Electronic Supplementary Information:

Minimizing CO_2 emissions with renewable energy: A comparative study of emerging technologies in the steel industry

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S1 Process diagrams of the scenarios

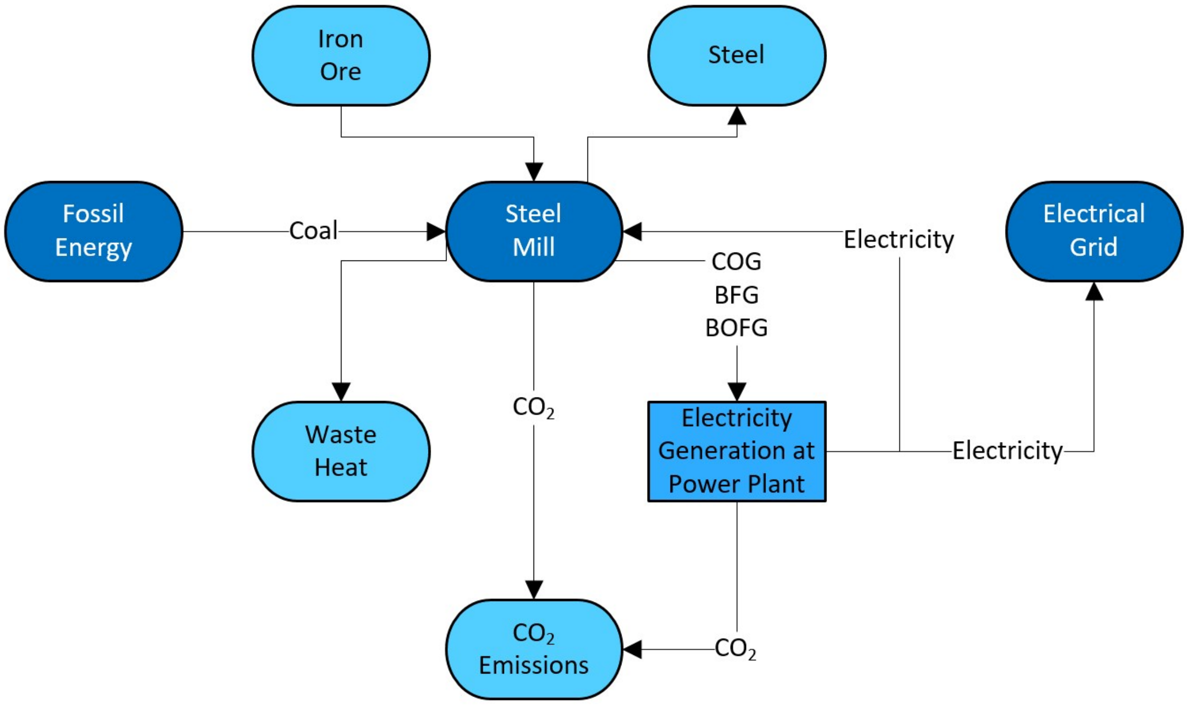

Figure S1. Carbon-based steel mill with power plant. (Scenario 1-CST)

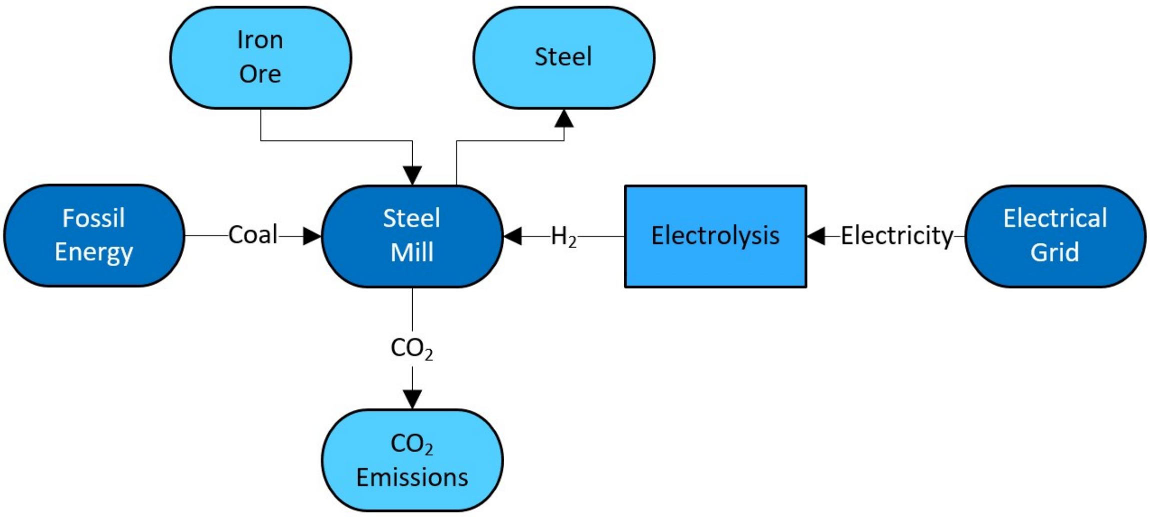

Figure S2. Hydrogen-based steel mill. (Scenario 2-HST)

