.4	215
Pressure, bar	42	25	25	58.3	61
Vapor Frac	0.523	0.684	1	0.986	1
Mole Flow, kmol/hr	2000	2212.38	152.722	10838.6	12105.2
Mass Flow, kg/hr	36030.6	42663.5	6721.27	112141	112141
Volume Flow, cum/hr	914.232	2221.62	200.92	5717.21	8233.6
Enthalpy, Gcal/hr	-120.4	-113.26	-14.211	-149.52	-124.14
Mass Flow, kg/hr					
CO_2	0	6721.27	6721.27	29684.2	37026.6
CH_4	0	9459.78	0	35348.8	35349.1
CO	0	0	0	8107.65	21173.1
H_2	0	0	0	13711.2	16600.8
WATER	36030.6	26482.5	0	3309.61	304.035
O_2	0	0	0	0	0
C	0	0	0	0	0
METHANOL	0	0	0	21979.3	1687.64
N_2	0	0	0	0	0

A.3 Tri-reforming of CO_2 into Methanol

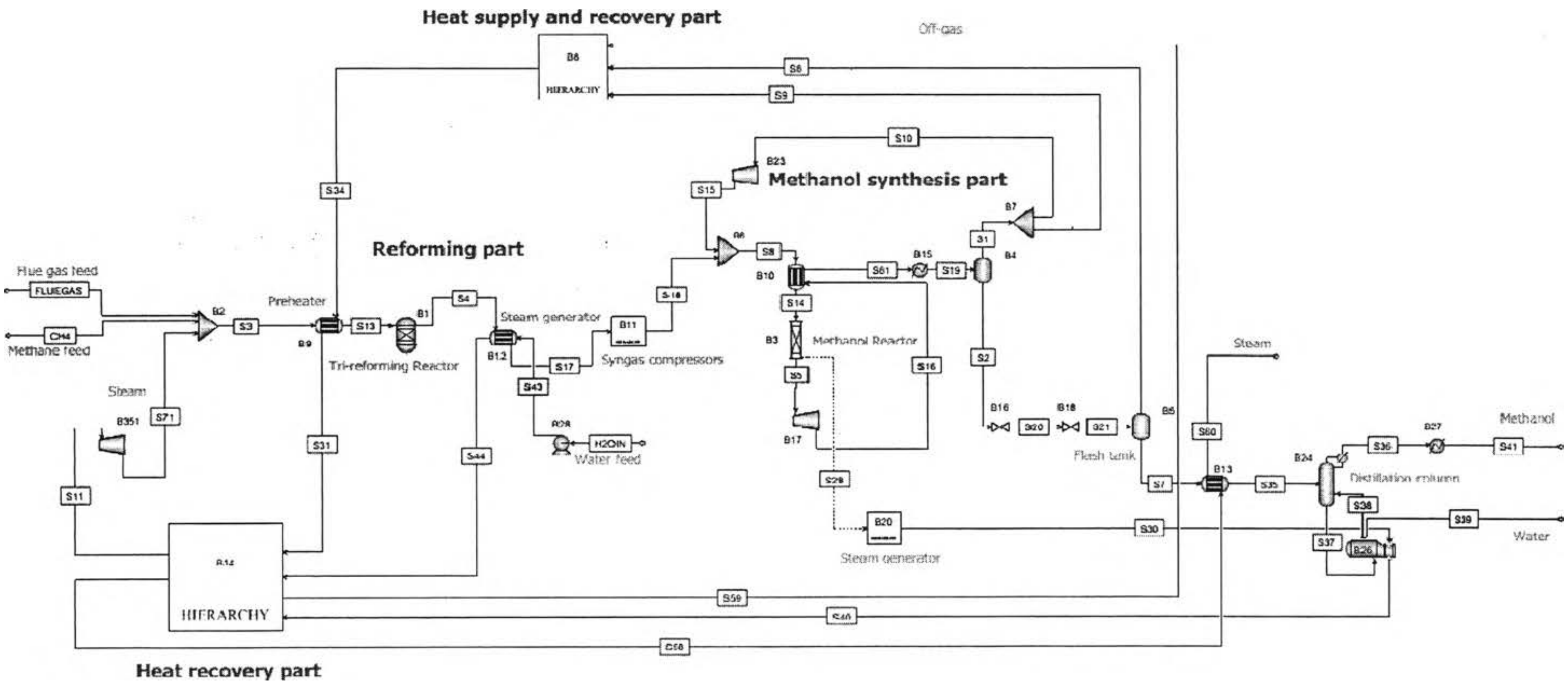

Figure A3.1 Flowsheet of the tri-reforming of CO_2 into methanol for the base case design.

Table A3.1 Stream table of tri-reforming of CO_2 into methanol for the base case design

	CH_4	FLUEGAS	H_2OIN	S1	S2	S3	S4	S5	S6	S7	S8	S9
Temperature, °C	25	150	25	35	35	123.1	850	235.1	31	31	48.9	35
Pressure, bar	1	1	1	62.3	62.3	1	1	63.357	1.2	1.2	65.3	62.3
Vapor Frac	1	1	0	1	0	1	1	1	1	0	1	1
Mole Flow, kmol/hr	569.212	1003.748	1414.03	40890.9	680.937	1966.24	3054.82	41571.8	31.954	648.983	42850.5	1022.27
Mass Flow, kg/hr	9131.73	29856.014	25474.1	935695	21367.6	46072.7	46072.7	957063	871.354	20496.2	957062	23392.4
Volume Flow, cum/hr	14086.4	35316.302	25.549	17170.1	35.911	64709.3	285329	28584.2	671.505	34.496	18030.5	429.253
Enthalpy, Gcal/hr	-10.134	-16.105	-96.592	-118.55	-37.955	-48.342	-7.005	-87.955	-0.641	-37.313	-132.32	-2.964
Mass Flow, kg/hr												
CO_2	0	6184.466	0	25616.8	168.462	6184.47	1451.31	25785.3	147.08	21.382	26427.6	640.421
CH_4	9131.73	0	0	3547.24	5.096	9131.73	93.794	3552.34	4.999	0.097	3552.37	88.681
CO	0	0	0	50215.3	36.74	0	18792.5	50252.1	36.491	0.249	67752.4	1255.38
H_2	0	0	0	16866.1	7.543	0	3036.45	16873.6	7.503	0.04	19480.9	421.653
WATER	0	1193.465	25474.1	48.362	390.741	8278.45	1441.07	439.103	1.163	389.578	176.131	1.209
O_2	0	1220.512	0	0	0	1220.51	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	0	0	0	8593.35	20272.2	0	0	28865.6	189.999	20082.2	8378.5	214.834
N_2	0	21257.571	0	830808	486.752	21257.6	21257.6	831295	484.118	2.634	831294	20770.2

Table A3.1 Stream table of tri-reforming of CO_2 into methanol for the base case design (con't.)

	S10	S11	S13	S14	S15	S16	S17	S18	S19	S20	S21	S30
Temperature, °C	35	391.7	700	220	40.1	233.4	55	172.5	35	34.4	31	253.3
Pressure, bar	62.3	6.51	1	65	65.3	62.3	1	65.3	62.3	10	1.2	42
Vapor Frac	1	1	1	1	1	1	1	1	0.984	0.035	0.047	1
Mole Flow, kmol/hr	39868.5	393.276	1966.24	42850.5	39868.5	41571.8	3054.82	2981.99	41571.8	680.937	680.937	876.928
Mass Flow, kg/hr	912301	7084.986	46072.7	957062	912301	957063	46072.7	44760.6	957063	21367.6	21367.6	15798.1
Volume Flow, cum/hr	16740.8	3309.316	159132	27927.1	16279.4	28961.1	83382.6	1749.04	17206	95.248	706.001	747.671
Enthalpy, Gcal/hr	-115.59	-21.54	-37.182	-77.762	-114.11	-88.478	-24.897	-18.205	-156.51	-37.955	-37.955	-49.735
Mass Flow, kg/hr												
CO_2	24976.3	0	6184.47	26427.6	24976.3	25785.3	1451.31	1451.3	25785.3	168.462	168.462	0
CH_4	3458.58	0	9131.73	3552.37	3458.58	3552.34	93.794	93.794	3552.34	5.096	5.096	0
CO	48959.9	0	0	67752.4	48959.9	50252.1	18792.5	18792.5	50252.1	36.74	36.74	0
H_2	16444.4	0	0	19480.9	16444.4	16873.6	3036.45	3036.45	16873.6	7.543	7.543	0
WATER	47.153	7084.986	8278.45	176.131	47.153	439.103	1441.07	128.978	439.103	390.741	390.741	15798.1
O_2	0	0	1220.51	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	8378.5	0	0	8378.5	8378.5	28865.6	0	0	28865.6	20272.2	20272.2	0
N_2	810036	0	21257.6	831294	810036	831295	21257.6	21257.6	831295	486.752	486.752	0

Table A3.1 Stream table of tri-reforming of CO_2 into methanol for the base case design (con't.)

	S31	S34	S35	S36	S37	S38	S39	S40	S41	S43	S44	S58
Temperature, °C	722	1000	80	64.4	75.5	86.1	86.1	253.3	40	26.1	337	232.1
Pressure, bar	1	1	1.1	1	1.1	1.1	1.1	42	1	42	42	1
Vapor Frac	1	1	1	1	0	1	0	0.534	0	0	1	1
Mole Flow, kmol/hr	4593.35	4593.352	648.983	627.299	339.104	317.42	21.684	876.928	627.299	1414.03	1414.03	1897.68
Mass Flow, kg/hr	126783	126782.56	20496.2	20055	8498.69	8057.48	441.211	15798.1	20055	25474.1	25474.1	34187.2
Volume Flow, cum/hr	380164	486343.44	17034.7	17298.3	13.832	8502.17	0.658	408.369	36.801	25.509	1557.77	79393.9
Enthalpy, Gcal/hr	-49.14	-37.98	-31.009	-29.912	-20.931	-16.528	-1.416	-52.723	-35.749	-96.542	-78.651	-106.5
Mass Flow, kg/hr												
CO_2	14596.2	14596.217	21.382	21.382	0	0	0	0	21.382	0	0	0
CH_4	0	0	0.097	0.097	0	0	0	0	0.097	0	0	0
CO	0.007	0.007	0.249	0.249	0	0	0	0	0.249	0	0	0
H_2	0.001	0.001	0.04	0.04	0	0	0	0	0.04	0	0	0
WATER	13442	13441.96	389.578	63.882	3039.93	2714.24	325.695	15798.1	63.882	25474.1	25474.1	34187.2
O_2	2100.12	2100.124	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	0	0	20082.2	19966.7	5458.76	5343.24	115.516	0	19966.7	0	0	0
N_2	96644.3	96644.252	2.634	2.634	0	0	0	0	2.634	0	0	0

Table A3.1 Stream table of tri-reforming of CO_2 into methanol for the base case design (con't.)

	S59	**S60**	**S61**	**S71**
Temperature, °C	473.4	99.6	61.9	222.1
Pressure, bar	1	1	62.3	1
Vapor Frac	1	0.775	0.998	1
Mole Flow, kmol/hr	4593.35	1897.678	41571.8	393.276
Mass Flow, kg/hr	126782	34187.203	957063	7084.99
Volume Flow, cum/hr	285201	44874.626	18984.8	16122.5
Enthalpy, Gcal/hr	-58.592	-112.799	-143.04	-22.104
Mass Flow, kg/hr				
CO_2	14596.2	0	25785.3	0
CH_4	0	0	3552.34	0
CO	0.007	0	50252.1	0
H_2	0.001	0	16873.6	0
WATER	13442	34187.203	439.103	7084.99
O_2	2100.12	0	0	0
C	0	0	0	0
METHANOL	0	0	28865.6	0
N_2	96644.2	0	831295	0

