Avoiding overestimations of mitigation potential and cost of CCUS in China's steel industry: a soft-linking approach

Supplementary information:

Supplementary tables: 11.

Supplementary figures: 7.

Supplementary notes: 3.

Supplementary references.

Table S1 The crude steel production outputs in three scenarios (Unit: Mt)

Time	REF	PDM	DME
2020	1053.0	1053.0	1053.0
2025	1043.8	1030.7	1029.6
2030	965.5	941.4	931.0
2035	920.3	885.8	879.8
2040	879.6	835.6	830.7
2045	843.6	790.9	782.0
2050	793.7	734.1	711.0
2055	759.6	693.1	634.6
2060	746.5	671.8	578.6

Note: Setting basis -

Reference (REF) scenario: the average of the reports by international agencies and a study[1–3];

Production demand mitigation (PDM) scenario: reducing the steel demand by 1.25% per five years compared with the REF scenario.

Deep material efficiency (DME) scenario: following the reports' prediction that the cumulative emission will decrease by 26% in 2060 from material efficiency[1] to set the production outputs.

Table S2 The list of oil field sinks

No.	Name	Storage capacity (Mt)	No.	Name	Storage capacity (Mt)
1	Saertu (Daqing Complex)	565.1	36	Panyu	18.4
2	Jiyuan (Changqing)	123.8	37	Shuguang (Liaohe) -1	17.9
3	Lamadian (Daqing Complex)	99.5	38	Shuguang (Liaohe) -2	16.0
4	Penglai	90.1	39	Binnan (Shengli Complex)	15.7
5	Xingshugang (Daqing Complex)	85.9	40	Chaoyanggou	15.6
6	Shengtuo (Shengli Complex)	73.7	41	Songfangtun	15.4
7	Bozhong	55.1	42	Shidong 1	15.1
8	Huanxiling (Liaohe Depression)	54.5	43	Chengdong (Shengli Complex)	14.7
9	Renqiu (Huabei Complex)	53.9	44	Aihu	14.5
10	Gudao (Shengli Complex)	52.4	45	Shinan	13.8
11	Karamay Complex	50.7	46	Xianhezhuang (Shengli Complex)	13.7
12	Xijiang 24-3	48.0	47	Liuhua 11-1	13.0
13	Gudong (Shengli Complex)	37.4	48	Nanpu (Jidong)	12.8
14	Huizhou	34.9	49	Longhupao	12.5
15	Gasikule	34.4	50	Liangjialou (Shengli Complex)	12.4
16	Linpan (Shengli Complex)	34.3	51	Yongle	12.4
17	Suizhong 36-1	34.0	52	Gulong (PetroChina-DQ)	12.3
18	Dongxin (Shengli Complex)	33.2	53	Huo'erguosi	12.1
19	Huanjiang	30.4	54	Shanghe (Shengli	11.7

	(Changqing)			Complex)	
20	Luda 5-2	30.2	55	Hadexun	11.3
21	Tahe Complex	29.0	56	Wuqi (Yanchang)	11.2
22	Qinhuangdao 32-6	28.9	57	Honghe	11.1
23	Kenli (Shengli Complex)	28.7	58	Hongshanzui	10.9
24	Chengdao (Shengli Complex)	25.2	59	Beier	10.9
25	Tazhong	24.0	60	Taipingtun (Daqing Complex)	10.9
26	Beidagang	23.8	61	Kunbei	10.8
27	Jingbian (Yanchang)	23.5	62	Luliang	10.7
28	Caofeidian 01-6	22.7	63	Bamianhe (Shengli Complex)	10.7
29	Lufeng 13-2	22.5	64	Lengjiapu (Liaohe Depression)	10.4
30	Xifeng (Changqing)	22.1	65	Chunfeng (Shengli Complex)	10.3
31	Fuyu	21.5	66	Nanliang (Changqing)	10.3
32	Jing'anpu (Damintun Sag)	21.1	67	Zhenbei (Changqing)	10.3
33	Daqingzijing	20.3	68	Moliqing	10.2
34	Baikouquan	20.3	69	Gaosheng (Liaohe Depression)	10.2
35	Da'an	19.9	70	Zhaozhou	10.0

(Source: Ref[4,5])

Table S3 The list of basin sinks

No.	Name	Storage capacity (Mt)
1	Hailar Basin	16100
2	Songliao Basin	227800
3	Bayanhuxu-Eren Basin	85000
4	Junggar Basin	197100
5	Turpan-Hami Basin	54000
6	Tarim Basin	745800
7	Bohai Bay Basin	323200
8	Jiuquan-Minle Basin	559
9	Ordos Basin	256500
10	Qaidam Basin	21500
11	North Yellow Sea Basin	31500
12	Quinshi-Linfen Basin	29000
13	Northern South Yellow Sea Basin	133800
14	Northern Jiangsu-Southern South Yellow Sea Basin	89900
15	East China Sea Shelf Basin	341800
16	Nanyang-Xiangfang Basin	7500
17	Sichuan Basin	77600
18	Jianghan Basin	26400
19	Dongting Basin	26400
20	Northwestern Taiwan Basin	11000
21	Southwestern Taiwan Basin	10000
22	Sanshui Basin	10000
23	Zhujiangkou (Pearl R. Mouth) Basin	68700
24	Beibu Gulf Basin	23800

