Electronic Supplementary Material (ESI) for Sustainable Energy & Fuels.

Flexible methanol and hydrogen production with negative emissions

Supplementary material

The supplementary material includes the following:

- Appendix A: tables with properties of the main streams of the four assessed plants, process modelling assumptions, comparison of calculated syngas compositions with literature.
- Appendix B: method for the economic analysis with assumption tables and breakdown of capital costs.

Appendix A

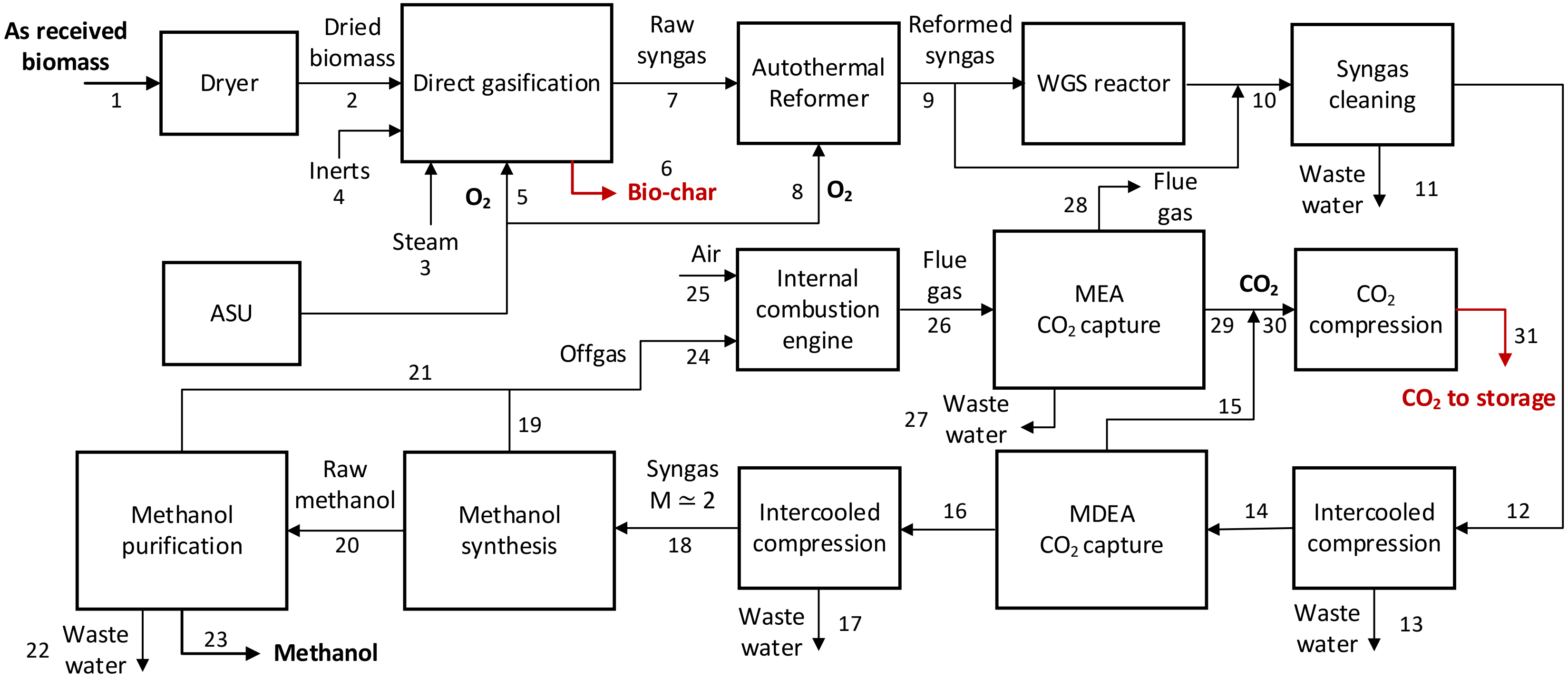

Figure A1 – Block diagram of the direct gasification-based Biomass-to-Methanol plant.

Table A1 - Plant stream properties DG-based Biomass-to-Methanol plant..

Stream #	**1**	**2**	**3**		**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**		**12**	**13**	**14**
Stream description	As-received biomass	Dried biomass	Steam input[1]		Inerts	Oxygen to gasifier	Bio-char[2]	Raw syngas	Oxygen to reformer	Reformed syngas	Shifted syngas	Waste water		Syngas	Waste water	Syngas
Temperature, °C	25.0	80.0	200.0	200.0	25.0	108.4	870.0	870.0	108.4	915.0	265.4	104.1	30.0	30.0	40.1	40.0
Pressure, bar	1.0	1.0	5.9	5.9	4.5	4.5	4.0	3.8	4.5	3.6	3.3	3.2	3.0	3.0	9.5	30.0
Mass flow rate, kg/s	10.27	6.64	2.66	0.80	0.21	1.93	0.19	12.04	0.64	12.68	12.68	3.33	0.10	9.25	0.07	9.17
Mole flow rate, kmol/h	-	-	531	160	26	216	-	2058	71	2349	2349	656	21	1672	14	1657
Composition, $\%_{mol}$	-	-														
H_2O	-	-	100	100	-	-	-	40.23	-	33.28	29.34	99.10	100	1.09	99.99	0.23
H_2	-	-	-	-	-	-	-	19.95	-	29.93	33.87	-	-	47.59	-	48.00
CO_2	-	-	-	-	-	-	-	17.22	-	15.82	19.76	0.87	-	27.42	0.01	27.66
CO	-	-	-	-	-	-	-	14.56	-	19.01	15.08	0.02	-	21.18	-	21.36
Methanol	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CH_4	-	-	-	-	-	-	-	4.43	-	0.39	0.39	0.01	-	0.54	-	0.55
C_xH_y	-	-	-	-	-	-	-	1.99	-	-	-	-	-	-	-	-
O_2	-	-	-	-	20.48	95.00	-	-	95.00	-	-	-	-	-	-	-
Ar	-	-	-	-	-	3.00	-	0.32	3.00	0.37	0.37	-	-	0.52	-	0.52
N_2	-	-	-	-	79.52	2.00	-	1.28	2.00	1.18	1.18	-	-	1.66	-	1.67
Ethanol	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DME	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LHV, MJ/kg	9.74	16.37	-	-	-	-	-	7.19	-	6.66	6.57	-	-	9.01	-	9.08
Power, MW_{LHV}	100.0	108.76	-	-	-	-	-	86.58	-	84.39	83.34	-	-	83.30	-	83.30

[1] The first row corresponds to the fluidization steam. The second row includes steam for sealing and cleaning purposes.

[2] The stream contains 67.42%wt of carbon and 32.58%wt of ashes.

Table A2 - Plant stream properties DG-based Biomass-to-Methanol plant

Stream #	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Stream description	CO_2 from MDEA	Syngas	Waste	Syngas to synthesis	Purge from synthesis	Methanol to purification	Purge from purification	Waste water	Methanol	Purge to ICE	Air to ICE	Flue gas from ICE	Waste water	Flue gas from MEA	CO_2 from MEA	CO_2 to compression	Compressed CO_2
Temperature, °C	40.0	40.0	40.0	115.2	33.3	41.5	32.3	88.2	64.5	33.3	25.0	100.0	40.0	40.0	40.0	40.0	89.5
Pressure, bar	1.2	30.0	52.5	92.0	2.0	2.0	1.4	1.0	1.0	1.4	1.0	1.0	1.0	1.0	1.2	1.2	150.0
Mass flow rate, kg/s	5.32	3.85	0.02	3.83	0.37	3.47	0.09	0.11	3.27	0.45	2.39	2.85	0.30	2.35	0.20	5.52	5.52
Mole flow rate, kmol/h	435	1222	4	1218	77	398	10	20	368	88	298	369	60	293	16	452	452
Composition, %$_{mol}$																	
H_2O	-	0.32	100	-	0.02	4.77	0.04	90.59	0.21	0.02	1.00	16.26	100	-	-	-	-
H_2	-	65.11	-	65.32	42.86	0.26	10.01	-	-	38.98	-	-	-	-	-	-	-
CO_2	100	1.88	-	1.88	1.48	0.73	28.29	-	-	4.65	0.03	4.65	-	0.29	100	100	100
CO	-	28.98	-	29.07	1.88	0.02	0.82	-	-	1.76	-	-	-	-	-	-	-
Methanol	-	-	-	-	0.61	93.07	17.92	9.18	99.77	2.65	-	-	-	-	-	-	-
CH_4	-	0.74	-	0.75	9.51	0.44	16.92	-	-	10.38	-	-	-	-	-	-	-
C_xH_y	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O_2	-	-	-	-	-	-	-	-	-	-	20.70	6.01	-	7.57	-	-	-
Ar	-	0.71	-	0.71	9.52	0.32	12.24	-	-	9.84	0.97	3.12	-	3.93	-	-	-
N_2	-	2.27	-	2.28	34.11	0.35	13.59	-	-	31.68	77.30	69.97	-	88.21	-	-	-
Ethanol	-	-	-	-	-	0.03	-	0.23	0.02	-	-	-	-	-	-	-	-
DME	-	-	-	-	-	-	0.18	-	-	0.02	-	-	-	-	-	-	-
LHV, MJ/kg	-	21.63	-	21.74	11.05	19.11	9.26	-	19.90	10.71	-	-	-	-	-	-	-
Power, MW_{LHV}	-	83.30	-	83.30	4.06	66.21	0.80	-	65.07	4.86	-	-	-	-	-	-	-

