Supplementary information for: The Role of Carbon Border Adjustment in Steel Decarbonization

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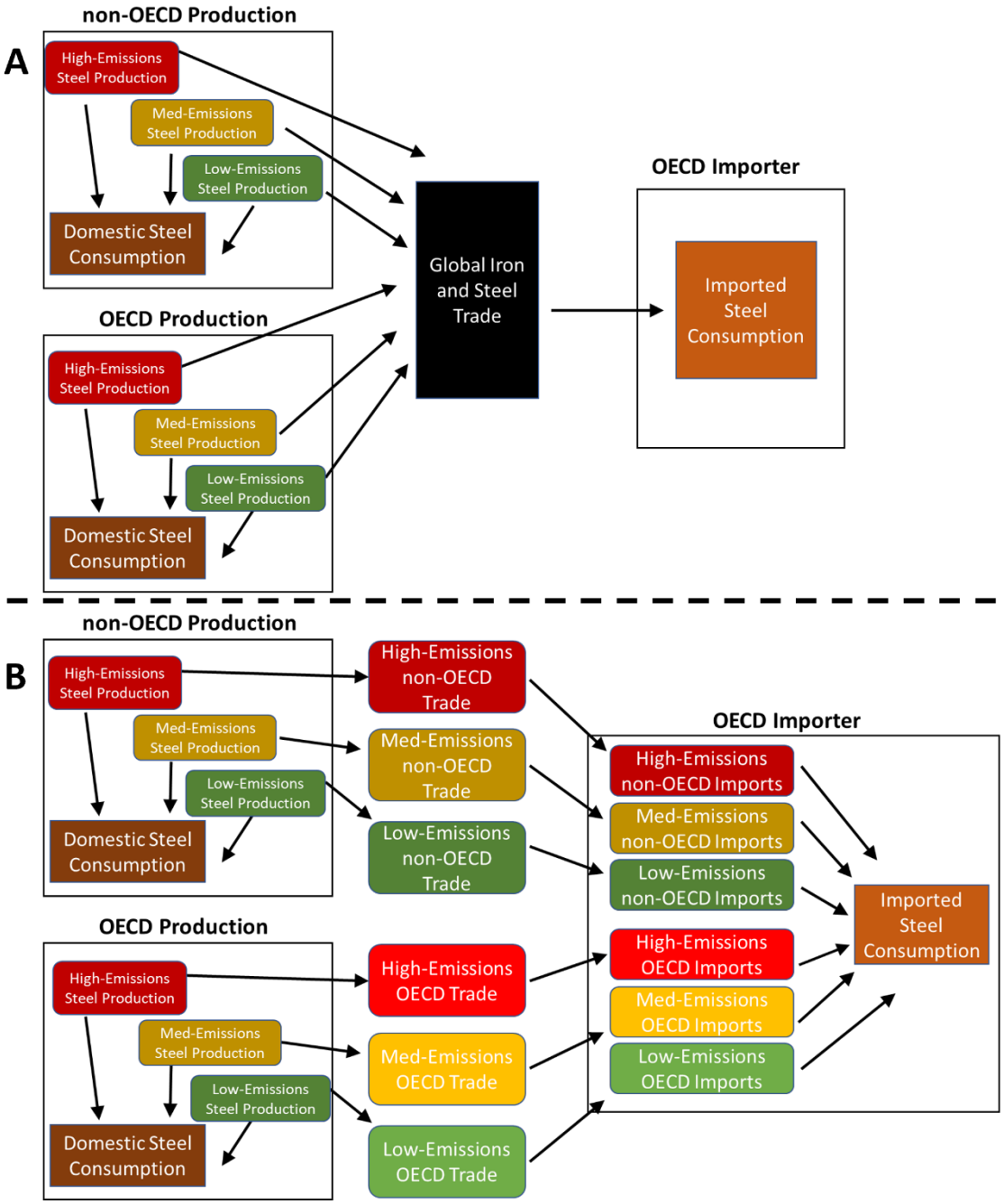
Supplementary Methodology Section

The Global Change Analysis Model (GCAM) is an integrated multisector model developed and maintained at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI, 2023). GCAM is an open-source community model. In this study, we use a modified version of GCAM 7.0. The documentation of the model is available at the GCAM documentation page (http://jgcri.github.io/gcam-doc/). GCAM includes representations of: economy, energy, agriculture, and water supply in 32 geopolitical regions across the globe; their GHG and air pollutant emissions and global GHG concentrations, radiative forcing, and temperature change; and the associated land allocation, water use and agriculture production across 384 land sub-regions and 235 water basins. The version of GCAM used in this study is available on Github (https://github.com/russellhz/gcam-core/tree/steel_cbam_production_differentiate).

