Supplementary Information for

Product-Specific Response Strategies for the EU CBAM: Balancing Carbon Mitigation and Economic Welfare

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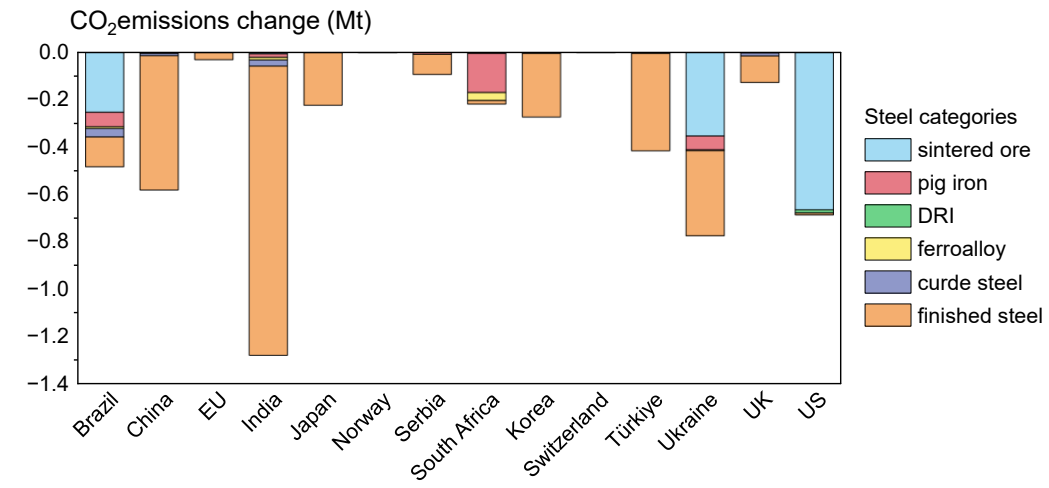
Supplementary Table 1 CBAM tariffs by steel category under the 50D_N scenario (%)

Region	Sintered ore	Pig iron	Ferroalloys	DRI	Crude steel	Finished steel
Brazil	12.1	17.8	4.1	0	13.2	11.9
China	0.3	18.4	2.5	0	7.1	5.2
India	8.4	30.3	6.8	6.4	18.4	18.4
Japan	0	0.3	4.9	0	0.2	8.9
South Korea	0	0.9	5.2	0	5.1	7.4
Serbia	0.2	44.4	0	0	5.3	10.6
South Africa	7.0	43.5	8.5	0	0.5	7.0
Türkiye	1.2	13.2	3.8	0	6.2	7.1
Ukraine	25.2	22.4	3.9	0	11.2	15
UK	8.8	10.6	0.7	0	4.2	5.9
US	34.8	0.3	0	8.5	3.4	0.7

Note: CBAM is exempt in Norway and Switzerland, so there are no CBAM tariffs in these two countries.



Supplementary Figure 1 CO_2 emission changes induced by the CBAM by steel category under the 50D_N scenario (Mt)

Supplementary Table 2 CO_2 emission changes induced by the CBAM by steel category under the 50D_N scenario (Mt)