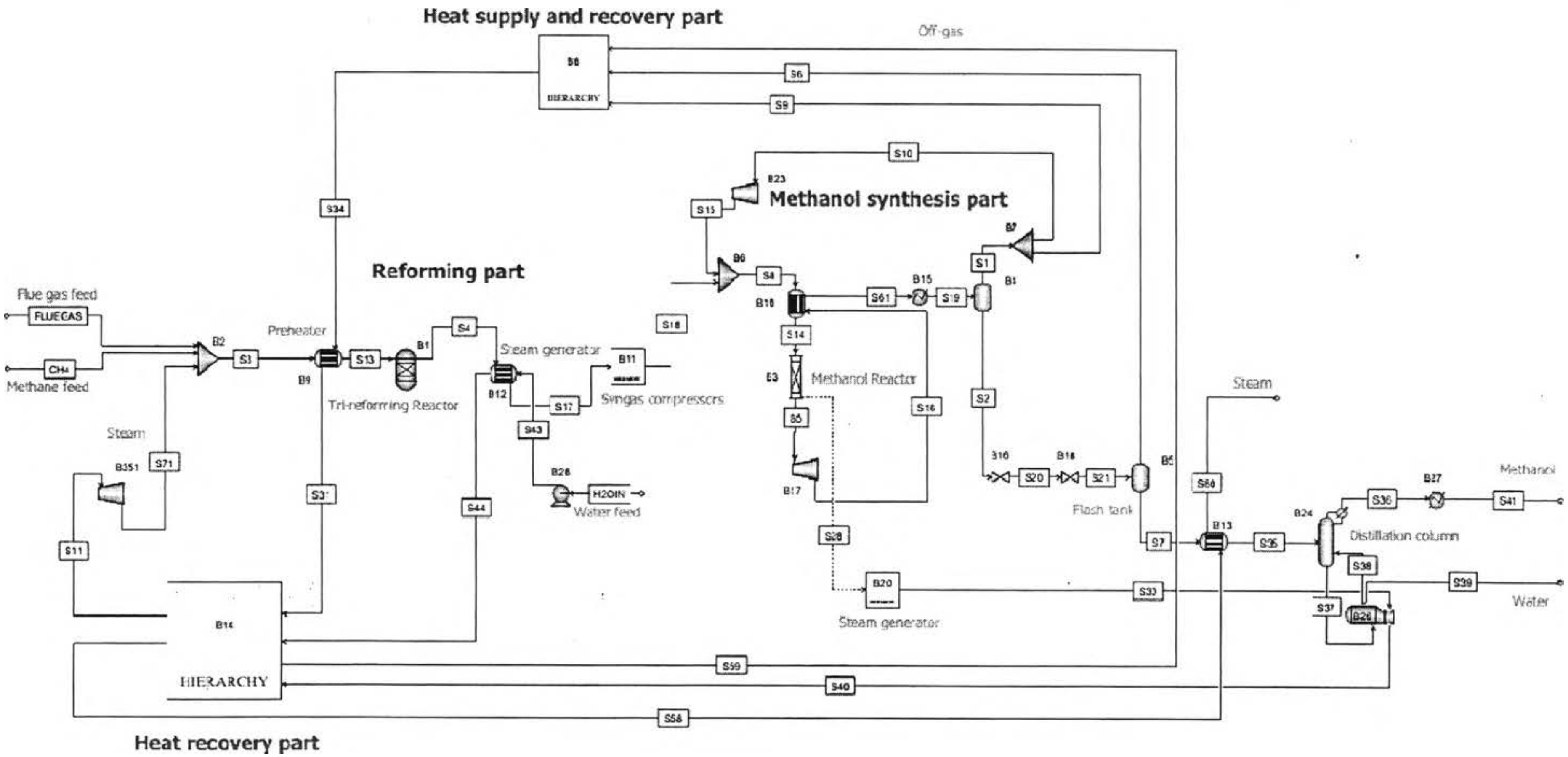

Figure A3.2 Flowsheet of the tri-reforming of CO_2 into methanol for the optimized case design.

Table A3.2 Stream table of tri-reforming of CO_2 into methanol for the optimized case design

	CH_4	FLUEGAS	H_2OIN	S1	S2	S3	S4	S5	S6	S7	S8	S9
Temperature, °C	25	150	25	35	35	122.5	840	225.2	31	31	48.6	35
Pressure, bar	1	1	1	56.3	56.3	1	1	57.25	1.2	1.2	59.3	56.3
Vapor Frac	1	1	0	1	0	1	1	1	1	0	1	1
Mole Flow, kmol/hr	569.212	1003.748	1414.03	40419.3	684.008	1972.88	3059.56	41103.4	29.642	654.366	42390.7	1010.48
Mass Flow, kg/hr	9131.73	29856.014	25474.1	932705	21474.3	46192.4	46192.4	954179	818.569	20655.8	954179	23317.6
Volume Flow, cum/hr	14086.4	35316.302	25.549	18721.5	36.087	64827	283228	30580.5	623.007	34.76	19555.8	468.037
Enthalpy, Gcal/hr	-10.134	-16.105	-96.592	-118.96	-38.261	-48.73	-7.654	-92.48	-0.627	-37.633	-133.08	-2.974
Mass Flow, kg/hr												
CO_2	0	6184.466	0	28614.5	177.422	6184.47	1578.31	28791.9	153.272	24.149	29477.2	715.361
CH_4	9131.73	0	0	4142.34	5.528	9131.73	109.116	4147.86	5.414	0.115	4147.86	103.558
CO	0	0	0	42492.3	28.696	0	18685	42521	28.485	0.211	60114.7	1062.31
H_2	0	0	0	16128.5	6.633	0	3036.49	16135.1	6.595	0.038	18761.7	403.211
WATER	0	1193.465	25474.1	53.6	408.293	8398.15	1525.99	461.892	1.123	407.169	181.262	1.34
O_2	0	1220.512	0	0	0	1220.51	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	0	0	0	9086.46	20398.2	0	0	29484.6	176.722	20221.4	8859.26	227.162
N_2	0	21257.571	0	832187	449.599	21257.6	21257.6	832637	446.958	2.642	832637	20804.7

Table A3.2 Stream table of tri-reforming of CO_2 into methanol for the optimized case design (con't.)

	S10	S11	S13	S14	S15	S16	S17	S18	S19	S20	S21	S30
Temperature, °C	35	386.1	700	210	40.6	223.6	55	158.4	35	34.3	31	253.3
Pressure, bar	56.3	6.51	1	59	59.3	56.3	1	59.3	56.3	10	1.2	42
Vapor Frac	1	1	1	1	1	1	1	1	0.983	0.031	0.043	1
Mole Flow, kmol/hr	39408.7	399.921	1972.88	42390.7	39408.7	41103.4	3059.56	2982.01	41103.4	684.008	684.008	886.507
Mass Flow, kg/hr	909383	7204.685	46192.4	954179	909383	954179	46192.4	44795.4	954179	21474.3	21474.3	15970.7
Volume Flow, cum/hr	18253.4	3335.981	159669	29734.1	17694.2	30982.6	83511.2	1860.25	18757.6	90.016	657.767	755.838
Enthalpy, Gcal/hr	-115.99	-21.924	-37.527	-82.217	-114.38	-92.983	-25.354	-18.697	-157.22	-38.261	-38.261	-50.278
Mass Flow, kg/hr												
CO_2	27898.9	0	6184.47	29477.2	27898.9	28791.9	1578.31	1578.3	28791.9	177.422	177.422	0
CH_4	4038.75	0	9131.73	4147.86	4038.75	4147.86	109.116	109.116	4147.86	5.528	5.528	0
CO	41429.8	0	0	60114.7	41429.8	42521	18685	18685	42521	28.696	28.696	0
H_2	15725.2	0	0	18761.7	15725.2	16135.1	3036.49	3036.49	16135.1	6.633	6.633	0
WATER	52.259	7204.685	8398.15	181.262	52.259	461.892	1525.99	129.003	461.892	408.293	408.293	15970.7
O_2	0	0	1220.51	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	8859.26	0	0	8859.26	8859.26	29484.6	0	0	29484.6	20398.2	20398.2	0
N_2	811379	0	21257.6	832637	811379	832637	21257.6	21257.6	832637	449.599	449.599	0

Table A3.2 Stream table of tri-reforming of CO_2 into methanol for the optimized case design (con't.)

	S31	S34	S35	S36	S37	S38	S39	S40	S41	S43	S44	S58
Temperature, °C	719.8	1000	80	64.4	74.7	84.5	84.5	253.3	40	26.1	325.1	227.6
Pressure, bar	1	1	1.1	1	1.1	1.1	1.1	42	1	42	42	1
Vapor Frac	1	1	1	1	0	1	0	0.539	0	0	1	1
Mole Flow, kmol/hr	4577.44	4577.437	654.366	630.767	342.842	319.244	23.598	886.507	630.767	1414.03	1414.03	1900.61
Mass Flow, kg/hr	126334	126334.25	20655.8	20164.7	8780.37	8289.31	491.066	15970.7	20164.7	25474.1	25474.1	34240.1
Volume Flow, cum/hr	378013	484658.32	17176.1	17394.3	14.408	8509.11	0.74	416.536	37.117	25.509	1513.96	78810.1
Enthalpy, Gcal/hr	-48.891	-37.687	-31.277	-30.081	-21.017	-16.496	-1.533	-53.266	-35.951	-96.542	-78.842	-106.73
Mass Flow, kg/hr												
CO_2	14493.6	14493.588	24.149	24.149	0	0	0	0	24.149	0	0	0
CH_4	0	0	0.115	0.115	0	0	0	0	0.115	0	0	0
CO	0.007	0.007	0.211	0.211	0	0	0	0	0.211	0	0	0
H_2	0.001	0.001	0.038	0.038	0	0	0	0	0.038	0	0	0
WATER	13377.5	13377.492	407.169	66.71	2832.01	2491.56	340.453	15970.7	66.71	25474.1	25474.1	34240.1
O_2	2092.58	2092.575	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	0	0	20221.4	20070.8	5948.36	5797.75	150.613	0	20070.8	0	0	0
N_2	96370.6	96370.589	2.642	2.642	0	0	0	0	2.642	0	0	0

Table A3.2 Stream table of tri-reforming of CO_2 into methanol for the optimized case design (con't.)

	S59	**S60**	**S61**	**S71**
Temperature, °C	468.3	99.6	61.4	217.6
Pressure, bar	1	1	56.3	1
Vapor Frac	1	0.768	0.999	1
Mole Flow, kmol/hr	4577.43	1900.612	41103.4	399.921
Mass Flow, kg/hr	126334	34240.063	954179	7204.69
Volume Flow, cum/hr	282291	44586.836	20676.6	16246
Enthalpy, Gcal/hr	-58.408	-113.087	-143.85	-22.492
Mass Flow, kg/hr				
CO_2	14493.6	0	28791.9	0
CH_4	0	0	4147.86	0
CO	0.007	0	42521	0
H_2	0.001	0	16135.1	0
WATER	13377.5	34240.063	461.892	7204.69
O_2	2092.57	0	0	0
C	0	0	0	0
METHANOL	0	0	29484.6	0
N_2	96370.4	0	832637	0

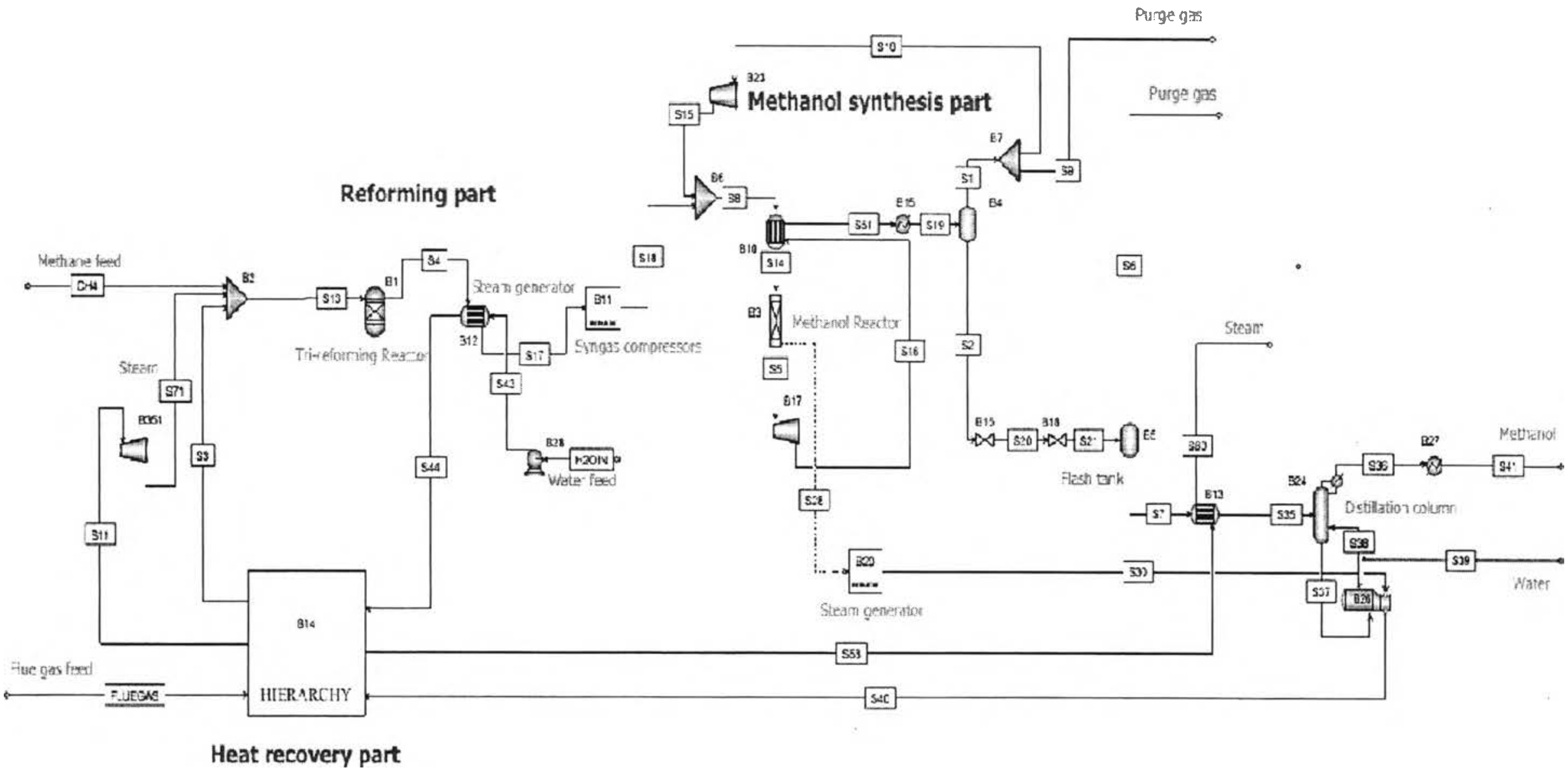

Figure A3.3 Flowsheet of the tri-reforming of CO_2 into methanol for the alternative case design.

