Supplementary Material

This file includes:

Supplementary Notes 1-2

Supplementary Figures 1-7

Supplementary Tables 1-13

Table S7. Steel production projection

Table S8. GHG emission factor for wastewater and waste treatment

Table S9. Mean and standard deviation of logarithmic distribution of air pollutants emission factor

Table S10. Mean and standard deviation of logarithmic distribution of GHG emission factor

Table S11. Mean and standard deviation of logarithmic distribution of GHG emission factor for wastewater and waste treatment

Table S12. The proportion of impact categories in the integrated environmental impact

Table S13. The impact of each impact category's weight (±10 %) on the integrated environmental impact

Supplementary Notes

Note 1. Terminal treatment technology

Terminal treatment technology for particulate matter (PM) included cyclones (CYC), wet scrubber (WS), electrostatic precipitators (EPS) and fabric filter (FF). CYC utilized centrifugal force to separate PM from flue gas. WS utilized water to capture PM from flue gas. EPS utilized high-voltage electricity fields to ionize flue gas, causing PM in the gas stream to become charged and separate from the flue gas. FF utilized the filtration properties of fibrous fabrics to filter PM. Terminal treatment technology for SO_2 included wet flume gas desulfurization (WFGD). WFGD utilized alkaline solutions to absorb SO_2 from flue gas. Terminal treatment technology for NO_x included lower NO_x burner (LN) and selective catalytic reduction (SCR). LN optimized combustion structure of device to reduce NO_x emissions. SCR used NH_3 as a reducing agent to catalyze the reduction of NO_x to N_2.

In China, ultra-low emission (UL) for PM, SO_2 and NO_x had been implemented in response to stringent environmental policy requirements. UL referred to the terminal treatment technology with enhanced removal efficiency through technological upgrades and modifications.

Note 2. Sensitivity analysis of PM2.5 and PM10

The use of assumptions (PM2.5 accounted for 40 % of the TSP and PM10 accounted for 50 % of the TSP) in the absence of certain data introduced errors. The impact of PM2.5 emission factors (±10 %) and PM10 emission factors (±10 %) on total GHG emissions was examined. Results indicated that the impact of PM2.5 emission factors and PM10 emission factors on total GHG emissions was relatively minor (±0.01 %).

