Energy and exergy analysis of Hydrogen-based fluidized bed direct reduction towards efficiently fossil-free ironmaking

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Table S1. Mass, heat, and exergy flows in F1 for case 1.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	25.000	7.170	-5913.69	83.560	0.000
	FeO	25.000	7.070	-1873.92	933.890	0.000
	CaO	25.000	0.030	-19.05	3.830	0.000
	SiO_2	25.000	0.280	-255.04	0.690	0.000
	MgO	25.000	0.110	-66.18	6.550	0.000
	Al_2O_3	25.000	0.110	-184.33	1.650	0.000
	$H_2(g)$	25.000	0.190	0.00	44.860	0.000
	$O_2(g)$	25.000	1.860	0.00	7.300	0.000
	$N_2(g)$	25.000	6.920	0.00	4.630	0.000
	$H_2O(g)$	400.000	3.650	-834.59	3.430	48.450
	$N_2(g)$	400.000	6.780	75.34	4.540	26.720
Out	Fe_2O_3	761.000	10.710	-7711.60	124.820	580.760
	FeO	761.000	0.000	0.00	0.000	0.000
	CaO	761.000	0.030	-17.96	3.830	0.550
	SiO_2	761.000	0.280	-241.67	0.690	6.950
	MgO	761.000	0.110	-62.36	6.550	1.940
	Al_2O_3	761.000	0.110	-175.25	1.650	4.680
	$H_2O(g)$	150.000	3.840	-912.75	3.610	35.570
	$N_2(g)$	150.000	13.700	49.97	9.180	8.250

Table S2. Mass, heat, and exergy flows in R^{1st} for case 1.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	761.000	10.710	-7711.60	124.820	580.76
	FeO	761.000	0.000	0.00	0.000	0
	CaO	761.000	0.030	-17.96	3.830	0.55
	SiO_2	761.000	0.280	-241.67	0.690	6.95
	MgO	761.000	0.110	-62.36	6.550	1.94
	Al_2O_3	761.000	0.110	-175.25	1.650	4.68
	$H_2(g)$	700.000	66.120	1308.20	15612.250	628.11
	$H_2O(g)$	700.000	20.340	-4412.33	19.100	421.5
Out	Fe	630.000	0.000	0.00	0.000	0
	FeO	630.000	21.410	-4967.04	2828.080	326.64
	CaO	630.000	0.030	-18.16	3.830	0.41
	SiO_2	630.000	0.280	-244.19	0.690	5.2
	MgO	630.000	0.110	-63.09	6.550	1.44
	Al_2O_3	630.000	0.110	-177.04	1.650	3.45
	$H_2(g)$	630.000	55.420	979.16	13085.770	446.44
	$H_2O(g)$	630.000	31.050	-6823.68	29.150	583.29

Table S3. Mass, heat, and exergy flows in R^{2nd} for case 1.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe	630.000	0.000	0.00	0.000	0
	FeO	630.000	21.410	-4967.04	2828.080	326.64
	CaO	630.000	0.030	-18.16	3.830	0.41
	SiO_2	630.000	0.280	-244.19	0.690	5.2
	MgO	630.000	0.110	-63.09	6.550	1.44
	Al_2O_3	630.000	0.110	-177.04	1.650	3.45
	H_2(g)	845.000	86.470	2095.13	20417.300	1096.01
Out	Fe	700.000	20.340	473.50	7613.260	241.49
	FeO	700.000	1.070	-243.84	141.340	19.32
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	H_2(g)	700.000	66.120	1308.20	15612.250	628.11
	H_2O(g)	700.000	20.340	-4412.33	19.100	421.5

Table S4. Mass, heat, and exergy flows in E for case 1.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	630.000	55.420	979.16	13085.770	446.44
	H_2O(g)	630.000	31.050	-6823.68	29.150	583.29
	H_2(g)	25.000	86.470	0.00	20417.300	0
Out	H_2(g)	150.000	55.420	199.56	13085.770	32.85
	H_2O(g)	150.000	31.050	-7380.48	29.150	287.59
	H_2(g)	556.000	86.470	1335.93	20417.300	570.81