Table A3.3 Stream table of tri-reforming of CO_2 into methanol for the alternative case design

	CH_4	FLUEGAS	H_2OIN	S1	S2	S3	S4	S5	S6	S7	S8	S9
Temperature, °C	25	1000	25	35	35	207.1	840	225.2	31	31	48.6	35
Pressure, bar	1	1	1	56.3	56.3	1	1	57.25	1.2	1.2	59.3	56.3
Vapor Frac	1	1	0	1	0	1	1	1	1	0	1	1
Mole Flow, kmol/hr	569.212	1003.748	1414.03	40423.2	684.021	1003.75	3059.65	41107.1	29.643	654.379	42394.7	1010.58
Mass Flow, kg/hr	9131.73	29856.014	25474.1	932793	21474.6	29856	46193.9	954265	818.614	20656	954269	23319.8
Volume Flow, cum/hr	14086.4	106277.36	25.549	18723.2	36.087	40086	283236	30583.5	623.026	34.76	19557.5	468.081
Enthalpy, Gcal/hr	-10.134	-8.967	-96.592	-118.99	-38.262	-15.67	-7.658	-92.5	-0.627	-37.634	-133.11	-2.975
Mass Flow, kg/hr												
CO_2	0	6184.466	0	28627.1	177.484	6184.47	1579.26	28804.6	153.327	24.157	29490.7	715.677
CH_4	9131.73	0	0	4140.64	5.525	0	109.043	4146.16	5.411	0.114	4146.17	103.516
CO	0	0	0	42490.2	28.692	0	18684.5	42519.1	28.481	0.211	60112.4	1062.26
H_2	0	0	0	16130.5	6.634	0	3036.56	16137	6.596	0.038	18763.8	403.261
WATER	0	1193.465	25474.1	53.632	408.512	1193.47	1526.99	462.143	1.124	407.388	181.296	1.341
O_2	0	1220.512	0	0	0	1220.51	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	0	0	0	9087.16	20398.2	0	0	29485.3	176.719	20221.4	8859.98	227.179
N_2	0	21257.571	0	832264	449.599	21257.6	21257.6	832711	446.957	2.642	832715	20806.6

Table A3.3 Stream table of tri-reforming of CO_2 into methanol for the alternative case design (con't.)

	S10	S11	S13	S14	S15	S16	S17	S18	S19	S20	S21	S30
Temperature, °C	35	266.9	129.4	210	40.6	223.6	55	158.4	35	34.3	31	253.3
Pressure, bar	56.3	6.51	1	59	59.3	56.3	1	59.3	56.3	10	1.2	42
Vapor Frac	1	1	1	1	1	1	1	1	0.983	0.031	0.043	1
Mole Flow, kmol/hr	39412.6	400.003	1972.96	42394.7	39412.6	41107.1	3059.65	2982.05	41107.1	684.021	684.021	886.444
Mass Flow, kg/hr	909473	7206.158	46193.9	954269	909473	954265	46193.9	44795.9	954265	21474.6	21474.6	15969.5
Volume Flow, cum/hr	18255.2	2702.558	65969.2	29736.9	17695.9	30985.4	83513.7	1860.27	18759.3	90.017	657.786	755.784
Enthalpy, Gcal/hr	-116.01	-22.358	-48.622	-82.238	-114.41	-93.003	-25.359	-18.699	-157.25	-38.262	-38.262	-50.275
Mass Flow, kg/hr												
CO_2	27911.4	0	6184.47	29490.7	27911.4	28804.6	1579.26	1579.26	28804.6	177.484	177.484	0
CH_4	4037.13	0	9131.73	4146.17	4037.13	4146.16	109.043	109.043	4146.16	5.525	5.525	0
CO	41428	0	0	60112.4	41428	42519.1	18684.5	18684.5	42519.1	28.692	28.692	0
H_2	15727.2	0	0	18763.8	15727.2	16137	3036.56	3036.56	16137	6.634	6.634	0
WATER	52.291	7206.158	8399.63	181.296	52.291	462.143	1526.99	129.004	462.143	408.512	408.512	15969.5
O_2	0	0	1220.51	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	8859.98	0	0	8859.98	8859.98	29485.3	0	0	29485.3	20398.2	20398.2	0
N_2	811457	0	21257.6	832715	811457	832711	21257.6	21257.6	832711	449.599	449.599	0

Table A3.3 Stream table of tri-reforming of CO_2 into methanol for the alternative case design (con't.)

	S35	S36	S37	S38	S39	S40	S41	S43	S44	S58	S60	S61	S71
Temperature, °C	80	64.4	74.7	84.5	84.5	253.3	40	26.1	325.1	133.2	99.6	61.4	123.2
Pressure, bar	1.1	1	1.1	1.1	1.1	42	1	42	42	1	1	56.3	1
Vapor Frac	1	1	0	1	0	0.539	0	0	1	1	0.686	0.999	1
Mole Flow, kmol/hr	654.379	630.776	342.833	319.229	23.603	886.444	630.776	1414.03	1414.03	1900.47	1900.47	41107.1	400.003
Mass Flow, kg/hr	20656	20164.92	8778.53	8287.46	491.069	15969.5	20164.9	25474.1	25474.1	34237.5	34237.5	954265	7206.16
Volume Flow, cum/hr	17176.4	17394.565	14.404	8509.07	0.74	416.482	37.118	25.509	1514.11	63558.1	39784.6	20678.4	13032.1
Enthalpy, Gcal/hr	-31.278	-30.082	-21.017	-16.497	-1.533	-53.262	-35.951	-96.542	-78.841	-108.25	-114.61	-143.87	-22.818
Mass Flow, kg/hr													
CO_2	24.157	24.157	0	0	0	0	24.157	0	0	0	0	28804.6	0
CH_4	0.114	0.114	0	0	0	0	0.114	0	0	0	0	4146.16	0
CO	0.211	0.211	0	0	0	0	0.211	0	0	0	0	42519.1	0
H_2	0.038	0.038	0	0	0	0	0.038	0	0	0	0	16137	0
WATER	407.388	66.748	2833.99	2493.35	340.643	15969.5	66.748	25474.1	25474.1	34237.5	34237.5	462.143	7206.16
O_2	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0	0
METHANOL	20221.4	20071.01	5944.54	5794.11	150.426	0	20071	0	0	0	0	29485.3	0
N_2	2.642	2.642	0	0	0	0	2.642	0	0	0	0	832711	0

Appendix B Economic Evaluation For Each Process

B.1 Hydrogenation of CO_2 into Methanol

B.1.1 Hydrogenation of CO_2 into Methanol for the Base Case Design

B.1.1.1 Raw Material, Product and Utilities Prices

Table B1.1 Raw material and product prices

Raw Material Price		
Raw Material	Value	Unit
Hydrogen method [1]		
Methane steam reforming	2.885	$/kgH_2$
Wind/electric	4.14	$/kgH_2$
Nuclear/steam electrolysis	6.42	$/kgH_2$
Solar thermal	3.07	$/kgH_2$
Biomass	1.59	$/kgH_2$
Hydroelectric	1.28	$/kgH_2$
CO_2 [2]	35.3	$/tCO_2$
Product Price		
Product	Value	Unit
Methanol [3]	0.48	$/kgMeOH

References:

[1] Yumurtaci *et al.* (2004); Bartels *et al.* (2010)

[2] Amann (2007)

[3] www.icis.com (12/2014)

Table B1.2 Utility price

Cooling Water		
	Value	Unit
Cooling water 28-40 °C*	0.35	$/GJ
Electricity		
	Value	Unit
Electricity*	18.42	$/GJ

* 2013 U.S. average cost

B.1.1.2 Raw Materials and Product Annual Prices

Table B1.3 Raw materials annual price

Raw Material	Quantity (kg/year)	Annual Price ($/year)
Hydrogen method		
Methane steam reforming	32141742.00	92,729,812.72
CO_2	233758128.00	8,251,661.92

Table B1.4 Products annual price

Product	Quantity (kg/day)	Quantity (kg/year)	Annual Price ($/year)
Methanol	484077.77	161197904.00	77,374,993.92

B.1.1.3 Annual Utility Cost

Table B1.5 Annual electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
C-29-10	451.09	239,018.55
C-29-19	756.26	400,719.49
C-29-21	692.60	366,986.74
C-29-23	651.19	345,044.72
C-29-24	591.81	313,583.27
C-33	631.29	334,502.06
C-9	2091.52	1,108,232.58
Total		3,108,087.41

Table B1.6 Annual cooling water cost

Equipment	Quantity (kW)	Annual Price ($/year)
E-29-18	320.69	3,266.00
E-29-20	701.80	7,148.00
E-29-22	678.26	6,908.00
E-29-25	739.04	7,527.00
E-11	10152.48	103,403.00
E-31	6651.53	67,746.00
E-19	162.30	1,653.00
Total		197,651.00

B.1.1.4 Equipment Sizing and Purchase Cost

Chemical engineering plant cost index (12/2014): 575.8

Table B1.7 Equipment sizing and purchase cost

Equipment		Size	Unit	Material	Purchase Cost ($)
V-5	Vessel	5.58	m	316 Stainless Steel	134,340.82
V-7	Vessel	5.49	m	316 Stainless Steel	46,350.02
V-13	Vessel	1.95	m	316 Stainless Steel	31,011.25
E-29-18	Heat Exchanger	57.16	m^2	SS shell&SS tube	15,398.62
E-29-20	Heat Exchanger	76.24	m^2	SS shell&SS tube	18,875.53
E-29-22	Heat Exchanger	76.93	m^2	SS shell&SS tube	20,331.00
E-29-25	Heat Exchanger	84.30	m^2	SS shell&SS tube	21,766.19
E-15	Heat Exchanger	3,369.44	m^2	CS shell&SS tube	412,116.00
E-11	Heat Exchanger	1,677.22	m^2	SS shell&SS tube	352,563.00
E-6	Heat Exchanger	34.69	m^2	SS shell&SS tube	12,436.96
E-31	Heat Exchanger	253.07	m^2	SS shell&SS tube	51,090.71
E-19	Heat Exchanger	13.01	m^2	SS shell&SS tube	7,355.47
R-1	Reactor	5,095.63	m^2	SS shell&SS tube	3,355,746.00
T-4	Tower Unit	20.62	m	316 Stainless Steel	753,791.88
tT-4	Valvetray	25.00	trays	Stainless Steel	136,648.28
cT-4	Heat Exchanger	464.06	m^2	SS shell&SS tube	171,051.24
E-12	Heat Exchanger	40.96	m^2	SS shell&SS tube	13,692.62
C-29-10	Compressor	451.09	kW	Carbon Steel	286,282.24
C-29-19	Compressor	756.26	kW	Carbon Steel	405,509.46
C-29-21	Compressor	692.60	kW	Carbon Steel	382,181.29
C-29-23	Compressor	651.19	kW	Carbon Steel	366,630.53
C-29-24	Compressor	591.81	kW	Carbon Steel	343,755.74
C-33	Compressor	631.29	kW	Carbon Steel	359,043.81
C-9	Compressor	2,091.52	kW	Carbon Steel	804,785.22
Total					8,502,753.91

B.1.1.5 Capital Cost Analysis

Table B1.8 Breakdown of capital cost

Description	%	Result ($)
I. Direct Costs		
Purchased Equipment Delivered (% of Purchase equipment cost)	110.00	9,353,029.30
Purchased Equipment Installation (% of Purchased Equipment Delivered)	47.00	4,395,923.77
Instrumentation and Controls (installed) (% of Purchased Equipment Delivered)	36.00	3,367,090.55
Piping (Installed) (% of Purchased Equipment Delivered)	68.00	6,360,059.92
Electrical Systems (Installed) (% of Purchased Equipment Delivered)	11.00	1,028,833.22
Buildings (Including Services) (% of Purchased Equipment Delivered)	18.00	1,683,545.27
Yard Improvement (% of Purchased Equipment Delivered)	10.00	935,302.93
Service Facilities (Installed) (% of Purchased Equipment Delivered)	70.00	6.547,120.51
Total Direct Cost		33,670,905.48
II. Indirect Costs (% of Purchased Equipment Delivered)		
Engineering and Supervision	33.00	3,086,499.67
Construction Expenses	41.00	3,834,742.01
Legal Expenses	4.00	374,121.17
Contractor's Fees	22.00	2,057,666.45
Contingency	44.00	4,115,332.89
Total Indirect Cost		13,468,362.19
III. Fixed-capital Investment (FCI) = Direct Cost + Indirect Cost		47,139,267.68
IV. Working Capital Investments (WC) (% of Purchased Equipment Delivered)	89.00	8,324,196.08
V. Total Capital Investment (TCI) = Fixed-Capital Investment + Working Capital		55,463,463.75