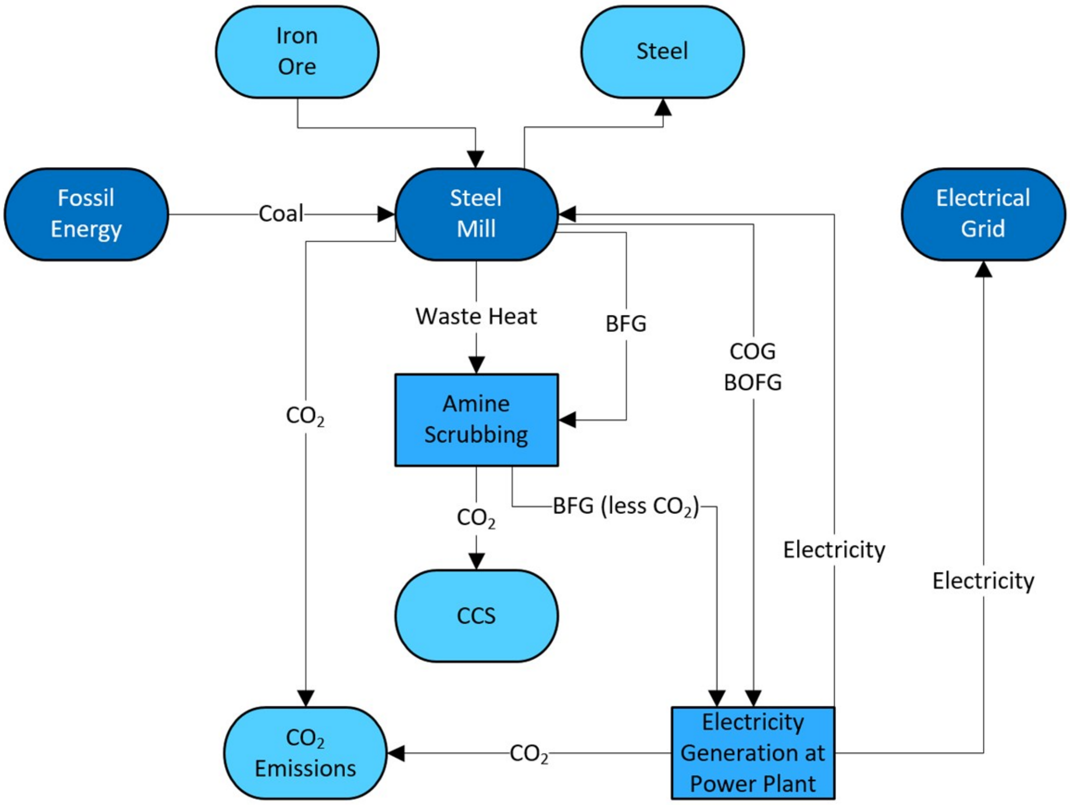

Figure S3. Carbon-based steel mill with power plant and pre-combustion CO_2 capture using the plant's waste heat. (Scenario 3-CST-WHC)

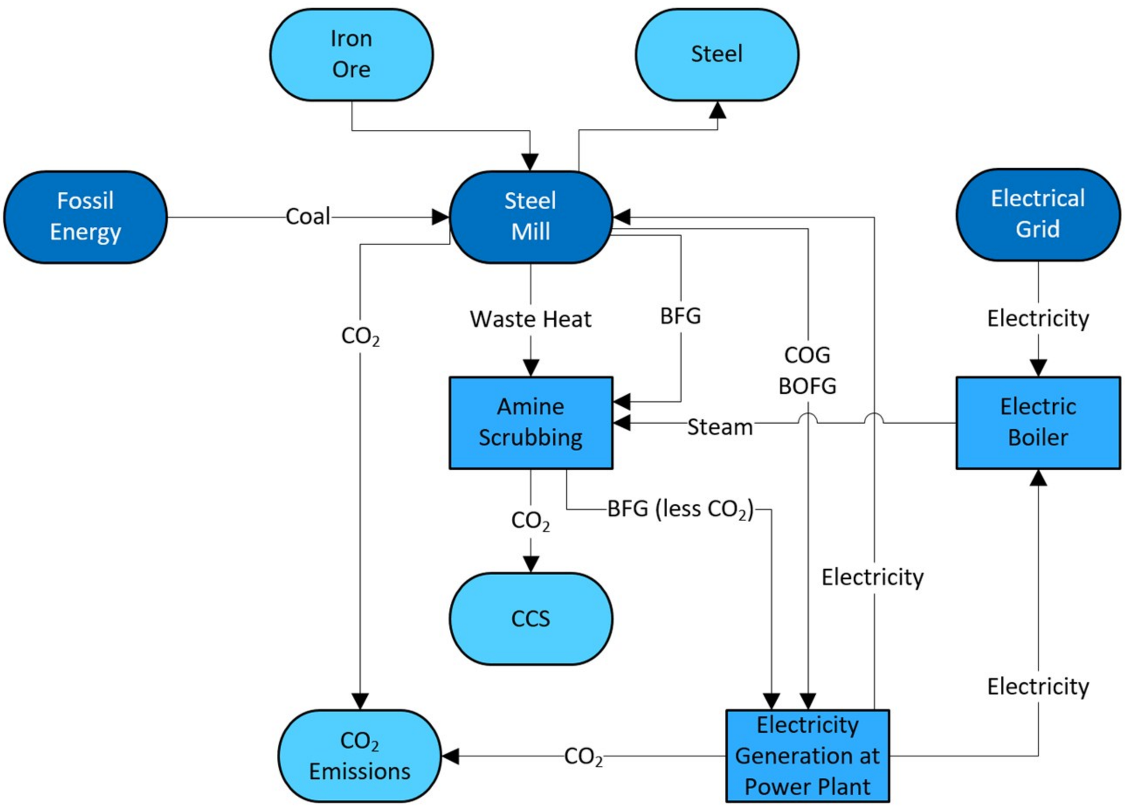

Figure S4. Carbon-based steel mill with power plant and pre-combustion CO_2 capture using the plant's waste heat and steam from an electric boiler. (Scenario 4-CST-EBC)

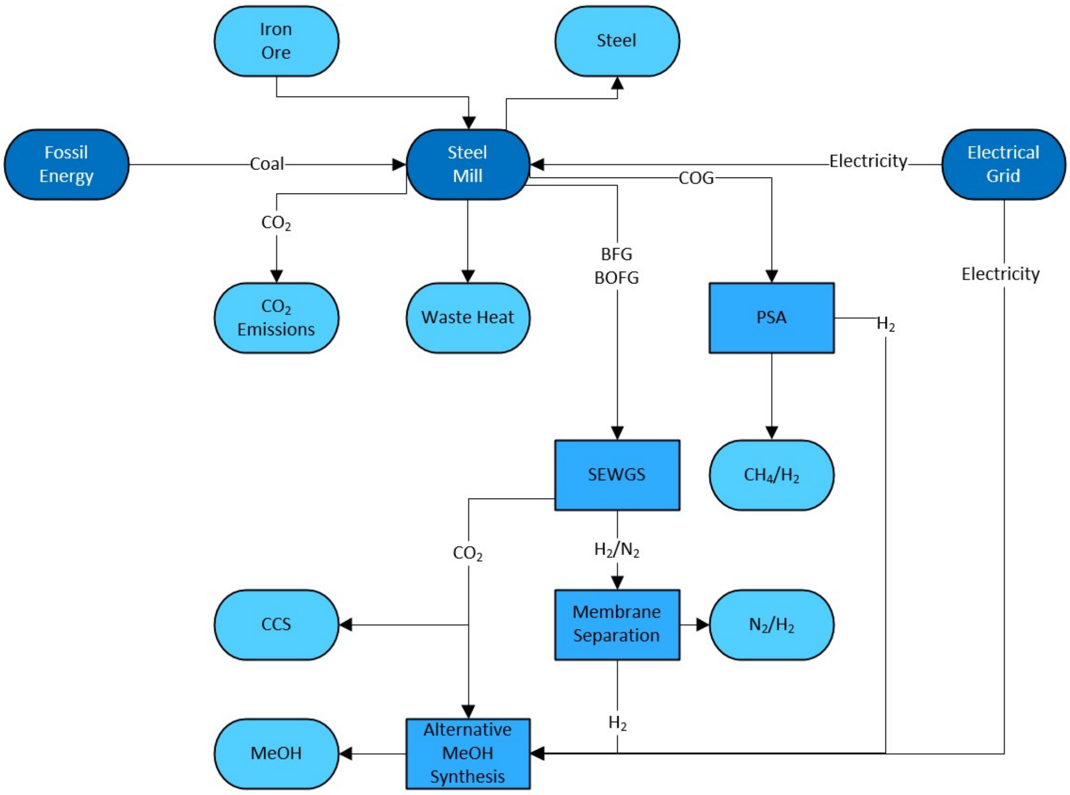

Figure S5. Carbon-based steel mill with treatment of the gases originally sent to the power plant, CO_2 storage and methanol production. (Scenario 5-CST-GPP-CCUS)