Table S5. Mass, heat, and exergy flows in F2 for case 1.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	556.000	86.470	1335.93	20417.300	570.81
	H_2(g)	25.000	3.650	0.00	861.840	0
	O_2(g)	25.000	1.830	0.00	7.150	0
	N_2(g)	25.000	6.780	0.00	4.540	0
Out	H_2(g)	845.000	86.470	2095.13	20417.300	1096.01
	H_2O(g)	400.000	3.650	-834.59	3.430	48.45
	N_2(g)	400.000	6.780	75.33	4.540	26.71

Table S6. Mass, heat, and exergy flows in F1 for case 2.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	25.000	7.170	-5913.69	83.560	0.000
	FeO	25.000	7.070	-1873.92	933.890	0.000
	CaO	25.000	0.030	-19.05	3.830	0.000
	SiO_2	25.000	0.280	-255.04	0.690	0.000
	MgO	25.000	0.110	-66.18	6.550	0.000
	Al_2O_3	25.000	0.110	-184.33	1.650	0.000
	$H_2(g)$	25.000	1.160	0.00	273.900	0.000
	$O_2(g)$	25.000	2.350	0.00	9.200	0.000
	$N_2(g)$	25.000	8.720	0.00	5.840	0.000
	$H_2O(g)$	400.000	3.460	-793.54	3.250	71.660
	$N_2(g)$	400.000	6.430	71.46	4.310	25.340
Out	Fe_2O_3	900.000	10.710	-7501.76	124.820	733.830
	FeO	900.000	0.000	0.00	0.000	0.000
	CaO	900.000	0.030	-17.74	3.830	0.710
	SiO_2	900.000	0.280	-238.37	0.690	9.350
	MgO	900.000	0.110	-61.58	6.550	2.520
	Al_2O_3	900.000	0.110	-173.32	1.650	6.090
	$H_2O(g)$	150.000	4.620	-1098.16	4.340	42.790
	$N_2(g)$	150.000	15.150	55.27	10.150	9.120

Table S7. Mass, heat, and exergy flows in R^{1st} for case 2.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	900.000	10.710	-7501.76	124.820	733.83
	FeO	900.000	0.000	0.00	0.000	0
	CaO	900.000	0.030	-17.74	3.830	0.71
	SiO_2	900.000	0.280	-238.37	0.690	9.35
	MgO	900.000	0.110	-61.58	6.550	2.52
	Al_2O_3	900.000	0.110	-173.32	1.650	6.09
	H_2(g)	700.000	45.240	895.08	10682.070	429.76
	H_2O(g)	700.000	13.920	-3019.65	13.070	288.46
	H_2(g)	776	74.1	1637.96	17496.49	825.1
Out	Fe	700.000	6.420	149.45	2403.010	76.22
	FeO	700.000	14.990	-3416.00	1980.050	270.73
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	H_2(g)	700.000	102.210	2022.30	24134.530	970.98
	H_2O(g)	700.000	31.050	-6735.42	29.150	643.42

Table S8. Mass, heat, and exergy flows in R^{2nd} for case 2.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe	700.000	6.420	149.45	2403.010	76.22
	FeO	700.000	14.990	-3416.00	1980.050	270.73
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	H_2(g)	811.200	59.160	1371.71	13968.860	704.85
Out	Fe	700.000	20.340	473.50	7613.260	241.49
	FeO	700.000	1.070	-243.84	141.340	19.32
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	H_2(g)	700.000	45.240	895.08	10682.070	429.76
	H_2O(g)	700.000	13.920	-3019.65	13.070	288.46

Table S9. Mass, heat, and exergy flows in E for case 2.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	700.000	102.210	2022.24	24133.830	970.96
	H_2O(g)	700.000	31.050	-6735.63	29.150	643.44
	H_2(g)	25.000	133.260	0.00	31465.350	0
Out	H_2(g)	150.000	102.210	368.04	24133.830	60.58
	H_2O(g)	150.000	31.050	-7380.48	29.150	287.59
	H_2(g)	614.000	133.260	2290.29	31465.350	1030.7