B.1.1.6 Production Cost Analysis

Table B1.9 Breakdown of production cost

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	100,981,474.64
Operating Labor	5.00	Fixed Capital Investment	2,356,963.50
Operating Supervision	15.00	Operating Labor	353,544.53
Utilities	-	-	3,305,738.41
Maintenance and Repairs	6.00	Fixed Capital Investment	2,828,356.06
Operating Supplies	15.00	Maintenance and Supplies	424,253.40
Laboratory Charges	15.00	Operating Labor	353,544.53
Royalties	1.00	Total Product Cost	1,282,891.20
Catalysts	-	-	293,954.26
Total Variable Cost			112,180,720.52
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	942,785.35
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	471,392.68
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			1,414,178.03
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	3,323,318.40
Total Manufacturing Cost			113,594,898.55
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	1,107,772.80
Distribution & selling	4.00	Total Product Cost	5,131,564.80
Research & Development	4.00	Total Product Cost	5,131,564.80
General Expense			11,370,902.40
V. Total Product Cost with Out Depreciation			128,289,120.00

B.1.1.7 Profitability Assumptions

Table B1.10 Profitability conditions

Project Details	
Project Life Time	20 years
Land Cost	$500,000.00
Construction Inflation Rate	2%
Product Inflation Rate	10%
TPC Inflation Rate	10%
Minimum Rate of Return, Mar	15%
Income Tax Rate	25%
Type of Depreciation	MACRS

B.1.2 Hydrogenation of CO_2 into Methanol for the Optimized and Alternative Case Designs

B.1.2.1 Raw Materials and Product Annual Prices

Table B1.11 Products annual price

Product	Quantity (kg/day)	Quantity (kg/year)	Annual Price ($/year)
Methanol	485,698.92	161,737,744.00	77,634,117.12

Table B1.12 Raw materials annual price

Raw Material	Quantity (kg/year)	Annual Price ($/year)
Hydrogen method		
Methane steam reforming	32141742.00	92,729,812.72
Wind/electric	32141742.00	132,915,666.98
Nuclear/steam electrolysis	32141742.00	206,418,500.49
Solar thermal	32141742.00	98,630,000.23
Biomass	32141742.00	51,252,375.12
Hydroelectric	32141742.00	41,168,729.12
CO_2	233758128.00	8,251,661.92

B.1.2.2 Annual Utility Cost

Table B1.13 Annual electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
C-29-10	451.09	239,018.55
C-29-19	756.26	400,719.49
C-29-21	692.60	366,986.74
C-29-23	651.19	345,044.72
C-29-24	371.74	196,972.98
C-33	1,307.49	692,799.75
C-9	924.19	489,700.49
Total		2,731,242.72

Table B1.14 Annual cooling water cost

Equipment	Quantity (kW)	Annual Price ($/year)
E-29-18	320.69	3,266.00
E-29-20	701.80	7,148.00
E-29-22	678.26	6,908.00
E-29-25	739.04	7,527.00
E-11	9,528.82	97,051.00
E-31	6,670.78	67,942.00
E-19	162.80	1,658.00
Total		191,500.00

B.1.2.3 Equipment Sizing and Purchase Cost

Chemical engineering plant cost index (12/2014): 575.8

Table B1.15 Equipment sizing and purchase cost

Equipment		Size	Unit	Material	Purchase Cost ($)
V-5	Vessel	5.57	m	316 Stainless Steel	134,255.63
V-7	Vessel	5.50	m	316 Stainless Steel	46,378.42
V-13	Vessel	1.95	m	316 Stainless Steel	20,583.56
E-29-18	Heat Exchanger	57.16	m^2	SS shell&SS tube	15,398.62
E-29-20	Heat Exchanger	76.24	m^2	SS shell&SS tube	18,875.53
E-29-22	Heat Exchanger	76.93	m^2	SS shell&SS tube	20,331.00
E-29-25	Heat Exchanger	84.30	m^2	SS shell&SS tube	21,766.19
E-15	Heat Exchanger	3,510.37	m^2	CS shell&SS tube	427,488.00
E-11	Heat Exchanger	1,740.51	m^2	SS shell&SS tube	365,247.00
E-6	Heat Exchanger	41.27	m^2	SS shell&SS tube	13,755.50
E-31	Heat Exchanger	253.97	m^2	SS shell&SS tube	51,253.00
C-29-10	Compressor	451.09	kW	Carbon Steel	286,282.24
C-29-19	Compressor	756.26	kW	Carbon Steel	405,509.46
C-29-21	Compressor	692.60	kW	Carbon Steel	382,181.29
C-29-23	Compressor	651.19	kW	Carbon Steel	366,630.53
C-29-24	Compressor	371.74	kW	Carbon Steel	251,292.02
C-9	Compressor	1,307.49	kW	Carbon Steel	586,420.40
C-33	Compressor	924.19	kW	Carbon Steel	464,175.74
R-1	Reactor	5,095.63	m^2	SS shell&SS tube	3,355,746.00
T-4	Tower Unit	20.62	m	316 Stainless Steel	753,791.88
tT-4	Valvetray	25.00	trays	Stainless Steel	137,174.69
cT-4	Heat Exchanger	466.15	m^2	SS shell&SS tube	171,375.81
E-12	Heat Exchanger	48.72	m^2	SS shell&SS tube	15,246.48
E-19	Heat Exchanger	13.05	m^2	SS shell&SS tube	7,362.57
Total					8,318,521.56

B.1.2.4 Capital Cost Analysis

Table B1.16 Breakdown of capital cost

Description	%	Result ($)
I. Direct Costs		
Purchased Equipment Delivered (% of Purchase equipment cost)	110.00	9,150,373.72
Purchased Equipment Installation (% of Purchased Equipment Delivered)	47.00	4,300,675.65
Instrumentation and Controls (installed) (% of Purchased Equipment Delivered)	36.00	3,294,134.54
Piping (Installed) (% of Purchased Equipment Delivered)	68.00	6,222,254.13
Electrical Systems (Installed) (% of Purchased Equipment Delivered)	11.00	1,006,541.11
Buildings (Including Services) (% of Purchased Equipment Delivered)	18.00	1,647,067.27
Yard Improvement (% of Purchased Equipment Delivered)	10.00	915,037.37
Service Facilities (Installed) (% of Purchased Equipment Delivered)	70.00	6,405,261.60
Total Direct Cost		32,941,345.38
II. Indirect Costs (% of Purchased Equipment Delivered)		
Engineering and Supervision	33.00	3,019,623.33
Construction Expenses	41.00	3,751,653.22
Legal Expenses	4.00	366,014.95
Contractor's Fees	22.00	2,013,082.22
Contingency	44.00	4,026,164.44
Total Indirect Cost		13,176,538.15
III. Fixed-capital Investment (FCI) = Direct Cost + Indirect Cost		46,117,883.53
IV. Working Capital Investments (WC) (% of Purchased Equipment Delivered)	89.00	8,143,832.61
V. Total Capital Investment (TCI) = Fixed-Capital Investment + Working Capital		54,261,716.14

B.1.2.5 Production Cost Analysis

Table B1.17 Breakdown of production cost for the methane steam reforming case

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	100,981,474.64
Operating Labor	5.00	Fixed Capital Investment	2,305,894.25
Operating Supervision	15.00	Operating Labor	345,884.14
Utilities	-	-	2,922,742.72
Maintenance and Repairs	6.00	Fixed Capital Investment	2,767,073.01
Operating Supplies	15.00	Maintenance and Supplies	415,060.95
Laboratory Charges	15.00	Operating Labor	345,884.14
Royalties	1.00	Total Product Cost	1,275,786.64
Catalysts	-	-	293,954.26
Total Variable Cost			111,653,754.75
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	922,357.67
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	461,178.84
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			1,383,536.51
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	3,251,310.90
Total Manufacturing Cost			113,037,291.25
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	1,083,770.30
Distribution & selling	4.00	Total Product Cost	5,103,146.56
Research & Development	4.00	Total Product Cost	5,103,146.56
General Expense			11,290,063.42
V. Total Product Cost with Out Depreciation			127,578,664.00

B.1.2.6 Production Cost Analysis

Table B1.18 Breakdown of production cost for the wind/electric case

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	141,167,328.90
Operating Labor	5.00	Fixed Capital Investment	2,305,894.25
Operating Supervision	15.00	Operating Labor	345,884.14
Utilities	-	-	2,922,742.72
Maintenance and Repairs	6.00	Fixed Capital Investment	2,767,073.01
Operating Supplies	15.00	Maintenance and Supplies	415,060.95
Laboratory Charges	15.00	Operating Labor	345,884.14
Royalties	1.00	Total Product Cost	1,717,389.44
Catalysts	-	-	293,954.26
Total Variable Cost			152,281,211.81
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	922,357.67
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	461,178.84
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			1,383,536.51
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	3,251,310.90
Total Manufacturing Cost			153,664,748.31
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	1,083,770.30
Distribution & selling	4.00	Total Product Cost	6,869,557.76
Research & Development	4.00	Total Product Cost	6,869,557.76
General Expense			14,822,885.82
V. Total Product Cost with Out Depreciation			171,738,944.00

Table B1.19 Breakdown of production cost for the nuclear/steam electrolysis

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	214,670,162.40
Operating Labor	5.00	Fixed Capital Investment	2,305,894.25
Operating Supervision	15.00	Operating Labor	345,884.14
Utilities	-	-	2,922,742.72
Maintenance and Repairs	6.00	Fixed Capital Investment	2,767,073.01
Operating Supplies	15.00	Maintenance and Supplies	415,060.95
Laboratory Charges	15.00	Operating Labor	345,884.14
Royalties	1.00	Total Product Cost	2,525,112.80
Catalysts	-	-	293,954.26
Total Variable Cost			226,591,768.67
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	922,357.67
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	461,178.84
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			1,383,536.51
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	3,251,310.90
Total Manufacturing Cost			227,975,305.18
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	1,083,770.30
Distribution & selling	4.00	Total Product Cost	10,100,451.20
Research & Development	4.00	Total Product Cost	10,100,451.20
General Expense			21,284,672.70
V. Total Product Cost with Out Depreciation			252,511,280.00

Table B1.20 Breakdown of production cost for the solar thermal case

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	106,881,662.15
Operating Labor	5.00	Fixed Capital Investment	2,305,894.25
Operating Supervision	15.00	Operating Labor	345,884.14
Utilities	-	-	2,922,742.72
Maintenance and Repairs	6.00	Fixed Capital Investment	2,767,073.01
Operating Supplies	15.00	Maintenance and Supplies	415,060.95
Laboratory Charges	15.00	Operating Labor	345,884.14
Royalties	1.00	Total Product Cost	1,340,623.92
Catalysts	-	-	293,954.26
Total Variable Cost			117,618,779.54
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	922,357.67
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	461,178.84
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			1,383,536.51
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	3,251,310.90
Total Manufacturing Cost			119,002,316.05
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	1,083,770.30
Distribution & selling	4.00	Total Product Cost	5,362,495.68
Research & Development	4.00	Total Product Cost	5,362,495.68
General Expense			11,808,761.66
V. Total Product Cost with Out Depreciation			134,062,392.00

Table B1.21 Breakdown of production cost for the biomass case

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	59,504,037.04
Operating Labor	5.00	Fixed Capital Investment	2,305,894.25
Operating Supervision	15.00	Operating Labor	345,884.14
Utilities	-	-	2,922,742.72
Maintenance and Repairs	6.00	Fixed Capital Investment	2,767,073.01
Operating Supplies	15.00	Maintenance and Supplies	415,060.95
Laboratory Charges	15.00	Operating Labor	345,884.14
Royalties	1.00	Total Product Cost	819,990.56
Catalysts	-	-	293,954.26
Total Variable Cost			69,720,521.07
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	922,357.67
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	461,178.84
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			1,383,536.51
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	3,251,310.90
Total Manufacturing Cost			71,104,057.58
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	1,083,770.30
Distribution & selling	4.00	Total Product Cost	3,279,962.24
Research & Development	4.00	Total Product Cost	3,279,962.24
General Expense			7,643,694.78
V. Total Product Cost with Out Depreciation			81,999,056.00

Table B1.22 Breakdown of production cost for the hydroelectric case

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	49,420,391.03
Operating Labor	5.00	Fixed Capital Investment	2,305,894.25
Operating Supervision	15.00	Operating Labor	345,884.14
Utilities	-	-	2,922,742.72
Maintenance and Repairs	6.00	Fixed Capital Investment	2,767,073.01
Operating Supplies	15.00	Maintenance and Supplies	415,060.95
Laboratory Charges	15.00	Operating Labor	345,884.14
Royalties	1.00	Total Product Cost	709,181.36
Catalysts	-	-	293,954.26
Total Variable Cost			59,526,065.86
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	922,357.67
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	461,178.84
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			1,383,536.51
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	3,251,310.90
Total Manufacturing Cost			60,909,602.37
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	1,083,770.30
Distribution & selling	4.00	Total Product Cost	2,836,725.44
Research & Development	4.00	Total Product Cost	2,836,725.44
General Expense			6,757,221.18
V. Total Product Cost with Out Depreciation			70,918,136.00