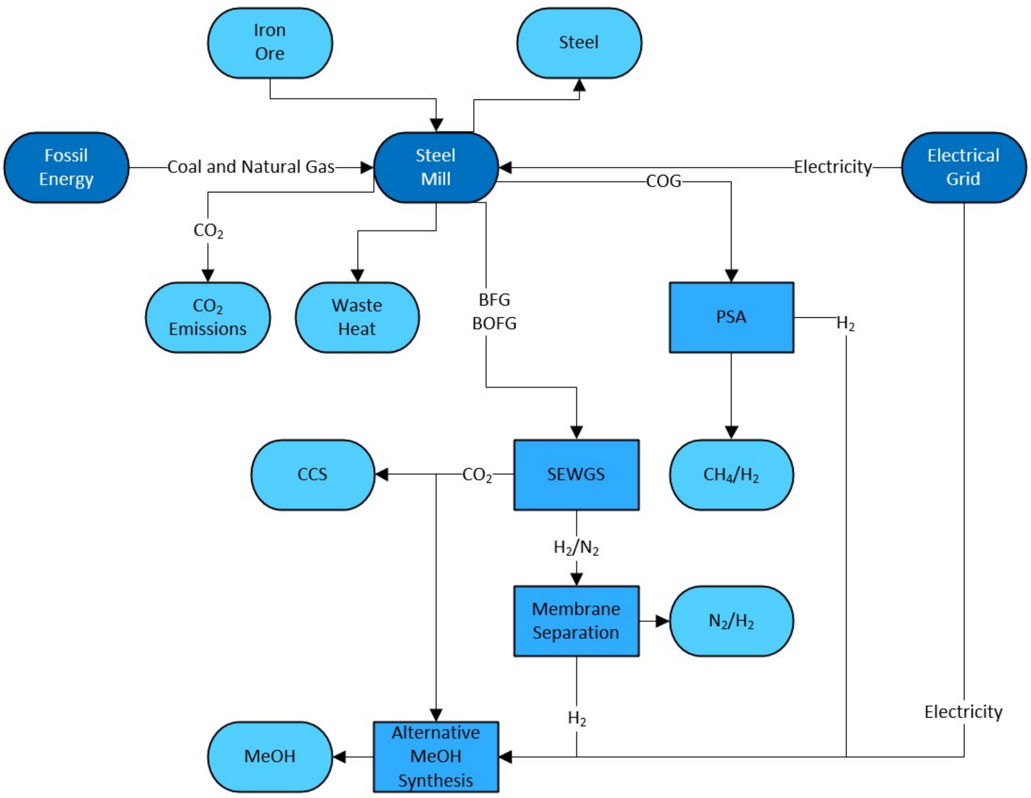

Figure S6. Carbon-based steel mill with treatment of the gases originally sent to the power plant and burned for heating on site, CO_2 storage and methanol production. (Scenario 6-CST-GPH-CCUS)

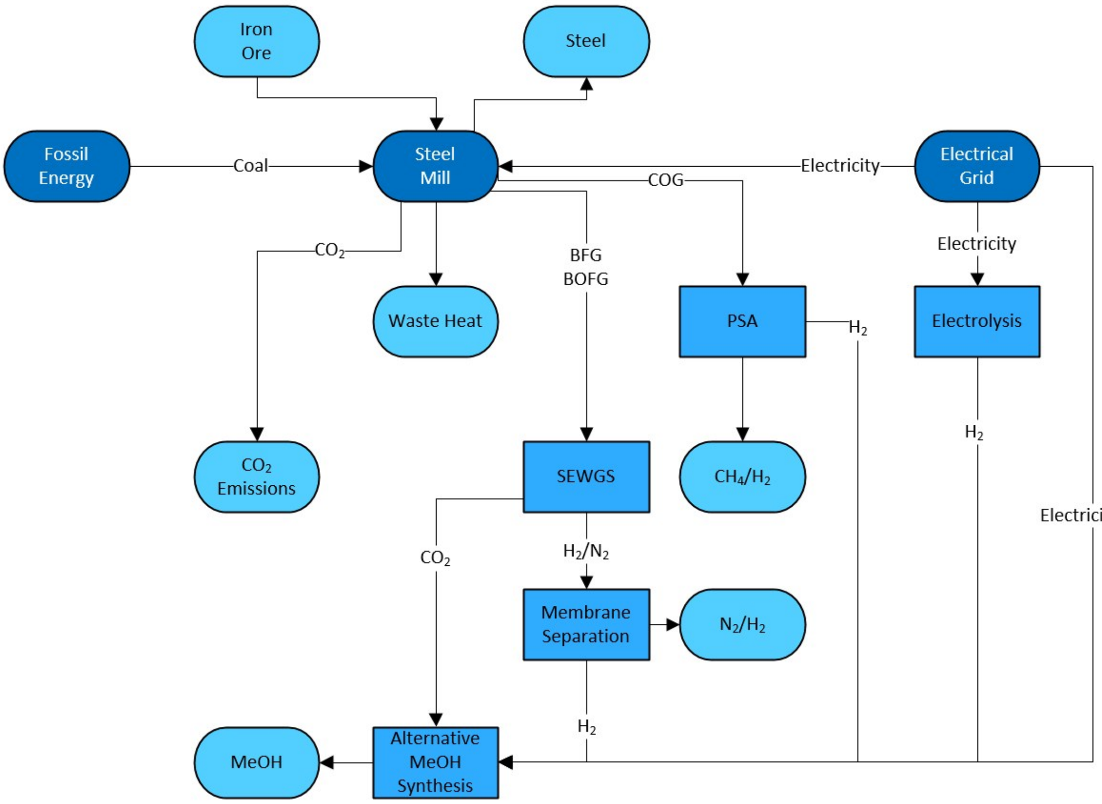

Figure S7. Carbon-based steel mill with treatment of the gases originally sent to the power plant, H_2 production by electrolysis and methanol production. (Scenario 7-CST-GPP-CCU)