Table S10. Mass, heat, and exergy flows in F2[1st] for case 2.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	614.000	74.100	1273.53	17496.490	573.13
	H_2(g)	25.000	1.750	0.00	413.210	0
	O_2(g)	25.000	0.880	0.00	3.430	0
	N_2(g)	25.000	3.250	0.00	2.180	0
Out	H_2(g)	776.000	74.100	1637.96	17496.490	825.1
	H_2O(g)	400.000	1.750	-400.14	1.640	23.23
	N_2(g)	400.000	3.250	36.12	2.180	12.81

Table S11. Mass, heat, and exergy flows in F2^{2nd} for case 2.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	614.000	59.160	1016.76	13968.860	457.57
	H_2(g)	25.000	1.710	0.00	403.770	0
	O_2(g)	25.000	0.860	0.00	3.350	0
	N_2(g)	25.000	3.180	0.00	2.130	0
Out	H_2(g)	811.200	59.160	1371.71	13968.860	704.85
	H_2O(g)	400.000	1.710	-391.00	1.610	22.7
	N_2(g)	400.000	3.180	35.29	2.130	12.51

Table S12. Mass, heat, and exergy flows in F1 for case 3.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	25.000	7.170	-5913.69	83.560	0.000
	FeO	25.000	7.070	-1873.92	933.890	0.000
	CaO	25.000	0.030	-19.05	3.830	0.000
	SiO_2	25.000	0.280	-255.04	0.690	0.000
	MgO	25.000	0.110	-66.18	6.550	0.000
	Al_2O_3	25.000	0.110	-184.33	1.650	0.000
	$H_2(g)$	25.000	1.150	0.00	271.540	0.000
	$O_2(g)$	25.000	2.340	0.00	9.180	0.000
	$N_2(g)$	25.000	8.700	0.00	5.830	0.000
	$H_2O(g)$	400.000	3.410	-779.71	3.200	45.260
	$N_2(g)$	400.000	6.330	70.34	4.240	24.940
Out	Fe_2O_3	900.000	10.710	-7501.76	124.820	733.830
	FeO	900.000	0.000	0.00	0.000	0.000
	CaO	900.000	0.030	-17.74	3.830	0.710
	SiO_2	900.000	0.280	-238.37	0.690	9.350
	MgO	900.000	0.110	-61.58	6.550	2.520
	Al_2O_3	900.000	0.110	-173.32	1.650	6.090
	$H_2O(g)$	150.000	4.560	-1083.90	4.280	42.240
	$N_2(g)$	150.000	15.030	54.83	10.070	9.050

Table S13. Mass, heat, and exergy flows in R for case 3.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	900.000	10.710	-7501.76	124.820	733.83
	FeO	900.000	0.000	0.00	0.000	0
	CaO	900.000	0.030	-17.74	3.830	0.71
	SiO_2	900.000	0.280	-238.37	0.690	9.35
	MgO	900.000	0.110	-61.58	6.550	2.52
	Al_2O_3	900.000	0.110	-173.32	1.650	6.09
	H_2(g)	792.1	132.6	2996.62	31309.51	1523.54
Out	Fe	700.000	20.340	473.50	7613.260	241.49
	FeO	700.000	1.070	-243.84	141.340	19.32
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	H_2(g)	700.000	101.550	2009.21	23978.250	964.7
	H_2O(g)	700.000	31.050	-6735.39	29.150	643.42

Table S14. Mass, heat, and exergy flows in E for case 3.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	700.000	102.210	2009.18	23977.990	964.69
	H_2O(g)	700.000	31.050	-6735.63	29.150	643.44
	H_2(g)	25.000	133.260	0.00	31309.510	0
Out	H_2(g)	150.000	101.550	365.66	23977.990	60.19
	H_2O(g)	150.000	31.050	-7380.48	29.150	287.59
	H_2(g)	616.300	132.600	2288.11	31309.510	1031.69

Table S15. Mass, heat, and exergy flows in F2 for case 3.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	616.300	132.600	2288.11	31309.510	1031.69
	H_2(g)	25.000	3.410	0.00	805.170	0
	O_2(g)	25.000	1.710	0.00	6.680	0
	N_2(g)	25.000	6.330	0.00	4.240	0
Out	H_2(g)	792.100	132.600	2996.62	31309.510	1523.54
	H_2O(g)	400.000	3.410	-779.71	3.200	45.26
	N_2(g)	400.000	6.330	70.38	4.240	24.95