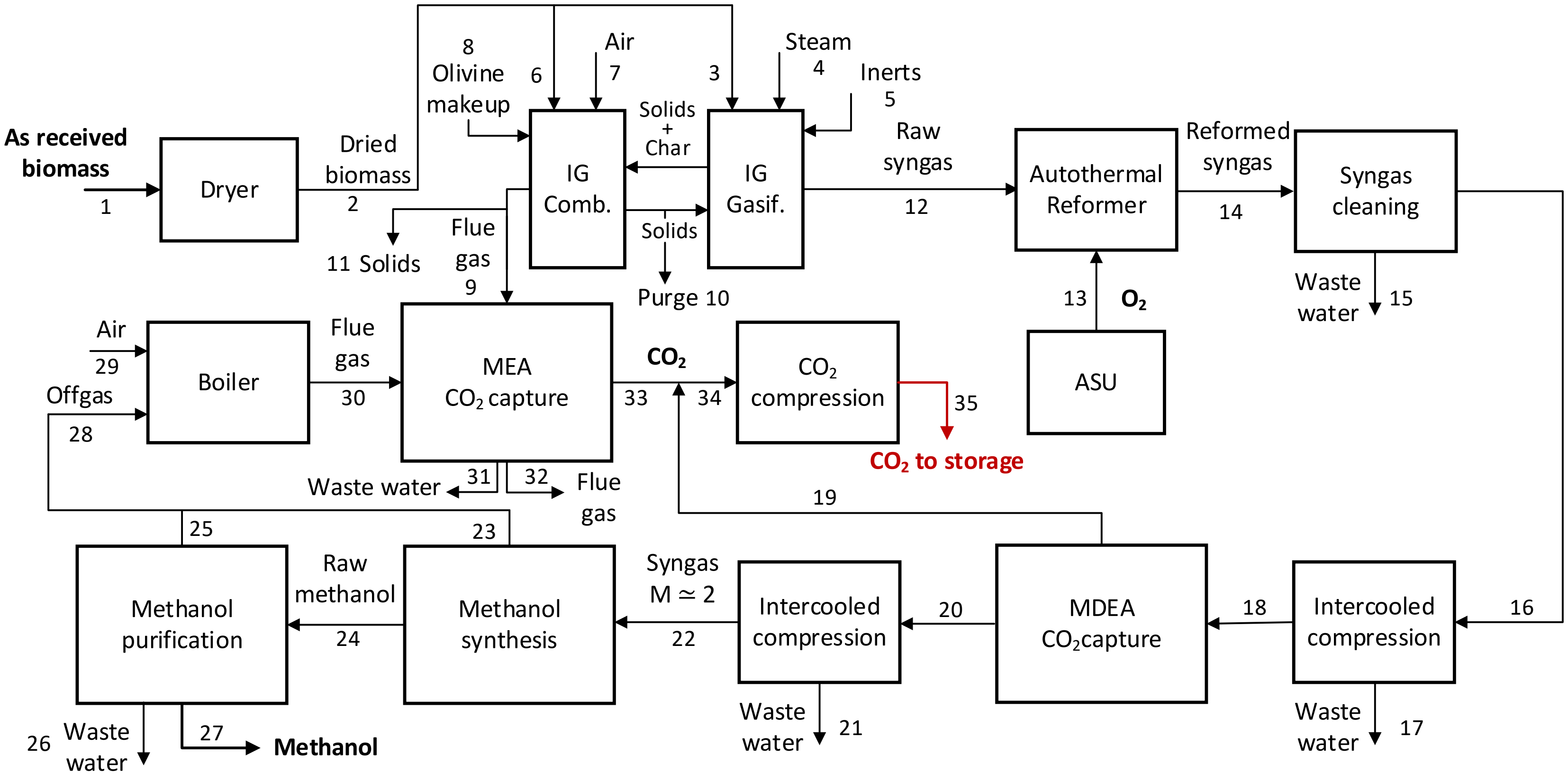

Figure A2 – Block diagram of the indirect gasification-based Biomass-to-Methanol plant.

Table A3 - Plant stream properties IG-based Biomass-to-Methanol plant

Stream #	**1**	**2**	**3**	**4**		**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Stream description	As-received biomass	Dried biomass	Biomass to gasifier	Steam input[1]		Inerts	Biomass to combustor	Air to combustor	Olivine makeup[2]	Flue gas from combustor	Solid purge[2]	Solids[2]	Raw syngas	Oxygen to reformer	Reformed syngas
Temperature, °C	25.0	80.0	80.0	400.0	180.0	25.0	80.0	270.0	25.0	140.1	910.0	140.1	815.0	150.0	800.0
Pressure, bar	1.0	1.0	1.0	3.9	3.9	1.6	1.0	1.6	1.0	1.1	1.4	1.1	1.2	2.0	1.1
Mass flow rate, kg/s	10.27	6.64	5.71	2.62	0.69	0.18	0.93	11.64	0.28	12.98	0.06	0.28	8.72	0.50	9.21
Mole flow rate, kmol/h	-	-	-	523	138	22	-	1452	-	1560	-	-	1707	56	1978
Composition, $\%_{mol}$															
H_2O	-	-	-	100	100	-	-	1.00	-	8.21	-	-	36.25	-	27.05
H_2	-	-	-	-	-	-	-	-	-	-	-	-	27.99	-	40.57
CO_2	-	-	-	-	-	-	-	0.03	-	15.91	-	-	12.48	-	12.84
CO	-	-	-	-	-	-	-	-	-	-	-	-	14.47	-	17.90
Methanol	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CH_4	-	-	-	-	-	-	-	-	-	-	-	-	6.07	-	0.52
C_xH_y	-	-	-	-	-	-	-	-	-	-	-	-	1.61	-	-
O_2	-	-	-	-	-	20.48	-	20.70	-	2.99	-	-	-	95.00	-
Ar	-	-	-	-	-	-	-	0.97	-	0.90	-	-	-	3.00	0.08
N_2	-	-	-	-	-	79.52	-	77.30	-	71.98	-	-	1.11	2.00	1.01
Ethanol	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DME	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LHV, MJ/kg	9.74	16.37	16.37	-	-	-	16.37	-	-	-	-	-	9.72	-	9.13
Power, MW_{LHV}	100.0	108.76	93.55	-	-	-	15.19	-	-	-	-	-	84.70	-	84.07

[1] The first row corresponds to the fluidization steam. The second row includes steam for sealing and cleaning purposes.

[2] Olivine makeup stream contains 50%wt olivine Fe-based and 50%wt olivine Mg-based. Solid purge stream contains 48.80%wt olivine Fe-based,48.80%wt olivine Mg-based, and 2.40%wt ashes. Solids stream contains 40.06%wt olivine Fe-based,40.06%wt olivine Mg-based, and 19.87%wt ashes.

Table A4 - Plant stream properties IG-based Biomass-to-Methanol plant

Stream #	15		16	17	18	19	20	21	22	23	24	25	26	27
Stream description	Waste water		Syngas	Waste water	Syngas	CO_2 from MDEA	Syngas	Waste water	Syngas to synthesis	Purge from synthesis	Methanol to purificatio n	Purge from purificatio n	Waste water	Methanol
Stream description														
Temperature, °C	74.1	30.0	30.0	40.1	40.0	40.0	40.0	40.0	115.0	34.6	41.7	34.1	89.2	64.5
Pressure, bar	1.1	1.1	1.1	3.2	30.0	1.2	30.0	52.5	92.0	2.0	2.0	1.4	1.0	1.0
Mass flow rate, kg/s	2.16	0.30	6.75	0.21	6.53	2.79	3.75	0.02	3.73	0.23	3.50	0.07	0.12	3.31
Mole flow rate, kmol/h	430	60	1487	43	1445	228	1217	3	1214	59	405	10	23	372
Composition, $\%_{mol}$														
H_2O	99.75	100	3.08	100	0.23	-	0.27	100	-	0.02	5.51	0.06	91.85	0.21
H_2	-	-	53.96	-	55.54	-	65.94	-	66.12	49.07	0.29	12.27	-	-
CO_2	0.23	-	17.01	-	17.52	100	2.07	-	2.08	1.19	0.59	24.76	-	-
CO	0.01	-	23.80	-	24.50	-	29.08	-	29.16	1.47	0.02	0.69	-	-
Methanol	-	-	-	-	-	-	-	-	-	0.59	92.54	19.48	7.95	99.77
CH_4	-	-	0.69	-	0.72	-	0.85	-	0.85	13.40	0.61	25.72	-	-
C_xH_y	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O_2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ar	-	-	0.11	-	0.12	-	0.14	-	0.14	2.31	0.08	3.21	-	-
N_2	-	-	1.35	-	1.39	-	1.65	-	1.65	31.94	0.32	13.63	-	-
Ethanol	-	-	-	-	-	-	-	-	-	-	0.03	-	0.20	0.02
DME	-	-	-	-	-	-	-	-	-	-	-	0.19	-	-
LHV, MJ/kg	-	-	12.46	-	12.86	-	22.42	-	22.52	16.56	19.16	13.57	2.77	19.90
Power, MW_{LHV}	-	-	84.04	-	84.04	-	84.04	-	84.04	3.81	67.09	0.97	0.35	65.77

Table A5 - Plant stream properties IG-based Biomass-to-Methanol plant

Stream #	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**
Stream description	Purge to boiler	Air to boiler	Flue gas from boiler	Waste water	Flue gas from MEA	CO_2 from MEA	CO_2 to compression	Compressed CO_2
Temperature, °C	34.6	131.5	80.0	40.0	40.0	40.0	40.0	89.5
Pressure, bar	1.4	1.0	1.0	1.0	1.0	1.2	1.2	150.0
Mass flow rate, kg/s	0.30	1.68	1.98	0.93	10.97	3.08	5.86	5.86
Mole flow rate, kmol/h	68	210	264	185	1387	252	479	479
Composition, $\%_{mol}$								
H_2O	0.03	1.00	21.70	100	-	-	-	-
H_2	43.89	-	-	-	-	-	-	-
CO_2	4.51	0.03	6.32	-	0.95	100	100	100
CO	1.36	-	-	-	-	-	-	-
Methanol	3.25	-	-	-	-	-	-	-
CH_4	15.13	-	-	-	-	-	-	-
C_xH_y	-	-	-	-	-	-	-	-
O_2	-	20.70	1.49	-	3.65	-	-	-
Ar	2.44	0.97	1.40	-	1.28	-	-	-
N_2	29.36	77.30	69.09	-	94.11	-	-	-
Ethanol	-	-	-	-	-	-	-	-
DME	0.03	-	-	-	-	-	-	-
LHV, MJ/kg	15.85	-	-	-	-	-	-	-
Power, MW_{LHV}	4.79	-	-	-	-	-	-	-

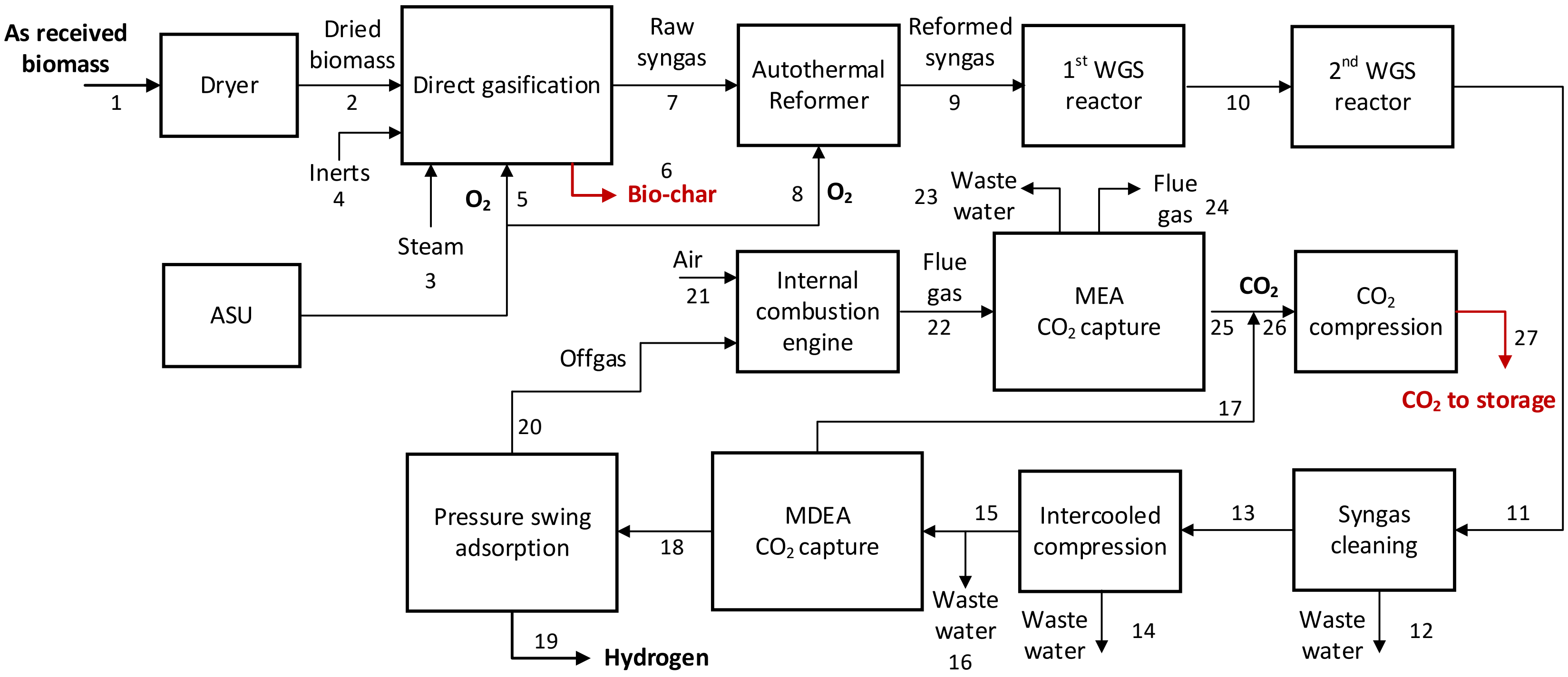

Figure A3 – Block diagram of the direct gasification-based Biomass-to-Hydrogen plant