(Source: Ref[6])

Table S4 The relationship between pipeline diameters and transportation capacities

Pipeline diameter (inch)	Transportation capacity (Mt/a)
8	0.54-1.13
12	1.13-3.25
16	3.25-6.86
20	6.86-12.26
24	12.26-19.69
30	19.69-35.16

(Source: Ref[7])

Table S5 The emission intensity of the production modes

Production mode	Emission intensity (t CO_2/t steel)
BF-BOF + Coal	2.20
BF-BOF + Coal & CCUS	0.81
BF-BOF + Coal & Hydrogen	1.21
DRI-EAF + Natural gas	1.08
DRI-EAF + Natural gas + CCUS	0.57
DRI-EAF + Hydrogen	0.44
Scrap-EAF	0.34

(Source: Ref[1,8,9])

Table S6 The list of energy-efficient technology

No.	Process	Technology	CO_2 mitigation effect (kg/t product)
T1	Coking	High temperature-pressure coke quenching	35.8
T2		Coal moisture control	9.9
T3		High thermal conductivity and density silicon brick for large coke oven	17.9
T4		Coke oven carbonization chamber waste gas recovery and automatic pressure adjustment	15.4
T5	Sintering	Heat recovery from sinter cooler	12.3
T6		Thick layer sintering	3.9
T7		Reducing sinter air leakage	4.8
T8	Ironmaking (BF)	Double preheating for hot blast stove	26.0
T9		Top-pressure recovery turbines	52.1
T10		High-efficiency coal injection	60.4
T11		Blast furnace dehumidification technology	30.2
T12		Rotary-cut high temperature top combustion blast stove	14.7
T13		Optimization technology of combustion system in carbon ring roaster	7.1
T14		Intelligent large-scale blast furnace based on optimization of furnace gas volume index	35.2
T15		Screw expansion power reutilization for driving energy	6.9
T16		Gas turbine energy replacement	14.2
T17		Comprehensive utilization of gaseous secondary energy rich in carbon monoxide	219.6
T18		Direct heat exchange of blast furnace slag flushing water to recover waste heat	28.8
T19	Steel making (BOF)	Converter negative energy steelmaking technology	21.8
T20		Energy monitoring and management	15.8
T21		Converter gas dry recovery	5.7
T22		Regenerative rotary hearth furnace	5.4

		for metallurgical dust treatment to recover iron and zinc	
T23		High-temperature flue gas dry purification and recycling from fully enclosed mine furnace	68.5
T24	Steel making (EAF)	Small ball sintering technology	13.1
T25		Overall optimization of cold stamping	1.6
T26		Optimization of power supply in EAF	9.3
T27		Scrap processing and pretreatment technology	3.9
T28		Replacement of electrode paste with special carbon electrode in ferroalloy smelting	143.0
T29		Flue gas waste heat recovery	7.7
T30	General technology	Black body strengthening radiation in heating furnace	25.5
T31		Medium and heavy plate online heat treatment technology	28.1
T32		Low-temperature rolling technology	30.8
T33		High ductility cold rolled ribbed steel plate screws	21.3
T34		Hot rolling residual heat recovery	26.5
T35		Cold rolling residual heat recovery	10.2
T36		Continuous casting technology	36.7
T37		Integrated casting and rolling	34.9
T38		Recuperative or regenerative burner	46.0
T39		Combined cycle power plant-CCPP	54.6
T40		Hot delivery and charging of casting billet	33.5
T41		Automated monitoring system	24.0

(Source: Ref[10–13])

Table S7 Steel product outputs by province in 2019 (Unit: Mt)

Province	Coke	Sinter	Pellet	Iron	Crude steel
Beijing	0.00	0.00	0.00	0.00	0.00
Tianjin	0.00	22.98	1.70	15.50	15.77
Hebei	19.94	364.02	85.70	244.74	261.70
Shanxi	5.57	65.72	19.10	44.50	53.59
Inner Mongolia	5.26	33.32	10.61	24.17	26.01
Liaoning	9.53	95.46	26.27	67.17	68.79
Jilin	2.92	9.37	3.38	6.25	10.12
Heilongjiang	1.23	4.17	1.57	4.35	7.36
Shanghai	6.35	17.59	0.00	14.52	13.55
Jiangsu	9.05	136.36	16.63	108.27	110.91
Zhejiang	2.20	12.28	0.35	6.37	13.17
Anhui	8.61	37.11	10.23	28.46	33.59
Fujian	0.90	21.70	1.18	15.77	25.04
Jiangxi	2.97	32.15	4.29	21.42	24.55
Shandong	9.78	123.71	8.88	83.18	77.61
Henan	1.60	35.92	5.05	28.00	34.66
Hubei	3.82	29.95	5.02	9.86	33.73
Hunan	1.29	29.17	2.41	19.82	23.77
Guangdong	7.03	26.85	4.01	22.45	33.94
Guangxi	6.50	35.44	3.35	25.39	33.19
Hainan	0.00	0.00	0.00	0.00	0.00
Chongqing	3.08	8.50	0.00	5.50	6.82
Sichuan	0.53	28.52	8.12	17.45	26.81
Guizhou	0.88	5.97	0.00	4.17	6.23
Yunnan	0.00	18.09	4.60	15.39	14.54
Tibet	0.00	0.00	0.00	0.00	0.00
Shaanxi	0.00	16.26	2.61	9.33	7.37