Table S16. Mass, heat, and exergy flows in F1 for η=1.0.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
	Fe_2O_3	25.000	7.170	-5913.69	83.560	0.000
	FeO	25.000	7.070	-1873.92	933.890	0.000
	CaO	25.000	0.030	-19.05	3.830	0.000
	SiO_2	25.000	0.280	-255.04	0.690	0.000
	MgO	25.000	0.110	-66.18	6.550	0.000
In	Al_2O_3	25.000	0.110	-184.33	1.650	0.000
	$H_2(g)$	25.000	1.650	0.00	389.600	0.000
	$O_2(g)$	25.000	2.590	0.00	10.160	0.000
	$N_2(g)$	25.000	9.630	0.00	6.450	0.000
	$H_2O(g)$	400.000	1.880	-429.87	1.770	24.950
	$N_2(g)$	400.000	3.490	38.78	2.340	13.750
	Fe_2O_3	951.500	10.710	-7423.91	124.820	792.320
	FeO	951.500	0.000	0.00	0.000	0.000
	CaO	951.500	0.030	-17.66	3.830	0.770
Out	SiO_2	951.500	0.280	-237.34	0.690	10.130
	MgO	951.500	0.110	-61.28	6.550	2.740
	Al_2O_3	951.500	0.110	-172.59	1.650	6.640
	$H_2O(g)$	150.000	3.530	-839.07	3.310	32.700
	$N_2(g)$	150.000	13.120	47.86	8.790	7.900

Table S17. Mass, heat, and exergy flows in R^{1st} for η=1.0.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	951.500	10.710	-7423.91	124.820	792.32
	FeO	951.500	0.000	0.00	0.000	0
	CaO	951.500	0.030	-17.66	3.830	0.77
	SiO_2	951.500	0.280	-237.34	0.690	10.13
	MgO	951.500	0.110	-61.28	6.550	2.74
	Al_2O_3	951.500	0.110	-172.59	1.650	6.64
	$H_2(g)$	700.000	46.170	913.50	10901.840	438.6
	$H_2O(g)$	700.000	20.340	-4412.84	19.100	421.55
Out	Fe	700.000	0.000	0.00	0.000	0
	FeO	700.000	21.410	-4879.03	2828.080	386.67
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	$H_2(g)$	700.000	35.460	701.67	8373.820	336.9
	$H_2O(g)$	700.000	31.050	-6735.39	29.150	643.42

Table S18. Mass, heat, and exergy flows in R^{2nd} for η=1.0.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe	700.000	0.000	0.00	0.000	0
	FeO	700.000	21.410	-4879.03	2828.080	386.67
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	H_2(g)	844.200	66.510	1609.94	15705.080	841.85
Out	Fe	700.000	20.340	473.50	7613.260	241.49
	FeO	700.000	1.070	-243.84	141.340	19.32
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	H_2(g)	700.000	46.170	913.48	10901.660	438.6
	H_2O(g)	700.000	20.340	-4412.33	19.100	421.5

Table S19. Mass, heat, and exergy flows in E for η=1.0.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	700.000	35.460	701.58	8372.820	336.86
	H_2O(g)	700.000	31.050	-6735.63	29.150	643.44
	H_2(g)	25.000	66.510	0.00	15705.080	0
Out	H_2(g)	150.000	35.460	127.68	8372.820	21.02
	H_2O(g)	150.000	31.050	-7380.48	29.150	287.59
	H_2(g)	651.500	66.510	1218.27	15705.080	564.85

Table S20. Mass, heat, and exergy flows in F2 for η=1.0.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	651.500	66.510	1218.22	15704.340	564.83
	H_2(g)	25.000	1.880	0.00	443.910	0
	O_2(g)	25.000	0.940	0.00	3.680	0
	N_2(g)	25.000	3.490	0.00	2.340	0
Out	H_2(g)	844.200	66.510	1609.87	15704.340	841.81
	H_2O(g)	400.000	1.880	-429.87	1.770	24.95
	N_2(g)	400.000	3.490	38.80	2.340	13.76