Table A6 - Plant stream properties DG-based Biomass-to-Hydrogen plant

Stream #	**1**	**2**	**3**		**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
Stream description	As-received biomass	Dried biomass	Steam input[1]		Inerts	Oxygen to gasifier	Bio-char[2]	Raw syngas	Oxygen to reformer	Reformed syngas	Shifted syngas	Shifted syngas	Waste water	
Temperature, °C	25.0	80.0	200.00	200.00	25.00	108.42	870.00	870.00	108.42	915.00	378.71	257.45	91.28	30.00
Pressure, bar	1.0	1.0	5.90	5.90	4.50	4.50	4.00	3.80	4.50	3.60	3.30	3.00	2.95	2.75
Mass flow rate, kg/s	10.27	6.64	2.66	0.80	0.21	1.93	0.19	12.04	0.64	12.68	12.68	12.68	1.64	0.13
Mole flow rate, kmol/h	-	-	531	160	26	216	-	2058	71	2349	2349	2349	320	26
Composition, $\%_{mol}$														
H_2O	-	-	100	100	-	-		40.23	-	33.28	18.92	15.57	98.54	100
H_2	-	-	-	-	-	-		19.95	-	29.93	44.29	47.64	-	-
CO_2	-	-	-	-	-	-		17.22	-	15.82	30.17	33.53	1.45	-
CO	-	-	-	-	-	-		14.56	-	19.01	4.66	1.31	-	-
Methanol	-	-	-	-	-	-		-	-	-	-	-	-	-
CH_4	-	-	-	-	-	-		4.43	-	0.39	0.39	0.39	0.01	-
C_xH_y	-	-	-	-	-	-		1.99	-	-	-	-	-	-
O_2	-	-	-	-	20.48	95.00		-	95.00	-	-	-	-	-
Ar	-	-	-	-	-	3.00		0.32	3.00	0.37	0.37	0.37	-	-
N_2	-	-	-	-	79.52	2.00		1.28	2.00	1.18	1.18	1.18	-	-
Ethanol	-	-	-	-	-	-		-	-	-	-	-	-	-
DME	-	-	-	-	-	-		-	-	-	-	-	-	-
LHV, MJ/kg	9.74	16.37	-	-	-	-		7.19	-	6.66	6.35	6.28	-	-
Power, MW_{LHV}	100.0	108.76	-	-	-	-	-	86.58	-	84.39	80.54	79.64	-	-

[1] The first row corresponds to the fluidization steam. The second row includes steam for sealing and cleaning purposes.

[2] The stream contains 67.42%wt of carbon and 32.58%wt of ashes.

Table A7 - Plant stream properties DG-based Biomass-to-Hydrogen plan

Stream #	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Stream description	Syngas	Waste water	Syngas	Waste water	CO_2 from MDEA	Syngas	Hydroge n	Purge to ICE	Air to ICE	Flue gas from ICE	Waste water	Flue gas from MEA	CO_2 from MEA	CO_2 to compress ion	Compres sed CO_2
Temperature, °C	30.0	40.1	40.0	40.0	40.0	40.0	40.0	40.0	25.0	100.0	40.0	40.0	40.0	40.0	89.5
Pressure, bar	2.8	9.1	30.2	30.2	1.2	30.2	30.0	1.0	1.0	1.0	1.0	1.0	1.2	1.2	150.0
Mass flow rate, kg/s	10.91	0.10	10.81	0.02	9.09	1.70	0.56	1.13	5.41	6.54	0.68	4.94	0.92	10.01	10.01
Mole flow rate, kmol/h	2002	19	1983	5	744	1234	1007	227	675	831	137	619	75	819	819
Composition, $\%_{mol}$															
H_2O	1.19	99.99	0.23	100	-	-	-	-	1.00	16.47	100	-	-	-	-
H_2	55.90	-	56.44	-	-	90.66	100	49.24	-	-	-	-	-	-	-
CO_2	39.11	0.01	39.49	-	100	3.17	-	17.23	0.03	9.53	-	0.64	100	100	100
CO	1.53	-	1.55	-	-	2.49	-	13.52	-	-	-	-	-	-	-
Methanol	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CH_4	0.45	-	0.46	-	-	0.74	-	4.01	-	-	-	-	-	-	-
C_xH_y	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O_2	-	-	-	-	-	-	-	-	20.70	6.04	-	8.12	-	-	-
Ar	0.43	-	0.43	-	-	0.70	-	3.79	0.97	1.82	-	2.45	-	-	-
N_2	1.39	-	1.40	-	-	2.25	-	12.21	77.30	66.14	-	88.79	-	-	-
Ethanol	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DME	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LHV, MJ/kg	7.30	-	7.36	-	-	46.93	119.96	10.56	-	-	-	-	-	-	-
Power, MW_{LHV}	79.61	-	79.61	-	-	79.61	67.65	11.96	-	-	-	-	-	-	-

t

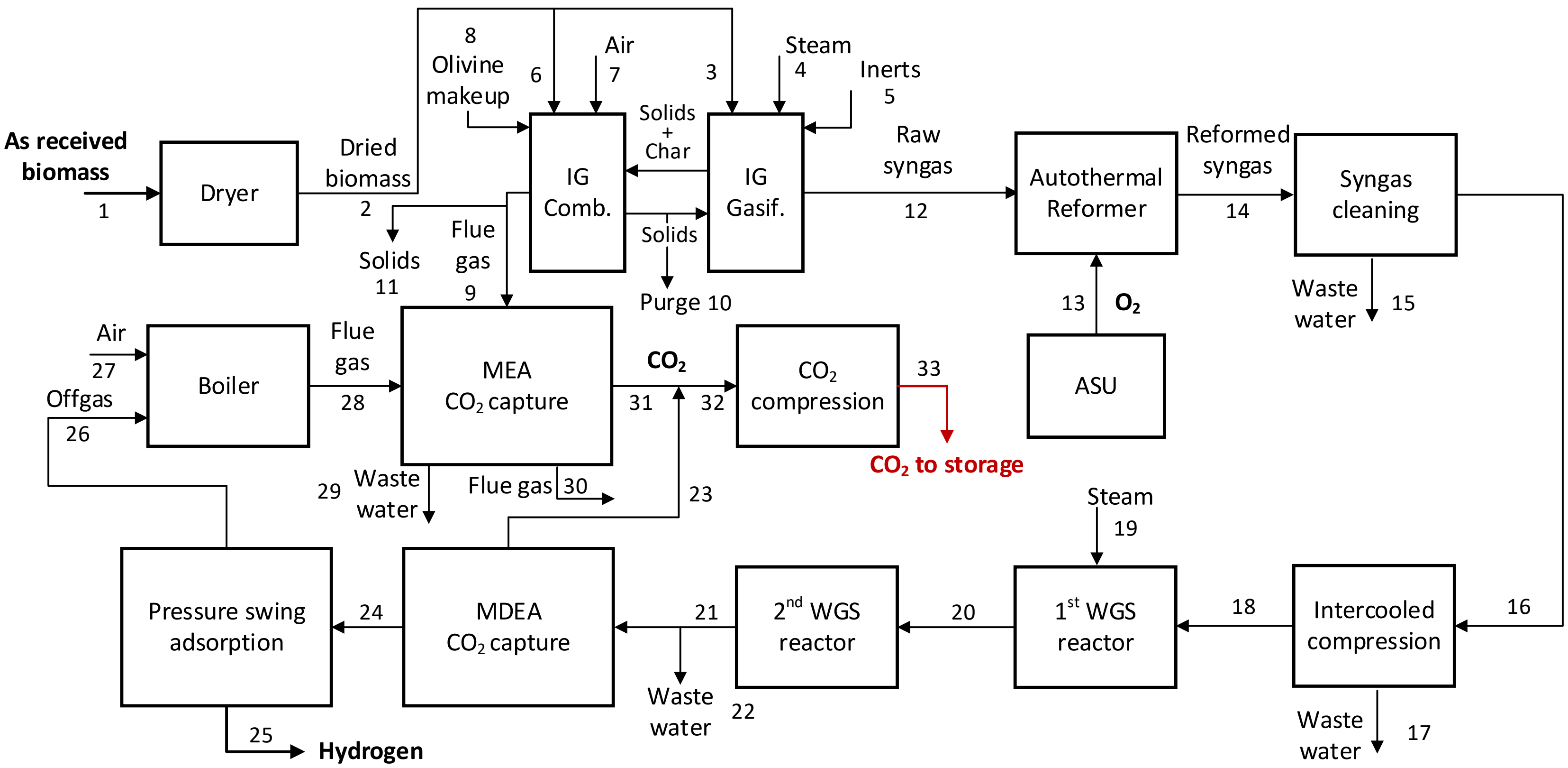

Figure A4 – Block diagram of the indirect gasification-based Biomass-to-Hydrogen plant