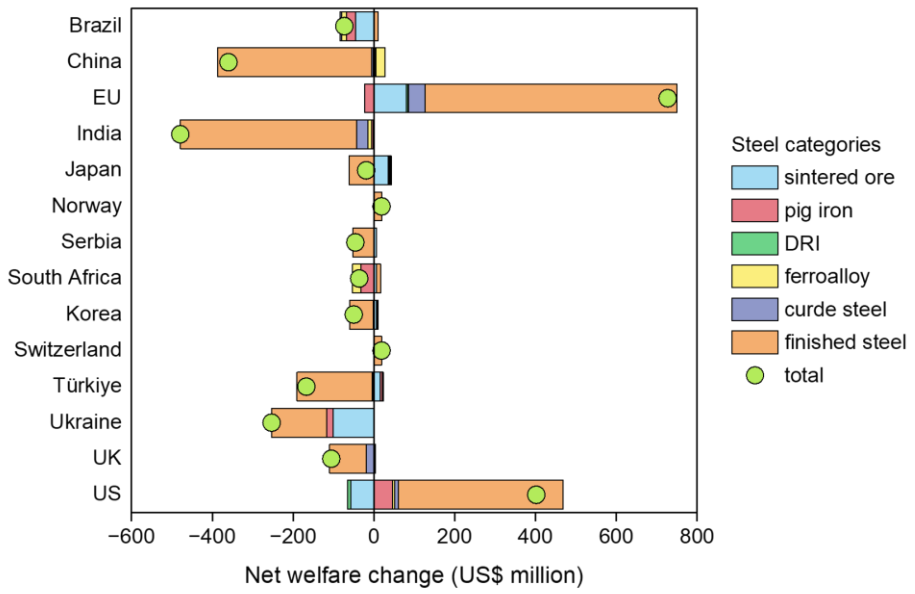
Region	Sintered ore	Pig iron	DRI	Ferroalloys	Crude steel	Finished steel	Total
Brazil	-0.25	-0.06	0.00	-0.01	-0.04	-0.13	-0.48
China	0.00	0.00	0.00	0.00	-0.01	-0.57	-0.58
EU27	0.00	0.00	0.00	0.00	0.00	-0.03	-0.03
India	-0.01	-0.02	0.00	-0.01	-0.03	-1.22	-1.28
Japan	0.00	0.00	0.00	0.00	0.00	-0.22	-0.22
Norway	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Serbia	0.00	-0.01	0.00	0.00	0.00	-0.08	-0.09
South Africa	0.00	-0.17	0.00	-0.03	0.00	-0.01	-0.22
South Korea	0.00	0.00	0.00	0.00	0.00	-0.27	-0.27
Switzerland	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Türkiye	0.00	0.00	0.00	0.00	0.00	-0.41	-0.41
Ukraine	-0.35	-0.06	0.00	0.00	0.00	-0.36	-0.77
UK	0.00	0.00	0.00	0.00	-0.01	-0.11	-0.13
US	-0.66	0.00	-0.01	0.00	0.00	-0.01	-0.69
Total	-1.28	-0.31	-0.01	-0.06	-0.09	-3.43	-5.18

Supplementary Table 3 Change rate in export values induced by the CBAM by steel category under the 50D_N scenario (%)

Region	Sintered ore	Pig iron	Ferroalloys	DRI	Crude steel	Finished steel
Brazil	-3	-2.3	-2.1	0	-1.3	-3.2
China	-0.5	-13.9	-0.9	-0.3	-3.1	-1.8
EU27	-0.2	0.2	-0.1	-0.1	-0.1	-0.2
India	-0.3	-4.7	-1.3	-1.3	-14.9	-10.6
Japan	0	-1.4	-0.5	-0.1	-0.2	-1.4
Norway	0.2	-0.1	-0.1	0	0	-0.1
Serbia	-0.3	-35.6	0	0	-2	-10.3
South Africa	-0.8	-21.8	-1.1	0	-0.3	-2.9
South Korea	0	-0.6	-0.8	-0.4	-3.4	-2
Switzerland	-0.7	-0.1	-0.1	0	0	-0.1
Türkiye	-2.5	6.6	-1.9	0	-6	-5.9
Ukraine	-21.1	-4	-0.6	-0.4	-11.8	-13.1
UK	-9.6	-7.2	-0.7	0	-4.3	-4.5
US	-21.2	4.8	-0.1	-5.1	-2.4	-0.4

Supplementary Table 4 Embedded emissions in exports by steel category in 2023 (Mt)