In order to implement a CBAM in GCAM, the iron and steel sector from GCAM 7.0 was modified. This includes an expansion of steel production technologies and the steel trade market. The typical 9 iron and steel production technologies were expanded to 18 technologies in this version, based on technology data from Agora Industry, Wuppertal Institute and Lund University. These new technologies include more diversity of options for carbon capture and sequestration, more specific fuel and finishing technologies for electric arc furnaces with scrap, the ability to combine direct reduced iron with smelting and a blast oxygen furnace, as well as novel technologies such as molten oxide electrolysis and alkaline electrolysis. Full technology specifications are included in Table 1 of the main article. A global limit to scrap-based technologies is applied to reflect availability constraints. Total scrap-based production – including secondary steel and an (assumed) use of 0.19 t scrap / t crude steel in primary steel production routes – is capped at approximately the scrap-production of the Stated Policy Scenario in IEA's Iron and Steel Technology Roadmap, reaching 1,090 Mt in 2050.

Furthermore, the steel trade market was modified to allow for greater tracing of a traded products' carbon content and region of production. For all traded commodities GCAM utilizes an Armington trade approach, with one global traded pool that holds exports from all regions. Regions then choose between consuming the domestically-produced commodity versus imports from the global trade pool. Here, the single global pool is expanded into six pools based on emissions intensity and region of production. Iron and steel exports are separated into three markets – "low emissions", "medium emissions", and "high emissions" – based on the direct emissions associated with production. The direct emissions and categories for each steel technology are included in the last 2 columns of Table 1 of the main article. This market separation allows regions to place a tax on imported iron and steel based on the average direct emissions associated with each steel market, favoring imports from the "low emissions" trade pool. Because policies differ between OECD and non-OECD regions, trade pools are further

disaggregated by origin. Each GCAM region can then import from one of six categories, based on the emissions intensity and OECD vs non-OECD origin of production. A schematic of this new trade market relative to the default trade market in GCAM 7.0 is shown in SI Figure 1. For each region, the split between OECD and non-OECD steel imports in 2015 are calibrated with Chatham House's resourcetrade.earth data[30] on iron and steel trade. Historical exports and imports by emissions group (low, medium, high) are assumed to follow the same proportions as production. Exports and imports by emissions category therefore mirror regional production shares



SI Figure 1: Steel trade in A) core GCAM 7.0 with one global trade market and B) modifications for this study, with six trade markets based on the region of origin and the carbon emissions embedded in the product.

Future steel demand in GCAM depends on income and price elasticities. Income elasticities are calculated based on GDP trajectories, assuming that at early stages of development, the

relative increase in steel demand is larger than at more advanced development stages. The price elasticity of steel is set at -0.1, which means for every doubling of steel prices, global demand decreases by 10%.

The described version of GCAM is used in this study to project the impacts of decarbonisation policy combined with trade policy. It operates on a recursive dynamic cost-optimisation basis, which means that it solves provided policy targets (e.g. an emissions target) by the least-cost energy system in a given period, before moving to the next time period and performing the same exercise. The model runs at 5-year time steps, with the last calibrated year being 2015 and the first modelling year 2020. Emission and steel production trends are soft-calibrated for 2020 to ensure a realistic starting point. Beyond the detailed representation of the steel and energy sector, the policy inputs defining the scenarios in this study are i) regional fossil CO_2 reduction targets, ii) sectors included within this constraint (to define free allowances for steel), and iii) steel import taxes applied (to define CBAM tariffs). Relevant GCAM outputs are steel production and trade by region and technology, sectoral CO_2 emissions and policy costs.