Gansu	3.10	7.87	5.65	7.69	10.49
Qinghai	0.00	1.66	0.00	1.08	1.26
Ningxia	0.00	4.54	0.07	3.10	3.05
Xinjiang	1.93	14.75	4.04	10.08	10.17
Total	114.14	1239.43	234.82	863.98	987.80

(Source: Ref[14–16])

Table S8 Direct emission intensity of the equipment

Process	Equipment	CO_2 emission intensity (kg/t product)
Coking	Coke oven <4.3 m	369.89
	Coke oven 4.3-6 m	357.96
	Coke oven >6 m	343.05
Sintering	Sintering machine <90 m^2	138.50
	Sintering machine 90-180 m^2	133.73
	Sintering machine 180-400 m^2	121.79
	Sintering machine >400 m^2	114.62
Pelleting	Shaft furnace	98.05
	Ribbon roasting furnace	59.82
	Grate-kiln oxidized pelleting	74.15
Ironmaking	BF 350-1000 m^3	1677.06
	BF 1000-2500 m^3	1626.31
	BF 2500-4000 m^3	1462.96
	BF >4000 m^3	1401.33
	DRI - Natural gas	250.00
	DRI - Hydrogen	0.00
Steel making	BOF <100 t	33.29
	BOF 100-200 t	31.70
	BOF >200 t	28.53
	EAF <50 t	0.00
	EAF 50-100 t	0.00
	EAF >100 t	0.00

(Source: Ref[10,17])

Table S9 The key parameter of the source-sink matching model

Parameter	Value	Reference
R_{cap}	0.95	Ref[18,19]
P_{cap}	95 CNY/t CO_2	Ref[20]
PC	145174 CNY/(inch·km)	Ref[7]
DMI	1.1	Ref[21]
δ	0.55	Ref[21]
r	0.08225	Ref[22]
θ	5.7 t CO_2/t oil	Ref[23]
P_{oil}	517.5 CNY/Barrel	Ref[24]
P_{sto}	22.5 CNY/t CO_2	Ref[20]

Table S10 Parameter of energy and water consumptions

Parameter	Value	Reference
EI_{cap}	2.3 GJ/t CO_2	Ref[25]
EI_{tra}	1.3 kWh/(t CO_2·km)	Ref[26]
EI_{sto}	10 kWh/t CO_2	Ref[26]
WI_{cap}	2.8 t/t CO_2	Ref[27]
WI_{tra}	0.42 t/t CO_2	Ref[28]
η	1.5 t/t CO_2	Ref[28]

Table S11 The summary of division approaches of the decarbonization pathways

Process	REF	PDM	DME
Coking	/	/	Eliminating all coke ovens <4.3 m
Sintering	Eliminating all sinter machine < 360 m^2	Eliminating all sinter machine < 360 m^2 and the machine = 360 m^2 in service before 2000	Eliminating all sinter machine < 360 m^2 and the machine = 360 m^2 in service before 2008
Pelleting	Enhancing the production outputs of Grate-kiln oxidized pelleting by 11.54 Mt	/	Eliminating all pelleting equipment in service before 2010
Ironmaking	Eliminating all blast furnace < 1080 m^3; Replacing all blast furnace between 1080-1680 m^3 with DRI equipment fueled by natural gas	Eliminating all blast furnace < 1080 m^3; Eliminating all blast furnace = 1080 m^3 in service before 2000; Replacing all blast furnace between 1080-2000 m^3 with DRI equipment fueled by natural gas	Eliminating all blast furnace < 1280 m^3; Replacing all blast furnace between 1280-2500 m^3 with DRI equipment fueled by natural gas