Table A8 - Plant stream properties IG-based Biomass-to-Hydrogen plan

Stream #	**1**	**2**	**3**	**4**		**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Stream description	As-received biomass	Dried biomass	Biomass to gasifier	Steam input[1]		Inerts	Biomass to combustor	Air to combustor	Olivine makeup[2]	Flue gas from combustor	Solid purge[2]	Solids[2]	Raw syngas	Oxygen to reformer	Reformed syngas
Temperature, °C	25.0	80.0	80.0	400.0	180.0	25.0	80.0	270.0	25.0	140.1	910.0	140.1	815.0	150.0	800.0
Pressure, bar	1.0	1.0	1.0	3.9	3.9	1.6	1.0	1.6	1.0	1.0	1.4	1.0	1.2	2.0	1.1
Mass flow rate, kg/s	10.27	6.64	5.71	2.62	0.69	0.18	0.93	11.64	0.28	12.98	0.06	0.28	8.72	0.50	9.21
Mole flow rate, kmol/h	-	-	0	523	138	22	-	1452	-	1560	-	-	1707	56	1978
Composition, $\%_{mol}$															
H_2O	-	-		100	100	-	-	1.00	-	8.21	-	-	36.25	-	27.05
H_2	-	-		-	-	-	-	-	-	-	-	-	27.99	-	40.57
CO_2	-	-		-	-	-	-	0.03	-	15.91	-	-	12.48	-	12.84
CO	-	-		-	-	-	-	-	-	-	-	-	14.47	-	17.90
Methanol	-	-		-	-	-	-	-	-	-	-	-	-	-	-
CH_4	-	-		-	-	-	-	-	-	-	-	-	6.07	-	0.52
C_xH_y	-	-		-	-	-	-	-	-	-	-	-	1.61	-	-
O_2	-	-		-	-	20.48	-	20.70	-	2.99	-	-	-	95.00	-
Ar	-	-		-	-	-	-	0.97	-	0.90	-	-	-	3.00	0.08
N_2	-	-		-	-	79.52	-	77.30	-	71.98	-	-	1.11	2.00	1.01
Ethanol	-	-		-	-	-	-	-	-	-	-	-	-	-	-
DME	-	-		-	-	-	-	-	-	-	-	-	-	-	-
LHV, MJ/kg	9.74	16.37	16.37	-	-	-	16.37	-	-	-	-	-	9.72	-	9.13
Power, MW_{LHV}	100.0	108.76	93.55	-	-	-	15.19	-	-	-	-	-	84.70	-	84.07

[1] The first row corresponds to the fluidization steam. The second row includes steam for sealing and cleaning purposes.

[2] Olivine makeup stream contains 50%wt olivine Fe-based and 50%wt olivine Mg-based. Solid purge stream contains 48.80%wt olivine Fe-based,48.80%wt olivine Mg-based, and 2.40%wt ashes. Solids stream contains 40.06%wt olivine Fe-based,40.06%wt olivine Mg-based, and 19.87%wt ashes.

Table A9 - Plant stream properties IG-based Biomass-to-Hydrogen plan

Stream #	**15**		**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Stream description	Waste water		Syngas	Waste water	Syngas	Steam input	Shifted syngas	Shifted syngas	Waste water	CO_2 from MDEA	Syngas	Hydrogen
Temperature, °C	74.1	30.0	30.0	40.1	334.0	250.0	418.2	238.6	40.0	40.0	40.0	40.0
Pressure, bar	1.1	1.1	1.1	3.3	33.0	33.0	32.8	31.4	30.2	1.2	30.2	30.0
Mass flow rate, kg/s	2.16	0.30	6.75	0.20	6.54	3.00	9.54	9.54	1.37	6.78	1.39	0.57
Mole flow rate, kmol/h	430	60	1487	41	1447	599	2046	2046	273	555	1218	1020
Composition, $\%_{mol}$												
H_2O	99.75	100	3.08	100	0.34	100	18.55	13.34	100	-	-	-
H_2	-	-	53.96	-	55.48	-	50.20	55.41	-	-	93.08	100
CO_2	0.23	-	17.01	-	17.50	-	23.34	28.55	-	100	2.40	-
CO	0.01	-	23.80	-	24.47	-	6.34	1.13	-	-	1.89	-
Methanol	-	-	-	-	-	-	-	-	-	-	-	-
CH_4	-	-	0.69	-	0.71	-	0.51	0.51	-	-	0.85	-
C_xH_y	-	-	-	-	-	-	-	-	-	-	-	-
O_2	-	-	-	-	-	-	-	-	-	-	-	-
Ar	-	-	0.11	-	0.12	-	0.08	0.08	-	-	0.14	-
N_2	-	-	1.35	-	1.38	-	0.98	0.98	-	-	1.64	-
Ethanol	-	-	-	-	-	-	-	-	-	-	-	-
DME	-	-	-	-	-	-	-	-	-	-	-	-
LHV, MJ/kg	-	-	12.46	-	12.85	-	8.54	8.41	-	-	57.68	119.96
Power, MW_{LHV}	-	-	84.04	-	84.04	-	81.48	80.26	-	-	80.26	68.53

Table A10 - Plant stream properties IG-based Biomass-to-Hydrogen plan

Stream #	26	27	28	29	30	31	32	33
Stream description	Purge to boiler	Air to boiler	Flue gas from boiler	Waste water	Flue gas from MEA	CO_2 from MEA	CO_2 to compression	Compressed CO_2
Temperature, °C	40.0	128.0	80.0	40.0	40.0	40.0	40.0	89.5
Pressure, bar	1.0	1.0	1.0	1.0	1.0	1.2	1.2	150.0
Mass flow rate, kg/s	0.82	3.79	4.61	1.33	12.65	3.61	10.39	10.39
Mole flow rate, kmol/h	198	473	602	267	1600	295	850	850
Composition, $\%_{mol}$								
H_2O	-	1.00	23.03	100	-	-	-	-
H_2	57.36	-	-	-	-	-	-	-
CO_2	14.78	0.03	10.41	-	0.97	100	100	100
CO	11.66	-	-	-	-	-	-	-
Methanol	-	-	-	-	-	-	-	-
CH_4	5.23	-	-	-	-	-	-	-
C_xH_y	-	-	-	-	-	-	-	-
O_2	-	20.70	1.50	-	3.48	-	-	-
Ar	0.84	0.97	1.04	-	1.27	-	-	-
N_2	10.14	77.30	64.02	-	94.27	-	-	-
Ethanol	-	-	-	-	-	-	-	-
DME	-	-	-	-	-	-	-	-
LHV, MJ/kg	14.30	-	-	-	-	-	-	-
Power, MW_{LHV}	11.73	-	-	-	-	-	-	-

Table A11 – Process modelling assumptions.

Assumptions	**BtM DG**	**BtM IG**	**BtH_2 DG**	**BtH_2 IG**
Input biomass (As received)				
LHV, MJ/kg_{AR}	9.74			
Moisture, $\%_{wt}$	45			
Proximate analysis, $\%_{wt,dry}$				
Fixed Carbon	18.84			
Volatile matter	80.0			
Ash	1.16			
Ultimate analysis, $\%_{wt,dry}$				
Carbon	51.19			
Hydrogen	6.08			
Nitrogen	0.2			
Chlorine	0.05			
Sulfur	0.02			
Oxygen	41.3			
Ash	1.16			
Biomass pre-treatment				
Biomass moisture at dryer outlet, $\%_{wt}$	15			
Biomass temperature at dryer outlet, °C	80			
Specific heat consumption, MWh/t_{H2O}	1.0			
Specific power consumption $kWh/t_{bio,dry}$	32			
Gasification				
Gasifier outlet temperature, °C	870	815	870	815
Gasifier and combustor pressure, bar	4.00	1.43	4.00	1.43
Char conversion in the gasifier, % of inlet C	95.50	83.00	95.50	83.00
Fluidizing steam input temperature, °C	200	400	200	400
Gas injection for sealing and filters, $kg/kg_{bio,dry}$	H_2O=0.12 Air = 0.03	H_2O=0.12 Air = 0.03	H_2O=0.12 Air = 0.03	H_2O=0.12 Air = 0.03

Combustor exit temperature, °C	-	910	-	910
Oxygen concentration in combustor flue gases, $\%_{mol}$	-	3.0	-	3.0
Combustor air temperature, °C	-	270	-	270
Overall pressure drop from combustor to stack, % of gas pressure at valve outlet	-	4.5	-	4.5
Total solid purge, % of inlet biomass	-	1.0	-	1.0
Combustor air fan isentropic/mech.-el efficiency, %	-	80/94	-	80/94
Gasifier/reformer oxygen compressor isentropic/mech.-el efficiency, %	80/94	-	80/94	-
Loss of solids from the BFB gasifier, % of the circulating solids	-	0.01	-	0.01
Combustor cyclone separation efficiency, %	-	Solids: 99.9; Ash:99	-	Solids: 99.9; Ash:99
Gasifier/combustor thermal losses, % of total thermal input	1.0	1.0/1.0	1.0	1.0/1.0
Syngas purification, conditioning and compression				
Reformer exit temperature, °C	915	800	915	800
CH_4 conversion in the reformer, %	90	90	90	90
S/C at reformer inlet	1.0	1.0	1.0	1.0
Oxygen purity, $\%_{mol}$	95	95	95	95
Oxygen temperature at ASU outlet, °C	15	15	15	15
Oxygen pressure at ASU outlet, bar	2.0	2.0	2.0	2.0
Oxygen preheating temperature, °C	- [1]	150	- [1]	150
Minimum syngas temperature upstream water scrubber, °C [2]	220	220	220	220
Scrubber pump hydraulic/mech.-el efficiency, %	75/90	75/90	75/90	75/90
Electric consumption of the desulfurization unit, $kWh/kg_{H2S,removed}$	1.35	1.35	1.35	1.35
Syngas compressor 1 stages	4	6	4	6
Syngas compressor 1 outlet pressure, bar	30.0	30.0	30.2	33.6
Syngas compressor 2 stages	2	2	-	-
Syngas compressor 2 outlet pressure, bar	92	92	-	-
Intercoolers outlet temperature, °C	40	40	40	40
Syngas compressors isentropic/mech.-el efficiency, %	72/92	72/92	72/92	72/92
1st WGS reactor inlet temperature, °C	220	-	220	300
1st WGS reactor pressure, bar	3.5	-	3.5	33.0

2^{nd} WGS reactor inlet temperature, °C	-	-	220	180
2^{nd} WGS reactor pressure, bar	-	-	3.2	31.6
CO_2 absorber pressure, bar	30	30	30	30
CO_2 separation efficiency, % of inlet CO_2	95	90	95	95
Methanol synthesis				
Reactor pressure, bar	90.0		-	
Tube length, m	6.0		-	
Tube diameter, mm	40.0		-	
Boiling water temperature, °C	238		-	
Catalyst density, kg/m^3	1712		-	
Catalyst diameter (cylinder), mm	6.0		-	
Catalyst height (cylinder), mm	3.5		-	
Bed voidage degree	0.39		-	
Flash unit temperature, °C	40		-	
GHSV in enhanced operation, h^{-1}	5000		-	
RR in enhanced operation, molar basis	5.0		-	
Syngas recycle compressor isentropic/mech.-el efficiency, %	80/94		-	
Methanol purification				
Stabilizing column pressure, bar	1.3	1.3	-	
Stabilizing column number of stages	20	20	-	
Concentration column pressure, bar	1.0	1.0	-	
Concentration column number of stages	40	40	-	
Final product methanol purity, $\%_{wt}$	99.85	99.85	-	
Hydrogen production				
Hydrogen separation efficiency, %	-		90	
Final product hydrogen purity, $\%_{vol}$	-		99.9	
Hydrogen pressure, bar	-		30	
CO_2 separation and compression				
MDEA regeneration thermal duty , MJ/kg$_{CO2,removed}$	1.0			
MEA regeneration thermal duty , MJ/kg$_{CO2,removed}$	3.7			

MDEA electric consumption, kWh/ $kg_{CO2,removed}$	0.012			
MEA electric consumption, kWh/ $kg_{CO2,removed}$	0.025			
CO_2 compressor stages	5			
CO_2 compressor outlet pressure, bar	80			
CO_2 compressors isentropic/mech.-el efficiency, %	80/92			
Intercoolers outlet temperature, °C	40			
Supercritical CO_2 pump hydraulic/mech.-el efficiency, %	75/90			
Supercritical CO_2 pump outlet pressure, bar	150			
Thermal integration				
ICE flue gas outlet temperature,°C	400	-	400	-
ICE flue gas temperature at the stack, °C	100	-	100	-
Boiler flue gas cooler exit temperature, °C	-	160	-	160
Boiler hot side air pre-heater exit temperature, °C	-	80	-	80

[1] The oxygen stream is not preheated, since it reaches 108°C after compression up to the gasification pressure.