B.2 Bi-reforming of CO_2 into Methanol

B.2.1 Bi-reforming of CO_2 into Methanol for the Base Case Design

B.2.1.1 Raw Material, Product and Utilities Prices

Table B2.1 Raw material and product prices

Raw Material Price		
Raw Material	Value	Unit
Methane[1]	198	$/tCH_4$
CO_2[2]	35.3	$/tCO_2$
Demineralized water[3]	1.62	$/tH_2O$
Product Price		
Product	Value	Unit
Methanol [4]	0.48	$/kgMeOH

References:

[1] http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm (12/2014)

[2] Amann (2007)

[3] www.alibaba.com (12/2014)

[4] www.icis.com (12/2014)

Table B2.2 Utility price

Cooling Water		
	Value	Unit
Cooling water 28-40 °C*	0.35	$/GJ
Electricity		
	Value	Unit
Electricity*	18.42	$/GJ

* 2013 U.S. average cost

B.2.1.2 Raw Materials and Product Annual Price

Table B2.3 Raw materials annual price

Raw Material	Quantity (kg/year)	Annual Price ($/year)
Methane	104,883,620.00	20,766,956.65
CO_2	53,716,348.00	1,896,187.08
Demineralized water	429,054,784.00	695,068.75

Table B2.4 Products annual price

Product	Quantity (kg/day)	Quantity (kg/year)	Annual Price ($/year)
Methanol	487,588.01	162,366,800.00	77,936,064.00

B.2.1.3 Annual Utility Cost

Table B2.5 Annual electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
C-30-10	189.79	100,562.54
C-30-19	181.44	96,138.50
C-30-23	177.02	93,799.89
C-5	2,710.86	1,436,401.68
C-23	468.16	248,062.45
PD-20-1	44.81	23,745.62
PD-28	91.46	48,460.45
Total		2,047,171.13

Table B2.6 Annual generated electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
TB-18-33	-935.64	-495,766.00
TB-18-35	-969.78	-513,859.00
TB-18-38	-1,879.65	-995,969.00
TB-18-351	-535.28	-283,628.00
Total		-2,289,222.00

Table B2.7 Annual cooling water

Equipment	Quantity (kW)	Annual Price ($/year)
E-30-1	193.42	1,970.00
E-30-18	172.52	1,757.00
E-201	10,117.96	103,051.00
E-15	13,768.33	140,230.00
E-9	396.03	4,034.00
Total		251,042.00

B.2.1.4 Equipment Sizing and Purchase Cost

Chemical engineering plant cost index (12/2014): 575.8

Table B2.8 Equipment sizing and purchase cost

Equipment		Size	Unit	Material	Purchase Cost ($)
V-4	Vessel	3.83	m	316 Stainless Steel	139,152.51
V-41	Vessel	5.16	m	316 Stainless Steel	129,052.43
V-20-2	Vessel	1.48	m	316 Stainless Steel	55,402.37
E-30-1	Heat Exchanger	18.56	m^2	SS shell&SS tube	8,367.71
E-30-18	Heat Exchanger	18.12	m^2	SS shell&SS tube	8,286.57
E-27	Heat Exchanger	203.27	m^2	SS shell&SS tube	44,958.45
E-3	Heat Exchanger	359.02	m^2	SS shell&SS tube	81,652.64
E-201	Heat Exchanger	684.81	m^2	SS shell&SS tube	144,160.00
E-6	Heat Exchanger	3,304.96	m^2	CS shell&SS tube	405,090.00
E-15	Heat Exchanger	2,193.89	m^2	SS shell&SS tube	461,588.00
E-18-1	Heat Exchanger	41.42	m^2	SS shell&SS tube	13,407.61
E-18-2	Heat Exchanger	170.72	m^2	SS shell&SS tube	38,612.17
E-18-3	Heat Exchanger	19.93	m^2	SS shell&SS tube	9,219.70
E-18-4	Heat Exchanger	58.78	m^2	SS shell&SS tube	16,792.22
E-18-5	Heat Exchanger	78.74	m^2	SS shell&SS tube	19,329.92
C-30-10	Compressor	189.79	kW	Carbon Steel	159,753.31
C-30-19	Compressor	181.44	kW	Carbon Steel	154,983.21
C-30-23	Compressor	177.02	kW	Carbon Steel	152,432.32
C-5	Compressor	2,710.86	kW	Carbon Steel	958,473.21
C-23	Compressor	468.16	kW	Carbon Steel	293,537.30
PD-20-1	Pump include drive	20.17	cubic.m /s*kPa	Stainless Steel	17,371.37
PD-28	Pump include drive	41.16	cubic.m /s*kPa	Stainless Steel	23,254.12
TB-18-33	Turbine	935.64	kW	Stainless Steel	549,673.47
TB-18-35	Turbine	969.78	kW	Stainless Steel	561,400.44
TB-18-38	Turbine	1,879.65	kW	Stainless Steel	828,940.02
TB-18-351	Turbine	535.28	kW	Stainless Steel	395,622.37
T-111	Tower Unit	7.22	m	316 Stainless Steel	424,543.21
tT-111	valvetray	3.00	trays	Stainless Steel	13,467.45

Table B2.8 Equipment sizing and purchase cost (con't.)

Equipment		Size	Unit	Material	Purchase Cost ($)
cT-111	Heat Exchanger	17.20	m^2	Carbon Steel	18,536.76
E-12	Heat Exchanger	24.05	m^2	SS shell&SS tube	10,865.85
T-19	Tower Unit	26.71	m	316 Stainless Steel	926,452.77
tT-19	valvetray	35.00	trays	Stainless Steel	132,385.32
cT-19	Heat Exchanger	686.40	m^2	SS shell&SS tube	201,744.01
E-21	Heat Exchanger	30.41	m^2	SS shell&SS tube	11,262.43
E-9	Heat Exchanger	20.20	m^2	SS shell&SS tube	8,664.89
R-7	Methanol synthesis reactor	2,261.95	m^2	SS shell&SS tube	1,488,477.00
R-10-29	Vessel	10.00	m	316 Stainless Steel	171,952.00
R-1	Bi-reforming reactor	1,456.49	m^2	SS shell&SS tube	751,608.00
Total					9,830,473.15

B.2.1.5 Capital Cost Analysis

Table B2.9 Breakdown of capital cost

Description	%	Result ($)
I. Direct Costs		
Purchased Equipment Delivered (% of Purchase equipment cost)	110.00	10,813,520.47
Purchased Equipment Installation (% of Purchased Equipment Delivered)	47.00	5,082,354.62
Instrumentation and Controls (installed) (% of Purchased Equipment Delivered)	36.00	3,892,867.37
Piping (Installed) (% of Purchased Equipment Delivered)	68.00	7,353,193.92
Electrical Systems (Installed) (% of Purchased Equipment Delivered)	11.00	1,189,487.25
Buildings (Including Services) (% of Purchased Equipment Delivered)	18.00	1,946,433.68
Yard Improvement (% of Purchased Equipment Delivered)	10.00	1,081,352.05
Service Facilities (Installed) (% of Purchased Equipment Delivered)	70.00	7,569,464.33
Total Direct Cost		38,928,673.67
II. Indirect Costs (% of Purchased Equipment Delivered)		
Engineering and Supervision	33.00	3,568,461.75
Construction Expenses	41.00	4,433,543.39
Legal Expenses	4.00	432,540.82
Contractor's Fees	22.00	2,378,974.50
Contingency	44.00	4,757,949.00
Total Indirect Cost		15,571,469.47
III. Fixed-capital Investment (FCI) = Direct Cost + Indirect Cost		54,500,143.14
IV. Working Capital Investments (WC) (% of Purchased Equipment Delivered)	89.00	9,624,033.21
V. Total Capital Investment (TCI) = Fixed-Capital Investment + Working Capital		64,124,176.36

B.2.1.6 Production Cost Analysis

Table B2.10 Breakdown of production cost

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	23,358,212.48
Operating Labor	25.00	Fixed Capital Investment	13,625,036.00
Operating Supervision	15.00	Operating Labor	2,043,755.40
Utilities	-	-	8,991.13
Maintenance and Repairs	6.00	Fixed Capital Investment	3,270,008.59
Operating Supplies	15.00	Maintenance and Supplies	490,501.28
Laboratory Charges	15.00	Operating Labor	2,043,755.40
Royalties	1.00	Total Product Cost	678,866.80
Catalysts	-	-	150,572.50
Total Variable Cost			45,669,699.57
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	1,090,002.86
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	545,001.43
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			1,635,004.29
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	11,363,280.00
Total Manufacturing Cost			47,304,703.87
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	3,787,760.00
Distribution & selling	4.00	Total Product Cost	2,715,467.20
Research & Development	4.00	Total Product Cost	2,715,467.20
General Expense			9,218,694.40
V. Total Product Cost with Out Depreciation			67,886,680.00

B.2.1.7 Profitability Assumptions

Table B2.11 Profitability conditions

Project Details	
Project Life Time	20 years
Land Cost	$1,000,000.00
Construction Inflation Rate	2%
Product Inflation Rate	10%
TPC Inflation Rate	10%
Minimum Rate of Return, Mar	15%
Income Tax Rate	30%
Type of Depreciation	MACRS

B.2.2 Bi-reforming of CO_2 into Methanol for the Optimized Case

B.2.2.1 Raw Materials and Product Annual Price

Table B2.12 Raw materials annual price

Raw Material	Quantity (kg/year)	Annual Price ($/year)
Methane	103,666,926.00	20,526,051.24
CO_2	53,716,348.00	1,896,187.08
Demineralized water	429,054,784.00	695,068.75

Table B2.13 Products annual price

Product	Quantity (kg/day)	Quantity (kg/year)	Annual Price ($/year)
Methanol	485,331.60	161,615,424.00	77,575,403.52

B.2.2.2 Annual Utility Cost

Table B2.14 Annual electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
C-5	2,590.50	1,372,626.17
C-23	488.70	258,946.90
PD-20-1	44.81	23,745.62
PD-28	91.46	48,460.45
C-30-10	189.79	100,562.54
C-30-19	181.44	96,138.50
C-30-23	177.02	93,799.89
Total		1,994,280.07

Table B2.15 Annual generated electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
TB-18-33	-919.76	-487,352.00
TB-18-35	-953.32	-505,138.00
TB-18-38	-1,847.75	-979,064.00
TB-18-351	-533.77	-282,830.00
Total		-2,254,384.00

Table B2.16 Annual cooling water

Equipment	Quantity (kW)	Annual Price ($/year)
E-30-1	193.42	1,970.00
E-30-18	172.52	1,757.00
E-201	10,077.79	102,642.00
E-15	13,742.55	139,968.00
E-9	396.07	4,034.00
Total		250,371.00

B.2.2.3 Equipment Sizing and Purchase Cost

Chemical engineering plant cost index (12/2014): 575.8

Table B2.17 Equipment sizing and purchase cost

Equipment		Size	Unit	Material	Purchase Cost ($)
V-4	Vessel	3.83	m	316 Stainless Steel	139,106.87
V-41	Vessel	5.15	m	316 Stainless Steel	128,904.35
V-20-2	Vessel	1.76	m	316 Stainless Steel	61,454.50
E-30-1	Heat Exchanger	18.56	m^2	SS shell&SS tube	8,367.71
E-30-18	Heat Exchanger	18.12	m^2	SS shell&SS tube	8,286.57
E-27	Heat Exchanger	203.75	m^2	SS shell&SS tube	45,051.76
E-3	Heat Exchanger	355.91	m^2	SS shell&SS tube	80,996.41
E-201	Heat Exchanger	682.09	m^2	SS shell&SS tube	143,630.00
E-6	Heat Exchanger	3,246.69	m^2	CS shell&SS tube	398,730.00
E-15	Heat Exchanger	2,216.61	m^2	SS shell&SS tube	466,140.00
E-18-1	Heat Exchanger	41.89	m^2	SS shell&SS tube	13,498.89
E-18-2	Heat Exchanger	186.63	m^2	SS shell&SS tube	41,714.82
E-18-3	Heat Exchanger	22.28	m^2	SS shell&SS tube	9,678.15
E-18-4	Heat Exchanger	66.50	m^2	SS shell&SS tube	18,297.40
E-18-5	Heat Exchanger	94.60	m^2	SS shell&SS tube	22,218.56
C-5	Compressor	2,590.50	kW	Carbon Steel	929,587.87
C-23	Compressor	488.70	kW	Carbon Steel	302,154.52
PD-20-1	Pump include drive	20.17	cubic.m /s*kPa	Stainless Steel	17,371.37
PD-28	Pump include drive	41.16	cubic.m /s*kPa	Stainless Steel	23,254.12
TB-18-33	Turbine	919.76	kW	Stainless Steel	544,160.92
TB-18-35	Turbine	953.32	kW	Stainless Steel	555,769.22
TB-18-38	Turbine	1,847.75	kW	Stainless Steel	820,626.06
TB-18-351	Turbine	533.77	kW	Stainless Steel	394,966.14
T-111	Tower Unit	7.22	m	316 Stainless Steel	424,543.21
tT-111	valvetray	3.00	trays	Stainless Steel	13,438.04
cT-111	Heat Exchanger	12.86	m^2	Carbon Steel	16,400.72
E-12	Heat Exchanger	24.07	m^2	SS shell&SS tube	10,869.91
T-19	Tower Unit	26.71	m	316 Stainless Steel	926,452.77

Table B2.17 Equipment sizing and purchase cost (con't.)