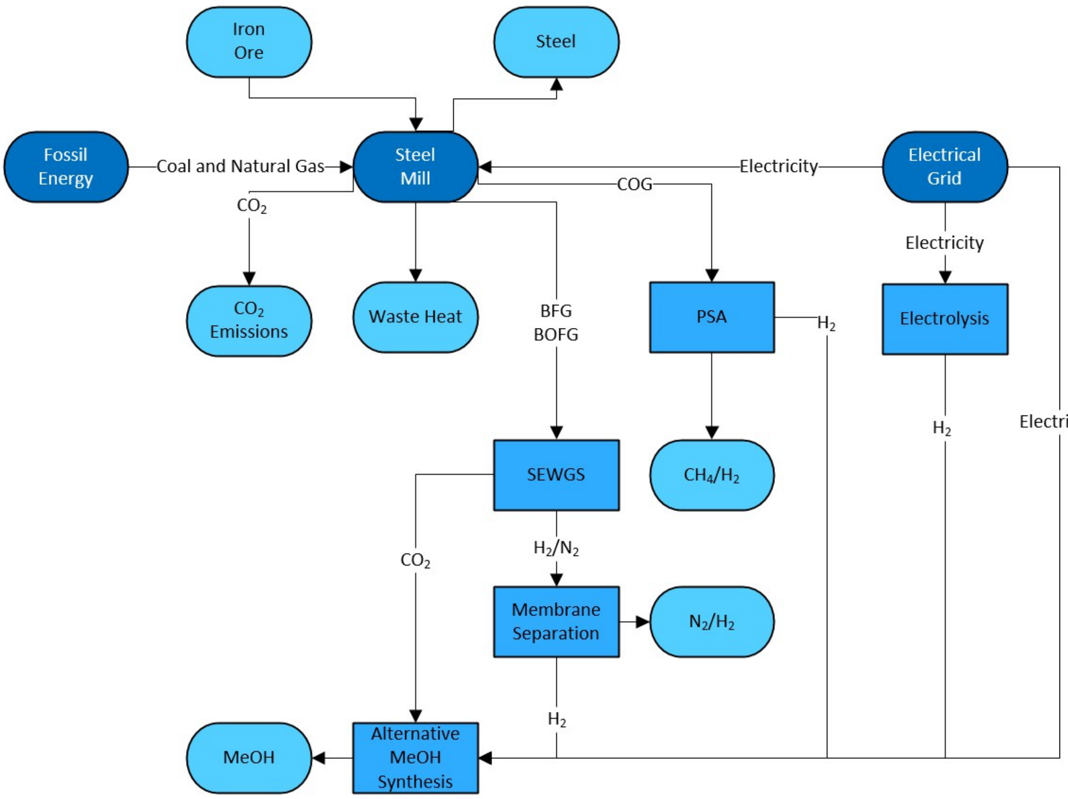

Figure S8. Carbon-based steel mill with treatment of the gases originally sent to the power plant and burned for heating on site, H_2 production by electrolysis and methanol production. (Scenario 8-CST-GPH-CCU)

S2 Effect of the Grid Emission Intensity (GEI) on the CO_2 emissions for the different scenarios

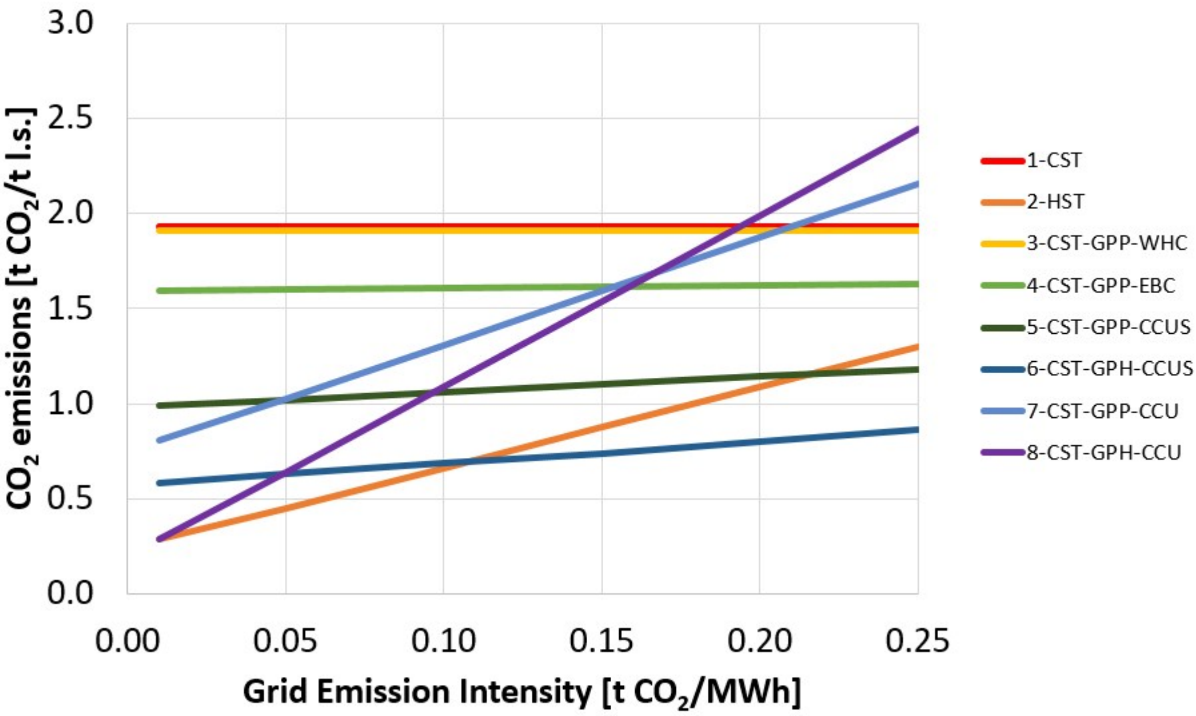

Figure S9. Sensitivity of the CO_2 emissions for the different scenarios on the Grid Emission Intensity (GEI).

S3 CO_2 stored and methanol produced in the scenarios

Table S1. CO_2 stored and methanol produced in the scenarios

Scenario	CO_2 Stored [t CO_2/t l.s.]	Methanol Produced [t methanol/t l.s.]
2 HST	0	0
3 CST-WHC	0.02	0
4 CST-EBC	0.34	0
5 CST-GPP-CCUS	0.63	0.14
6 CST-GPH-CCUS	1.0	0.22
7 CST-GPP-CCU	0	0.59
8 CST-GPH-CCU	0	0.96

S4 Data for the scenarios

Table S2. Data for the conventional steel plant

Description	Value	Units	Source
Feedstock for the steel plant	14	GJ/t l.s.	Gross and net fuel input for the hot metal production of a conventional steel plant[1].
Feedstock for heating in the steel plant	3.2	GJ/t l.s.	Own calculation based on the replacement of the steel mill gases with natural gas[1]
Waste heat from the steel plant available for amine scrubbing	-0.047	GJ/t l.s.	Waste heat over 150 ºC[2, 3]
Electricity required at the steel plant	0.23	MWh/t l.s.	Electricity consumption of a conventional steel plant[1].
Electricity generated in the power plant	-0.45	MWh/t l.s	Own calculation based on the composition of the gases sent to the power plant and a 32.1% of thermal efficiency[1].
CO_2 emissions from the steel plant (not-related to electricity)	1.0	t CO_2/t l.s.	Includes the CO_2 emissions from the pellet plant[4], sinter plant, lime plant, the combustion of part of the steel mill gases to generate heat in the plant and flared gases[1].
CO_2 emissions from the use of natural gas as heating in the plant	0.18	t CO_2/t l.s.	Own calculation based on the composition of the natural gas pipeline available in the steel plant[1].
CO_2 emissions from the power plant	0.93	t CO_2/t l.s.	Own calculations based on the composition of the gases sent to the power plant in a conventional steel plant[1].