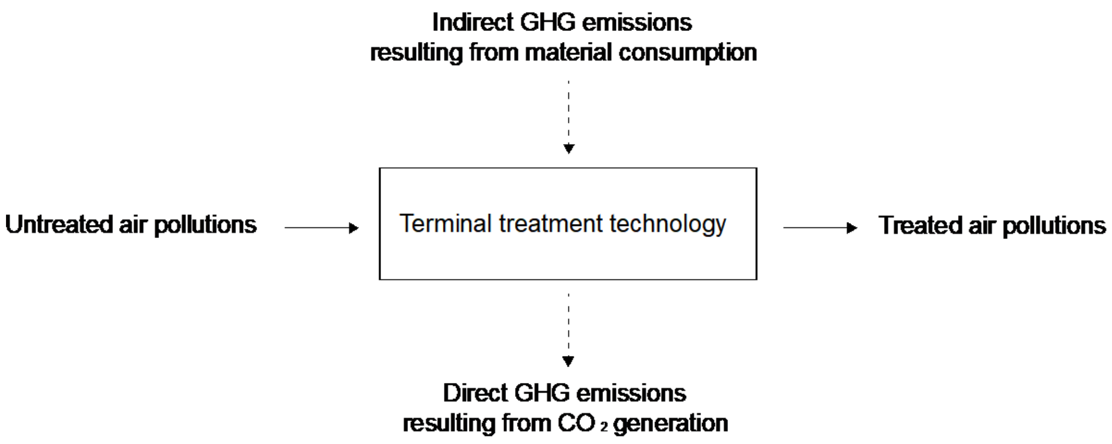

Fig. S1. System boundary for GHG emissions from terminal treatment technology

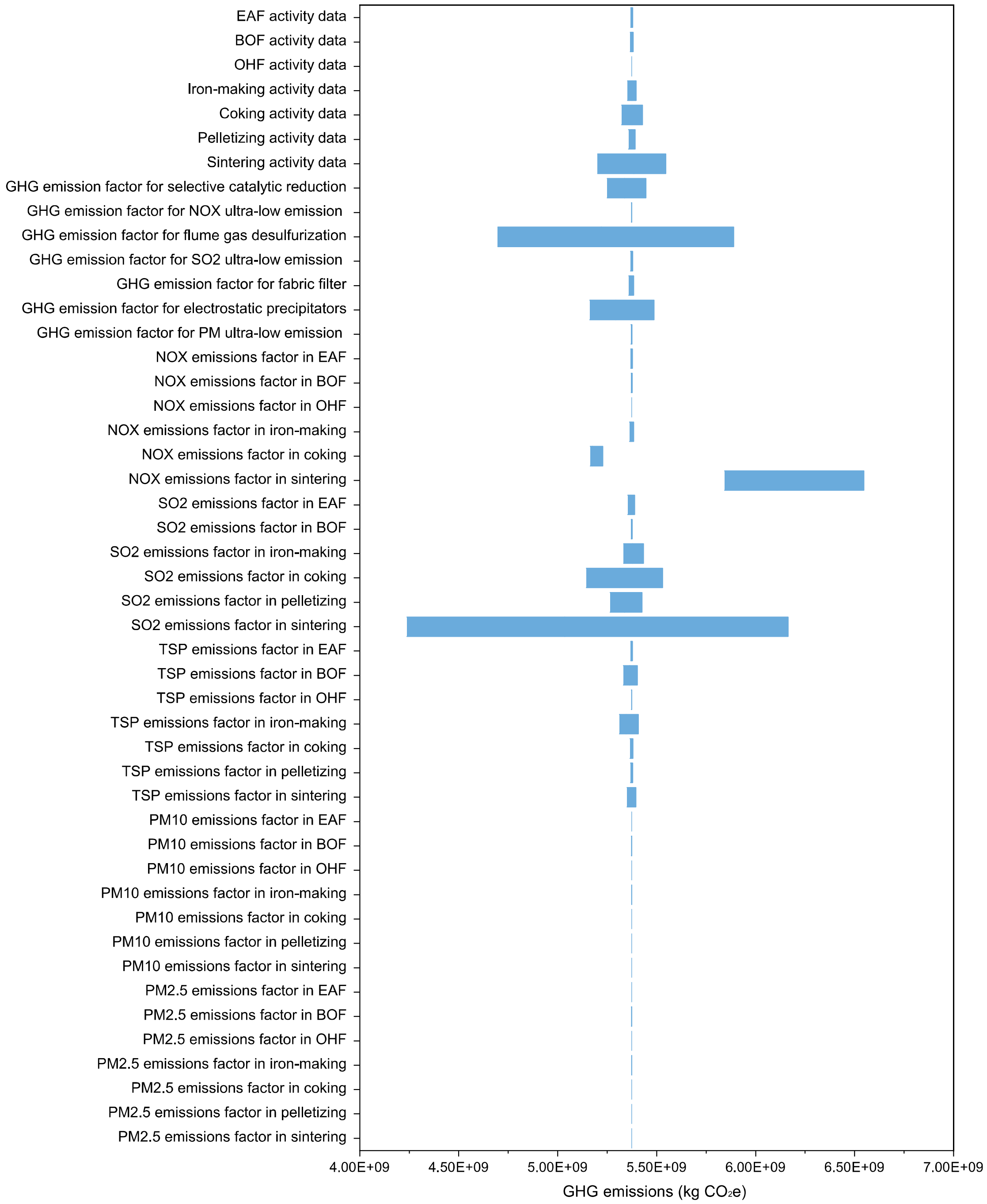

Fig. S2. Sensitivity analysis of the impact of various factors on total GHG emissions