Equipment		Size	Unit	Material	Purchase Cost ($)
tT-19	valvetray	35.00	trays	Stainless Steel	131,791.97
cT-19	Heat Exchanger	682.27	m^2	SS shell&SS tube	201,231.81
E-21	Heat Exchanger	32.32	m^2	SS shell&SS tube	11,633.66
E-9	Heat Exchanger	20.16	m^2	SS shell&SS tube	8,658.81
C-30-10	Compressor	189.79	kW	Carbon Steel	159,753.00
C-30-19	Compressor	181.44	kW	Carbon Steel	154,983.00
C-30-23	Compressor	177.02	kW	Carbon Steel	152,433.00
R-7	Methanol synthesis reactor	2,261.95	m^2	SS shell&SS tube	1,488,477.00
R-10-29	Vessel	10.00	m	316 Stainless Steel	171,952.00
R-1	Bi-reforming reactor	1,439.50	m^2	SS shell&SS tube	743,328.00
Total					9,789,913.09

B.2.2.4 Capital Cost Analysis

Table B2.18 Breakdown of capital cost

Description	%	Result ($)
I. Direct Costs		
Purchased Equipment Delivered (% of Purchase equipment cost)	110.00	10,768,904.40
Purchased Equipment Installation (% of Purchased Equipment Delivered)	47.00	5,061,385.07
Instrumentation and Controls (installed) (% of Purchased Equipment Delivered)	36.00	3,876,805.58
Piping (Installed) (% of Purchased Equipment Delivered)	68.00	7,322,854.99
Electrical Systems (Installed) (% of Purchased Equipment Delivered)	11.00	1,184,579.48
Buildings (Including Services) (% of Purchased Equipment Delivered)	18.00	1,938,402.79
Yard Improvement (% of Purchased Equipment Delivered)	10.00	1,076,890.44
Service Facilities (Installed) (% of Purchased Equipment Delivered)	70.00	7,538,233.08
Total Direct Cost		38,768,055.84
II. Indirect Costs (% of Purchased Equipment Delivered)		
Engineering and Supervision	33.00	3,553,738.45
Construction Expenses	41.00	4,415,250.80
Legal Expenses	4.00	430,756.18
Contractor's Fees	22.00	2,369,158.97
Contingency	44.00	4,738,317.94
Total Indirect Cost		15,507,222.33
III. Fixed-capital Investment (FCI) = Direct Cost + Indirect Cost		54,275,278.17
IV. Working Capital Investments (WC) (% of Purchased Equipment Delivered)	89.00	9,584,324.92
V. Total Capital Investment (TCI) = Fixed-Capital Investment + Working Capital		63,859,603.09

B.2.2.5 Production Cost Analysis

Table B2.19 Breakdown of production cost

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	23,117,307.07
Operating Labor	25.00	Fixed Capital Investment	13,568,820.00
Operating Supervision	15.00	Operating Labor	2,035,323.00
Utilities	-	-	-9,732.93
Maintenance and Repairs	6.00	Fixed Capital Investment	3,256,516.69
Operating Supplies	15.00	Maintenance and Supplies	488,477.51
Laboratory Charges	15.00	Operating Labor	2,035,323.00
Royalties	1.00	Total Product Cost	674,274.80
Catalysts	-	-	150,186.05
Total Variable Cost			45,316,495.19
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	1,085,505.56
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	542,752.78
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			1,628,258.35
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	11,316,396.00
Total Manufacturing Cost			46,944,753.53
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	3,772,132.00
Distribution & selling	4.00	Total Product Cost	2,697,099.20
Research & Development	4.00	Total Product Cost	2,697,099.20
General Expense			9,166,330.40
V. Total Product Cost with Out Depreciation			67,427,480.00

B.2.3 Bi-reforming of CO_2 into Methanol for the Alternative Case

B.2.3.1 Raw Materials and Product Annual Price

Table B2.20 Raw materials annual price

Raw Material	Quantity (kg/year)	Annual Price ($/year)
Methane	75,602,544.00	14,969,303.63
CO_2	53,716,348.00	1,896,187.17
Demineralized water	429,054,784.00	695,068.75

Table B2.21 Products annual price

Product	Quantity (kg/day)	Quantity (kg/year)	Annual Price ($/year)
Methanol	485,334.14	161,616,272.00	77,575,810.56

B.2.3.2 Annual Utility Cost

Table B2.22 Annual electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
C-30-10	189.79	100,562.54
C-30-19	181.44	96,138.50
C-30-23	177.02	93,799.89
C-5	2,590.51	1,372,635.14
C-23	488.68	258,934.16
PD-20-1	44.81	23,745.62
PD-28	91.46	48,460.45
Total		1,994,276.30

Table B2.23 Annual cooling water

Equipment	Quantity (kW)	Annual Price ($/year)
E-30-1	193.42	1,970.00
E-30-18	172.52	1,757.00
E-201	10,077.93	102,644.00
E-15	13,742.29	139,965.00
E-9	396.07	4,034.00
Total		250,370.00

B.2.3.3 Equipment Sizing and Purchase Cost

Chemical engineering plant cost index (12/2014): 575.8

Table B2.24 Equipment sizing and purchase cost

Equipment		Size	Unit	Material	Purchase Cost ($)
V-4	Vessel	3.83	m	316 Stainless Steel	139,109.00
V-41	Vessel	5.15	m	316 Stainless Steel	128,904.00
V-20-2	Vessel	1.76	m	316 Stainless Steel	61,449.00
E-30-1	Heat Exchanger	18.56	m^2	SS shell&SS tube	8,367.00
E-30-18	Heat Exchanger	18.12	m^2	SS shell&SS tube	8,287.00
E-3	Heat Exchanger	355.93	m^2	SS shell&SS tube	81,000.00
E-201	Heat Exchanger	682.10	m^2	SS shell&SS tube	143,632.00
E-6	Heat Exchanger	3,246.51	m^2	CS shell&SS tube	398,712.00
E-15	Heat Exchanger	2,216.54	m^2	SS shell&SS tube	466,124.00
E-91	Heat Exchanger	20.16	m^2	SS shell&SS tube	8,659.00
C-30-10	Compressor	189.79	kW	Carbon Steel	159,753.00
C-30-19	Compressor	181.44	kW	Carbon Steel	154,983.00
C-30-23	Compressor	177.02	kW	Carbon Steel	152,433.00
C-5	Compressor	2,590.51	kW	Carbon Steel	929,592.00
C-23	Compressor	488.68	kW	Carbon Steel	302,144.00
PD-20-1	Pump include drive	20.17	cubic.m /s*kPa	Stainless Steel	17,372.00
PD-28	Pump include drive	41.16	cubic.m /s*kPa	Stainless Steel	23,254.00
T-111	Tower Unit	7.22	m	316 Stainless Steel	424,543.00
tT-111	valvetray	3.00	trays	Stainless Steel	13,438.00
cT-111	Heat Exchanger	12.86	m^2	SS shell&SS tube	16,402.00
E-12	Heat Exchanger	24.07	m^2	SS shell&SS tube	10,870.00
T-19	Tower Unit	26.71	m	316 Stainless Steel	926,453.00
tT-19	valvetray	35.00	trays	Stainless Steel	131,793.00
cT-19	Heat Exchanger	682.28	m^2	SS shell&SS tube	201,233.00
E-21	Heat Exchanger	32.32	m^2	SS shell&SS tube	11,634.00
R-7	Methanol synthesis reactor	2,261.95	m^2	SS shell&SS tube	1,488,477.00
R-1	Bi-reforming reactor	2,139.57	m^2	SS shell&SS tube	1,105,452.00
Total					7,514,069.00

B.2.3.4 Capital Cost Analysis

Table B2.25 Breakdown of capital cost

Description	%	Result ($)
I. Direct Costs		
Purchased Equipment Delivered (% of Purchase equipment cost)	110.00	8,265,475.90
Purchased Equipment Installation (% of Purchased Equipment Delivered)	47.00	3,884,773.67
Instrumentation and Controls (installed) (% of Purchased Equipment Delivered)	36.00	2,975,571.32
Piping (Installed) (% of Purchased Equipment Delivered)	68.00	5,620,523.61
Electrical Systems (Installed) (% of Purchased Equipment Delivered)	11.00	909,202.35
Buildings (Including Services) (% of Purchased Equipment Delivered)	18.00	1,487,785.66
Yard Improvement (% of Purchased Equipment Delivered)	10.00	826,547.59
Service Facilities (Installed) (% of Purchased Equipment Delivered)	70.00	5,785,833.13
Total Direct Cost		29,755,713.24
II. Indirect costs (% of Purchased Equipment Delivered)		
Engineering and Supervision	33.00	2,727,607.05
Construction Expenses	41.00	3,388,845.12
Legal Expenses	4.00	330,619.04
Contractor's Fees	22.00	1,818,404.70
Contingency	44.00	3,636,809.40
Total Indirect Cost		11,902,285.30
III. Fixed-capital Investment (FCI) = Direct Cost + Indirect Cost		41,657,998.54
IV. Working Capital Investments (WC) (% of Purchased Equipment Delivered)	89.00	7,356,273.55
V. Total Capital Investment (TCI) = Fixed-capital Investment + Working Capital		49,014,272.09

B.2.3.5. Production Cost Analysis

Table B2.26 Breakdown of production cost

Items of Production Cost	**% of Basis**	**Basis**	**Cost, $/year**
I. Variable Cost			
Raw Material	-	-	17,560,559.54
Operating Labor	25.00	Fixed Capital Investment	10,414,500.00
Operating Supervision	15.00	Operating Labor	1,562,175.00
Utilities	-	-	2,244,646.30
Maintenance and Repairs	6.00	Fixed Capital Investment	2,499,479.91
Operating Supplies	15.00	Maintenance and Supplies	374,922.00
Laboratory Charges	15.00	Operating Labor	1,562,175.00
Royalties	1.00	Total Product Cost	540,826.76
Catalysts	-	-	166,112.55
Total Variable Cost			36,925,397.07
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	833,159.97
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	416,579.99
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			1,249,739.96
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	8,685,693.00
Total Manufacturing Cost			38,175,137.02
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	2,895,231.00
Distribution & selling	4.00	Total Product Cost	2,163,307.04
Research & Development	4.00	Total Product Cost	2,163,307.04
General Expense			7,221,845.08
V. Total Product Cost with Out Depreciation			54,082,676.00

B.3 Tri-reforming of CO_2 into Methanol

B.3.1 Tri-reforming of CO_2 into Methanol for the Base Case

B.3.1.1 Raw Material, Product and Utilities Prices

Table B3.1 Raw material and product prices

Raw Material Price		
Raw Material	Value	Unit
Methane[1]	198	$/tCH_4$
Demineralized water[2]	1.62	$/tH_2O$
Product Price		
Product	Value	Unit
Methanol [3]	0.48	$/kgMeOH

References:

[1] http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm (12/2014)

[2] www.alibaba.com (12/2014)

[3] www.icis.com (12/2014)

Table B3.2 Utility price

Cooling Water		
	Value	Unit
Cooling water 28-40 °C*	0.35	$/GJ
Electricity		
	Value	Unit
Electricity*	18.42	$/GJ

* 2013 U.S. average cost

B.3.1.2 Raw Materials and Product Annual Price

Table B3.3 Raw materials annual price

Raw Material	Quantity (kg/year)	Annual Price ($/year)
Methane	104,789,038.00	20,748,229.41
Demineralized water	331,729,408.00	537,401.64

Table B3.4 Products annual price

Product	Quantity (kg/day)	Quantity (kg/year)	Annual Price ($/year)
Methanol	481,319.64	160,279,440.00	76,934,131.20

B.3.1.3 Annual Utility Cost

Table B3.5 Annual electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
C-11-10	3,706.28	1,963,843.32
C-11-19	3,684.25	1,952,172.59
C-11-23	3,661.22	1,939,971.24
C-11-24	3,709.67	1,965,640.18
C-23	1,907.37	1,010,656.23
PD-20-1	40.70	21,564.90
PD-28	64.66	34,262.18
Total		8,888,110.64

Table B3.6 Annual generated electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
TB-14-33	-1,963.54	-1,040,422.00
TB-14-35	-1,980.07	-1,049,180.00
TB-14-38	-3,165.39	-1,677,245.00
TB-351	-656.00	-347,594.00
TB-17	-608.02	-322,171.00
TB-8-261	-703.69	-372,862.00
TB-8-171	-587.63	-311,368.00
TB-8-271	-1,357.80	-719,456.00
Total		-5,840,298.00

Table B3.7 Annual cooling water cost

Equipment	Quantity (kW)	Annual Price ($/year)
E-11-1	422.44	4,303.00
E-11-18	3,671.14	37,391.00
E-11-20	3,771.68	38,415.00
E-11-4	3,462.64	35,267.00
E-15	15,670.34	159,603.00
E-27	6,788.86	69,145.00
Total		344,124.00

