The amounts of heat required to achieve carbon neutrality in ironmaking processes

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The table below*[1] summarizes the CO_2 reduction performance of ironmaking (I.M.) processes and their heat consumptions to achieve carbon neutrality (CN) with CCUS*[2]. Except SimpLE method, >10,000kWh/tp of green power is required when supplementary using CCU (CO_2 recycle), or limited resource of CO_2 storage would be in the risk of much earlier depletion when using CCS (CO_2 storage) since conventional BF, the largest source of CO_2 emissions, is the most energy efficient (= economy) with CCS.

SimplLE can reduce fossil fuel-derived CO_2 by more than 80% without depending on CCUS, while reducing gross energy*[3] for I.M. by more than 20% from conv.BF. It can also achieve 30% negative emissions without DAC(direct air capture) by recovery of the CO_2 derived from CN fuels. SimpLE is the only solution that can achieve a high level of both CO2 reduction and energy efficiency.

				Conv. BF		**Conv.BF＋CO_2 Meas.**		***SimpLE*（Post-fossil fuel BF）**				**DRF＋Melter**	
				2013 year	current	H_2Injection	CCU-CH_4	V.1.ck	V.1.ckh$_2$	V.1.0	V.2 (V.3)	CH_4 basis	H_2 basis
①	**Fossil derived C (Offshore Procurement)**	Coking coal	kg/tp	475	409	409		223		75		57	57
		Non-coking coal, Heavy oil	kg/tp	Coal 136	Coal 160	0	0	Coal 35		Coal 208	0	H.oil 35	0
		CH_4	kg/tp	0	0	0	0	CH_4 **63～0**	0	CH_4 53	0	CH_4 212	CH_4 17
		others	kg/tp	Flux 35		Flux 31		Flux 27			Flux 31	Burnt Flx42, Electrode4	
		Total	**kg/tp**	**645**	**604**	**440**	**440**	**348～286**	**285**	**364**	**106**	**349**	**120**
	Fossil fuel heat		GJ/tp	**23.9**	**22.2**	**15.9**	**15.9**	**14.3**	**10.1**	**14.8**	**2.9**	**18.5**	**3.9**
②	**Green energy**	Fuels	kg/tp			**H_2 52**	**CH_4 126**		**H_2 35**		**Waste 18*[3]GJ/tp**		**H_2 94**
		Electricity(heating, melting)	kWh/tp									**778**	**1,500**
③	**Surplus energy from I.M.**	incl. LDG, Tar	GJ/tp	7.9	7.4							0.5	0.5
④	**Net Energy for I.M.**	excl. heat loss making ②	GJ/tp	**16.9**	**15.7**	**15.7**	**16.4**	**15.2**	**15.2**	**15.7**	**10.3*[6]**	**20.6**	**21.9**
⑤	**Utility power**	Green power in green box	kWh/tp	120	120	160	160	160	160	160	200	200	200
⑥	**Gross Energy for I.M.**	incl. ②heat loss,④,⑤	GJ/tp	**18.1**	**16.9**	**32.6**	**40.2**	**16.8**	**32.8**	**17.3**	**12.4*[5]**	**28.6**	**74.7**
⑦	**CO_2**	derived from ①	tCO_2/tp	**2.4**	**2.2**	**1.6**	**1.6**	**1.3**	**1.0**	**1.3**	**0.4**	**1.3**	**0.44**
⑧	**CO_2 reduction rate**		%	**100**	**6**	**32**	**32**	**46**	**56**	**44**	**84**	**46**	**81**
Overall Green energy required for Carbon neutrality								*De-CO_2 heat is mostly included in ④.*					
⑨	**De-CO_2**	CO_2 separation heat for ⑩,⑪	MWh/tp	4.73	4.43	3.22	3.22	0.51	0.00	0.51	0.00	2.56	0.88
⑩	**CCU(CH_4)**	Required green H_2(incl.②)	kg/tp	~~430~~	~~403~~	~~345~~	~~356~~	~~232~~	~~225~~	~~243~~	71	~~233~~	~~174~~
		Total green PWR(incl.②⑤)*[2]	MWh/tp	~~**23.3**~~	~~**21.8**~~	~~**18.8**~~	~~**19.4**~~	~~**13.2**~~	~~**12.8**~~	~~**13.7**~~	**4.2**	~~**14.0**~~	~~**11.4**~~
	Gross green fuels*[1]	η = 35%	GJ/tp	~~**201**~~	~~**188**~~	~~**167**~~	~~**174**~~	~~**113**~~	~~**112**~~	~~**118**~~	**44**	~~**123**~~	~~**110**~~
	Gross Energy*[1] for I.M.	including ①	GJ/tp	~~**225**~~	~~**211**~~	~~**183**~~	~~**190**~~	~~**128**~~	~~**123**~~	~~**133**~~	**48**	~~**141**~~	~~**114**~~
⑪	**CCS(Liquid CO_2)**	CO_2 liquefying heat	MWh/tp	0.47	0.44	0.32	0.32	0.26	0.21	0.27	0.08	0.26	0.09
		Required green H_2(incl.②)	kg/tp	0	0	52	63	0	35	0	0	0	94
		Total green PWR(incl.②⑤)*[2]	MWh/tp	**-0.20**	**-0.18**	**2.7**	**3.3**	**0.42**	**2.3**	**0.43**	**0.28**	**1.2**	**7.0**
	Gross green fuels	η = 35%	GJ/tp	**2.7**	**2.6**	**31**	**37**	**4.8**	**24**	**4.9**	**11.4**	**15**	**73**
	Gross Energy*[1] for I.M.	including ①	GJ/tp	**29**	**27**	**63**	**78**	**22**	**57**	**22**	**15**	**33**	**77**