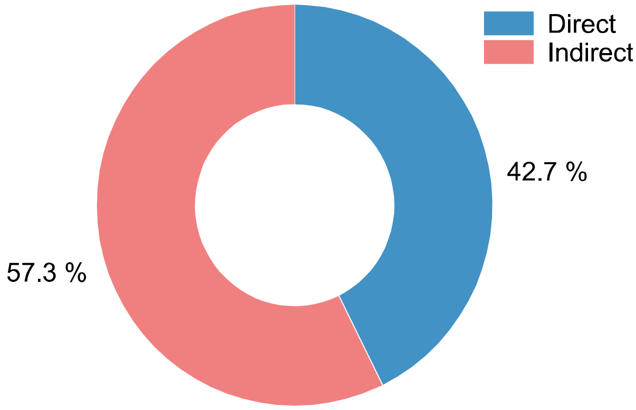

Fig. S3. Direct and indirect GHG emissions from SO_2 treatment

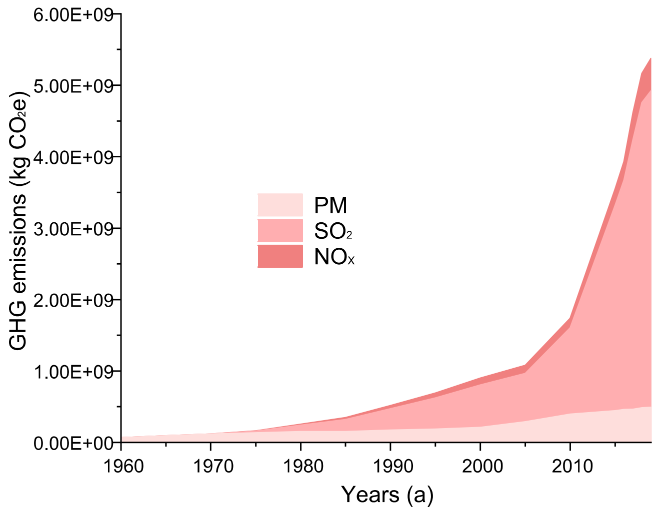

Fig. S4. Temporal distribution of GHG emissions from air pollutants treatment

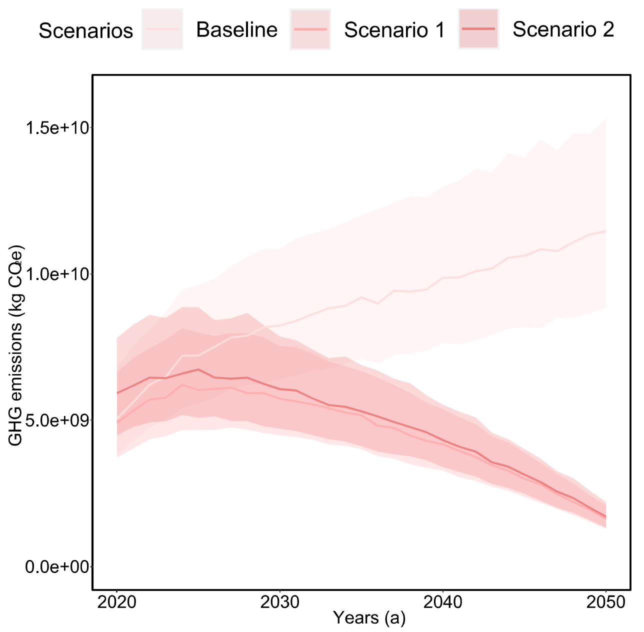

Fig. S5. Future GHG emissions from total air pollutants treatment

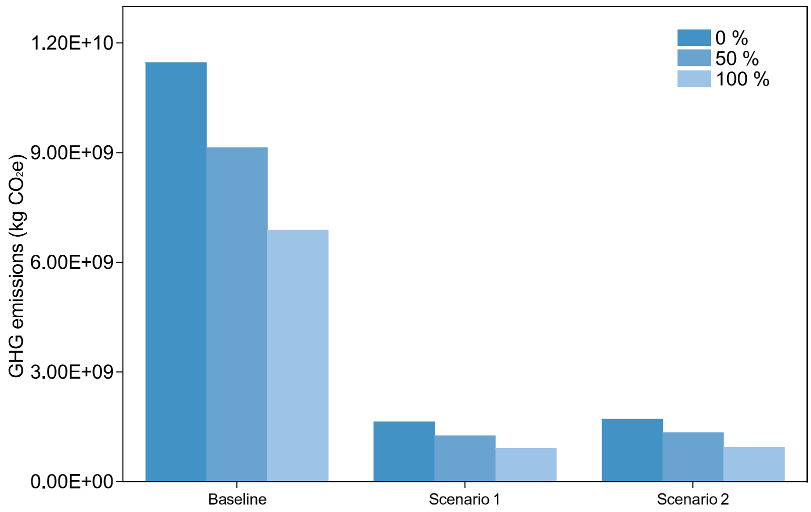

Fig. S6. The impact of electricity decarbonization levels on GHG emissions

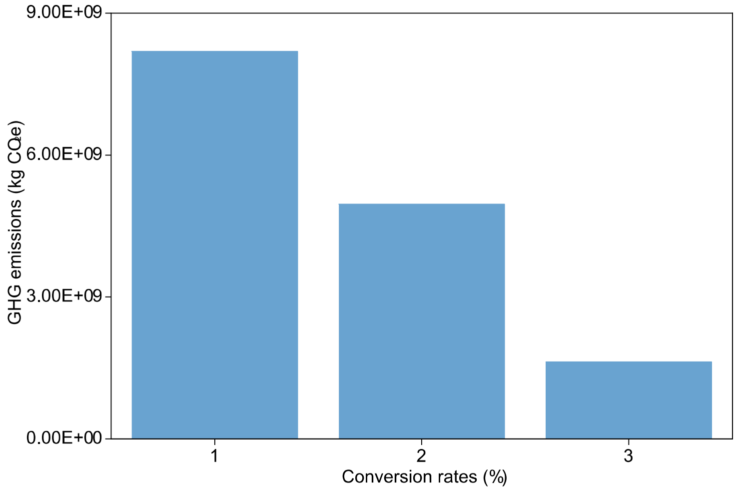

Fig. S7. The impact of conversion rates on GHG emissions

Table S1. Air pollutants emission factor (kg pollutant/t product) [a]

Process	$PM_{2.5}$	PM_{10}	TSP	SO_2	NO_x	Reference
Sintering	0.85	2.04	12.81	1.56	0.48	(Klimont et al., 2002; Fu et al., 2013; Wang et al., 2016b; Guo et al., 2017; Huang et al., 2017; He, 2018; Li et al., 2020; China, 2021; Yi et al., 2021; Zhang et al., 2023)
Pelletizing	0.70	1.61	10.73	0.34	0 [b]	(Permadi et al., 2017; China, 2021; Zhang et al., 2023)
Coking	3.75	5.49	9.64	1.58	2.15	(Klimont et al., 2002; Lei, 2008; Huang et al., 2011; Lei et al., 2011; Fu et al., 2013; Sun et al., 2016; Huang et al., 2017; China, 2021; CSES, 2024)
Iron-making	2.25	3.54	13.32	0.18	0.10	(Klimont et al., 2002; Fu et al., 2013; Wang et al., 2016b; He, 2018; China, 2021; Zhang et al., 2023)
OHF	10.89	15.07	18.15	0 [b]	0.05	(Klimont et al., 2002; Lei et al., 2011; Huang et al., 2017; Zhang et al., 2023)