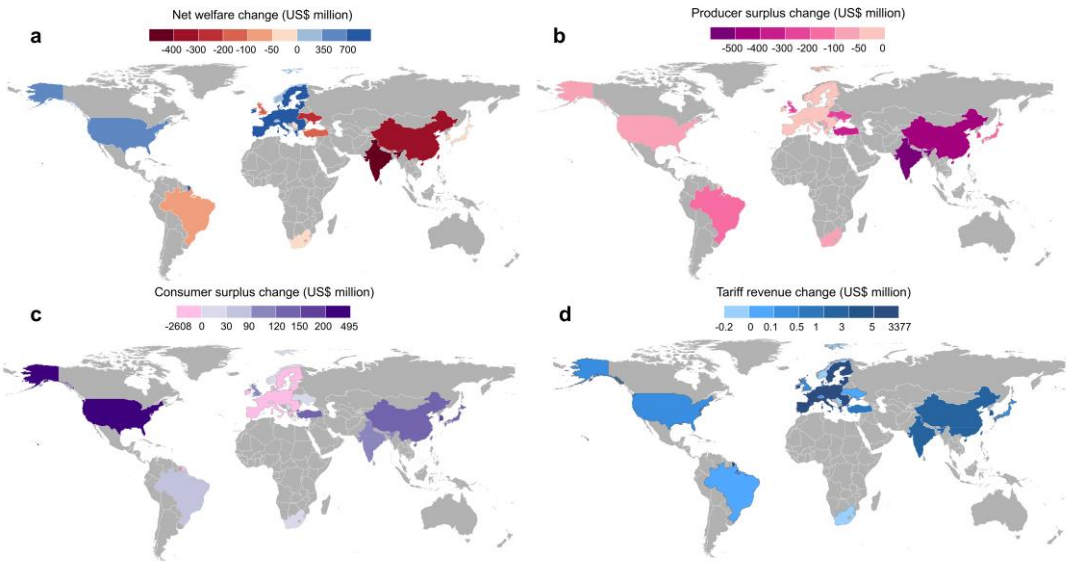
Region	Sintered ore	Pig iron	Ferroalloys	DRI	Crude steel	Finished steel	Total
Brazil	1.19	0.54	0.33	0.00	0.08	1.78	3.92
China	0.00	0.06	0.02	0.00	0.13	12.37	12.58
India	0.03	0.10	0.25	0.00	0.92	17.30	18.61
Japan	0.00	0.00	0.00	0.00	0.00	3.92	3.93
Norway	0.01	0.56	0.22	0.00	0.00	0.47	1.27
Serbia	0.00	0.04	0.00	0.00	0.00	1.95	1.99
South Africa	0.00	1.05	0.52	0.00	0.00	0.20	1.77
South Korea	0.00	0.00	0.04	0.00	0.07	6.28	6.39
Switzerland	0.00	0.00	0.00	0.00	0.00	0.33	0.34
Türkiye	0.00	0.00	0.06	0.00	0.08	8.76	8.90
Ukraine	3.72	0.41	0.01	0.00	0.07	5.51	9.72
UK	0.03	0.00	0.00	0.00	0.55	5.14	5.72
US	2.23	0.00	0.00	0.25	0.02	0.35	2.84
Total	7.21	2.77	1.47	0.25	1.92	64.37	77.98



Supplementary Figure 2 Net welfare changes induced by the CBAM by steel category under the 50D_N scenario (US$ million)

Supplementary Table 5 Net welfare changes induced by the CBAM by steel category under the 50D_N scenario (US$ million)

Region	Sintered ore	Pig iron	Ferroalloys	DRI	Crude steel	Finished steel	Total
Brazil	-45.8	-22.5	-12.0	0.0	-3.2	10.4	-45.8
China	3.9	-1.6	22.8	0.6	-3.7	-381.9	3.9
EU27	80.8	-23.3	1.2	3.4	41.8	623.2	80.8
India	-2.2	-3.4	-9.3	0.0	-28.3	-436.0	-2.2
Japan	35.9	1.0	2.9	0.7	2.4	-62.0	35.9
Norway	0.4	0.0	-0.2	0.0	0.1	18.9	0.4
Serbia	6.4	-1.1	0.1	0.0	0.0	-51.0	6.4
South Africa	5.8	-32.8	-20.1	0.0	0.1	10.8	5.8
South Korea	6.3	1.2	2.3	0.3	-2.0	-58.1	6.3
Switzerland	0.0	0.0	0.0	0.0	0.0	18.7	0.0
Türkiye	15.6	4.5	-1.5	3.3	-2.8	-185.9	15.6
Ukraine	-101.5	-15.2	-0.2	0.0	-0.7	-135.6	-101.5
UK	2.1	1.1	0.9	0.0	-19.4	-90.4	2.1
US	-56.6	45.7	4.8	-9.3	9.7	407.6	-56.6
Total	-49.0	-46.3	-8.2	-1.1	-5.9	-311.5	-49.0