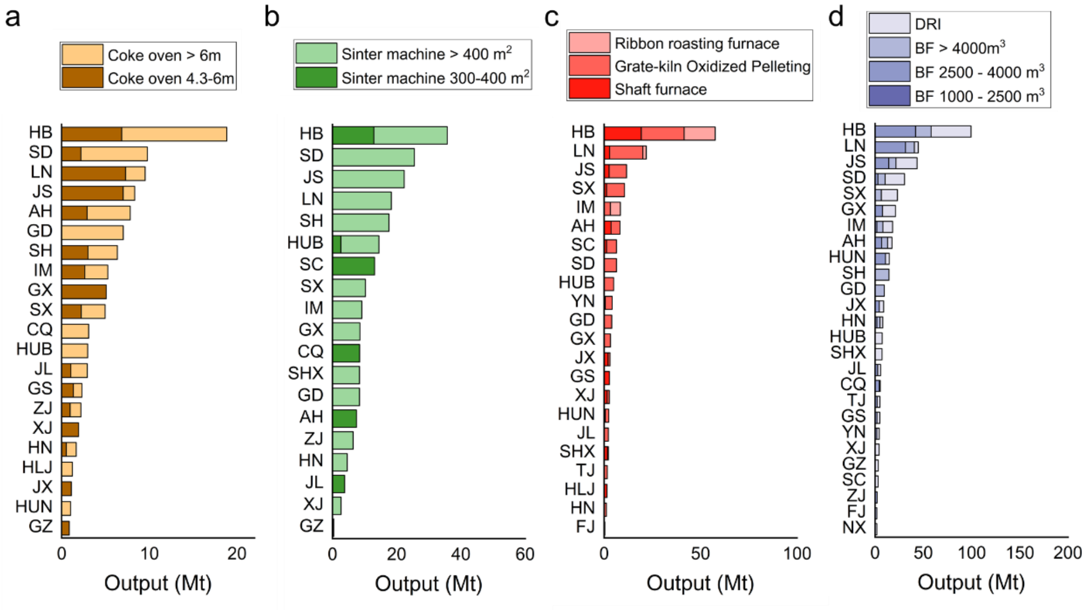

Fig. S1 The production structures of **a** coke, **b** sinter, **c** pellet, and **d** pig iron in each province by equipment type in PDM scenario

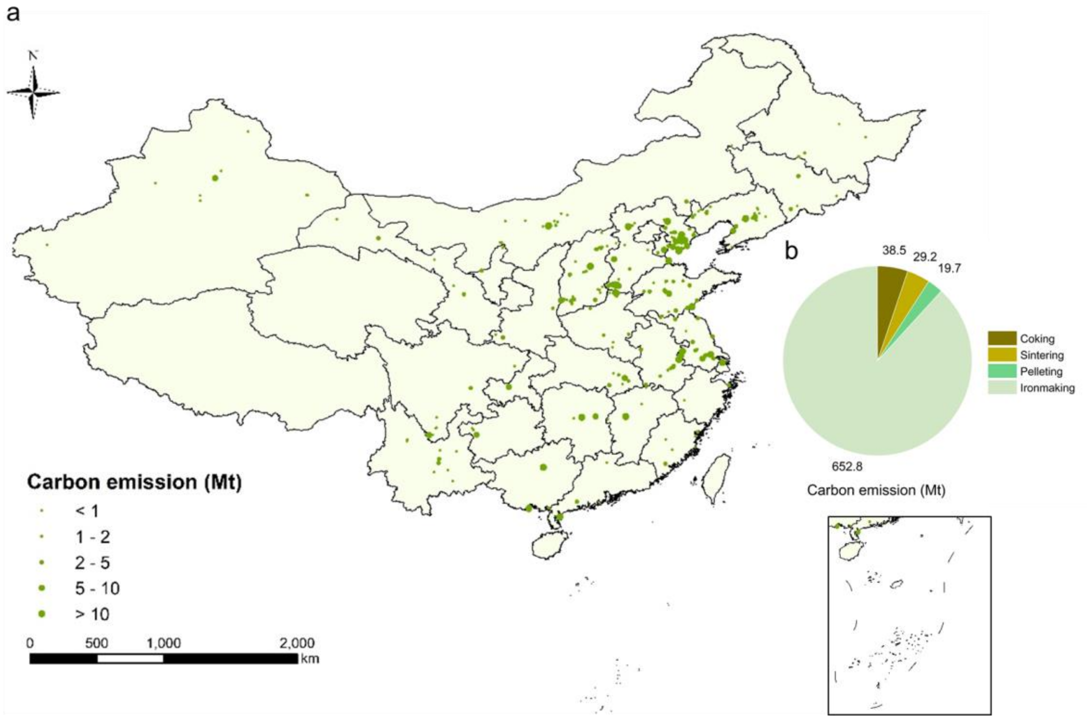

Fig. S2 The **a** spatial distribution of carbon emissions from the steel production units and **b** summary by products in PDM scenario.