BOF	10.15	14.21	20.31	0.003	0.02	(Klimont et al., 2002; Lei et al., 2011; Wang et al., 2016b; Huang et al., 2017; China, 2021; Zhang et al., 2023)
EAF	8.19	11.04	19.03	0.11	0.12	(Klimont et al., 2002; Lei et al., 2011; Wang et al., 2016b; Huang et al., 2017; Li et al., 2020; China, 2021; Zhang et al., 2023)

[a]: Product referred to the corresponding product in each production process (eg, pig iron during iron-making).

[b]: The air pollutant emission factor was not considered because there were few EFs reported in the literature.

Table S2. GHG emission factor

Terminal treatment technology	GHG emission factor	Reference
Cyclones	0 [a]	
Wet scrubber	0 [a]	
Electrostatic precipitators	0.0092 kg CO_2e/kg PM	(Hong, 2015; Han, 2016; Zhang, 2018; Dong et al., 2021)
Fabric filter	0.0028 kg CO_2e/kg PM	(Hong, 2015; Gao, 2023)
Flume gas desulfurization	1.91 kg CO_2e/kg SO_2	(Feng and Ma, 2011; Wang, 2012; Hong, 2015; Shi, 2016; Zhang, 2018; Ba, 2020; Dong et al., 2021; Gao, 2023)
Lower NO_x burner	0 [a]	
Selective catalytic reduction	0.69 kg CO_2e/kg NO_x	(Hong, 2015; Dong et al., 2021)
Ultra-low emission (PM)	0.0090 kg CO_2e/kg PM	(Zhang, 2018; Dong et al., 2021; Gao, 2023)
Ultra-low emission (SO_2)	1.87 kg CO_2e/kg SO_2	(Zhang, 2018; Ba, 2020; Dong et al., 2021)
Ultra-low emission (NO_x)	0.53 kg CO_2e/kg NO_x	(Zhang, 2018; Dong et al., 2021)

[a]: The GHG emission factor was not considered because there were few EFs reported in the literature.