Table S3. Data for the capture of CO_2 from the pre-combustion BFG.

Description	Value	Units	Source
Electricity for the amine scrubber	0.22	MWh/t CO_2	Modelled values in Aspen Plus based on the compression of BFG to 6 bar[3] and the compression of CO_2 to 110 bar[1].
Electricity required for the electric boilers	0.29	MWh/t l.s.	Own calculation based on 2.4 GJ/t $CO_{2\ captured}$ are required at 150 ºC[3] and an efficiency of 97% of the electric boilers[5].

Table S4. Collected data for the H_2-based steel plant

Description	Value	Units	Source
Coal in the EAF	0.85	GJ/t l.s.	Input of 27 kg of coal in the EAF (31.1 MJ/kg coal[1]), considering that half of the carbon stays in the steel and the other half is emitted as 50 kg CO_2/t l.s.[6].
Electricity required at the direct reduction plant and EAF	0.63	MWh/t l.s.	Based on literature[7].
Electricity required for the production of H_2.	3.6	MWh/t l.s	Own calculation based on 94% of metallization[7] (1.06 t DRI/t l.s.), 8.2 GJ/t DRI of hydrogen[6, 8] and 4.5 kWh/Nm^3 H_2[9].
CO_2 emissions from pellet production	0.12	t CO_2/t l.s.	Based on literature[4]
CO_2 emissions from carbon addition to the EAF	0.050	t CO_2/t l.s.	Based on literature[6]
CO_2 emissions from lime production	0.056	t CO_2/t l.s.	Based on literature[1]
CO_2 emissions from the decomposition of the electrodes in the EAF	0.0070	t CO_2/t l.s.	Based on literature[10]

Table S5. Data for conventional methanol production

Description	Value	Units	Source
Feedstock for the fossil methanol production	25	GJ/t methanol	Natural gas[5].
Fuel for the fossil methanol production	14	GJ/t methanol	Natural gas[5].
Steam exported from the methanol production	-2.0	GJ/t methanol	Based on literature[5].
Direct CO_2 emissions from the steel plant (not-related to electricity)	0.52	t CO_2/t methanol	Based on literature[5].

Table S6. Data for alternative methanol production

Description	Value	Units	Source
Electricity for alternative methanol synthesis	1.5	MWh/t methanol	Based on literature[5].
Electricity for the PSA unit	GPP: 0.015 GPH: 0.027	MWh/t l.s.	Process modelling based on the composition of the COG[1] and a recent patent for the recovery of 90% of the H_2[11].
Electricity for the SEWGS process	GPP: 0.29 GPH: 0.46	MWh/t l.s.	Process modelling based on the composition of the BFG and BOFG[1], gas compression to 26 bar[12], the compression of the H_2-rich gas for the 2-stages membrane separation[13] and the electrical requirement of the steam boilers with 97% of efficiency[5]
CO_2 emissions from the combustion of the N_2-rich gas after membrane separation	GPP: 0.048 GPH: 0.077	t CO_2/t l.s.	Process modelling based on the composition of BFG and BOFG[1] and the 2-stages membrane separation[13]
Electricity for the production of H_2	4.5	kWh/Nm^3 H_2	Based on literature[9].

Table S7. Electricity requirements

Scenario	Steel Mill [MWh/t l.s.]	Carbon Storage [MWh/t l.s.]	Alternative Methanol Plant [MWh/t l.s.]	Electrolyzer [MWh/t l.s.]	Total [MWh/t l.s.]
1 CST	-0.22	-	-	-	**-0.22**
2 HST	4.2	-	-	-	**4.2**
3 CST-WHC	-0.22	0.0043	-	-	**-0.22**
4 CST-EBC	-0.22	0.36	-	-	**0.14**
5 CST-GPP-CCUS	0.20	0.078	0.51	-	**0.79**
6 CST-GPH-CCUS	0.19	0.13	0.82	-	**1.1**
7 CST-GPP-CCU	0.13	-	1.2	4.2	**5.6**
8	0.064	-	1.9	6.9	**8.9**

CST-GPH-CCU	

S5 CO_2 emissions in the scenarios

Table S8. CO_2 emissions in the scenarios with a GEI_1 = 0.25 t CO_2/MWh

Scenario	Steel Mill [t CO_2/t l.s.]	CO_2 capture and storage [t CO_2/t l.s.]	Alternative Methanol Plant [t CO_2/t l.s.]	Electrolyzer [t CO_2/t l.s.]	Total [t CO_2/t l.s.]
1 CST	1.9	-	-	-	**1.9**
2 HST	0.4	-	-	0.9	**1.3**
3 CST-WHC	1.9	0.0011	-	-	**1.9**
4 CST-EBC	1.6	0.036	-	-	**1.6**
5 CST-GPP-CCUS	0.99	0.020	0.17	-	**1.2**
6 CST-GPH-CCUS	0.55	0.03	0.28	-	**0.86**
7 CST-GPP-CCU	0.75	-	0.35	1.1	**2.2**
8 CST-GPH-CCU	0.17	-	0.56	1.7	**2.4**

Table S9. CO_2 emissions in the scenarios with a GEI_2 = 0.01 t CO_2/t MWh

Scenario	Steel Mill [t CO_2/t l.s.]	CO_2 capture and storage [t CO_2/t l.s.]	Alternative Methanol Plant [t CO_2/t l.s.]	Electrolyzer [t CO_2/t l.s.]	Total [t CO_2/t l.s.]
1 CST	1.9	-	-	-	**1.9**
2 HST	0.25	-	-	0.040	**0.29**
3 CST-WHC	1.9	0.000047	-	-	**1.9**
4 CST-EBC	1.6	0.0016	-	-	**1.6**
5 CST-GPP-CCUS	0.93	0.00086	0.053	-	**0.99**
6 CST-GPH-CCUS	0.49	0.0014	0.086	-	**0.58**
7 CST-GPP-CCU	0.70	-	0.061	0.047	**0.80**
8 CST-GPH-CCU	0.11	-	0.098	0.076	**0.29**

S6 Efficiency of the use of energy for the reduction of CO_2 emissions in the scenarios

Table S10: Electricity consumed per CO_2 removed.

Scenario	GEI_1 = 0.25 t $CO_{2\ emitted}/MWh_{produced}$ [$MWh_{consumed}$/t $CO_{2\ captured}$]	GEI_2 = 0.01 t $CO_{2\ emitted}/MWh_{produced}$ [$MWh_{consumed}$/t $CO_{2\ captured}$]
2 HST	7.1	2.7
3 CST-WHC	-	-
4 CST-EBC	0.5	0.4
5 CST-GPP-CCUS	1.3	1.1
6 CST-GPH-CCUS	1.3	1.0
7 CST-GPP-CCU	-	5.1
8 CST-GPH-CCU	-	5.5

S7 Methodology for mass and energy balances of the scenarios 1-CST, 2-HST and 8-CST-GPH-CCU.