B.3.1.4 Equipment Sizing and Purchase Cost

Chemical engineering plant cost index (12/2014): 575.8

Table B3.8 Equipment sizing and purchase cost

Equipment		Size	Unit	Material	Purchase Cost ($)
V-11-2	Vessel	1.17	m	316 Stainless Steel	27,701.69
V-11-3	Vessel	1.30	m	316 Stainless Steel	27,701.69
V-11-5	Vessel	0.91	m	316 Stainless Steel	55,402.37
V-4	Vessel	4.96	m	316 Stainless Steel	126,471.12
V-5	Vessel	4.89	m	316 Stainless Steel	43,689.60
V-20-2	Vessel	1.00	m	316 Stainless Steel	55,402.37
E-9	Heat Exchanger	176.57	m^2	SS shell&SS tube	37,152.64
E-12	Heat Exchanger	494.33	m^2	SS shell&SS tube	110,248.91
E-11-1	Heat Exchanger	136.88	m^2	SS shell&SS tube	29,922.94
E-11-18	Heat Exchanger	311.61	m^2	SS shell&SS tube	61,754.73
E-11-20	Heat Exchanger	319.63	m^2	SS shell&SS tube	63,215.27
E-11-4	Heat Exchanger	292.93	m^2	SS shell&SS tube	67,688.20
E-10	Heat Exchanger	28,258.70	m^2	CS shell&SS tube	3,416,715.00
E-15	Heat Exchanger	4,796.43	m^2	SS shell&SS tube	1,005,064.00
E-13	Heat Exchanger	19.97	m^2	SS shell&SS tube	8,623.31
E-27	Heat Exchanger	341.79	m^2	SS shell&SS tube	67,253.07
E-14-30	Heat Exchanger	32.60	m^2	SS shell&SS tube	11,689.44
E-14-32	Heat Exchanger	34.60	m^2	SS shell&SS tube	12,079.93
E-14-34	Heat Exchanger	33.56	m^2	SS shell&SS tube	11,876.07
E-14-36	Heat Exchanger	64.74	m^2	SS shell&SS tube	16,779.04
E-14-39	Heat Exchanger	3.03	m^2	SS shell&SS tube	5,627.16
E-8-131	Heat Exchanger	15.63	m^2	SS shell&SS tube	8,117.19
E-8-141	Heat Exchanger	13.62	m^2	SS shell&SS tube	7,706.41
E-8-191	Heat Exchanger	29.39	m^2	SS shell&SS tube	8,589.84
C-11-10	Compressor	3,706.28	kW	Carbon Steel	1,183,322.25
C-11-19	Compressor	3,684.25	kW	Carbon Steel	1,178,579.53
C-11-23	Compressor	3,661.22	kW	Carbon Steel	1,173,610.63
C-11-24	Compressor	3,709.67	kW	Carbon Steel	1,184,051.51

Table B3.8 Equipment sizing and purchase cost (con't.)

Equipment		Size	Unit	Material	Purchase Cost ($)
C-23	Compressor	1,907.37	kW	Carbon Steel	756,326.54
PD-20-1	Pump include drive	18.31	cubic.m /s*kPa	Stainless Steel	16,817.58
PD-28	Pump include drive	29.10	cubic.m /s*kPa	Stainless Steel	19,938.48
TB-14-33	Turbine	1,963.54	kW	Stainless Steel	850,532.77
TB-14-35	Turbine	1,980.07	kW	Stainless Steel	854,741.98
TB-14-38	Turbine	3,165.39	kW	Stainless Steel	1,126,734.20
TB-351	Turbine	656.00	kW	Stainless Steel	445,957.45
TB-17	Turbine	608.02	kW	Stainless Steel	213,225.53
TB-8-261	Turbine	703.69	kW	Stainless Steel	232,386.06
TB-8-171	Turbine	587.63	kW	Stainless Steel	208,984.87
TB-8-271	Turbine	1,357.80	kW	Stainless Steel	342,228.26
R-3	Methanol synthesis reactor	20,216.15	m^2	SS shell&SS tube	13,493,550.00
T-24	Tower Unit	21.83	m	316 Stainless Steel	789,313.58
tT-24	valvetray	27.00	trays	Stainless Steel	92,972.89
cT-24	Heat Exchanger	229.95	m^2	SS shell&SS tube	127,223.70
E-26	Heat Exchanger	11.83	m^2	SS shell&SS tube	7,639.47
R-1	Tri-reforming reactor	1,232.73	m^2	SS shell&SS tube	399,640.00
R-8-29	Vessel	10.00	m	316 Stainless Steel	171,952.00
Total					30,156,201.25

B.3.1.5 Capital Cost Analysis

Table B3.9 Breakdown of capital cost

Description	%	Result ($)
I. Direct Costs		
Purchased Equipment Delivered (% of Purchase equipment cost)	110.00	33,171,821.38
Purchased Equipment Installation (% of Purchased Equipment Delivered)	47.00	15,590,756.05
Instrumentation and Controls (installed) (% of Purchased Equipment Delivered)	36.00	11,941,855.70
Piping (Installed) (% of Purchased Equipment Delivered)	68.00	22,556,838.54
Electrical Systems (Installed) (% of Purchased Equipment Delivered)	11.00	3,648,900.35
Buildings (Including Services) (% of Purchased Equipment Delivered)	18.00	5,970,927.85
Yard Improvement (% of Purchased Equipment Delivered)	10.00	3,317,182.14
Service Facilities (Installed) (% of Purchased Equipment Delivered)	70.00	23,220,274.96
Total Direct Cost		119,418,556.95
II. Indirect Costs (% of Purchased Equipment Delivered)		
Engineering and Supervision	33.00	10,946,701.05
Construction Expenses	41.00	13,600,446.76
Legal Expenses	4.00	1,326,872.86
Contractor's Fees	22.00	7,297,800.70
Contingency	44.00	14,595,601.41
Total Indirect Cost		47,767,422.78
III. Fixed-capital Investment (FCI) = Direct Cost + Indirect Cost		167,185,979.73
IV. Working Capital Investments (WC) (% of Purchased Equipment Delivered)	89.00	29,522,921.02
V. Total Capital Investment (TCI) = Fixed-capital Investment + Working Capital		196,708,900.75

B.3.1.6 Production Cost Analysis

Table B3.10 Breakdown of production cost

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	21,285,631.05
Operating Labor	10.00	Fixed Capital Investment	16,718,598.00
Operating Supervision	15.00	Operating Labor	2,507,789.70
Utilities	-	-	3,391,936.64
Maintenance and Repairs	6.00	Fixed Capital Investment	10,031,158.78
Operating Supplies	15.00	Maintenance and Supplies	1,504,673.85
Laboratory Charges	15.00	Operating Labor	2,507,789.70
Royalties	1.00	Total Product Cost	960,919.60
Catalysts	-	-	1,074,486.69
Total Variable Cost			59,982,984.01
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	3,343,719.59
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	1,671,859.80
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			5,015,579.39
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	17,554,527.60
Total Manufacturing Cost			64,998,563.40
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	5,851,509.20
Distribution & selling	4.00	Total Product Cost	3,843,678.40
Research & Development	4.00	Total Product Cost	3,843,678.40
General Expense			13,538,866.00
V. Total Product Cost with Out Depreciation			96,091,960.00

B.3.1.7 Profitability Assumptions

Table B3.11· Profitability conditions

Project Details	
Project Life Time	20 years
Land Cost	$1,000,000.00
Construction Inflation Rate	2%
Product Inflation Rate	10%
TPC Inflation Rate	10%
Minimum Rate of Return, Mar	15%
Income Tax Rate	30%
Type of Depreciation	MACRS

B.3.2 Tri-reforming of CO_2 into Methanol for the Optimized Case

B.3.2.1 Raw Materials and Product Annual Price

Table B3.12 Raw materials annual price

Raw Material	Quantity (kg/year)	Annual Price ($/year)
Methane	105,055,966.00	20,801,081.16
Demineralized water	331,729,408.00	537,401.64

Table B3.13 Products annual price

Product	Quantity (kg/day)	Quantity (kg/year)	Annual Price ($/year)
Methanol	483,952.75	161,156,272.00	77,355,010.56

B.3.2.2 Annual Utility Cost

Table B3.14 Annual electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
C-11-10	3,711.66	1,966,697.63
C-11-19	3,684.04	1,952,059.72
C-11-23	3,660.98	1,939,843.36
C-11-24	3,315.79	1,756,938.35
C-23	2,076.32	1,100,178.79
PD-20-1	40.70	21,564.90
PD-28	64.66	34,262.18
Total		8,771,544.93

Table B3.15 Annual generated electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
TB-14-33	-1,944.92	-1,030,553.00
TB-14-35	-1,966.36	-1,041,914.00
TB-14-38	-3,141.67	-1,664,673.00
TB-351	-661.17	-350,332.00
TB-17	-584.44	-309,675.00
TB-8-261	-641.72	-340,027.00
TB-8-171	-589.99	-312,617.00
TB-8-271	-1,357.95	-719,539.00
Total		-5,769,330.00

Table B3.16 Annual cooling water cost

Equipment	Quantity (kW)	Annual Price ($/year)
E-11-1	423.36	4,312.00
E-11-18	3,737.19	38,063.00
E-11-20	3,771.56	38,413.00
E-11-4	3,462.61	35,267.00
E-15	15,561.05	158,489.00
E-27	6,826.24	69,525.00
Total		344,069.00

B.3.2.3 Equipment Sizing and Purchase Cost

Chemical engineering plant cost index (12/2014): 575.8

Table B3.17 Equipment sizing and purchase cost

Equipment		Size	Unit	Material	Purchase cost ($)
V-11-2	Vessel	1.24	m	316 Stainless Steel	27,701.69
V-11-3	Vessel	1.30	m	316 Stainless Steel	27,701.69
V-11-5	Vessel	0.91	m	316 Stainless Steel	55,402.37
V-4	Vessel	4.97	m	316 Stainless Steel	126,576.60
V-5	Vessel	4.91	m	316 Stainless Steel	43,746.40
V-20-2	Vessel	0.65	m	316 Stainless Steel	55,402.37
E-9	Heat Exchanger	177.53	m^2	SS shell&SS tube	37,328.11
E-12	Heat Exchanger	487.81	m^2	SS shell&SS tube	100,424.71
E-11-1	Heat Exchanger	137.18	m^2	SS shell&SS tube	29,976.69
E-11-18	Heat Exchanger	317.40	m^2	SS shell&SS tube	62,808.55
E-11-20	Heat Exchanger	319.74	m^2	SS shell&SS tube	63,235.56
E-11-4	Heat Exchanger	293.04	m^2	SS shell&SS tube	58,372.14
E-10	Heat Exchanger	26,393.78	m^2	CS shell&SS tube	3,191,034.00
E-15	Heat Exchanger	4,828.58	m^2	SS shell&SS tube	1,011,504.00
E-13	Heat Exchanger	20.48	m^2	SS shell&SS tube	8,716.62
E-27	Heat Exchanger	343.63	m^2	SS shell&SS tube	67,586.77
E-14-30	Heat Exchanger	32.78	m^2	SS shell&SS tube	12,710.81
E-14-32	Heat Exchanger	34.82	m^2	SS shell&SS tube	13,140.86
E-14-34	Heat Exchanger	33.54	m^2	SS shell&SS tube	12,870.05
E-14-36	Heat Exchanger	64.68	m^2	SS shell&SS tube	16,767.88
E-14-39	Heat Exchanger	3.04	m^2	SS shell&SS tube	5,627.16
E-8-131	Heat Exchanger	15.61	m^2	SS shell&SS tube	8,115.16
E-8-141	Heat Exchanger	13.96	m^2	SS shell&SS tube	7,737.85
E-8-191	Heat Exchanger	30.37	m^2	SS shell&SS tube	8,675.04
C-11-10	Compressor	3,711.66	kW	Carbon Steel	1,184,480.54
C-11-19	Compressor	3,684.04	kW	Carbon Steel	1,178,532.88
C-11-23	Compressor	3,660.98	kW	Carbon Steel	1,173,558.90
C-11-24	Compressor	3,315.79	kW	Carbon Steel	1,097,803.22

Table B3.17 Equipment sizing and purchase cost (con't.)