Table S3. Parameters applied to calculate the proportion of terminal treatment technology for PM

Production process	Terminal treatment technology [b]	Parameters	Country			
			The USA	Other developed countries	China	Other developing countries
All	UL	IP			0	
		FP			1	
		s			2018	
		r			5.5	
Sintering, pelleting, coking, ironmaking [a]	UC	IP	1	1	1	1
		FP	0	0	0	0
		s	1907	1915	1955	1945
		r	25	25	20	25
	CYC		0	0	0.06	0.13
	WS		0.16	0.16	0.1	0.1
	ESP		0.74	0.74	0.76	0.72
	FF		0.1	0.1	0.08	0.05
EAF [a]	UC	IP	1	1	1	1
		FP	0	0	0	0
		s	1907	1915	1955	1945
		r	25	25	20	25
	CYC		0	0	0.05	0.12
	WS		0.6	0.6	0.55	0.55
	ESP		0.3	0.3	0.28	0.28
	FF		0.1	0.1	0.12	0.05
OHF [a]	UC	IP	1	1	1	1
		FP	0	0	0	0
		s	1907	1915	1955	1945
		r	25	25	20	25
	CYC		0	0	0	0
	WS		0.52	0.52	0.6	0.6
	ESP		0.48	0.48	0.4	0.4
	FF		0	0	0	0
BOF [a]	UC	IP	1	1	1	1
		FP	0	0	0	0
		s	1907	1915	1955	1945
		r	25	25	20	25
	CYC		0	0	0	0
	WS		0	0	0	0
	ESP		0.4	0.4	0.4	0.5
	FF		0.6	0.6	0.6	0.5

[a]: The proportion of UC was determined first, then the proportion of terminal treatment technology was directly determined based on the proportion among them.

[b]: UL: ultra-low emission; UC: uncontrolled; CYC: Cyclones; WS: wet scrubber; ESP: electrostatic precipitators; FF: fabric filter.

Table S4. Parameters applied to calculate the proportion of terminal treatment technology for SO_2

Production process	Terminal treatment technology [a]	Parameters	Country			
			The USA	Other developed countries	China [b]	Other developing countries
All	UL	IP			0	
		FP			1	
		s			2018	
		r			5.5	
	WFGD	IP	0	0	0	0
		FP	0.98	0.98	1	1
		s	1970	1970	2005	2004
		r	20	25	10	30
	UC					

[a]: UL: ultra-low emission; WFGD: wet flume gas desulfurization; UC: uncontrolled.

[b]: The proportion of terminal treatment technology for China in 2010-2019 needed to be adjusted, and the adjusted value refers to the study by Zhang et al. (2023).

Table S5. Parameters applied to calculate the proportion of terminal treatment technology for NO_x

Production process	Terminal treatment technology [a]	Parameters	Country			
			The USA	Other developed countries	China [b, c]	Other developing countries
All	UL	IP			0	
		FP			1	
		s			2018	
		r			5.5	
	SCR	IP	0	0	0	0
		FP	1	1	1	1
		s	1970	1990	2007	2015
		r	40	40	20	30
	LN	IP	0	0		0
		FP	1	1		1
		s	1976	1986		1990
		r	10	9.2		33
	UC	IP			1	
		FP			0	
		s			2006	
		r			20	

[a]: UL: ultra-low emission; SCR: selective catalytic reduction; LN: lower NO_x burner; UC: uncontrolled.

[b]: The proportion of UC for NO_x was calculated before lower NO_x burner technology for China.

[c]: The proportion of terminal treatment technology in 2010-2019 for China needed to be adjusted, and the adjusted value refers to the study by Zhang et al. (2023).