the most efficient **except SimpLE**, if CCS can be used
but **CCS cost will be the most** and it **will deplete CO_2 storage much earlier**

30% Negative Emissions with CCS for 1.1 t CO_2/tp
(Additional Green power is 0.14 MWh/tp only)

*1) The values are our estimations. See home page (https://simple-labo.co.jp/en) and note that CO_2 from the transportation of any materials are not taken into account.

*2) CCU is assumed a methanation(to CH_4) with 100% conversion efficiency. CCS is assumed that CO_2 is liquefied and transported by sea, of which liquefying energy is only considered here.

*3) Gross energy means the heat equivalent to primary energy. ⑩Gross green fuels are the values after subtracting the latent heat of CH_4 produced in CCU from them.

*4) Surplus energy from "conventional BF" and "DRF + Melter" is deducted from the "total green PWR" on the assumption that it will all be converted into power.

*5) The amount of heat input from waste is assumed 18 GJ/t (wet LCV), assuming that the thermal efficiency decreases to 2/3 of the fossil fuels when using waste.

*6) Converting waste usage stops the heat loss (11.5 GJ/tp) of incineration plants, which is subtracted from gross energy for I.M. (same as surplus energy). See Home Page/"SimplLE" Page 9/11.

Discussions

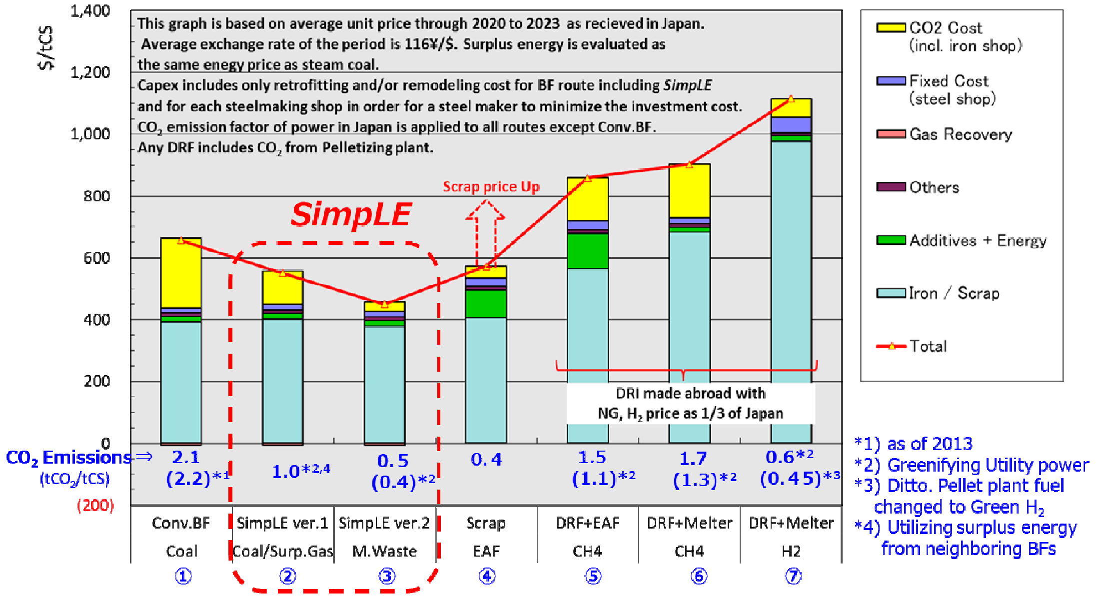
1. "H_2 reduction DRF (direct reduction furnace) + Melter (electric melter)" is a trend in CO_2 reduction measures. In order to reduce CO_2 by 80% and to produce 1 ton of pig iron, it requires roughly 1,000Nm^3 of hydrogen, 7,000kWh of green power, and 5 times the gross I.M. energy of conv.BFs. And further 20% CO_2 reduction is required for carbon neutrality (CN). With CCU, 1,000Nm^3 of hydrogen, 4,000kWh of green power, and twice the gross I.M. energy of conv.BFs are additionally required. With CCS, additional heat will be saved, but it is much more advantageous to chose other processes.
2. Europe prioritizes CO_2 reduction, but there are **issues from an energy efficiency perspective** since steelmaking consumes large energy in itself. Moreover, most of CO_2 emissions from steelmaking occur outside of Europe (and Japan), and **energy-intensive CO_2 reduction measures will lead to energy shortages and cannot be widely adopted worldwide**. Therefore, **the emergence of another CO_2 reduction process is eagerly awaited to achieve global CO_2 reduction ASAP**.
3. Europe is introducing "Natural gas DRF+Melter" at the 1st Step due to hydrogen infrastructure limitations and as technical steps. But if CCS is allowed to use, **retaining natural gas DRF is far better in terms of gross energy for I.M.** as shown in the table above. Also, there are many places suitable for CO_2 storage in Europe, they could potentially finalize with 1st Step + CCS. In Japan, however, due to higher price of natural gas and lack of suitable sites for CO_2 storage, it is better to reconsider this approach.