Table S21. Mass, heat, and exergy flows in F1 for η=1.5.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	25.000	7.170	-5913.69	83.560	0.000
	FeO	25.000	7.070	-1873.92	933.890	0.000
	CaO	25.000	0.030	-19.05	3.830	0.000
	SiO_2	25.000	0.280	-255.04	0.690	0.000
	MgO	25.000	0.110	-66.18	6.550	0.000
	Al_2O_3	25.000	0.110	-184.33	1.650	0.000
	O_2(g)	25.000	10.100	0.00	39.590	0.000
	N_2(g)	25.000	37.510	0.00	25.130	0.000
	H_2O(g)	400.000	4.690	-1075.64	4.400	97.140
	N_2(g)	400.000	8.930	99.24	5.980	35.190
Out	Fe_2O_3	663.500	10.710	-7873.37	124.820	468.080
	FeO	663.500	0.000	0.00	0.000	0.000
	CaO	663.500	0.030	-18.11	3.830	0.450
	SiO_2	663.500	0.280	-243.55	0.690	5.640
	MgO	663.500	0.110	-62.91	6.550	1.560
	Al_2O_3	663.500	0.110	-176.59	1.650	3.750
	H_2O(g)	150.000	4.690	-1114.80	4.400	43.440
	O_2(g)	150.000	8.330	31.04	32.670	5.140
	N_2(g)	150.000	46.440	169.46	31.120	27.960

Table S22. Mass, heat, and exergy flows in R^{1st} for η=1.5.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	663.500	10.710	-7873.37	124.820	468.08
	FeO	663.500	0.000	0.00	0.000	0
	CaO	663.500	0.030	-18.11	3.830	0.45
	SiO_2	663.500	0.280	-243.55	0.690	5.64
	MgO	663.500	0.110	-62.91	6.550	1.56
	Al_2O_3	663.500	0.110	-176.59	1.650	3.75
	$H_2(g)$	700.000	79.430	1571.48	18754.380	754.53
	$H_2O(g)$	700.000	20.340	-4412.84	19.100	421.55
Out	Fe	600.000	0.000	0.00	0.000	0
	FeO	600.000	21.410	-5004.41	2828.080	301.82
	CaO	600.000	0.030	-18.20	3.830	0.38
	SiO_2	600.000	0.280	-244.76	0.690	4.83
	MgO	600.000	0.110	-63.26	6.550	1.33
	Al_2O_3	600.000	0.110	-177.45	1.650	3.18
	$H_2(g)$	600.000	68.720	1152.19	16226.350	512.42
	$H_2O(g)$	600.000	31.050	-6860.58	29.150	558.55

Table S23. Mass, heat, and exergy flows in R^{2nd} for η=1.5.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe	600.000	0.000	0.00	0.000	0
	FeO	600.000	21.410	-5004.41	2828.080	301.82
	CaO	600.000	0.030	-18.20	3.830	0.38
	SiO_2	600.000	0.280	-244.76	0.690	4.83
	MgO	600.000	0.110	-63.26	6.550	1.33
	Al_2O_3	600.000	0.110	-177.45	1.650	3.18
	H_2(g)	838.500	99.770	2397.33	23557.620	1249.9
Out	Fe	700.000	20.340	473.50	7613.260	241.49
	FeO	700.000	1.070	-243.84	141.340	19.32
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	H_2(g)	700.000	79.430	1571.54	18755.010	754.55
	H_2O(g)	700.000	20.340	-4412.33	19.100	421.5

Table S24. Mass, heat, and exergy flows in E for η=1.5.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	600.000	68.720	1152.17	16226.170	512.41
	H_2O(g)	600.000	31.050	-6860.83	29.150	558.57
	H_2(g)	25.000	99.770	0.00	23557.620	0
Out	H_2(g)	150.000	68.720	247.45	16226.170	40.73
	H_2O(g)	150.000	31.050	-7380.48	29.150	287.59
	H_2(g)	516.500	99.770	1424.09	23557.620	584.51