A. 1-CST

A reference integrated steel mill was selected from a study by the International Energy Agency (IEA)[1]. The mass and energy balances correspond to the production of 1 ton of liquid steel from the Basic Oxygen Furnace. Hence, the ladle metallurgy, continuous casting and rolling sections were not considered in this analysis. A detailed description of the steel mill's off gases is shown in Table 1. Part of the gases is used to generate heat in the steel production process and another part is sent to the power plant to generate 450 kWh/t l.s. of electricity, see Figure S10. The electricity required by the steel mill is 230 kWh/t l.s., indicating that the power plant produces more electricity than required by the steel plant.

B. 2-HST

The mass and energy balances of a H_2-based steel plant were performed with the information given in Table S4. All the data was collected from literature and the balances were performed as shown in Figure 11.

C. 8-CST-GPH-CCU

The reference steel mill 1-CST is used as the base for the calculation of this scenario. All the steel mill gases were sent to the gas treatment plant and natural gas was used to generate the heat required in the steel plant; this calculation is shown in Figure S12. The mass balances and electricity requirements of the gas treatment plant were calculated with Aspen Plus, Matlab and data collected from literature as presented in Tables S2, S5 and S6. A summary of the calculations is displayed in Figures S12 and S13.

In the gas treatment plant, 90% of H_2 from COG was recovered via PSA and the CH_4-rich stream was exported to a natural-gas-consuming plant, hence the CO_2 emitted by combusting this stream was avoided by the steel plant. In scenario 1-CST, this CH_4 is combusted in the power plant.

The BFG and BOFG were sent to a SEWGS process where additional steam was used to transform CO into H_2 and CO_2 while simultaneously separating the CO_2-rich and H_2-rich streams. The process was modeled in Aspen Plus to recover 95% of the CO_2 in the CO_2-rich stream at 95% purity. The H_2-rich stream contains most of the N_2, which was then separated by a 2-stage H_2/N_2 separation using polymeric membranes. The heat requirements of the SEWGS process were supplied by combustion of the N_2-rich stream after membrane separation and by electric boilers.

The mass balance for the membrane separation was calculated considering the permeance of the gases, solving the equation systems with Matlab and implementing the resulting gas composition from each stage in the Aspen Plus model for the SEWGS process. In the membranes section, the gas was at 26 bar for the first separation stage, the outlet pressure was at 2 bar for 97% H_2 recovery and an area of 230 m². For the second stage, the gas was recompressed to 9 bar before flowing through the second membrane with 210 m² of area, so 90% of the H_2 entering the separation section was recovered at 1 bar. The N_2-rich gas contained 10% of the H_2 and was combusted to recover heat for the SEWGS process.

The methanol plant was modelled in Aspen Plus to validate the data from literature. An overview of the methanol synthesis loop flowsheet is shown in Figure S14.

1-CST Steel plant

Section	COG [Nm³/t l.s.]	BFG [Nm³/t l.s.]	BOFG [Nm³/t l.s.]	Electricity consumption [kWh/t l.s.]	Steam consumption [kg/t l.s.]	CO_2 emissions [t CO_2 /t l.s.]
Coke production	123	-170	0	13	57	0.18
Sinter and pellets production	-4.3	0	0	33	0	0.30
Hot metal production	-8.0	1028	0	95	7.3	0.41
Crude steel production	0	0	82	20	-71	0.047
Lime production	-16	0	0	2.4	0	0.067
Oxygen production	0	0	0	62	6.8	0
Total	**95**	**858**	**82**	**226**	**0.0**	**1.0**
	Gases sent to the power plant					

Power plant

Component	From COG [Nm³/t l.s.]	From BFG [Nm³/t l.s.]	From BOFG [Nm³/t l.s.]	Total [Nm³/t l.s.]	LHV [MJ/Nm³]	[MJ/t l.s.]	CO_2 emissions [t CO_2 /t l.s.]
CH_4	21.9	0	0	21.9	36	785	0.043
H_2	56.6	31.1	2.2	89.9	11	972	0
CO	3.7	191.6	46.6	241.8	13	3073	0.47
CO_2	0.9	189.6	11.8	202.3	0	0	0.40
Other HC (CxHy)	2.6	0	0	2.6	63	162	0.010
					Total [MJ/t l.s.]	**4992**	**0.92**

Considering 32.1% efficiency in the power plant:	
Electricity produced:	1603 MJ/t l.s.
Electricity produced:	**445 kWh/t l.s.**
Carbon intensity of the electricity:	**2.1 t CO_2/MWh**

Summary

Section	Electricity consumption [MWh/t l.s.]	Non-related to electricity CO_2 emissions [t CO_2 /t l.s.]
Steel plant	226	1.0
Power plant	-445	0.92
Total	**-220**	**1.9**

Figure S10. Methodology for mass and energy balances of the scenario 1-CST.

2-HST Steel plant

			Ref.
Energy consumption for Direct Reduction with 100% H_2 in ENERGIRON plants	8.2	GJ H_2/t DRI	8
Lower Heating Value H_2	0.011	GJ H_2/Nm³	
Metallization	94	%	7
t DRI/t l.s. ratio based in metallization	1.1	t DRI/t l.s.	
Electricity for H_2 production in electrolyzers	4.5	kWh/Nm³	9
Electricity required for H_2 production	**3.6**	**MWh/t l.s.**	

$$\frac{8.2\ GJ\ H_2}{t\ DRI} \cdot \frac{Nm^3\ H_2}{0.011\ GJ\ H_2} \cdot \frac{t\ DRI}{0.94\ t\ l.s.} \cdot \frac{4.5\ kWh}{Nm^3\ H_2} \cdot \frac{MWh}{1000\ kWh} = \mathbf{3.6}\ \frac{\mathbf{MWh}}{\mathbf{t\ l.s.}}$$

Section	Electricity consumption [MWh/t l.s.]	Non-related to electricity CO_2 emissions [t CO_2 /t l.s.]	Ref.
Pellet production	-	0.13	4
Lime production	0.002	0.056	1
Electricity for H_2 production	3.6	Depends on GEI	
Carbon addition in EAF	-	0.05	6
Electricity for EAF	0.63	Depends on GEI	7
Decomposition electrodes in EAF	-	0.007	10
Total	**4.2**	**0.24**	

Total emissions when GEI = 0.25 t CO_2/MWh	**1.3**	**t CO_2 /t l.s.**
Total emissions when GEI = 0.01 t CO_2/MWh	**0.29**	**t CO_2 /t l.s.**

Figure S11. Methodology for mass and energy balances of the scenario 2-HST.