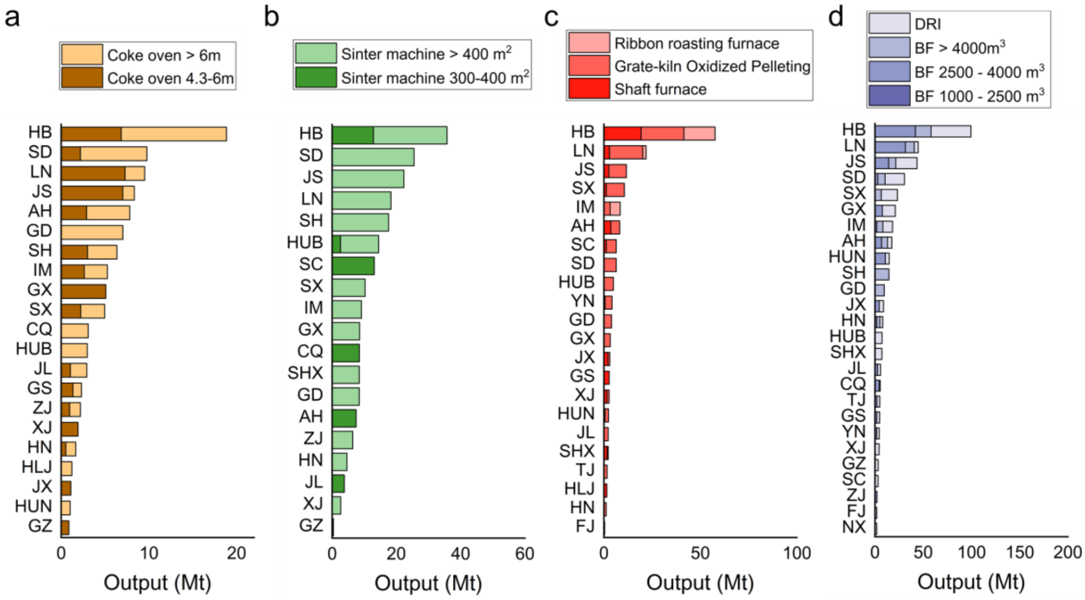

Fig. S3 The production structures of **a** coke, **b** sinter, **c** pellet, and **d** pig iron in each province by equipment type in DME scenario

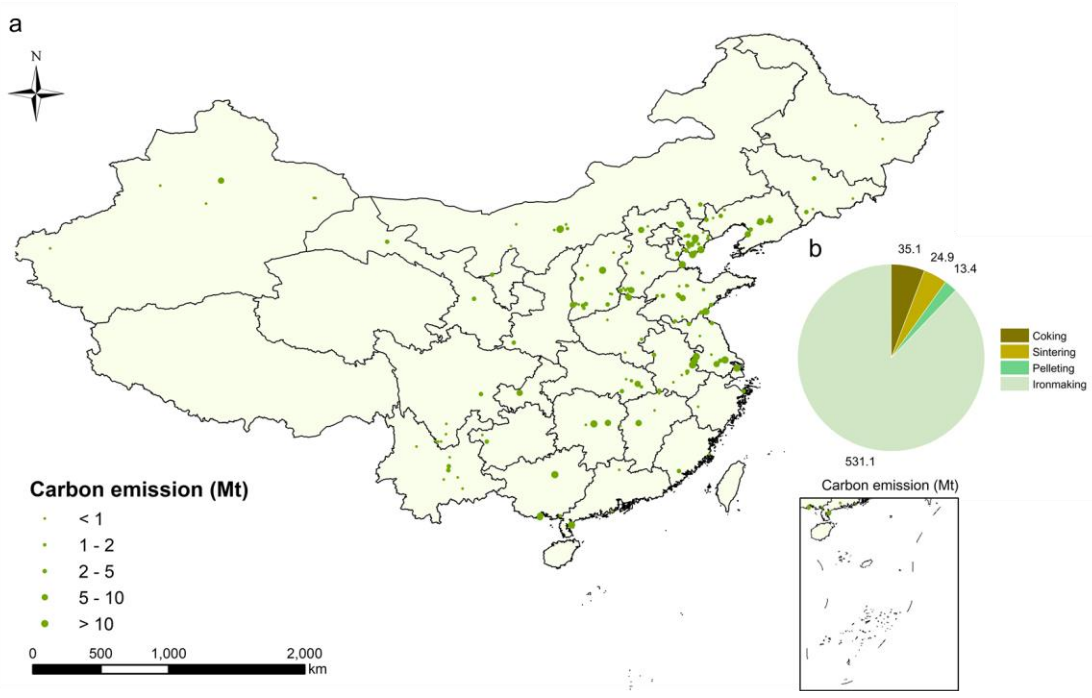

Fig. S4 The **a** spatial distribution of carbon emissions from the steel production units and **b** summary by products in DME scenario.