Equipment		Size	Unit	Material	Purchase cost ($)
C-23	Compressor	2,076.32	kW	Carbon Steel	800,839.72
PD-20-1	Pump include drive	18.31	cubic.m /s*kPa	Stainless Steel	16,817.58
PD-28	Pump include drive	29.10	cubic.m /s*kPa	Stainless Steel	19,938.48
TB-14-33	Turbine	1,944.92	kW	Stainless Steel	845,772.81
TB-14-35	Turbine	1,966.36	kW	Stainless Steel	851,250.87
TB-14-38	Turbine	3,141.67	kW	Stainless Steel	1,121,752.12
TB-351	Turbine	661.17	kW	Stainless Steel	448,023.52
TB-17	Turbine	584.44	kW	Stainless Steel	208,315.45
TB-8-261	Turbine	641.72	kW	Stainless Steel	220,107.33
TB-8-171	Turbine	589.99	kW	Stainless Steel	209,478.82
TB-8-271	Turbine	1,357.95	kW	Stainless Steel	342,251.58
R-3	Methanol synthesis reactor	20,216.15	m^2	SS shell&SS tube	13,493,550.00
T-24	Tower Unit	21.83	m	316 Stainless Steel	789,313.58
tT-24	valvetray	27.00	trays	Stainless Steel	93,356.28
cT-24	Heat Exchanger	231.18	m^2	SS shell&SS tube	127,509.73
E-26	Heat Exchanger	11.74	m^2	SS shell&SS tube	7,623.24
R-1	Tri-reforming reactor	1,220.31	m^2	SS shell&SS tube	396,786.00
R-8-29	Vessel	10.00	m	316 Stainless Steel	171,952.00
Total					29,852,177.73

B.3.2.4 Capital Cost Analysis

Table B3.18 Breakdown of capital cost

Description	%	Result ($)
I. Direct Costs		
Purchased Equipment Delivered (% of Purchase equipment cost)	110.00	32,837,395.50
Purchased Equipment Installation (% of Purchased Equipment Delivered)	47.00	15,433,575.89
Instrumentation and Controls (installed) (% of Purchased Equipment Delivered)	36.00	11,821,462.38
Piping (Installed) (% of Purchased Equipment Delivered)	68.00	22,329,428.94
Electrical Systems (Installed) (% of Purchased Equipment Delivered)	11.00	3,612,113.51
Buildings (Including Services) (% of Purchased Equipment Delivered)	18.00	5,910,731.19
Yard Improvement (% of Purchased Equipment Delivered)	10.00	3,283,739.55
Service Facilities (Installed) (% of Purchased Equipment Delivered)	70.00	22,986,176.85
Total Direct Cost		118,214,623.81
II. Indirect Costs (% of Purchased Equipment Delivered)		
Engineering and Supervision	33.00	10,836,340.52
Construction Expenses	41.00	13,463,332.16
Legal Expenses	4.00	1,313,495.82
Contractor's Fees	22.00	7,224,227.01
Contingency	44.00	14,448,454.02
Total Indirect Cost		47,285,849.52
III. Fixed-capital Investment (FCI) = Direct Cost + Indirect Cost		165,500,473.34
IV. Working Capital Investments (WC) (% of Purchased Equipment Delivered)	89.00	29,225,282.00
V. Total Capital Investment (TCI) = Fixed-capital Investment + Working Capital		194,725,755.33

B.3.2.5 Production Cost Analysis

Table B3.19 Breakdown of production cost

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	21,338,482.79
Operating Labor	10.00	Fixed Capital Investment	16,550,048.00
Operating Supervision	15.00	Operating Labor	2,482,507.20
Utilities	-	-	3,346,283.93
Maintenance and Repairs	6.00	Fixed Capital Investment	9,930,028.40
Operating Supplies	15.00	Maintenance and Supplies	1,489,504.20
Laboratory Charges	15.00	Operating Labor	2,482,507.20
Royalties	1.00	Total Product Cost	942,356.48
Catalysts	-	-	21,338,482.79
Total Variable Cost			58,561,718.20
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	3,310,009.47
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	1,655,004.73
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			4,965,014.20
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	17,377,550.40
Total Manufacturing Cost			63,526,732.40
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	5,792,516.80
Distribution & selling	4.00	Total Product Cost	3,769,425.92
Research & Development	4.00	Total Product Cost	3,769,425.92
General Expense			13,331,368.64
V. Total Product Cost with Out Depreciation			94,235,648.00

B.3.3 Tri-reforming of CO_2 into Methanol for the Alternative Case

B.3.3.1 Raw Materials and Product Annual Price

Table B3.20 Raw materials annual price

Raw Material	Quantity (kg/year)	Annual Price ($/year)
Methane	72,980,760.00	14,450,190.40
Demineralized water	331,729,408.00	537,401.64

Table B3.21 Products annual price

Product	Quantity (kg/day)	Quantity (kg/year)	Annual Price ($/year)
Methanol	483,958.17	161,158,064.00	77,355,870.72

B.3.3.2 Annual Utility Cost

Table B3.22 Annual electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
C-11-10	3,711.73	1,966,732.86
C-11-19	3,684.06	1,952,073.71
C-11-23	3,661.01	1,939,857.22
C-11-24	3,315.82	1,756,950.82
C-23	2,076.23	1,100,131.56
PD-20-1	40.70	21,564.90
PD-28	64.66	34,262.18
Total		8,771,573.25

Table B3.23 Annual generated electricity cost

Equipment	Quantity (kW)	Annual Price ($/year)
TB-14-33	-1,824.42	-966,706.00
TB-14-35	-1,686.78	-893,776.00
TB-14-38	-2,545.38	-1,348,718.00
TB-351	-535.75	-283,877.00
TB-17	-584.51	-309,712.00
Total		-3,802,789.00

Table B3.24 Annual cooling water cost

Equipment	Quantity (kW)	Annual Price ($/year)
E-11-1	423.37	4,312.00
E-11-18	3,737.68	38,068.00
E-11-20	3,771.58	38,414.00
E-11-4	3,462.63	35,267.00
E-15	15,560.86	158,487.00
E-27	6,826.32	69,526.00
Total		344,074.00

B.3.3.3 Equipment Sizing and Purchase Cost

Chemical engineering plant cost index (12/2014): 575.8

Table B3.25 Equipment sizing and purchase cost

Equipment		Size	Unit	Material	Purchase cost ($)
V-11-2	Vessel	1.24	m	316 Stainless Steel	27,701.69
V-11-3	Vessel	1.30	m	316 Stainless Steel	27,701.69
V-11-5	Vessel	0.91	m	316 Stainless Steel	55,402.37
V-4	Vessel	4.97	m	316 Stainless Steel	126,576.60
V-5	Vessel	4.91	m	316 Stainless Steel	43,746.40
V-20-2	Vessel	0.65	m	316 Stainless Steel	55,402.37
E-12	Heat Exchanger	487.84	m^2	SS shell&SS tube	100,429.78
E-11-1	Heat Exchanger	137.18	m^2	SS shell&SS tube	29,977.71
E-11-18	Heat Exchanger	317.44	m^2	SS shell&SS tube	62,816.67
E-11-20	Heat Exchanger	319.74	m^2	SS shell&SS tube	63,235.56
E-11-4	Heat Exchanger	293.05	m^2	SS shell&SS tube	62,458.63
E-10	Heat Exchanger	26,392.87	m^2	CS shell&SS tube	3,190,908.00
E-15	Heat Exchanger	4,828.43	m^2	SS shell&SS tube	1,011,472.00
E-13	Heat Exchanger	34.87	m^2	SS shell&SS tube	11,338.50
E-27	Heat Exchanger	343.63	m^2	SS shell&SS tube	67,587.78
E-14-30	Heat Exchanger	24.92	m^2	SS shell&SS tube	10,193.39
E-14-32	Heat Exchanger	24.31	m^2	SS shell&SS tube	10,072.70
E-14-34	Heat Exchanger	16.88	m^2	SS shell&SS tube	8,624.32
E-14-36	Heat Exchanger	91.39	m^2	SS shell&SS tube	21,634.34
E-14-39	Heat Exchanger	8.50	m^2	SS shell&SS tube	6,532.90
C-11-10	Compressor	3,711.73	kW	Carbon Steel	1,184,494.74
C-11-19	Compressor	3,684.06	kW	Carbon Steel	1,178,538.96
C-11-23	Compressor	3,661.01	kW	Carbon Steel	1,173,563.98
C-11-24	Compressor	3,315.82	kW	Carbon Steel	1,097,808.29
C-23	Compressor	2,076.23	kW	Carbon Steel	800,816.39
PD-20-1	Pump include drive	18.31	cubic.m /s*kPa	Stainless Steel	16,817.58
PD-28	Pump include drive	29.10	cubic.m /s*kPa	Stainless Steel	19,938.48
TB-14-33	Turbine	1,824.42	kW	Stainless Steel	814,510.03

Table B3.25 Equipment sizing and purchase cost (con't.)

Equipment		Size	Unit	Material	Purchase cost ($)
TB-14-35	Turbine	1,686.78	kW	Stainless Steel	777,740.78
TB-14-38	Turbine	2,545.38	kW	Stainless Steel	990,984.56
TB-351	Turbine	535.75	kW	Stainless Steel	395,826.24
TB-17	Turbine	584.51	kW	Stainless Steel	416,659.31
R-3	Methanol synthesis reactor	20,216.15	m^2	SS shell&SS tube	13,493,550.00
T-24	Tower Unit	21.83	m	316 Stainless Steel	789,313.58
tT-24	valvetray	27.00	trays	Stainless Steel	93,357.29
cT-24	Heat Exchanger	231.19	m^2	SS shell&SS tube	127,510.74
E-26	Heat Exchanger	11.74	m^2	SS shell&SS tube	7,623.24
R-1	Tri-reforming reactor	1,673.38	m^2	SS shell&SS tube	503,780.00
Total					28,876,647.59

B.3.3.4 Capital Cost Analysis

Table B3.26 Breakdown of capital cost

Description	%	Result ($)
I. Direct Costs		
Purchased Equipment Delivered (% of Purchase equipment cost)	110.00	31,764,312.35
Purchased Equipment Installation (% of Purchased Equipment Delivered)	47.00	14,929,226.80
Instrumentation and Controls (installed) (% of Purchased Equipment Delivered)	36.00	11,435,152.45
Piping (Installed) (% of Purchased Equipment Delivered)	68.00	21,599,732.40
Electrical Systems (Installed) (% of Purchased Equipment Delivered)	11.00	3,494,074.36
Buildings (Including Services) (% of Purchased Equipment Delivered)	18.00	5,717,576.22
Yard Improvement (% of Purchased Equipment Delivered)	10.00	3,176,431.23
Service Facilities (Installed) (% of Purchased Equipment Delivered)	70.00	22,235,018.64
Total Direct Cost		114,351,524.46
II. Indirect Costs (% of Purchased Equipment Delivered)		
Engineering and Supervision	33.00	10,482,223.08
Construction Expenses	41.00	13,023,368.06
Legal Expenses	4.00	1,270,572.49
Contractor's Fees	22.00	6,988,148.72
Contingency	44.00	13,976,297.43
Total Indirect Cost		45,740,609.78
III. Fixed-capital Investment (FCI) = Direct Cost + Indirect Cost		160,092,134.24
IV. Working Capital Investments (WC) (% of Purchased Equipment Delivered)	89.00	28,270,237.99
V. Total Capital Investment (TCI) = Fixed-capital Investment + Working Capital		188,362,372.23

B.3.3.5 Production Cost Analysis

Table B3.27 Breakdown of production cost

Items of Production Cost	% of Basis	Basis	Cost, $/year
I. Variable Cost			
Raw Material	-	-	14,987,592.04
Operating Labor	10.00	Fixed Capital Investment	16,009,214.00
Operating Supervision	15.00	Operating Labor	2,401,382.10
Utilities	-	-	5,312,858.25
Maintenance and Repairs	6.00	Fixed Capital Investment	9,605,528.05
Operating Supplies	15.00	Maintenance and Supplies	1,440,829.20
Laboratory Charges	15.00	Operating Labor	2,401,382.10
Royalties	1.00	Total Product Cost	885,043.60
Catalysts	-	-	1,164,517.64
Total Variable Cost			54,208,346.99
II. Fixed Charges			
Property Taxes	2.00	Fixed Capital Investment	3,201,842.68
Financing (interest)	0.00	Fixed Capital Investment	0.00
Insurance	1.00	Fixed Capital Investment	1,600,921.34
Rent	0.00	Fixed Capital Investment	0.00
Total Fixed Charges			4,802,764.03
III. Manufacturing Cost			
Plant Overhead	60.00	Labor + Supervision + Maintenance	16,809,674.40
Total Manufacturing Cost			59,011,111.01
IV. General Expense			
Administration	20.00	Labor + Supervision + Maintenance	5,603,224.80
Distribution & selling	4.00	Total Product Cost	3,540,174.40
Research & Development	4.00	Total Product Cost	3,540,174.40
General Expense			12,683,573.60
V. Total Product Cost with Out Depreciation			88,504,360.00

Appendix C Calculation of Indirect CO_2 Emission

Table C1 Indirect CO_2 emission from the hydrogenation of CO_2 into methanol for the base case

Electricity Usage (kW)	CO_2 Emission Factor ($kgCO_2/J$)	Indirect CO_2 Emission ($kgCO_2/hr$)
5865.775	2.008e-07	4240.2

Table C2 Indirect CO_2 emission from the bi-reforming of CO_2 into methanol for the base case

Electricity Requirement (kW)	Electricity Generated from Turbines (kW)	Electricity Usage (kW)	CO_2 Emission Factor ($kgCO_2/J$)	Indirect CO_2 Emission ($kgCO_2/hr$)
3863.538	-4320.350	-456.812	2.008e-07	-330.2

Table C3 Indirect CO_2 emission from the tri-reforming of CO_2 into methanol for the base case

Electricity Requirement (kW)	Electricity Generated from Turbines (kW)	Electricity Usage (kW)	CO_2 Emission Factor ($kgCO_2/J$)	Indirect CO_2 Emission ($kgCO_2/hr$)
16774.138	-11022.149	5751.989	2.008e-07	4158.0

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Proceedings:

1. Roh, K.; Nguyen, B.H.T.; Suriyapraphadilok, U.; Jay, H. L., and Rafiqul, G. (2015, May 31) Development of sustainable CO2 conversion processes for the methanol production. Paper presented at Proceedings of the 12th International Symposium on Process Systems Engineering and 25th European Symposium of Computer Aided Process Engineering, Copenhagen, Denmark.

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