8-CST-GPH-CCU Steel, gas treatment and methanol plants.

Steel plant:

Section	COG [Nm³/t l.s.]	BFG [Nm³/t l.s.]	BOFG [Nm³/t l.s.]	Electricity consumption [kWh/t l.s.]	Natural gas consumption [MJ/t l.s.]	Steam consumption [kg/t l.s.]	CO_2 emissions [t CO_2 /t l.s.]
Coke production	166	0	0	13.2	1280.2	56.5	0.077
Sinter and pellets production	0	0	0	32.9	74.5	0	0.30
Hot metal production	0	1467	0	95.2	1545.5	7.3	0.11
Crude steel production	0	0	81.8	20.0	0	-70.6	0.046
Lime production	0	0	0	2.4	277.3	0	0.072
Oxygen production	0	0	0	61.8	0	6.8	0
Total	**166**	**1467**	**82**	**226**	**3178**	**0.0**	**0.60**
	Gases sent to gas treatment plant				**78 Nm³ NG/t l.s.**		

Gas treatment plant - PSA (literature and Aspen Plus)

Component	COG in [Nm³/t l.s.]	COG in [kmol/t l.s.]	H_2 rich gas [kmol/t l.s.]	PSA off-gas [kmol/t l.s.]	LHV [MJ/Nm³]	[MJ/t l.s.]	
CH_4	38	1.7	0.0	1.7	36	1369	
H_2	99	4.4	4.0	0.44	11	107	
CO	6.4	0.28	0.0	0.28	13	81	
CO_2	1.6	0.071	0.0	0.07	0	0	
N_2	9.6	0.43	0.0	0.43	0	0	
O_2	0.32	0.014	0.0	0.014	0	0	
H_2O	6.6	0.29	0.0	0.29	0	0	Exported to a natural
Other HC (CxHy)	4.5	0.20	0.0	0.20	63	282	gas consuming plant.
			to methanol plant		**Total [MJ/t l.s.]**	1838	24 MJ/Nm³

Electricity required (from Aspen Plus model):	**27 kWh/t l.s.**

Figure S12. Methodology for mass and energy balances of the scenario 8-CST-GPH-CCU (part A).

Gas treatment plant - SEWGS (Aspen Plus)

Component	BFG+BOFG in (dry basis) [Nm^3/t l.s.]	BFG+BOFG in (dry basis) [kmol/t l.s.]	After SEWGS (dry basis) CO_2 rich gas [kmol/t l.s.]	After SEWGS (dry basis) H_2 rich gas [kmol/t l.s.]
H_2	55	2.5	0.59	18
CO	373	17	0.013	0.39
CO_2	334	15	30	1.6
N_2	723	32	1.0	31
			to methanol plant	to H_2/N_2 separation

Gas treatment plant - H_2/N_2 separation (Matlab)

Component	After SEWGS in (dry basis) [kmol/t l.s.]	H_2 rich gas out of 1st membrane (dry basis) [kmol/t l.s.]	H_2 rich gas out of 2nd membrane (dry basis) [kmol/t l.s.]	H_2 lean gas out of H_2/N_2 separation (dry basis) [kmol/t l.s.]
H_2	18	18	16	1.8
CO	0.39	0.012	0.003	0.39
CO_2	1.6	0.52	0.16	1.4
N_2	31	0.54	0.008	31
		to 2nd membrane	to methanol plant	Burned for energy recovery

0.08 t CO_2/t l.s.
Emissions

Methanol plant (literature and Aspen Plus)

Component	H_2 rich gas from PSA (dry basis) [kmol/t l.s.]	CO_2 rich gas from SEWGS (dry basis) [kmol/t l.s.]	H_2 rich gas from H_2/N_2 separation (dry basis) [kmol/t l.s.]	H_2 from electrolyzer[kmol/t l.s.]
H_2	4.0	0.59	16	68
CO	0.0	0.013	0.003	0.0
CO_2	0.0	30	0.16	0.0
N_2	0.0	1.0	0.008	0.0

Methanol produced	**0.96**	**t methanol/t l.s.**
Electricity for methanol production	1.5	MWh/t methanol
Electricity required	**1.4**	**MWh/t l.s.**

Replacement of conventional methanol:

Electricity credit	-0.16	kWh/t l.s.
CO_2 credit	-0.50	t CO_2/t l.s.

Electrolyzer

H_2 required	1534	Nm^3/t l.s.
Electrity in the electrolyzer	4.5	kWh/Nm^3
Electricity required	**6.9**	**MWh/t l.s.**

Summary

Section	Electricity consumption [MWh/t l.s.]	Non-related to electricity CO_2 emissions [t CO_2 /t l.s.]
Steel plant	0.23	0.61
PSA	0.027	0
SEWGS + H_2/N_2 separation	0.46	0.079
Methanol plant	1.4	0
Electrolyzer	6.9	0
Replacement of conventional methanol synthesis	-0.16	-0.50
Total	**8.9**	**0.19**

Total emissions when:
GEI = 0.25 t CO_2/MWh
2.4 t CO_2/t l.s.
GEI = 0.01 t CO_2/MWh
0.29 t CO_2/t l.s.

Figure S13. Methodology for mass and energy balances of the scenario 8-CST-GPH-CCU (part B).

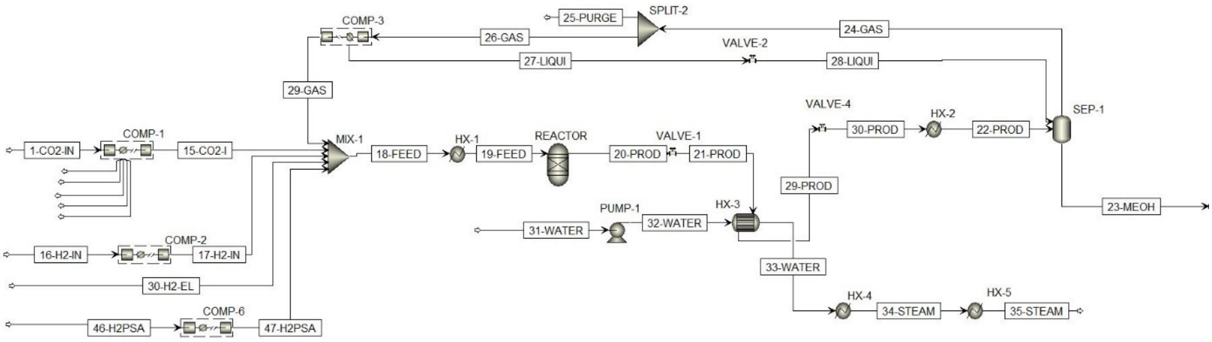

Figure S14. Methanol synthesis loop section of the Aspen Plus validation model.

S8 Selected values and sensitivity analysis of key process variables.