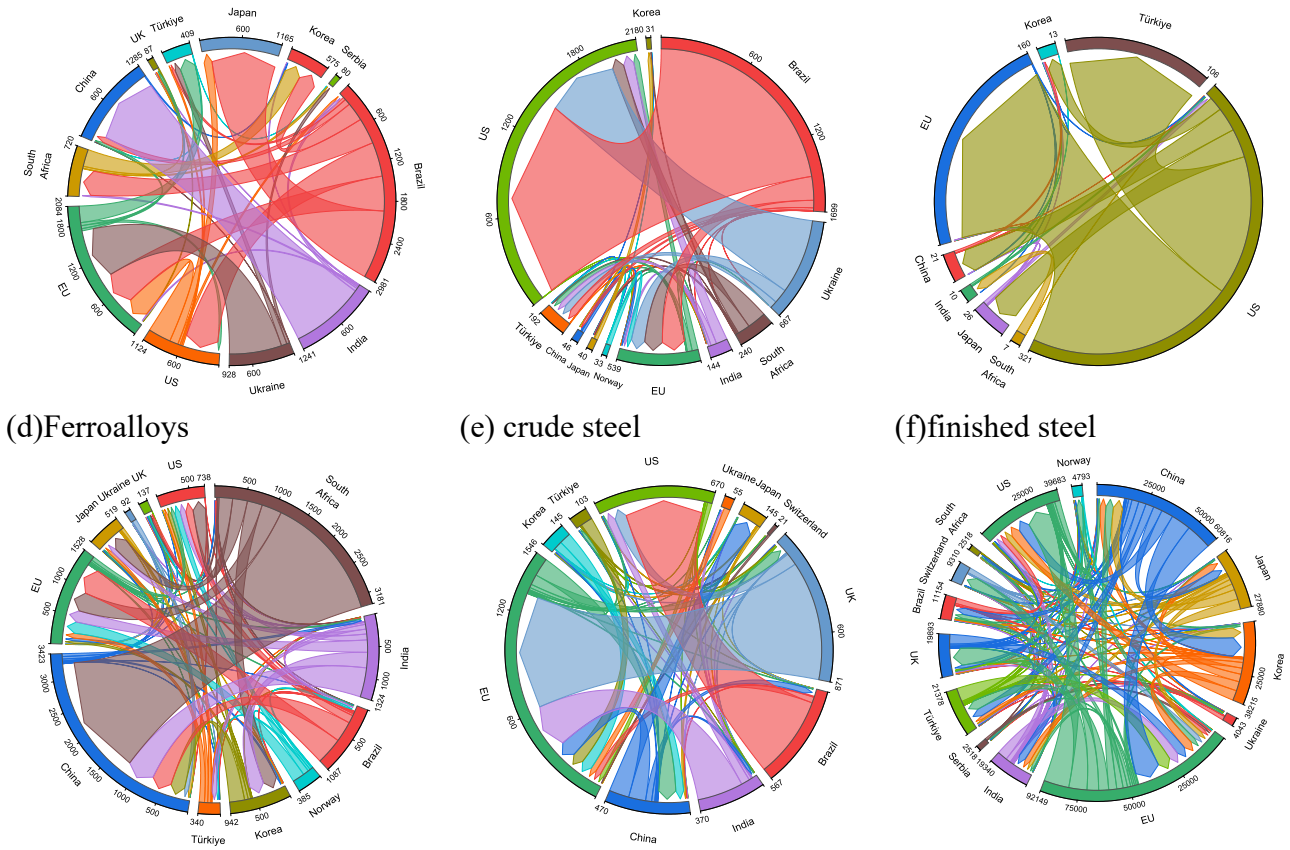
Supplementary Figure 3 Net welfare changes induced by the CBAM in the EU and major exporters. The net welfare (a) is divided into producer surplus (b); consumer surplus (c) and tariff revenue (d) under the 50D_N scenario.

Supplementary Table 6 Changes in welfare type induced by the CBAM under the 50D_N scenario (US$ million)

Region	Producer surplus	Consumer surplus	Tariff revenue	Net welfare
Brazil	-156.9	83.8	0.1	-73.1
China	-495.7	133.6	2.2	-359.9
EU27	-42.2	-2608.3	3377.4	727.0
India	-590.2	108.2	2.9	-479.1
Japan	-157.6	138.4	0.2	-19.1
Norway	-0.5	19.6	0.0	19.1
Serbia	-67.8	22.3	-0.2	-45.7
South Africa	-62.3	26.1	-0.1	-36.3
South Korea	-249.2	194.2	5.0	-50.0
Switzerland	-1.0	19.5	0.3	18.8
Türkiye	-313.2	145.6	0.6	-166.9
Ukraine	-279.3	26.1	0.0	-253.2
UK	-204.0	98.2	0.2	-105.6
US	-93.1	494.7	0.3	402.0
Total	-2712.9	-1098.0	3388.9	-422.0

Supplementary Table 7 Export values by steel category in 2023 (US$ million)

Region	Sintered ore	Pig iron	Ferroalloys	DRI	Crude steel	Finished steel	Total
Brazil	2900	1702	991	0	523	3629	9746
China	18	24	165	3	291	47407	47908
EU27	376	85	154	1	232	46628	47477
India	1241	134	1256	2	342	9076	12050
Japan	0	26	88	4	20	18747	18886
Norway	19	32	385	0	1	742	1179
Serbia	0	5	0	0	0	1090	1095
South Africa	298	240	3151	7	0	461	4158
South Korea	0	0	377	0	121	21405	21903
Switzerland	0	1	11	0	11	3003	3027
Türkiye	5	4	209	0	81	8852	9151
Ukraine	931	671	82	0	35	2237	3956
UK	16	0	7	2	789	6896	7709
US	557	1	4	316	44	6671	7592
Total	6360	2926	6880	335	2492	176845	195837