Table S25. Mass, heat, and exergy flows in F2 for η=1.5.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	516.500	99.770	1424.10	23557.690	584.51
	H_2(g)	25.000	4.690	0.00	1107.400	0
	O_2(g)	25.000	2.350	0.00	9.190	0
	N_2(g)	25.000	8.930	0.00	5.990	0
Out	H_2(g)	838.500	99.770	2397.34	23557.690	1249.9
	H_2O(g)	400.000	4.690	-1072.39	4.400	62.25
	N_2(g)	400.000	8.930	99.27	5.990	35.2

Table S26. Mass, heat, and exergy flows in F1 for η=1.8.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	25.000	7.170	-5913.69	83.560	0.000
	FeO	25.000	7.070	-1873.92	933.890	0.000
	CaO	25.000	0.030	-19.05	3.830	0.000
	SiO_2	25.000	0.280	-255.04	0.690	0.000
	MgO	25.000	0.110	-66.18	6.550	0.000
	Al_2O_3	25.000	0.110	-184.33	1.650	0.000
	$H_2(g)$	25.000	0.000	0.00	0.000	0.000
	$O_2(g)$	25.000	24.000	0.00	94.080	0.000
	$N_2(g)$	25.000	89.140	0.00	59.730	0.000
	$H_2O(g)$	400.000	6.120	-1403.61	5.750	126.760
Out	Fe_2O_3	548.500	10.710	-8078.77	124.820	332.360
	FeO	548.500	0.000	0.00	0.000	0.000
	CaO	548.500	0.030	-18.28	3.830	0.330
	SiO_2	548.500	0.280	-245.99	0.690	4.030
	MgO	548.500	0.110	-63.54	6.550	1.150
	Al_2O_3	548.500	0.110	-178.14	1.650	2.730
	$H_2O(g)$	150.000	6.120	-1454.70	5.750	56.680
	$O_2(g)$	150.000	22.230	82.81	87.150	13.720
	$N_2(g)$	150.000	100.510	366.74	67.340	60.510

Table S27. Mass, heat, and exergy flows in R^{1st} for η=1.8.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	548.500	10.710	-8078.77	124.820	332.36
	FeO	548.500	0.000	0.00	0.000	0
	CaO	548.500	0.030	-18.28	3.830	0.33
	SiO_2	548.500	0.280	-245.99	0.690	4.03
	MgO	548.500	0.110	-63.54	6.550	1.15
	Al_2O_3	548.500	0.110	-178.14	1.650	2.73
	$H_2(g)$	700.000	99.380	1966.28	23465.900	944.08
	$H_2O(g)$	700.000	20.340	-4417.97	19.100	578.29
Out	Fe	570.000	0.000	0.00	0.000	0
	FeO	570.000	21.410	-5041.61	2828.080	277.55
	CaO	570.000	0.030	-18.25	3.830	0.35
	SiO_2	570.000	0.280	-245.54	0.690	4.32
	MgO	570.000	0.110	-63.42	6.550	1.22
	Al_2O_3	570.000	0.110	-177.85	1.650	2.91
	$H_2(g)$	570.000	88.670	1407.07	20937.880	609.22
	$H_2O(g)$	570.000	31.050	-6897.37	29.150	534.51

Table S28. Mass, heat, and exergy flows in R^{2nd} for η=1.8.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe	570.000	0.000	0.00	0.000	0
	FeO	570.000	21.410	-5041.61	2828.080	277.55
	CaO	570.000	0.030	-18.25	3.830	0.35
	SiO_2	570.000	0.280	-245.54	0.690	4.32
	MgO	570.000	0.110	-63.42	6.550	1.22
	Al_2O_3	570.000	0.110	-177.85	1.650	2.91
	H_2(g)	826.000	119.720	2830.59	28269.140	1466.13
Out	Fe	700.000	20.340	473.50	7613.260	241.49
	FeO	700.000	1.070	-243.84	141.340	19.32
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	H_2(g)	700.000	99.380	1966.25	23465.610	944.07
	H_2O(g)	700.000	20.340	-4412.33	19.100	421.5