Table S11. Key process variables and selected values

Variable	Selected Value	Range	Source
Power plant efficiency	32.1%	-	Based on literature[1].
H_2 required in the H_2-based steel-making	8.2 GJ H_2/t DRI	-	Based on literature[6].
DRI metallization	94%	94-96%	Based on literature[7].
Power in electrolyzer	4.5 kWh/Nm³	3.2 – 6.1 kWh/Nm³	Based on literature[6, 9].
Power in EAF	630 kWh/t l.s.	Cold DRI: ~670 kWh/t l.s. Hot DRI: ~580 kWh/t l.s.	Based on literature[7].
H_2 recovery after PSA	90%	70-90%	Based on literature[11] and PSA provider.
SEWGS	CO_2 capture: 95% CO_2 purity: 95%	Latest campaign: CO_2 capture > 90% CO_2 purity > 90%	Based on their latest campaign[14].
Methanol synthesis	100% gas conversion	Reached 100% with the lowest purge.	Based on literature[5] and confirmed with Aspen Plus model.

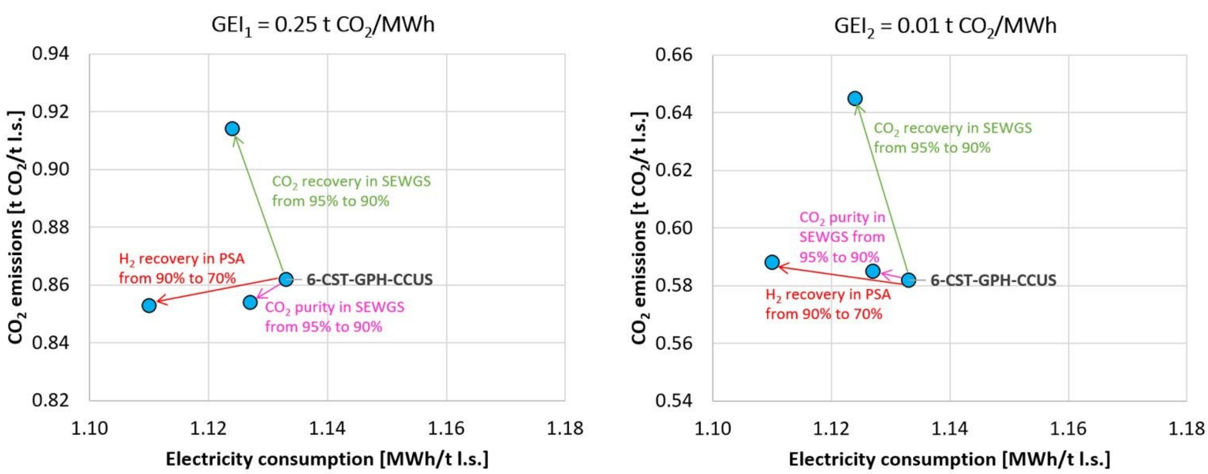

Figure S15. Sensitivity analysis for 3 key performance parameters for CCUS scenario 6 using electricity from a mixed and a renewable grid.

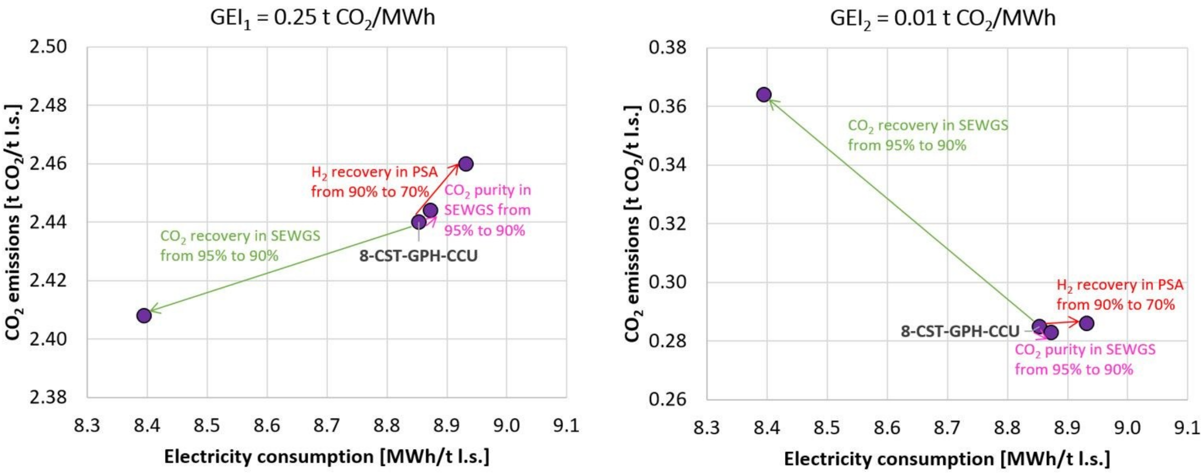

Figure S16. Sensitivity analysis for 3 key process performance parameters for CCU scenario 8 using electricity from a mixed and a renewable grid.

References

1. *Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill)*, IEA, 2013.
2. M. Sprecher, H. Bodo Lüngen, B. Stranzinger, H. Rosemann and W. Adler, *Abwärmenutzungspotenziale in Anlagen integrierter Hüttenwerke der Stahlindustrie*, Stahlinstitut VDEh, 2019.
3. M. Dreillard, P. Broutin, P. Briot, T. Huard and A. Lettat, *Energy Procedia*, 2017, **114**, 2573-2589.
4. A. Volpatti, presented in part at the World DRI & Pellet Congress, Abu Dhabi, 2013.
5. *Low carbon energy and feedstock for the European chemical industry*, DECHEMA, 2017.
6. P. Duarte, *Hydrogen-based steelmaking*, Tenova HYL, 2018.
7. A. Hertrich, presented in part at the 7th World DRI & Pellet Congress, Dubai, 2019.
8. P. Argenta, M. Marcozzi, M. Dorndorf, P. Duarte, S. Maggiolino and O. Demir, *Conventional Steelmaking Route Being Subject to Transformation*, Tenova.
9. P. Häussinger, R. Lohmüller and A. M. Watson, in *Ullmann's Encyclopedia of Industrial Chemistry*, Wiley-VCH, Weinheim, 2011, vol. 18, pp. 249-307.
10. A. Babich and D. Senk, in *The Coal Handbook: Towards Cleaner Production*, ed. D. Osborne, Woodhead Publishing, 2013, vol. 2, pp. 267-311.
11. *US Pat.,* US20180036671A1, 2018.
12. H. A. J. van Dijk, P. D. Cobden, L. Lukashuk, L. v. de Water, M. Lundqvist, G. Manzolini, C.-C. Cormos, C. van Dijk, L. Mancuso, J. Johns and D. Bellqvist, *Johnson Matthey Technology Review*, 2018, **62**, 395-402.
13. W. L. McCabe and J. C. Harriot, *Unit Operations in Chemical Engineering*, McGraw-Hill, New York, 5th edition edn., 1993.
14. STEPWISE, How - Main Achievements, https://www.stepwise.eu/project/how/, (accessed April, 2020).