Supplementary Figure 4 Trade flows between the EU and its major exporters by steel category in 2023 (US$ million)

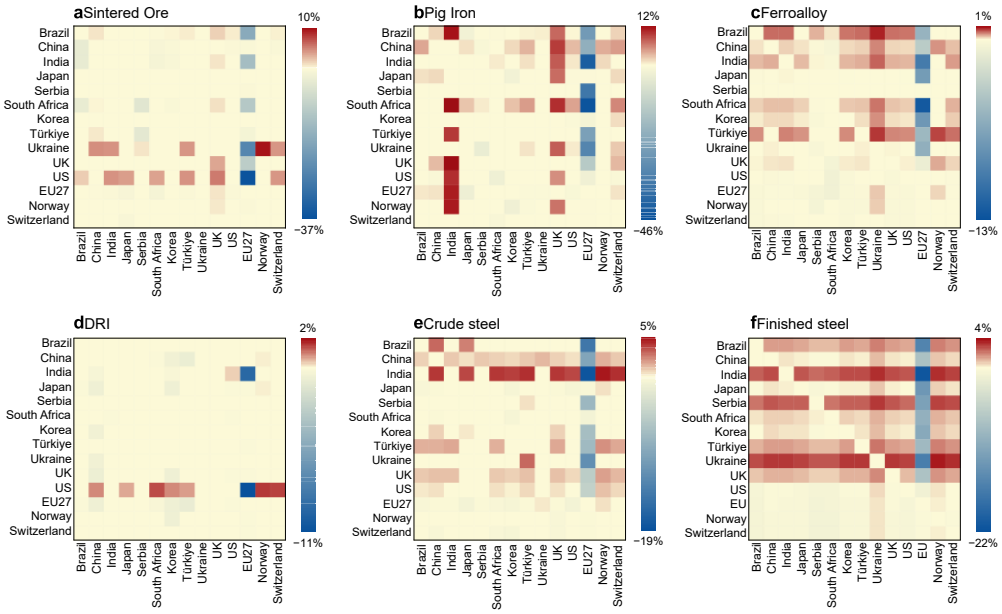
Supplementary Table 8 Vulnerable products under the CBAM and their CBAM abatement costs (USD/tCO_2)

Region	Sintered ore	Pig iron	Ferroalloys	DRI	Crude steel	Finished steel
Brazil	-181	-366	-1488		-127	
China		-401			-397	-715
India	-381	-221	-856	-139	-1116	-353
Japan						-300
South Korea					-1026	-208
Norway		-60				
Serbia		-139				-543
South Africa		-145	-606	-978		
Switzerland						
Türkiye			-1328		-1090	-545
Ukraine	-288	-261	-138		-632	-419
UK					-1529	-728
US	-85			-657	-1090	-545

Note: Vulnerable products are marked by cells containing values.

Supplementary Table 9 Vulnerable regions under the CBAM and their welfare losses (US$ million)

Vulnerable regions	Net welfare losses
Brazil	-73
China	-360
India	-479
Japan	-19
Serbia	-46
South Africa	-36
South Korea	-50
Türkiye	-167
Ukraine	-253
UK	-106



Supplementary Figure 5 Global trade pattern impacted by the CBAM by steel category. These matrices depict the trade flows among 14 regions, with the horizontal axis representing importing countries and the vertical axis representing the exporting countries. The color of each square in matrices indicates the change rate of trade values under the CBAM. The 50D_N scenario is used here as an example.

68 **Supplementary Table 10** The CN and HS6 code of by steel category covered by the CBAM