Table S29. Mass, heat, and exergy flows in E for η=1.8.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	570.000	88.670	1407.00	20936.760	609.19
	H_2O(g)	570.000	31.050	-6909.12	29.150	771.49
	H_2(g)	25.000	119.720	0.00	28269.140	0
Out	H_2(g)	150.000	88.670	319.28	20936.760	52.56
	H_2O(g)	150.000	31.050	-7380.48	29.150	287.59
	H_2(g)	474.000	119.720	1558.19	28269.140	609.19

Table S30. Mass, heat, and exergy flows in F2 for η=1.8.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	474.000	119.720	1558.15	28268.290	609.17
	H_2(g)	25.000	6.120	0.00	1445.050	0
	O_2(g)	25.000	3.060	0.00	12.000	0
	N_2(g)	25.000	11.370	0.00	7.620	0
Out	H_2(g)	826.000	119.720	2830.51	28268.290	1466.09
	H_2O(g)	400.000	6.120	-1399.36	5.750	81.23
	N_2(g)	400.000	11.370	126.30	7.620	44.78

Table S31. Mass, heat, and exergy flows in F1 for η=2.1.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	25.000	7.170	-5913.69	83.560	0.000
	FeO	25.000	7.070	-1873.92	933.890	0.000
	CaO	25.000	0.030	-19.05	3.830	0.000
	SiO_2	25.000	0.280	-255.04	0.690	0.000
	MgO	25.000	0.110	-66.18	6.550	0.000
	Al_2O_3	25.000	0.110	-184.33	1.650	0.000
	$H_2(g)$	25.000	1.020	0.00	240.840	0.000
	$O_2(g)$	25.000	2.280	0.00	8.930	0.000
	$N_2(g)$	25.000	8.460	0.00	5.670	0.000
	$H_2O(g)$	400.000	4.860	-1114.63	4.560	100.660
	$N_2(g)$	400.000	9.030	100.35	6.050	35.580
Out	Fe_2O_3	900.000	10.710	-7501.76	124.820	733.830
	FeO	900.000	0.000	0.00	0.000	0.000
	CaO	900.000	0.030	-17.74	3.830	0.710
	SiO_2	900.000	0.280	-238.37	0.690	9.350
	MgO	900.000	0.110	-61.58	6.550	2.520
	Al_2O_3	900.000	0.110	-173.32	1.650	6.090
	$H_2O(g)$	150.000	5.880	-1397.66	5.520	54.460
	$N_2(g)$	150.000	17.490	63.80	11.720	10.530

Table S32. Mass, heat, and exergy flows in R for η=2.1.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	900.000	10.710	-7501.76	124.820	733.83
	FeO	900.000	0.000	0.00	0.000	0
	CaO	900.000	0.030	-17.74	3.830	0.71
	SiO_2	900.000	0.280	-238.37	0.690	9.35
	MgO	900.000	0.110	-61.58	6.550	2.52
	Al_2O_3	900.000	0.110	-173.32	1.650	6.09
	H_2(g)	757.2	214.2	4611.5	50576.9	2297.14
Out	Fe	700.000	20.340	473.50	7613.260	241.49
	FeO	700.000	1.070	-243.84	141.340	19.32
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	H_2(g)	700.000	183.150	3623.68	43245.640	1739.87
	H_2O(g)	700.000	31.050	-6735.39	29.150	643.42

Table S33. Mass, heat, and exergy flows in E for η=2.1.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	700.000	183.150	3623.65	43245.380	1739.86
	H_2O(g)	700.000	31.050	-6743.45	29.150	882.69
	H_2(g)	25.000	214.200	0.00	50576.900	0
Out	H_2(g)	150.000	183.150	659.49	43245.380	108.55
	H_2O(g)	150.000	31.050	-7380.48	29.150	287.59
	H_2(g)	601.500	214.200	3600.96	50576.900	1603.54