[2] Minimum syngas temperature to avoid condensation of residual tars upstream their complete removal within the water scrubber.

Table A12 - Comparison of simulated syngas composition with literature data for direct and indirect gasification.

Syngas composition, $\%_{mol}$ dry, N_2, Ar free	Direct gasifier		Indirect gasifier	
	This work	Reference [1]	This work	Reference [2]
CH_4	7.6	7.5	9.7	9.1
C_xH_y	3.4	3.0	2.6	2.4
CO	25.0	25.4	23.1	25.3
CO_2	29.6	32.8	19.9	21.0
H_2	34.3	31.3	44.7	42.2

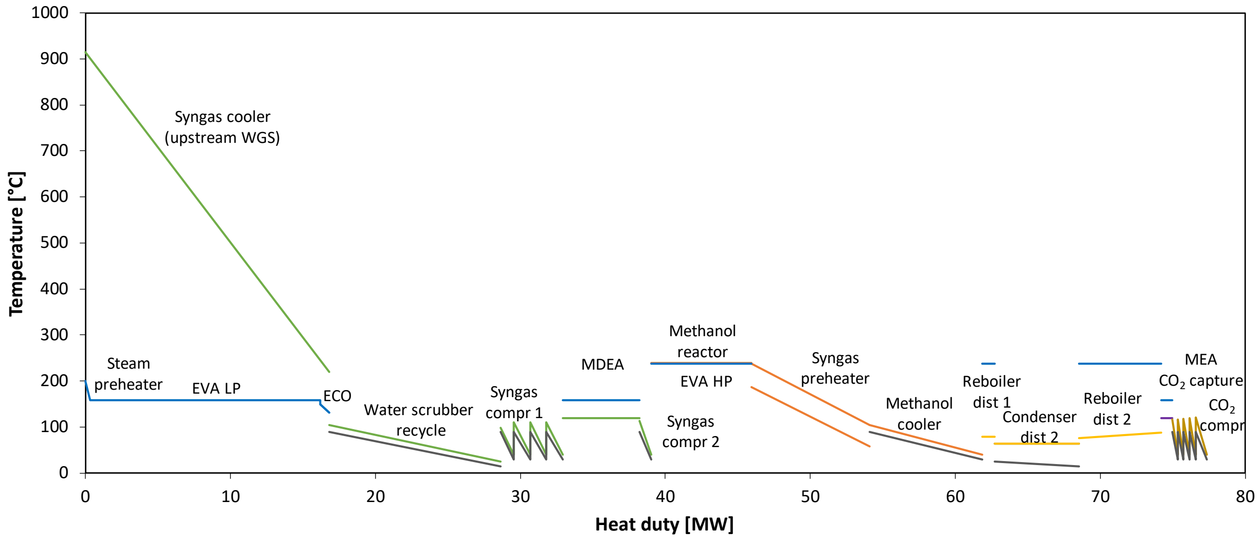

Figure A5 – TQ diagram of the BtM DG plant (recovering heat from ICE flue gas is not necessary).

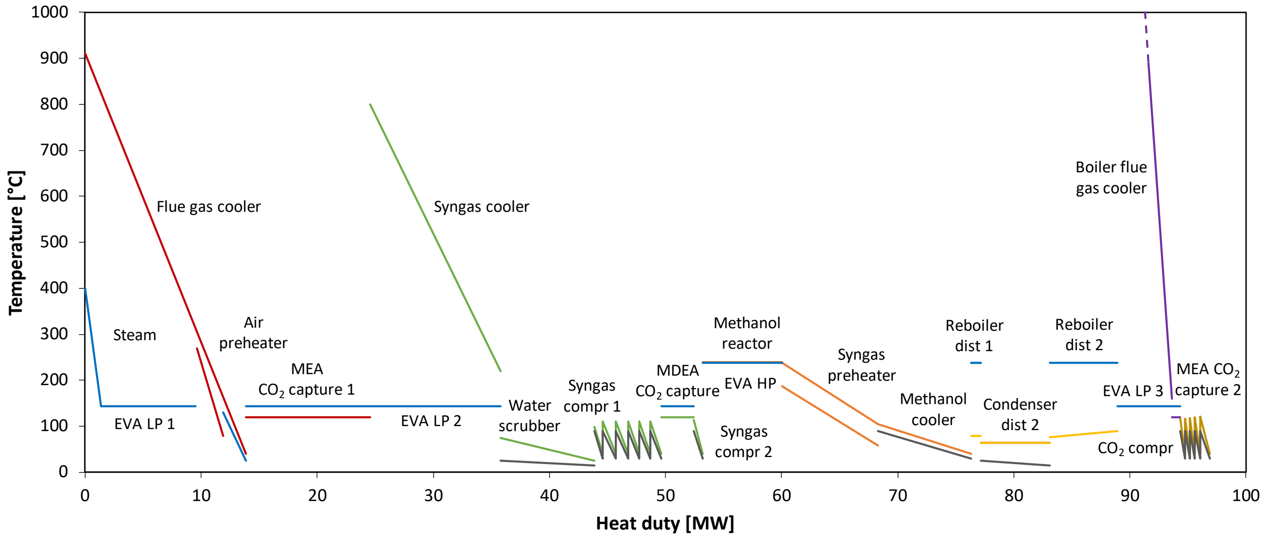

Figure A6 – TQ diagram of the BtM IG plant (flue gas from boiler available at 1880°C).

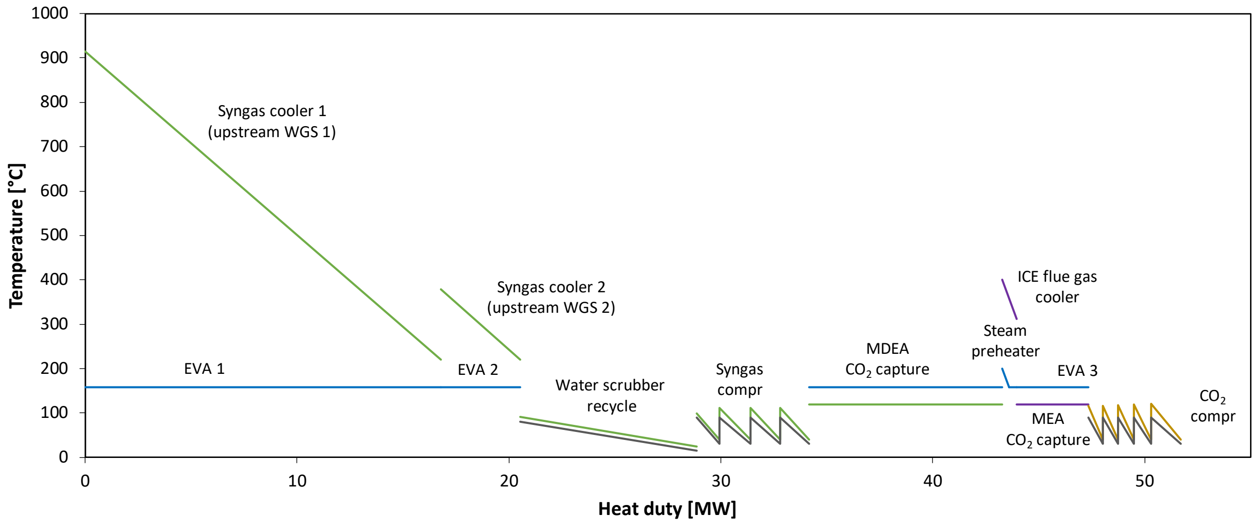

Figure A7 – TQ diagram of the BtH_2 DG plant.

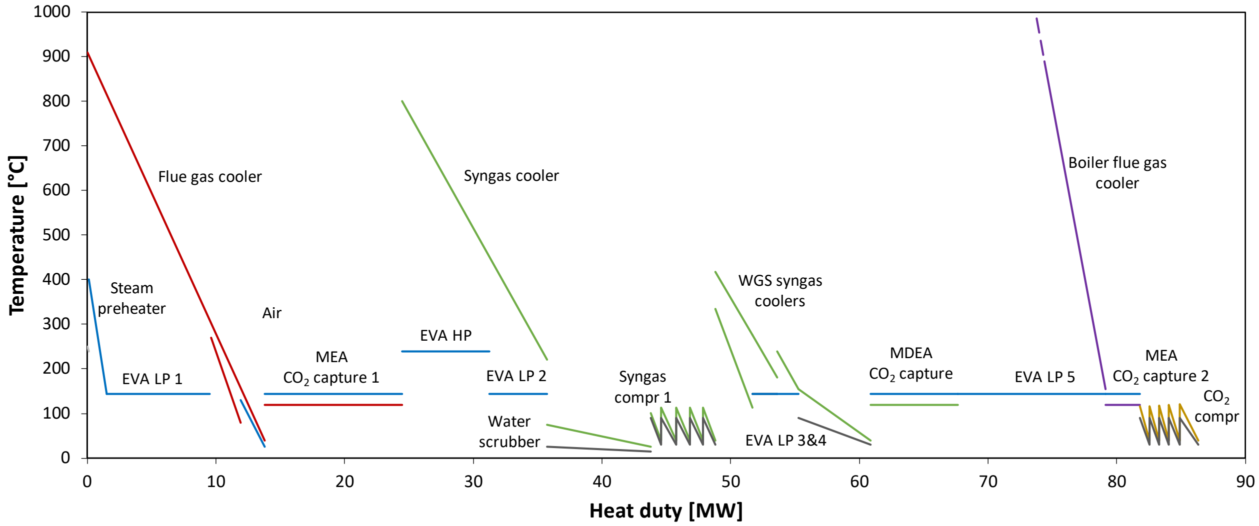

Figure A8 – TQ diagram of the BtH$_2$ IG plant. (flue gas from boiler available at 1933°C).