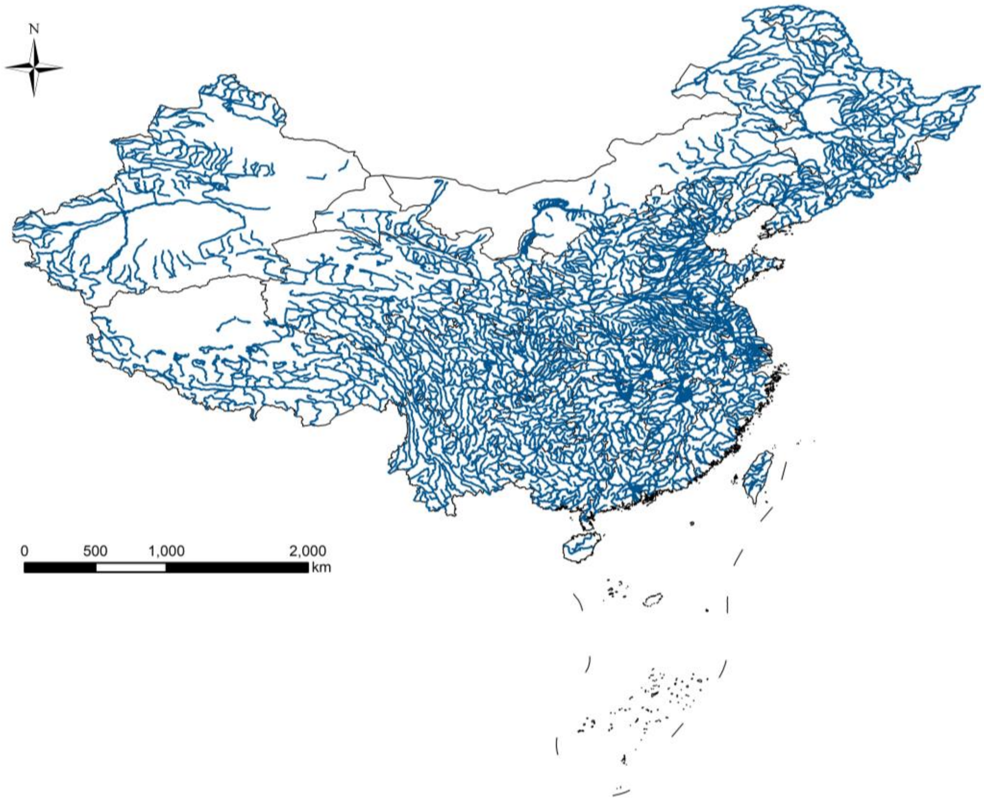

Fig. S5 The spatial distribution of river obstacles

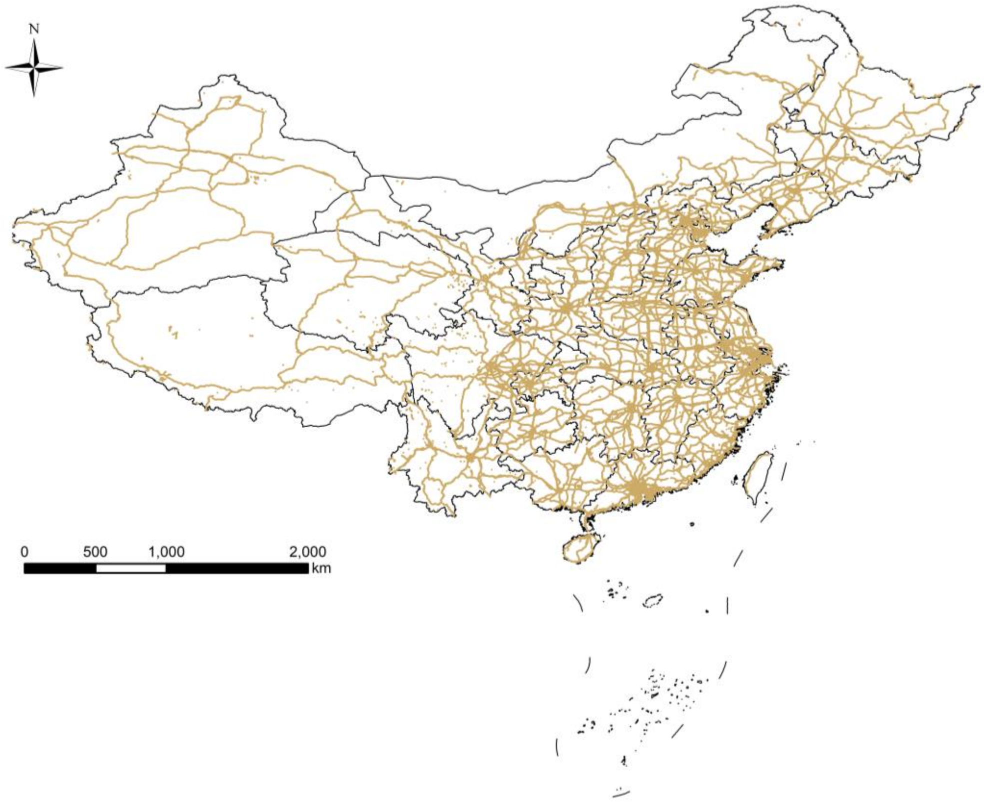

Fig. S6 The spatial distribution of road obstacles

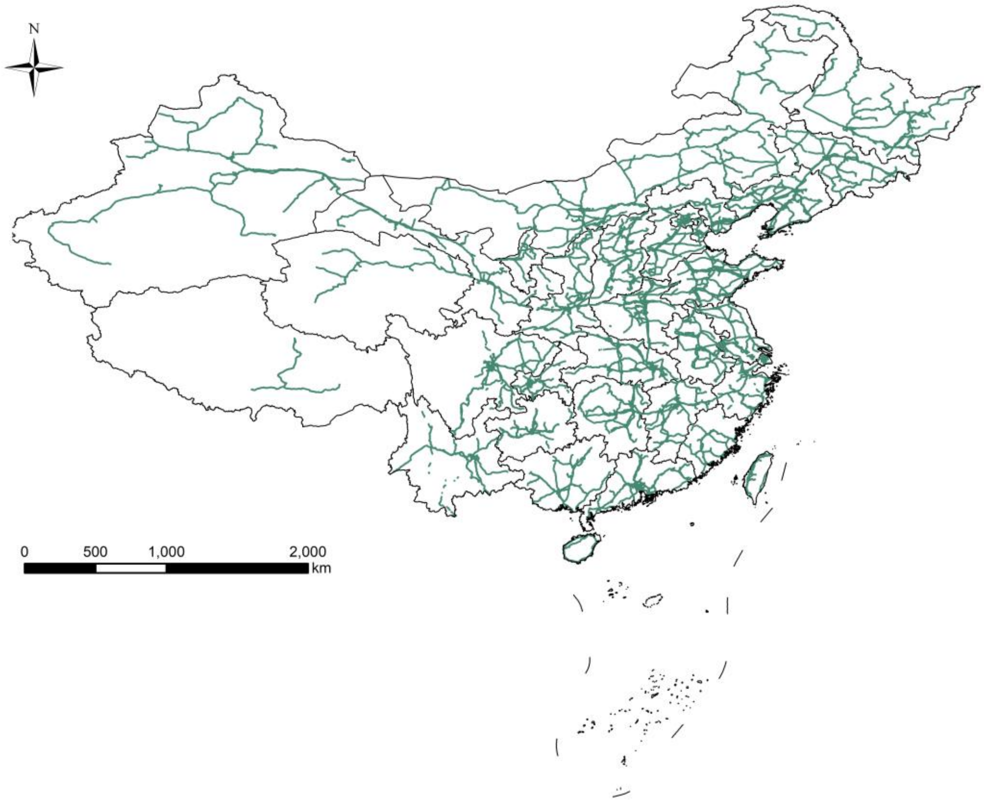

Fig. S7 The spatial distribution of railway obstacles

Supplementary Note 1: The prediction of production mode and EETs in China's steel industry

This study predicts the proportions of the eight production modes and the penetration rates of the EETs to find feasible decarbonization pathways. The first parameter for prediction is the proportions of long- and short-process production mode. The long-process production mode adopts iron ore as raw materials to produce sinter by sintering machine, followed by ironmaking and steel making processes with blast furnace (BF) and basic oxygen furnace (BOF) equipment. On the contrary, short-process adopts the pellet or steel scrap as raw material. The iron oxidation is reduced by natural gas or hydrogen and refined by electric arc furnace (EAF) to produce the crude steel. The short process is much less emission-intensive as it abandons the BF furnace, so it is estimated to promote widely in the future. Previous studies estimated that the proportions of DRI-EAF and scrap-EAF modes will exceed 55% in 2060[3,8]. However, a key limitation to the short process's promotion is the supply of steel scrap, and thus the proportions have upper boundaries. Considering these two factors, this study sets the proportions of short-process production mode as 56% under REF scenario and 60% under PDM and DME scenarios. The proportions are higher under PDM and DME scenarios since the total steel production outputs are less than REF scenario, requiring less scrap supplies.

For the short process, it is estimated that to achieve the carbon neutral target, all BF-BOF production mode, without retrofitting by CCUS technology or hydrogen, will be eliminated gradually before 2060[29]. In this situation, this study predicts that the proportions of BF-BOF production mode will decline by 12-15% per five years from the current level, and finally fall down to 0% in 2060. In terms of the two retrofitting measures, CCUS technology and hydrogen, they are all suffering high costs for wide application, while the large-scale hydrogen metallurgy technology is much more immature[30,31]. The National Energy Administration has issued a medium- and long-term planning about the hydrogen