Steel Category	CN code	Number of HS6 code	HS6 code
Sintered ore	26011200	1	260112
Pig iron	7201	2	720110 720150
DRI	7203	7	720310 720390
Ferroalloys	72021 72024 72026		720211 720219 720241 720249 720260
Crude steel	7206 7218 7224	7	720610 720690 721810 721891 721899 722410 722490
Finished steel	7205 7207 7208	205	720510 720521 720529 720711 720712 720719 720720 720810 720825 720826 720827 720836 720837 720838 720839
	7209 7210 7211		720840 720851 720852 720853 720890 720915 720916 720917 720918 720925 720926 720927 720928 720990 721011
	7212 7213 7214		721012 721020 721030 721041 721049 721050 721061721069 721070 721090 721113 721114 721119 732690721123
	7215 7216 7217		721129 721190 721210 721220 721230 721240 721250 721260 721310 721320 721391 721399 721410 721420 721430
	7219 7220 7221		721491 721499 721510 721550 721590 721610 721621 721622 721631 721632 721633 721640 721650 721661 721669
	7222 7223 7225		721691 721699 721710 721720 721730 721790 721911 721912 721913 721914 721921 721922 721923 721924 721931
	7226 7227 7228		721932 721933 721934 721935 721990 722011 722012 722020 722090 722100 722211 722219 722220 722230 722240
	7229 7301 7302		722300 722511 722519 722530 722540 722550 722591 722592 722599 722611 722619 722620 722691 722692 722699
	7303 7304 7305		722710 722720 722790 722810 722820 722830 722840 722850 722860 722870 722880 722920 722990 730110 730120
	7306 7307 7308		730210 730230 730240 730290 730300 730411 730419 730422 730423 730424 730429 730431 730439 740441 730449
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			731816 731819 731821 731822 731823 731824 731829 732611 732619 732620 732619

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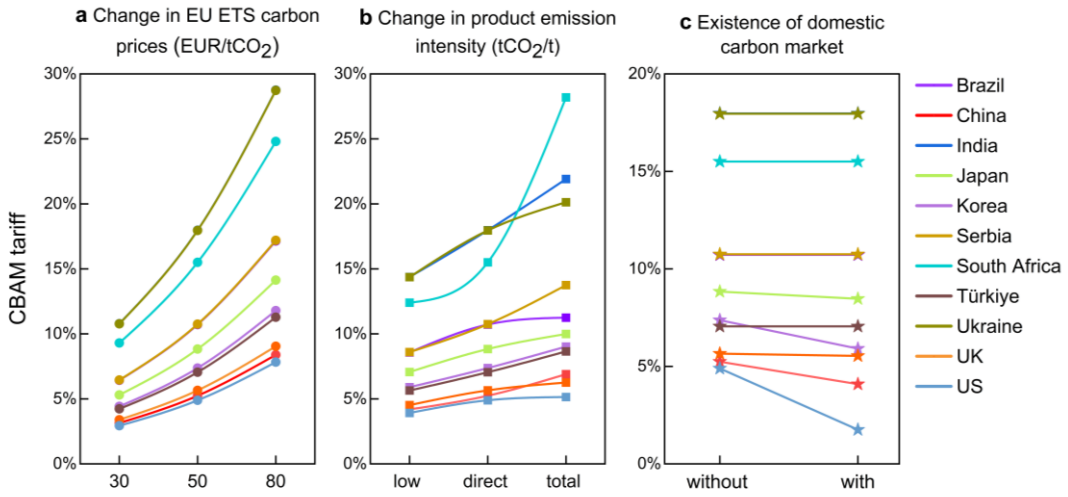
Supplementary Note 1 CBAM tariffs under 18 scenarios

Three key elements are central to determining CBAM tariffs: the carbon price of the EU ETS, the emissions intensity of products, and the establishment of domestic carbon markets in exporting countries. Given the uncertainty of the CBAM rules, several assumptions are made regarding these elements, such as variations in the EU ETS carbon price over time, whether the emissions coverage includes indirect emissions from electricity, and whether exporting countries establish domestic carbon markets (see Methods). Supplementary Figure 6 presents how these key elements influence national CBAM tariffs (see detailed data in Supplementary Table 11). Unsurprisingly, an increase in the EU ETS carbon prices and the expansion of emission coverage progressively raise CBAM tariffs, while establishing domestic carbon markets reduces them. Specifically, raising the EU ETS carbon price from 30 EUR/tCO_2 to 80 EUR/tCO_2 increases CBAM tariffs from 2.9%~9.3% to 7.8%~24.8% (Supplementary Figure 6a). Including indirect emissions amplifies the impact of emissions intensity on CBAM tariffs across all countries, particularly in South Africa, where tariffs rise from 15.5% to 28.2% (Supplementary Figure 6b). Thus, an effective strategy for South Africa to reduce the CBAM tariffs could be generating electricity with greener energy when the scope is expanded to include indirect emissions. Establishing domestic carbon markets has a less pronounced impact on CBAM tariffs (Supplementary Figure 6c). For example, paying carbon costs in domestic carbon markets could reduce CBAM tariffs for the US and South Korea by up to 3.1% and 1.5%, respectively, while reductions for the UK and Japan would be limited to 0.1% and 0.4%. It is based on the assumption that countries with existing carbon markets expand their scope to include the steel sector and maintain the carbon price in 2023. While higher carbon prices in domestic markets could further reduce CBAM tariffs in the long run, establishing these markets typically requires several years and entails significant policy implementation costs.