Appendix B

Part of the equipment cost estimate derives from in-house estimation in the framework of the FLEDGED project [3,4]. The purchase equipment delivered is increased to the fixed capital investment by using the Lang factors computed from Table B1. The remaining capital cost estimates are selected from scientific literature. The total direct cost of the equipment is obtained from the references, later the fixed capital investment is computed by means Lang factors derived from Table B1. The heat exchanger cost of the steam/water loops is computed by using the area as scaling parameter. The values of the global heat transfer coefficient (U) depending on the thermodynamic characteristics of the working fluids are reported in Table B9. The product of the area and the overall heat transfer coefficient (UA) is divided by U to compute the heat transfer area which is used in the economic evaluation.

Table B1 - Multiplying factors for estimating the total capital investment based on delivered-equipment cost.

	Percent of delivered-equipment cost for		
	Solid processing plant	***Solid-fluid processing plant***	***Fluid processing plant***
Direct costs			
Purchased equipment delivered	100	100	100
Purchased equipment installation	45	39	47
Instrumentation and controls (installed)	18	26	36
Piping (installed)	16	31	68
Electrical systems (installed)	10	10	11
Buildings (including services)	25	29	18
Yard improvements	15	12	10
Service facilities (installed)	40	55	70
Total direct plant cost	269	302	360
Indirect costs			
Engineering and supervision	33	32	33
Construction expenses	39	34	41
Legal expenses	4	4	4
Contractors fee	17	19	22
Contingency	35	37	44
Total indirect plant cost	128	126	144
Fixed capital investment	397	428	504
Working capital	70	75	89
Total capital investment	467	503	593

Table B2 – Parameters and assumptions for the evaluation of the LCOF.

Economic parameters	**Value**
Discount rate, %	10.0
Lifetime, y	20
Capital Charge Factor, %	11.75
Annual availability, h/year	7884
Variable Opex	
Biomass feedstock cost, €/t	45.72
2019 Denmark average electricity price, €/MWh	38.49
CO_2 transport and injection/storage costs, €/t	13.39
Fixed Opex	
Maintenance and repairs, % FCI	5
Operating supplies, % FCI	0.5
Operating labor, % Opex	10
Laboratory costs, % Opex	2.5
Local taxes, % FCI	1
Insurance, % FCI	1
Catalyst cost, €/kg	18.12
Catalyst lifetime, y	4

Table B3 – BtM DG plant capital costs detail.

Capital costs	Cost scaling parameter	Reference capacity	Scaling exponent	Reference purchase equipment delivered, M€	Plant capacity	Lang factor	Reference	Fixed capital investment, M€
Biomass-to-syngas island								***95.54***
Feedstock handling [1]	Feed, MWth	157	0.31	*6.94*	100	1.48	Hannula 2016 [5] (2010 €)	8.91
Belt dryer [1]	Water evap., kg/s	0.342	0.28	*2.49*	3.62	1.48	Hannula 2016 [5] (2010€)	7.11
ASU (O_2 at 1.05 bar) (air compr. included) [1]	Pure oxygen, t/d	1839.00	0.5	*47.96*	221.79	1.40	Kreutz 2005 [6] (2002 $)	23.32
Oxygen compressor (from 1.05 bar)	Compressor work, MWel	0.41	0.67	0.44	0.46	5.04	In-house estimate [3,4] (2019 €)	2.35
Pressurized O_2 CFB gasifier [1]	Dry biom., kg/s	17.80	0.75	*49.38*	5.65	1.42	Hannula 2016 [5] (2010€)	29.58
Ceramic hot-gas filter [1]	Syngas, kmol/s	1.47	0.67	*8.91*	0.57	1.48	Hannula 2016 [5] (2010 €)	6.99
Catalytic reformer [1]	Syngas, kmol/s	2.037	0.67	*28.55*	0.57	1.42	Hannula 2016 [5] (2010 €)	17.27
Cleaning and conditioning island								***50.71***
Scrubber	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.270	0.65	5.04	In-house estimate [3,4] (2019 €)	1.38
Liquid redox	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.565	0.65	5.04	In-house estimate [3,4] (2019 €)	2.90
Syngas compressor 1	Compressor work, MWel	7.01	0.67	7.501	4.49	5.04	In-house estimate [3,4] (2019 €)	14.56
Syngas compressor 2	Compressor work, MWel	7.01	0.67	7.501	1.66	5.04	In-house estimate [3,4] (2019 €)	7.49
Activated carbon	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.092	0.65	3.97	In-house estimate [3,4] (2019 €)	0.37
Waste water treatment	Waste water, m^3/h	22.56	0.67	0.453	12.45	5.04	In-house estimate [3,4] (2019 €)	1.53
WGS reactor	Syngas , kmol/s	0.263	0.67	1.60	0.18	4.28	In-house estimate [3,4] (2019 €)	5.30
CO_2 removal pre-combustion (MDEA) [1]	CO_2 captured, kg/h	46600	0.67	*16.69*	19168	1.40	IEAGHG 2017 [7] (2015 €)	12.89
CO_2 removal post-combustion (MEA) [1]	CO_2 captured, kg/h	80048	0.67	*72.17*	717	1.40	IEAGHG 2017 [7] (2015 €)	4.29

Syngas-to-methanol island								***10.99***
Methanol synthesis BWR	Syngas molar flow, kmol/s	2.20	0.67	1.72	2.0	4.28	In-house estimate [3,4] (2019 €)	6.97
Recycle compressor	Compressor work, MWel	0.41	0.67	0.44	0.385	5.04	In-house estimate [3,4] (2019 €)	2.10
Stabilizing column	Raw methanol, kmol/s	0.15	0.67	0.10	0.11	5.04	In-house estimate [3,4] (2019 €)	0.41
Concentration column	Raw methanol, kmol/s	0.14	0.67	0.36	0.11	5.04	In-house estimate [3,4] (2019 €)	1.52
Heat recovery island								***2.97***
CHP internal combustion engine [1]	Fuel input, kWth	13783	0.95	*2.480*	4861	1.40	Zatti 2018 [8] (2017 €)	1.29
ECO (WGS)	Area, m^2	10000	0.68	0.957	107	5.04	Elsido 2021 [9] (2019 €)	0.22
EVA (WGS)	Area, m^2	5000	0.79	1.164	839	5.04	Elsido 2021 [9] (2019 €)	1.44
SH (WGS)	Area, m^2	505	0.74	0.127	8	5.04	Elsido 2021 [9] (2019 €)	0.03
CO_2 compression island								***14.40***
CO_2 compression and dehydration unit [1]	Compressor work, MWel	3.005	0.67	*12.97*	2.1	1.40	IEAGHG 2017 [7] (2015 €)	14.40
Fixed capital investment								174.60
Working capital								30.75
Total capital investment								205.35

[1] The cost reported in the column “reference equipment delivered" is a direct cost which includes installation and BOP. The corresponding Lang factors have been modified accordingly.

Table B4 – BtM IG plant capital costs detail.

Capital costs	Cost scaling parameter	Reference capacity	Scaling exponent	Reference purchase equipment delivered, M€	Plant capacity	Lang factor	Reference	Fixed capital investment, M€
Biomass-to-syngas island								***92.22***
Feedstock handling [1]	Feed, MWth	157	0.31	*6.94*	100	1.48	Hannula 2016 [5] (2010 €)	8.91
Belt dryer [1]	Water evap., kg/s	0.342	0.28	*2.49*	3.62	1.48	Hannula 2016 [5] (2010 €)	7.11
ASU (O_2 at 1.05 bar (air compr. included) [1]	Pure oxygen, t/d	1839.00	0.5	*47.96*	42.86	1.40	Kreutz 2005 [6] (2002 $)	10.25
Oxygen compressor	Compressor work, MWel	0.41	0.67	0.44	0.04	5.04	In-house estimate [3,4] (2019 €)	0.43
Atm steam CFB gasifier [1]	Dry biom., kg/s	17.80	0.75	*24.75*	4.86	1.42	Hannula 2016 [5] (2010 €)	13.25
Combustor with fluegas treatment [1]	Fuel input, MWth	5.9	0.65	*7.727*	29.06	1.42	Hannula 2016 [5] (2010 €)	30.87
Ceramic hot-gas filter [1]	Syngas, kmol/s	1.47	0.67	*8.91*	0.47	1.48	Hannula 2016 [5] (2010 €)	6.17
Catalytic reformer [1]	Syngas, kmol/s	2.037	0.67	*28.55*	0.47	1.42	Hannula 2016 [5] (2010 €)	15.24
Cleaning and conditioning island								***65.39***
Scrubber	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.270	0.55	5.04	In-house estimate [3,4] (2019 €)	1.23
Liquid redox	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.565	0.55	5.04	In-house estimate [3,4] (2019 €)	2.58
Syngas compressor 1	Compressor work, MWel	7.01	0.67	7.501	5.77	5.04	In-house estimate [3,4] (2019 €)	17.23
Syngas compressor 2	Compressor work, MWel	7.01	0.67	7.501	1.66	5.04	In-house estimate [3,4] (2019 €)	7.48
Activated carbon	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.092	0.55	3.97	In-house estimate [3,4] (2019 €)	0.33
Waste water treatment	Waste water, m^3/h	22.56	0.67	0.453	10.14	5.04	In-house estimate [3,4] (2019 €)	1.34
CO_2 removal pre-combustion (MDEA) [1]	CO_2 captured, kg/s	46600	0.67	*16.69*	10027	1.40	IEAGHG 2017 [7] (2015 €)	8.35
CO_2 removal post-combustion (MEA) [1]	CO_2 captured, kg/s	80048	0.67	*72.17*	11073	1.40	IEAGHG 2017 [7] (2015 €)	26.85
Syngas-to-methanol island								***10.98***

Methanol synthesis BWR	Syngas molar flow, kmol/s	2.20	0.67	1.72	2.0	4.28	In-house estimate [3,4] (2019 €)	6.95
Recycle compressor	Compressor work, MWel	0.41	0.67	0.44	0.381	5.04	In-house estimate [3,4] (2019 €)	2.09
Stabilizing column	Raw methanol, kmol/s	0.15	0.67	0.10	0.11	5.04	In-house estimate [3,4] (2019 €)	0.41
Concentration column	Raw methanol, kmol/s	0.14	0.67	0.36	0.11	5.04	In-house estimate [3,4] (2019 €)	1.53
Heat recovery island								***2.52***
Boiler [1]	Fuel input, kWth	10000	0.92	*0.598*	4789	1.40	Zatti 2018 [8] (2017 €)	0.43
EVA 1 (syngas cooler)	Area, m^2	5000	0.79	1.164	682	5.04	Elsido 2021 [9] (2019 €)	1.22
EVA2 (flue gas cooler)	Area, m^2	5000	0.79	1.164	376	5.04	Elsido 2021 [9] (2019 €)	0.76
SH (GAS 1) (flue gas cooler)	Area, m^2	505	0.74	0.127	40	5.04	Elsido 2021 [9] (2019 €)	0.10
SH (GAS 2) (flue gas cooler)	Area, m^3	505	0.74	0.127	1	5.04	Elsido 2021 [9] (2019 €)	0.01
CO_2 compression island								***14.98***
CO_2 compression and dehydration unit [1]	Compressor work, MWel	3.005	0.67	*12.97*	2.3	1.40	IEAGHG 2017 [7] (2015 €)	14.98
Fixed capital investment								186.09
Working capital								32.77
Total capital investment								218.86

[1] The cost reported in the column “reference equipment delivered" is a direct cost which includes installation and BOP. The corresponding Lang factors have been modified accordingly.