4. Regarding blue hydrogen with CCS, blue hydrogen should consider H_2 conversion efficiency and transportation efficiency. "CH_4 to H_2 conversion + CCS + H_2 transport" is clearly inferior to "CH_4 direct use + CO_2 transport + CCS" (in the table) in terms of CO_2 storage volume and energy efficiency, so it is excluded from the comparison table.
5. **To achieve carbon neutrality using CCS, "H_2 DRF+Melter" or any other process using H_2 requires the gross energy for I.M. by more than 2 times.** And "conv.BFs with CCS" will be the best in energy efficinecy and production cost. However, since **CO_2 storage capacity is finite and geographically limited, its usage will be regulated and limiitted to avoid depletion**, resulting in that CCS cost will be expensive and countries that cannot use CCS economically or politically will continue to emit CO_2 .

Conclusion & Proposal

With *SimpLE*, in **Step 1**, by **reducing coking coal and surplus energy**, CO_2 can be reduced by 40-50% while not increasing the gross energy for iron-making. In **Step 2**, by **using waste instead of coal**, CO_2 can be reduced by 80% total while actually reducing the gross energy by >25%*^{6}. And in **Step 3**, by **also using CCS**, CO_2 can be reduced by 130% total without the need for DAC while actually reducing the gross energy by 10%.

In terms of **gross energy for ironmaking, any "DRF+Melter" requires more than twice as much as *SimpLE* to achieve CN with CCS**, and **"conv.BF+CCS" is the 2nd best. But its cost of CCS will be so large** as shown yeloow in Fig.1 (see Home Page/Steelmaking routes/ "CO_2 emissions and economic viability of major steelmaking routes" page 9/10). Even if the **CCS cost for CN** in Fig.1 is set so low as 100 \$/tCO_2, it **will be a large economic buden for the other routes than SimpLE** (② = Step 1, ③ = Step 2 in Fig.1).

SimpLE is **the only method satisfying CO_2 reduction, energy efficiency and economic efficiency.**



This graph is based on average unit price through 2020 to 2023 as recieved in Japan. Average exchange rate of the period is 116¥/\$. Surplus energy is evaluated as the same enegy price as steam coal.

Capex includes only retrofitting and/or remodeling cost for BF route including *SimpLE* and for each steelmaking shop in order for a steel maker to minimize the investment cost.

CO_2 emission factor of power in Japan is applied to all routes except Conv.BF.

Any DRF includes CO_2 from Pelletizing plant.

DRI made abroad with NG, H_2 price as 1/3 of Japan

*1) as of 2013

*2) Greenifying Utility power

*3) Ditto. Pellet plant fuel changed to Green H_2

*4) Utilizing surplus energy from neighboring BFs

Fig.1 Slab production cost (CP＝100\$/tCO_2)