Table S6. Air pollutants removal efficiency (%) for terminal treatment technology

Terminal treatment technology [a]	$PM_{>10}$	$PM_{2.5\text{-}10}$	$PM_{2.5}$	SO_2	NO_x	Reference
CYC	90.00	75.00	15.00			(Huang et al., 2014; Zhang et al., 2023)
WS	96.50	85.00	60.00			(Huang et al., 2014; Zhang et al., 2023)
ESP	99.50	97.00	92.50			(Huang et al., 2014; Zhang et al., 2023)
FF	99.95	99.70	99.30			(Huang et al., 2014; Zhang et al., 2023)
WFGD				90.00		(Asghar et al., 2021; Zhang et al., 2023)
LN					45.00	(Asghar et al., 2021; Zhang et al., 2023)
SCR					80.00	(Asghar et al., 2021; Zhang et al., 2023)
UL	99.99	99.99	99.99	85.00	85.00	(Zhang et al., 2023)

[a]: CYC: Cyclones; WS: wet scrubber; ESP: electrostatic precipitators; FF: fabric filter; WFGD: wet flume gas desulfurization; LN: lower NO_x burner; SCR: selective catalytic reduction; UL: ultra-low emission.

Table S7. Steel production projection

Country	Annual growth rate (%)	Reference
China	-0.4	(Zhang et al., 2023)
Other developing countries	5.35	(Zhang et al., 2023)
The USA	0.3	(Zhang et al., 2023)
Other developed countries	0.24	(Zhang et al., 2023)

Table S8. GHG emission factor for wastewater and waste treatment

Type		GHG emission factor	Reference
Wastewater	Electricity	2.25 kg CO_2e/m^3	(Qin et al., 2022)
	Direct GHG emission	13.91 kg CO_2e/m^3	(Qin et al., 2022)
	Chemicals	2.06 kg CO_2e/m^3	(Qin et al., 2022)
Waste	Electricity	3.23 kg CO_2e/t slag	(Wang et al., 2016a)

Table S9. Mean and standard deviation of logarithmic distribution of air pollutants emission factor

Process	$PM_{2.5}$	PM_{10}	TSP	SO_2	NO_x	Reference
Sintering	-0.19, 0.21	0.70, 0.16	2.52, 0.25	0.31, 0.53	-0.89, 0.55	(Klimont et al., 2002; Fu et al., 2013; Wang et al., 2016b; Guo et al., 2017; Huang et al., 2017; He, 2018; Li et al., 2020; China, 2021; Yi et al., 2021; Zhang et al., 2023)
Pelletizing	-0.37, 0.18	0.46, 0.18	2.36, 0.18	-1.20, 0.5 [a]		(Permadi et al., 2017; China, 2021; Zhang et al., 2023)
Coking	1.22, 0.45	1.57, 0.51	2.17, 0.45	0.39, 0.37	-1.91, 2.31	(Klimont et al., 2002; Lei, 2008; Huang et al., 2011; Lei et al., 2011; Fu et al., 2013; Sun et al., 2016; Huang et al., 2017; China, 2021; CSES, 2024)
Iron-making	0.30, 1.01	0.77, 0.99	2.37, 0.67	-1.77, 0.25	-2.41, 0.5 [a]	(Klimont et al., 2002; Fu et al., 2013; Wang et al., 2016b; He, 2018; China, 2021; Zhang et al., 2023)
OHF	2.24, 0.55	2.56, 0.55	2.75, 0.55		-3.22, 0.5 [a]	(Klimont et al., 2002; Lei et al., 2011; Huang et al., 2017; Zhang et al., 2023)
BOF	2.24, 0.39	2.58, 0.39	2.93, 0.39	-5.81, 0.5 [a]	-3.91, 0.5 [a]	(Klimont et al., 2002; Lei et al., 2011; Wang et al., 2016b; Huang et al., 2017; China, 2021; Zhang et al., 2023)
EAF	2.07, 0.25	2.37, 0.25	2.91, 0.25	-2.30, 0.5 [a]	-2.21, 0.5 [a]	(Klimont et al., 2002; Lei et al., 2011; Wang et al., 2016b; Huang et al., 2017; Li et al., 2020; China, 2021; Zhang et al., 2023)

[a]: The standard deviation of logarithmic distribution was assumed to be 0.5 when only one air pollutants emission factor was collected.