Table B5 – BtH_2 DG plant capital costs detail.

Capital costs	Cost scaling parameter	Reference capacity	Scaling exponent	Reference purchase equipment delivered, M€	Plant capacity	Lang factor	Reference	Fixed capital investment, M€
Biomass-to-syngas island								***95.54***
Feedstock handling [1]	Feed, MWth	157	0.31	*6.94*	100	1.48	Hannula 2016 [5] (2010 €)	8.91
Belt dryer [1]	Water evap., kg/s	0.342	0.28	*2.49*	3.62	1.48	Hannula 2016 [5] (2010€)	7.11
ASU (O_2 at 1.05 bar) (air compr. included) [1]	Pure oxygen, t/d	1839.00	0.5	*47.96*	221.79	1.40	Kreutz 2005 [6] (2002 $)	23.32
Oxygen compressor (from 1.05 bar)	Compressor work, MWel	0.41	0.67	0.44	0.46	5.04	In-house estimate [3,4] (2019 €)	2.35
Pressurized O_2 CFB gasifier [1]	Dry biom., kg/s	17.80	0.75	*49.38*	5.65	1.42	Hannula 2016 [5] (2010€)	29.58
Ceramic hot-gas filter [1]	Syngas, kmol/s	1.47	0.67	*8.91*	0.57	1.48	Hannula 2016 [5] (2010 €)	6.99
Catalytic reformer [1]	Syngas, kmol/s	2.037	0.67	*28.55*	0.57	1.42	Hannula 2016 [5] (2010 €)	17.27
Cleaning and conditioning island								***84.40***
Scrubber	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.270	0.65	5.04	In-house estimate [3,4] (2019 €)	1.38
Liquid redox	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.565	0.65	5.04	In-house estimate [3,4] (2019 €)	2.90
Syngas compressor	Compressor work, MWel	7.01	0.67	7.501	5.58	5.04	In-house estimate [3,4] (2019 €)	16.84
Activated carbon	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.092	0.65	3.97	In-house estimate [3,4] (2019 €)	0.37
Waste water treatment	Waste water, m^3/h	22.56	0.67	0.453	6.79	5.04	In-house estimate [3,4] (2019 €)	1.02
WGS reactors [2]	Syngas , kmol/s	0.263	0.67	4.00	0.65	4.28	In-house estimate [3,4] (2019 €)	31.48
CO_2 removal pre-combustion (MDEA) [1]	CO_2 captured, kg/s	46600	0.67	*16.69*	32732	1.40	IEAGHG 2017 [7] (2015 €)	18.44
CO_2 removal post-combustion (MEA) [1]	CO_2 captured, kg/s	80048	0.67	*72.17*	3310	1.40	IEAGHG 2017 [7] (2015 €)	11.96
Syngas-to-hydrogen island								***3.63***
PSA [1]	Syngas, m^3/s	4.63	1.00	*39.49*	0.30	1.42	Riva 2018 (2017€) [10]	3.63

Heat recovery island								***5.55***
CHP internal combustion engine [1]	Fuel input, kWth	13783	0.95	*2.480*	11962	1.40	Zatti 2018 [8] (2017 €)	3.03
EVA 1 (WGS 1st reactor)	Area, m^2	5000	0.79	1.164	945	5.04	Elsido 2021 [9] (2019 €)	1.58
EVA2 (WGS 2nd reactor)	Area, m^2	5000	0.79	1.164	489	5.04	Elsido 2021 [9] (2019 €)	0.94
CO_2 compression island								***21.44***
CO_2 compression and dehydration unit [1]	Compressor work, MWel	3.005	0.67	*12.97*	3.9	1.40	IEAGHG 2017 [7] (2015 €)	21.44
Fixed capital investment								210.56
Working capital								37.07
Total capital investment								247.63

[1] The cost reported in the column "reference equipment delivered" is a direct cost which includes installation and BOP. The corresponding Lang factors have been modified accordingly.

[2] The cost of the reference purchase equipment delivered has been modified in such a way that the cost for single-stage system is 40% of the cost of the two-stage system as indicated in [11].

Table B6 – BtH_2 IG plant capital costs detail.

Capital costs	Cost scaling parameter	Reference capacity	Scaling exponent	Reference purchase equipment delivered, M€	Plant capacity	Lang factor	Reference	Fixed capital investment, M€
Biomass-to-syngas island								***92.22***
Feedstock handling [1]	Feed, MWth	157	0.31	*6.94*	100	1.48	Hannula 2016 [5] (2010 €)	8.91
Belt dryer [1]	Water evap., kg/s	0.342	0.28	*2.49*	3.62	1.48	Hannula 2016 [5] (2010 €)	7.11
ASU (O_2 at 1.05 bar (air compr. included) [1]	Pure oxygen, t/d	1839.00	0.5	*47.96*	42.86	1.40	Kreutz 2005 [6] (2002 $)	10.25
Oxygen compressor	Compressor work, MWel	0.41	0.67	0.44	0.04	5.04	In-house estimate [3,4] (2019 €)	0.43
Atm steam CFB gasifier [1]	Dry biom., kg/s	17.80	0.75	*24.75*	4.86	1.42	Hannula 2016 [5] (2010 €)	13.25
Combustor with fluegas treatment [1]	Fuel input, MWth	5.9	0.65	*7.727*	29.06	1.42	Hannula 2016 [5] (2010 €)	30.87
Ceramic hot-gas filter [1]	Syngas, kmol/s	1.47	0.67	*8.91*	0.47	1.48	Hannula 2016 [5] (2010 €)	6.17
Catalytic reformer [1]	Syngas, kmol/s	2.037	0.67	*28.55*	0.47	1.42	Hannula 2016 [5] (2010 €)	15.24
Cleaning and conditioning island								***97.24***
Scrubber	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.270	0.55	5.04	In-house estimate [3,4] (2019 €)	1.23
Liquid redox	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.565	0.55	5.04	In-house estimate [3,4] (2019 €)	2.58
Syngas compressor	Compressor work, MWel	7.01	0.67	7.501	5.98	5.04	In-house estimate [3,4] (2019 €)	17.65
Activated carbon	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.092	0.55	3.97	In-house estimate [3,4] (2019 €)	0.33
Waste water treatment	Waste water, m^3/h	22.56	0.67	0.453	14.51	5.04	In-house estimate [3,4] (2019 €)	1.70
WGS reactors [2]	Syngas , kmol/s	0.263	0.67	4.000	0.57	4.28	In-house estimate [3,4] (2019 €)	28.70
CO_2 removal pre-combustion (MDEA) [1]	CO_2 captured, kg/s	46600	0.67	*16.69*	24417.52	1.40	IEAGHG 2017 [7] (2015 €)	15.16
CO_2 removal post-combustion (MEA) [1]	CO_2 captured, kg/s	80048	0.67	*72.17*	12998.62	1.40	IEAGHG 2017 [7] (2015 €)	29.89
Syngas-to-hydrogen								***3.59***

island								
PSA [1]	Syngas, m^3/s	4.63	1.00	*39.49*	0.30	1.42	Riva 2018 (2017€) [10]	3.59
Heat recovery island								***3.72***
Boiler [1]	Fuel input, kWth	10000	0.92	*0.598*	11729.537	1.40	Zatti 2018 [8] (2017 €)	0.97
EVA 1 (syngas cooler)	Area, m^2	5000	0.79	1.164	440	5.04	Elsido 2021 [9] (2019 €)	0.86
EVA2 (flue gas cooler)	Area, m^2	5000	0.79	1.164	373	5.04	Elsido 2021 [9] (2019 €)	0.76
EVA 3 (WGS 1st-2nd reactor)	Area, m^2	5000	0.79	1.164	51	5.04	Elsido 2021 [9] (2019 €)	0.16
EVA 5 (WGS 2nd reactor)	Area, m^2	5000	0.79	1.164	83	5.04	Elsido 2021 [9] (2019 €)	0.23
EVA HP (syngas cooler)	Area, m^2	5000	0.79	1.164	290	5.04	Elsido 2021 [9] (2019 €)	0.62
SH (GAS 1) (flue gas cooler)	Area, m^2	505	0.74	0.127	40	5.04	Elsido 2021 [9] (2019 €)	0.10
SH (GAS 2) (flue gas cooler)	Area, m^2	505	0.74	0.127	1	5.04	Elsido 2021 [9] (2019 €)	0.01
SH (WGS) (flue gas cooler)	Area, m^3	505	0.74	0.127	3	5.04	Elsido 2021 [9] (2019 €)	0.01
CO_2 compression island								***21.99***
CO_2 compression and dehydration unit [1]	Compressor work, MWel	3.005	0.67	*12.97*	4.0	1.40	IEAGHG 2017 [7] (2015 €)	21.99
Fixed capital investment								218.77
Working capital								38.50
Total capital investment								257.27

[1] The cost reported in the column "reference equipment delivered" is a direct cost which includes installation and BOP. The corresponding Lang factors have been modified accordingly.

[2] The cost of the reference purchase equipment delivered has been modified in such a way that the cost for single-stage system is 40% of the cost of the two-stage system as indicated in [11].

Table B7 – BtMH$_2$ DG plant capital costs detail.

Capital costs	Cost scaling parameter	Reference capacity	Scaling exponent	Reference purchase equipment delivered, M€	Plant capacity	Lang factor	Reference	Fixed capital investment, M€
Biomass-to-syngas island								***95.54***
Feedstock handling [1]	Feed, MWth	157	0.31	*6.94*	100	1.48	Hannula 2016 [5] (2010 €)	8.91
Belt dryer [1]	Water evap., kg/s	0.342	0.28	*2.49*	3.62	1.48	Hannula 2016 [5] (2010€)	7.11
ASU (O_2 at 1.05 bar) (air compr. included) [1]	Pure oxygen, t/d	1839.00	0.5	*47.96*	221.79	1.40	Kreutz 2005 [6] (2002 $)	23.32
Oxygen compressor (from 1.05 bar)	Compressor work, MWel	0.41	0.67	0.44	0.46	5.04	In-house estimate [3,4] (2019 €)	2.35
Pressurized O_2 CFB gasifier [1]	Dry biom., kg/s	17.80	0.75	*49.38*	5.65	1.42	Hannula 2016 [5] (2010€)	29.58
Ceramic hot-gas filter [1]	Syngas, kmol/s	1.47	0.67	*8.91*	0.57	1.48	Hannula 2016 [5] (2010 €)	6.99
Catalytic reformer [1]	Syngas, kmol/s	2.037	0.67	*28.55*	0.57	1.42	Hannula 2016 [5] (2010 €)	17.27
Cleaning and conditioning island								***92.40***
Scrubber	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.270	0.65	5.04	In-house estimate [3,4] (2019 €)	1.38
Liquid redox	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.565	0.65	5.04	In-house estimate [3,4] (2019 €)	2.90
Syngas compressor 1	Compressor work, MWel	7.01	0.67	7.501	5.58	5.04	In-house estimate [3,4] (2019 €)	16.84
Syngas compressor 2	Compressor work, MWel	7.01	0.67	7.501	1.66	5.04	In-house estimate [3,4] (2019 €)	7.49
Activated carbon	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.092	0.65	3.97	In-house estimate [3,4] (2019 €)	0.37
Waste water treatment	Waste water, m^3/h	22.56	0.67	0.453	12.45	5.04	In-house estimate [3,4] (2019 €)	1.53
WGS reactors [2]	Syngas , kmol/s	0.263	0.67	4.00	0.65	4.28	In-house estimate [3,4] (2019 €)	31.48
CO_2 removal pre-combustion (MDEA) [1]	CO_2 captured, kg/s	46600	0.67	*16.69*	32732	1.40	IEAGHG 2017 [7] (2015 €)	18.44
CO_2 removal post-combustion (MEA) [1]	CO_2 captured, kg/s	80048	0.67	*72.17*	3310	1.40	IEAGHG 2017 [7] (2015 €)	11.96
Syngas-to-methanol & hydrogen island								***14.62***