Supplementary Figure 6 The impact of key elements on CBAM tariffs for exporting countries. Note that CBAM is exempted for Norway and Switzerland, so there are no CBAM tariffs in these two countries.

100 **Supplementary Table 11** CBAM tariffs under 18 scenarios (%)

	without domestic ETS									with domestic ETS								
	30D	50D	80D	30T	50T	80T	30L	50L	80L	30D	50D	80D	30T	50T	80T	30L	50L	80L
Brazil	6.4	10.7	17.1	6.7	11.2	18.0	5.1	8.6	13.7	6.4	10.7	17.1	6.7	11.2	18.0	5.1	8.6	13.7
China	3.1	5.2	8.4	4.1	6.9	11.0	2.5	4.2	6.7	2.0	4.1	7.2	3.0	5.8	9.9	1.4	3.0	5.6
India	10.8	18.0	28.8	13.1	21.9	35.1	8.6	14.4	23.0	10.8	18.0	28.8	13.1	21.9	35.1	8.6	14.4	23.0
Japan	5.3	8.8	14.1	6.0	10.0	16.0	4.2	7.1	11.3	4.9	8.5	13.8	5.6	9.6	15.6	3.9	6.7	10.9
Korea	4.4	7.4	11.8	5.4	9.0	14.4	3.5	5.9	9.4	3.0	5.9	10.3	4.0	7.6	13.0	2.1	4.4	8.0
Russia	19.4	32.4	51.8	20.5	34.2	54.7	15.5	25.9	41.4	19.4	32.4	51.8	20.5	34.2	54.7	15.5	25.9	41.4
Serbia	6.4	10.7	17.2	8.3	13.8	22.0	5.2	8.6	13.8	6.4	10.7	17.2	8.3	13.8	22.0	5.2	8.6	13.8
South Africa	9.3	15.5	24.8	16.9	28.2	45.1	7.4	12.4	19.8	9.3	15.5	24.8	16.9	28.2	45.1	7.4	12.4	19.8
Türkiye	4.2	7.1	11.3	5.2	8.7	13.8	3.4	5.6	9.0	4.2	7.1	11.3	5.2	8.7	13.8	3.4	5.6	9.0
Ukraine	10.8	18.0	28.8	12.1	20.1	32.2	8.6	14.4	23.0	10.8	18.0	28.8	12.1	20.1	32.2	8.6	14.4	23.0
UK	3.4	5.7	9.1	3.8	6.3	10.0	2.7	4.5	7.2	3.3	5.5	8.9	3.6	6.1	9.9	2.6	4.4	7.1
US	2.9	4.9	7.8	3.1	5.1	8.2	2.4	3.9	6.3	0.0	1.8	4.7	0.0	2.0	5.1	0.0	0.8	3.1

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Supplementary Note 2 Regression analysis of CBAM-induced CO_2 emissions and welfare changes

Depending on the steel category, contributions to emission reduction are heterogeneous in different countries. Even within the same product category, there are both positive welfare impacts in some countries and negative ones in others. To better understand this heterogeneity, we try to explain the effects of CBAM on welfare and emissions variations by steel product characteristics in different regions. Three characteristics of steel products are considered based on the impact mechanism of CBAM (see Method): total export values in the base year, export dependence on the EU (defined as the proportion of exports to the EU relative to total exports), and average emission intensity of steel categories exported to the EU (defined as the ratio of embedded emissions to export values to the EU). We linearly regress them on steel categories' characteristics related to the CBAM. The variance inflation factor (VIF) test shows that there is no multicollinearity in these variables.

Results show that countries with higher embedded emissions in sintered ore tend to experience greater welfare losses. Moreover, the impact of sintered ore on welfare is the largest among the six steel categories. Countries with higher export values of pig iron tend to decrease more national welfare. Besides, CBAM tends to reduce more CO_2 emissions in countries with higher export values and higher emission intensity for products, except for DRI. Indeed, it means that CBAM raises the additional cost of products, especially for emission-intensive products, which incentivizes exporting countries to reduce emissions to maintain competitiveness. DRI is not as responsive to the CBAM as other categories, which might be due to it not yet being widespread enough to make a large immediate impact. As export values increase, crude steel exports tend to reduce emissions the most, while sintered ore exports reduce the least. As emission intensity increases, finished steel's exports tend to reduce emissions the most, while DRI's exports tend to reduce emissions the least. Additionally, for finished steel, countries with greater dependence on EU exports tend to suffer greater welfare losses and emission reductions, with the impact extent being the largest among the six steel categories.