Table S10. Mean and standard deviation of logarithmic distribution of GHG emission factor

Terminal treatment technology	Mean	Standard deviation	Reference
Cyclones			
Wet scrubber			
Electrostatic precipitators	-4.92	0.68	(Hong, 2015; Han, 2016; Zhang, 2018; Dong et al., 2021)
Fabric filter	-5.95	0.3	(Hong, 2015; Gao, 2023)
Flume gas desulfurization	0.62	0.20	(Feng and Ma, 2011; Wang, 2012; Hong, 2015; Shi, 2016; Zhang, 2018; Ba, 2020; Dong et al., 2021; Gao, 2023)
Lower NO_x burner			
Selective catalytic reduction	-0.44	0.35	(Hong, 2015; Dong et al., 2021)
Ultra-low emission (PM)	-4.82	0.46	(Zhang, 2018; Dong et al., 2021; Gao, 2023)
Ultra-low emission (SO_2)	0.62	0.11	(Zhang, 2018; Ba, 2020; Dong et al., 2021)
Ultra-low emission (NO_x)	-0.64	0.10	(Zhang, 2018; Dong et al., 2021)

Table S11. Mean and standard deviation of logarithmic distribution of GHG emission factor for wastewater and waste treatment

Type		Mean	Standard deviation	Reference
Wastewater	Electricity	0.81	0.019	(Qin et al., 2022)
	Direct GHG emissions	2.63	0.056	(Qin et al., 2022)
	Chemicals	0.63	0.44	(Qin et al., 2022)
Waste	Electricity	0.95	0.67	(Wang et al., 2016a)

Table S12. The proportion of impact categories in the integrated environmental impact

Type	PM (DE)	PM (T)	PM (UL)	SO_2 (DE)	SO_2 (T)	SO_2 (UL)	NO_x (DE)	NO_x (T)	NO_x (UL)
Abiotic depletion (%)	0.00	0.02	0.03	0.00	0.03	0.03	0.00	0.19	0.19
Abiotic depletion (fossil fuels) (%)	0.00	2.28	2.50	0.00	2.47	2.56	0.00	3.75	3.67
Global warming (GWP100a) (%)	0.00	1.31	1.46	0.00	2.12	2.36	0.00	1.51	1.47
Ozone layer depletion (ODP) (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Human toxicity (%)	100.00	0.32	0.32	0.03	0.32	0.32	0.56	0.43	0.42
Fresh water aquatic ecotoxicity (%)	0.00	5.19	5.13	0.00	5.10	5.07	0.00	4.15	4.11
Marine aquatic ecotoxicity (%)	0.00	88.43	88.00	0.00	87.44	87.07	0.00	87.00	87.19
Terrestrial ecotoxicity (%)	0.00	0.27	0.28	0.00	0.27	0.28	0.00	0.24	0.24
Photochemical oxidation (%)	0.00	0.13	0.15	11.73	0.15	0.15	0.00	0.30	0.30
Acidification (%)	0.00	1.01	1.08	88.24	1.07	1.11	63.94	1.74	1.75
Eutrophication (%)	0.00	1.03	1.04	0.00	1.03	1.05	35.50	0.67	0.65

Table S13. The impact of impact category's weight (±10 %) on the integrated environmental impact

Type	PM (DE)	PM (T)	PM (UL)	SO_2 (DE)	SO_2 (T)	SO_2 (UL)	NO_x (DE)	NO_x (T)	NO_x (UL)
Abiotic depletion (± %)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02
Abiotic depletion (fossil fuels) (± %)	0.00	0.23	0.25	0.00	0.25	0.26	0.00	0.38	0.37
Global warming (GWP100a) (± %)	0.00	0.13	0.15	0.00	0.21	0.24	0.00	0.15	0.15
Ozone layer depletion (ODP) (± %)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Human toxicity (± %)	10.00	0.03	0.03	0.00	0.03	0.03	0.06	0.04	0.04
Fresh water aquatic ecotoxicity (± %)	0.00	0.52	0.51	0.00	0.51	0.51	0.00	0.42	0.41
Marine aquatic ecotoxicity (± %)	0.00	8.84	8.80	0.00	8.74	8.71	0.00	8.70	8.72
Terrestrial ecotoxicity (± %)	0.00	0.03	0.03	0.00	0.03	0.03	0.00	0.02	0.02
Photochemical oxidation (± %)	0.00	0.01	0.01	1.17	0.01	0.02	0.00	0.03	0.03
Acidification (± %)	0.00	0.10	0.11	8.82	0.11	0.11	6.39	0.17	0.17
Eutrophication (± %)	0.00	0.10	0.10	0.00	0.10	0.10	3.55	0.07	0.07

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