industry. According to the plan[32], the technology of hydrogen production by renewable energy will become mature in 2030, while the application of hydrogen energy will be promoted before 2035. Therefore, this study predicts that the BF-BOF & Coal + Hydrogen production mode will appear in 2030 and promote by 1-2% per five years. Following this trend, the proportions of this mode are predicted to be 8%, 4%, and 4% under REF, PDM, and DME scenarios. The rest short-process production mode is all retrofitted by CCUS, whose proportions are predicted to be 36% under all three scenarios.

For the short process, there are totally four types of production mode: scrap-EAF, DRI-EAF + Natural gas, DRI-EAF + Natural gas & CCUS, and DRI-EAF + Hydrogen. Though scrap-EAF is the production mode with lowest emission intensity, the promotion is affected by the scrap supplies from retired machinery, vehicle, or buildings[33,34]. Therefore, this study predicts that the proportions of scrap-EAF will rise by 2-3% per five years since 2020, which will reach 22%, 24%, and 29% in 2060 under REF, PDM, and DME scenarios. Moreover, since hydrogen is a strong reducing agent, it is estimated to have higher applications in DRI equipment than in BF one. In this situation, this study predicts that the proportions of DRI-EAF + Hydrogen production mode will promote by 2% per five years since 2030, and reach 12% under the three scenarios. In addition, since natural gas is much less emission-intensive than coal, not all DRI-EAF equipment should be retrofitted. Thus, there are still 10-12% of crude steel that is produced by DRI-EAF + Natural gas production mode. Therefore, the proportions of DRI-EAF + Natural gas & CCUS are predicted to increase gradually by time, reaching 12%, 10%, and 9% under REF, PDM, and DME scenarios, respectively.

Finally, this study assumes that the EETs will promote continuously until they exceed the upper boundary of their application production equipment. The penetration rates, i.e. the proportions of steel outputs using a technology to the total outputs, is predicted to increase by 1% per year. The upper boundary of the EETs depends on the proportions of the related production mode. For example, the BF-BOF production modes are predicted to have the proportions of 44% in 2060 under REF scenario, and thus the penetration rates of the EETs applying to sintering, coking, and ironmaking (blast furnace) processes should not exceed 44%.