Table S34. Mass, heat, and exergy flows in F2 for η=2.1.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	601.500	214.200	3600.96	50576.900	1603.54
	H_2(g)	25.000	4.860	0.00	1147.540	0
	O_2(g)	25.000	2.430	0.00	9.530	0
	N_2(g)	25.000	9.030	0.00	6.050	0
Out	H_2(g)	757.200	214.200	4611.50	50576.900	2297.14
	H_2O(g)	400.000	4.860	-1111.26	4.560	64.51
	N_2(g)	400.000	9.030	100.30	6.050	35.56

Table S35. Mass, heat, and exergy flows in F1 for η=2.5.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	25.000	7.170	-5913.69	83.560	0.000
	FeO	25.000	7.070	-1873.92	933.890	0.000
	CaO	25.000	0.030	-19.05	3.830	0.000
	SiO_2	25.000	0.280	-255.04	0.690	0.000
	MgO	25.000	0.110	-66.18	6.550	0.000
	Al_2O_3	25.000	0.110	-184.33	1.650	0.000
	$H_2(g)$	25.000	0.950	0.00	224.310	0.000
	$O_2(g)$	25.000	2.240	0.00	8.790	0.000
	$N_2(g)$	25.000	8.330	0.00	5.580	0.000
	$H_2O(g)$	400.000	5.570	-1277.47	5.230	115.370
	$N_2(g)$	400.000	10.340	114.91	6.930	40.740
Out	Fe_2O_3	900.000	10.710	-7501.76	124.820	733.830
	FeO	900.000	0.000	0.00	0.000	0.000
	CaO	900.000	0.030	-17.74	3.830	0.710
	SiO_2	900.000	0.280	-238.37	0.690	9.350
	MgO	900.000	0.110	-61.58	6.550	2.520
	Al_2O_3	900.000	0.110	-173.32	1.650	6.090
	$H_2O(g)$	150.000	6.520	-1549.78	6.120	60.390
	$N_2(g)$	150.000	18.670	68.11	12.510	11.240

Table S36. Mass, heat, and exergy flows in R for η=2.5.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	Fe_2O_3	900.000	10.710	-7501.76	124.820	733.83
	FeO	900.000	0.000	0.00	0.000	0
	CaO	900.000	0.030	-17.74	3.830	0.71
	SiO_2	900.000	0.280	-238.37	0.690	9.35
	MgO	900.000	0.110	-61.58	6.550	2.52
	Al_2O_3	900.000	0.110	-173.32	1.650	6.09
	H_2(g)	748.1	255	5418.93	60210.6	2684.36
Out	Fe	700.000	20.340	473.50	7613.260	241.49
	FeO	700.000	1.070	-243.84	141.340	19.32
	CaO	700.000	0.030	-18.05	3.830	0.48
	SiO_2	700.000	0.280	-242.85	0.690	6.12
	MgO	700.000	0.110	-62.70	6.550	1.7
	Al_2O_3	700.000	0.110	-176.09	1.650	4.1
	H_2(g)	700.000	223.950	4430.91	52879.340	2127.45
	H_2O(g)	700.000	31.050	-6735.39	29.150	643.42

Table S37. Mass, heat, and exergy flows in E for η=2.5.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	700.000	223.950	4430.89	52879.070	2127.44
	H_2O(g)	700.000	31.050	-6743.45	29.150	882.69
	H_2(g)	25.000	255.000	0.00	60210.600	0
Out	H_2(g)	150.000	223.950	806.40	52879.070	132.74
	H_2O(g)	150.000	31.050	-7380.48	29.150	287.59
	H_2(g)	598.100	255.000	4260.85	60210.600	1891.85

Table S38. Mass, heat, and exergy flows in F2 for η=2.5.

		T(°C)	m_i (kmol/h)	h_i (MJ/h)	E_i^{ch} (MJ/h)	E_i^{ph} (MJ/h)
In	H_2(g)	598.100	255.000	4260.85	60210.600	1891.85
	H_2(g)	25.000	5.570	0.00	1315.190	0
	O_2(g)	25.000	2.790	0.00	10.920	0
	N_2(g)	25.000	10.340	0.00	6.930	0
Out	H_2(g)	748.100	255.000	5418.93	60210.600	2684.36
	H_2O(g)	400.000	5.570	-1273.60	5.230	73.93
	N_2(g)	400.000	10.340	114.95	6.930	40.76