Methanol synthesis BWR	Syngas molar flow, kmol/s	2.20	0.67	1.72	2.03	4.28	In-house estimate [3,4] (2019 €)	6.97
Recycle compressor	Compressor work, MWel	0.41	0.67	0.44	0.39	5.04	In-house estimate [3,4] (2019 €)	2.10
Stabilizing column	Raw methanol, kmol/s	0.15	0.67	0.10	0.11	5.04	In-house estimate [3,4] (2019 €)	0.41
Concentration column	Raw methanol, kmol/s	0.14	0.67	0.36	0.11	5.04	In-house estimate [3,4] (2019 €)	1.52
PSA [1]	Syngas, m^3/s	4.63	1.00	*39.49*	0.30	1.42	Riva 2018 (2017€) [10]	3.63
Heat recovery island								***5.77***
CHP internal combustion engine [1]	Fuel input, kWth	13783	0.95	*2.480*	11962	1.40	Zatti 2018 [8] (2017 €)	3.03
ECO (WGS)	Area, m^2	10000	0.68	0.957	107	5.04	Elsido 2021 [9] (2019 €)	0.22
EVA 1 (WGS 1st reactor)	Area, m^2	5000	0.79	1.164	945	5.04	Elsido 2021 [9] (2019 €)	1.58
EVA2 (WGS 2nd reactor)	Area, m^2	5000	0.79	1.164	489	5.04	Elsido 2021 [9] (2019 €)	0.94
CO_2 compression island								***21.44***
CO_2 compression and dehydration unit [1]	Compressor work, MWel	3.005	0.67	*12.97*	3.9	1.40	IEAGHG 2017 [7] (2015 €)	21.44
Fixed capital investment								229.77
Working capital								40.45
Total capital investment								270.22

[1] The cost reported in the column "reference equipment delivered" is a direct cost which includes installation and BOP. The corresponding Lang factors have been modified accordingly.

[2] The cost of the reference purchase equipment delivered has been modified in such a way that the cost for single-stage system is 40% of the cost of the two-stage system as indicated in [11].

Table B8 – $BtMH_2$ IG plant capital costs detail.

Capital costs	Cost scaling parameter	Reference capacity	Scaling exponent	Reference purchase equipment delivered, M€	Plant capacity	Lang factor	Reference	Fixed capital investment, M€
Biomass-to-syngas island								***92.22***
Feedstock handling [1]	Feed, MWth	157	0.31	*6.94*	100	1.48	Hannula 2016 [5] (2010 €)	8.91
Belt dryer [1]	Water evap., kg/s	0.342	0.28	*2.49*	3.62	1.48	Hannula 2016 [5] (2010 €)	7.11
ASU (O_2 at 1.05 bar (air compr. included) [1]	Pure oxygen, t/d	1839.00	0.5	*47.96*	42.86	1.40	Kreutz 2005 [6] (2002 $)	10.25
Oxygen compressor	Compressor work, MWel	0.41	0.67	0.44	0.04	5.04	In-house estimate [3,4] (2019 €)	0.43
Atm steam CFB gasifier [1]	Dry biom., kg/s	17.80	0.75	*24.75*	4.86	1.42	Hannula 2016 [5] (2010 €)	13.25
Combustor with fluegas treatment [1]	Fuel input, MWth	5.9	0.65	*7.727*	29.06	1.42	Hannula 2016 [5] (2010 €)	30.87
Ceramic hot-gas filter [1]	Syngas, kmol/s	1.47	0.67	*8.91*	0.47	1.48	Hannula 2016 [5] (2010 €)	6.17
Catalytic reformer [1]	Syngas, kmol/s	2.037	0.67	*28.55*	0.47	1.42	Hannula 2016 [5] (2010 €)	15.24
Cleaning and conditioning island								***104.72***
Scrubber	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.270	0.55	5.04	In-house estimate [3,4] (2019 €)	1.23
Liquid redox	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.565	0.55	5.04	In-house estimate [3,4] (2019 €)	2.58
Syngas compressor 1	Compressor work, MWel	7.01	0.67	7.501	5.98	5.04	In-house estimate [3,4] (2019 €)	17.65
Syngas compressor 2	Compressor work, MWel	7.01	0.67	7.501	1.66	5.04	In-house estimate [3,4] (2019 €)	7.48
Activated carbon	Syngas at cleaning inlet, kmol/s	0.64	0.67	0.092	0.55	3.97	In-house estimate [3,4] (2019 €)	0.33
Waste water treatment	Waste water, m^3/h	22.56	0.67	0.453	14.51	5.04	In-house estimate [3,4] (2019 €)	1.70
WGS reactors [2]	Syngas , kmol/s	0.263	0.67	4.000	0.57	4.28	In-house estimate [3,4] (2019 €)	28.70
CO_2 removal pre-combustion (MDEA) [1]	CO_2 captured, kg/s	46600	0.67	*16.69*	24417.52	1.40	IEAGHG 2017 [7] (2015 €)	15.16
CO_2 removal post-combustion (MEA) [1]	CO_2 captured, kg/s	80048	0.67	*72.17*	12998.62	1.40	IEAGHG 2017 [7] (2015 €)	29.89

Syngas-to-methanol & hydrogen island								***14.57***
Methanol synthesis BWR	Syngas molar flow, kmol/s	2.20	0.67	1.72	2.02	4.28	In-house estimate [3,4] (2019 €)	6.95
Recycle compressor	Compressor work, MWel	0.41	0.67	0.44	0.38	5.04	In-house estimate [3,4] (2019 €)	2.09
Stabilizing column	Raw methanol, kmol/s	0.15	0.67	0.10	0.11	5.04	In-house estimate [3,4] (2019 €)	0.41
Concentration column	Raw methanol, kmol/s	0.14	0.67	0.36	0.11	5.04	In-house estimate [3,4] (2019 €)	1.53
PSA [1]	Syngas, m^3/s	4.63	1.00	*39.49*	0.30	1.42	Riva 2018 (2017€) [10]	3.59
Heat recovery island								***4.09***
Boiler [1]	Fuel input, kWth	10000	0.92	*0.598*	11729.537	1.40	Zatti 2018 [8] (2017 €)	0.97
EVA 1 (syngas cooler)	Area, m^2	5000	0.79	1.164	682	5.04	Elsido 2021 [9] (2019 €)	1.22
EVA2 (flue gas cooler)	Area, m^2	5000	0.79	1.164	376	5.04	Elsido 2021 [9] (2019 €)	0.76
EVA 3 (WGS 1st-2nd reactor)	Area, m^2	5000	0.79	1.164	51	5.04	Elsido 2021 [9] (2019 €)	0.16
EVA 5 (WGS 2nd reactor)	Area, m^2	5000	0.79	1.164	83	5.04	Elsido 2021 [9] (2019 €)	0.23
EVA HP (syngas cooler)	Area, m^2	5000	0.79	1.164	290	5.04	Elsido 2021 [9] (2019 €)	0.62
SH (GAS 1) (flue gas cooler)	Area, m^2	505	0.74	0.127	40	5.04	Elsido 2021 [9] (2019 €)	0.10
SH (GAS 2) (flue gas cooler)	Area, m^2	505	0.74	0.127	1	5.04	Elsido 2021 [9] (2019 €)	0.01
SH (WGS) (flue gas cooler)	Area, m^3	505	0.74	0.127	3	5.04	Elsido 2021 [9] (2019 €)	0.01
CO_2 compression island								***21.99***
CO_2 compression and dehydration unit [1]	Compressor work, MWel	3.005	0.67	*12.97*	4.0	1.40	IEAGHG 2017 [7] (2015 €)	21.99
Fixed capital investment								237.59
Working capital								41.82
Total capital investment								279.40

[1] The cost reported in the column “reference equipment delivered" is a direct cost which includes installation and BOP. The corresponding Lang factors have been modified accordingly.

[2] The cost of the reference purchase equipment delivered has been modified in such a way that the cost for single-stage system is 40% of the cost of the two-stage system as indicated in [11].

Table B8 – Global heat transfer coefficients dependent on working fluid thermodynamic conditions.

U [W/m^2 K]	Fluids
60	Low pressure gas vs. water/steam
30	Low pressure gas vs. low pressure gas
400	High pressure gas vs. high pressure gas
500	High pressure gas vs. water/steam

References

1 J. Palonen, 2012.

2 H. Thunman, M. Seemann, T. Berdugo Vilches, J. Maric, D. Pallares, H. Ström, G. Berndes, P. Knutsson, A. Larsson, C. Breitholtz and O. Santos, *Energy Sci. Eng.*, 2018, **6**, 6–34.

3 A. Poluzzi, G. Guandalini, S. Guffanti, C. Elsido, S. Moioli, P. Huttenhuis, G. Rexwinkel, E. Martelli, G. Groppi and M. C. Romano, *Fuel*, 2022, **310**, 122113.

4 A. Poluzzi, G. Guandalini, S. Guffanti, M. Martinelli, S. Moioli, P. Huttenhuis, G. Rexwinkel, J. Palonen, E. Martelli, G. Groppi and M. C. Romano, *Front. Energy Res.*, , DOI:10.3389/fenrg.2021.795673.

5 I. Hannula, *Energy*, 2016, **104**, 199–212.

6 T. Kreutz, R. Williams, S. Consonni and P. Chiesa, *Int. J. Hydrogen Energy*, 2005, **30**, 769–784.

7 IEAGHG, *Tech. Rev. 2017-02*, 2017, 286.

8 M. Zatti, M. Gabba, M. Rossi, M. Morini, A. Gambarotta and E. Martelli, *Environ. Eng. Manag. J.*, 2018, **17**, 2409–2419.

9 C. Elsido, E. Martelli and I. E. Grossmann, *Comput. Chem. Eng.*, 2021, **149**, 107293.

10 L. Riva, I. Martínez, M. Martini, F. Gallucci, M. van Sint Annaland and M. C. Romano, *Int. J. Hydrogen Energy*, 2018, **43**, 15720–15738.

11 E. D. Larson, H. Jin and F. E. Celik, *Biofuels, Bioprod. Biorefining*, 2009, **3**, 174–194.