Supplementary Note 2: The division approach of the decarbonization pathways

Though feasible pathways for China's steel industry are put forward to reach carbon neutrality targets under different scenarios, it is still difficult to simulate the emission sources because of several reasons. First, the categories of the steel production units are much more diverse than the production mode. For example, all coking, sintering, ironmaking (BF), and steel making (BOF) units belong to BF-BOF production routes, while all pelleting and steel making (EAF) belong to EAF ones. However, these units may locate in different enterprises, and thus the changes of an individual production mode will influence a series of units in practice. Second, the principles of division approaches are unclear. For example, all BF-BOF + Coal production mode will be either eliminated or retrofitted by CCUS and hydrogen, but it is difficult to choose what measures to be taken for each unit. Though the National Development and Reform Committee issued a document to guide the promotion and elimination of the equipment and technology, it can only provide general guidance before 2035 and cannot support the division of pathways. In addition, since the purpose of this study is to find the optimal CCUS layouts, the emission sources without retrofitting by CCUS and hydrogen (the substitution measure of CCUS) should be simulated. This is a virtual situation that will not happen in practice, and thus furtherly enhance the difficulties for proper division.

Consequently, this study proposes a division approach of the decarbonization pathways. This two-phase approach is fulfilled by integrating the production units' detailed features to the pathways. The first phase is to set the outputs of each process products. This study refers to the concept of steel ratio, i.e. the ratio between the mass of other products and the mass of crude steel ones, to simulate the outputs. Due to the law of conservation of mass, the steel ratios are estimated to keep unchanged in the future. By referring to previous research[35–38], this study sets the coke/BF-BOF steel, sinter/ BF-BOF steel, and pellet/DRI-EAF, and iron/steel ratios as 0.45, 0.97, 0.97, and 0.99, respectively. The outputs of the products are predicted according to the production mode structure of the pathways. Under REF scenario, the outputs of coke, sinter, pellet, and pig iron are 147.80 Mt, 318.60 Mt, 246.19 Mt, and 576.44 Mt, respectively.

Meanwhile, the outputs of these four products are 120.93 Mt, 260.67 Mt, 234.61 Mt, and 505.49 Mt under PDM scenario and 101.54 Mt, 218.88 Mt, 179.60 Mt, and 406.70 Mt under DME scenario, respectively.

The second phase is to select the units to take the measures. This study considers the key features of each type of equipment, e.g. the height of coke oven, the square of sinter machine, and the volume of blast furnace. In the case of screening the measures to take in some of the units at the same level, the study selects them in order from the year they are in service. Then, the measures are taken in order from the backward to the advanced equipment, e.g. from shorter to higher coke oven, from smaller to higher sinter machine, and from smaller to higher blast furnace. Based on this principle and the assumptions in Methods section, this study sets the division approaches of the pathways under the three scenarios, which is summarized in Table S11.

By these two-phase approach, the material efficiency and natural gas measures are divided into the unit level. In terms of the other measures, the electrification and scrap recycling measures mainly cause indirect carbon emissions from electricity consumption. Hence, these two measures will not affect the emission sources of the steel industry and are not divided. For the EETs, since the unit-level technology application data is lacking, this study assumes that the emission mitigation effects by the EETs will be distributed evenly in each unit. Therefore, the emission intensities of the equipment will decrease by the EETs. See equation (2) for the calculation methods.

Supplementary Note 3: The details of obstacle weighted index method

This study collects the locations of river, railway, and road in China from the National Basic Geographic Information Database[39]. This database divides the whole land area of China into 77 vector graphics at a scale of 1:1000000, containing a series of basic geographical elements. To obtain the full vector graphics, this study merges these 77 graphics and selects river, railway, and road as the obstacles, which are shown in Fig. S5-7.

To count the times each feasible route crosses the obstacles, this study uses ArcGIS software, a widely-used GIS platform to generate all feasible routes (i.e. the routes with straight line distances of less than 800 km). One should note that the feasible routes between an emission source and a basin will be diverse since the carbon can be transported to the border of the basin. The crossing times are counted by using the "Evaluate intersection count" tools. Then, the obstacle weighted index (OWI) of each route is calculated by Eq. (3) in Methods section.

The OWI can work as an effective tool to select the route with least obstacles, especially in terms of source or sink clusters. While a source or sink cluster is linked together and considered as a whole object, every source or sink point in the cluster can be used to transport carbon from other sites. Taking REF scenario as a case, more than 50% of the selected emission sources and half of the oil fields are considered as 20 emission source and 8 sink clusters. In this situation, there will be a series of feasible routes to be selected. In this study, the OWI values of 3530, 2913, and 2268 feasible routes under REF, PDM, and DME scenario are evaluated to select 1642, 1541, and 1219 candidate routes for optimization. According to previous study[5], though the candidate routes are not the spatially nearest ones, it can avoid excessive difficulties in pipeline construction and enhance the feasibility of the optimal layouts.

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