However, these characteristics we consider do not fully capture the impact of CBAM, as part of the variations remain unexplained (R^2 values of the regressions are between 0.084 and 0.97). Yet, the purpose of the regressions is to provide a viewpoint that identifies the impact of CBAM based on product characteristics.

Supplementary Table 12 Impact of product characteristics on emission reductions under the CBAM

	Dependent variable: log(ER)					
	Sintered ore	Pig iron	DRI	ferroalloy	Crude steel	Finished steel
log(TE)	**0.959*****	**1.222*****	0.266	**1.163*****	**1.449*****	**1.407*****
	(8.97)	(5.23)	(1.15)	(4.31)	(6.43)	(3.48)
log(DEU)	0.086	0.152	0.846	-0.784	0.251	**1.516***
	(0.59)	(0.59)	(1.2)	(-0.97)	(0.71)	(1.88)
log(AEI)	**3.348*****	-0.394	**1.678***	**2.134****	**3.285*****	**4.619*****
	(3.42)	(-0.3)	(2.21)	(2.74)	(3.15)	(4.84)
Constant	**3.082*****	**1.775****	**1.581***	**-1.447***	**-1.074***	-1.403
	(4.96)	(2.83)	(2.01)	(-1.95)	(-2.15)	(-0.99)
R squared	0.970	0.807	0.571	0.804	0.882	0.765

Note: ER, CBAM-induced emission reductions, tCO_2. TE, initial total export values, US$ million; DEU, export dependence on the EU; AEI, average emission intensity of steel categories exported to the EU, tCO_2/t. *p<0.1; **p<0.05; ***p<0.01 (two-sided test)

Supplementary Table 13 Impact of product characteristics on welfare variation under the CBAM.

	Dependent variable: WV					
	Sintered ore	Pig iron	DRI	ferroalloy	Crude steel	Finished steel
log(TE)	3.241	**-8.638****	-0.943	-2.533	0.086	-176.03
	(0.71)	(-2.49)	(-1.77)	(-1.08)	(0.02)	(-1.23)
log(DEU)	-9.588	-3.459	-1.266	-1.803	-5.558	**-614.438***
	(-1.43)	(-0.87)	(-0.78)	(-0.26)	(-0.87)	(-2.15)
log(AEI)	**-1117.283****	3.858	0.005	-0.275	-8.799	-473.665
	(-3)	(0.2)	(0.00)	(-0.04)	(-0.47)	(-1.4)
Constant	**-86.403****	2.195	-1.603	2.877	-1.363	532.622
	(-3.15)	(0.25)	(-0.88)	(0.45)	(-0.15)	(1.07)
R squared	0.580	0.403	0.324	0.125	0.084	0.349

Note: WV, CBAM-induced welfare variation, US$ million. *p<0.1; **p<0.05; ***p<0.01 (two-sided test).

Supplementary Note 3 Monte Carlo Analysis

The Monte Carlo simulation is used to analyze the uncertainty and verify the stability of the data. It is assumed that the direct emission factors of 198 steel products follow a distribution, with the upper and lower bounds defined as the minimum and maximum values among the collected data. The posterior distributions of the parameters are obtained after conducting 1,000 simulations separately for the 198 steel products from each country. Table S11 represents the Monte Carlo simulation results by aggregating the 198 products for each region. The simulation results reveal that the standard deviation values of the direct emissions factors for all countries are small, indicating that the emission factors are highly robust.

Supplementary Table 14 Monte Carlo simulations of emission intensity data

Region	Mean	Standard Deviation	5th%	95th%
Brazil	0.12	0.01	0.12	0.12
China	0.06	0.01	0.06	0.06
India	0.14	0.01	0.14	0.15
Japan	0.03	0.00	0.03	0.03
Norway	0.20	0.02	0.19	0.20
Serbia	0.12	0.01	0.12	0.12
South Africa	0.13	0.01	0.13	0.13
South Korea	0.05	0.00	0.05	0.05
Switzerland	0.01	0.00	0.01	0.01
Türkiye	0.05	0.01	0.05	0.05
Ukraine	0.13	0.01	0.13	0.13
UK	0.05	0.01	0.05	0.05
US	0.07	0.01	0.07	0.07