Supplementary Tables

SI Table 1: OECD regions in this study, countries in red are not in the OECD, but are included based on GCAM regions

GCAM Region	Country		
Argentina*	Argentina*		
Australia_NZ	Australia	New Zealand	
Canada	Canada		
Colombia	Colombia		
EU-12	Bulgaria Cyprus Czechia Estonia Croatia Hungary Lithuania	Latvia Malta Poland Romania Slovakia Slovenia	
EU-15	Andorra Austria Belgium Germany Denmark Spain Finland France	Greece Greenland Ireland Italy Luxembourg Netherlands Portugal Sweden	Note: Chile, Costa Rica, and Israel are OECD members, but are not included in our OECD definition due to their grouped GCAM regions. Argentina is included because it is an OECD candidate country with ambitious climate targets, despite not being an official OECD member.
Europe_Non_EU	Albania Bosnia and Herzegovina Macedonia	Serbia and Montenegro Turkey	
European Free Trade Association	Switzerland United Kingdom Iceland	Liechtenstein Norway	
Japan	Japan		
Mexico	Mexico		
South Korea	South Korea		
USA	USA		

SI Table 2: Global limit on output of steel production with scrap

Year	Scrap-based Steel Limit (Mt output)
2020	392
2025	537
2030	624
2035	742
2040	851
2045	970
2050	1090

SI Table 3: Steel production by technology and region, for scenarios without free emissions allowances

		No Free Emissions Allowances			
region	sector	NoCBAM	CBAM-OECD	CBAM-OECD_Reb	CBAM-OECD_Subs
2015					
OECD	BF_BOF	272.2	272.2	272.2	272.2
OECD	DRI_EAF_NG	31.5	31.5	31.5	31.5
OECD	EAF_scrap_fossil_NG_finish	194.7	194.7	194.7	194.7
nonOECD	BF_BOF	898.8	898.8	898.8	898.8
nonOECD	DRI_EAF_NG	52.2	52.2	52.2	52.2
nonOECD	DRI_EAF_coal	21.8	21.8	21.8	21.8
nonOECD	EAF_scrap_fossil_NG_finish	150.3	150.3	150.3	150.3
2030					
OECD	BF_BOF	37.4	51.0	109.5	47.2
OECD	BF_BOF_BECCSmax	3.0	3.9	3.8	5.0
OECD	BF_BOF_BECCSmin	3.0	4.1	3.9	5.1
OECD	BF_BOF_CCS_73%	2.9	3.9	4.0	3.5
OECD	BF_BOF_CCS_86%	2.1	2.8	2.7	4.2
OECD	DRI_EAF_BECCS	1.7	2.2	2.2	3.0
OECD	DRI_EAF_H2	2.0	2.6	2.6	3.3
OECD	DRI_EAF_NG	28.6	38.3	39.7	34.4
OECD	DRI_EAF_NG_CCS	3.0	4.0	3.9	5.5
OECD	DRI_EAF_coal_CCS	0.6	0.7	0.7	1.0
OECD	DRI_SAF_BOF_BECCS	1.5	1.9	1.9	2.9
OECD	DRI_SAF_BOF_H2	2.8	3.8	3.7	5.4
OECD	DRI_SAF_BOF_NG	7.9	10.5	10.9	9.5
OECD	EAF_scrap_bio_NG_finish	31.5	37.1	37.3	38.4
OECD	EAF_scrap_fossil_NG_finish	171.9	202.4	203.5	210.2
OECD	SR_BOF	1.5	2.0	4.3	1.8
OECD	SR_BOF_CCS	2.1	2.8	2.7	3.8
nonOECD	BF_BOF	1133.7	1084.2	1033.9	1084.4
nonOECD	BF_BOF_BECCSmax	17.7	18.7	18.2	18.6
nonOECD	BF_BOF_BECCSmin	19.9	21.0	20.5	21.0
nonOECD	BF_BOF_CCS_73%	34.9	36.1	35.4	36.2
nonOECD	BF_BOF_CCS_86%	23.4	24.7	24.1	24.7
nonOECD	DRI_EAF_BECCS	1.9	2.0	1.9	1.9
nonOECD	DRI_EAF_H2	2.2	2.4	2.3	2.4
nonOECD	DRI_EAF_NG	93.7	96.8	92.9	96.5
nonOECD	DRI_EAF_NG_CCS	7.9	8.3	8.0	8.3
nonOECD	DRI_EAF_coal	41.3	41.3	40.2	41.4
nonOECD	DRI_EAF_coal_CCS	1.5	1.6	1.5	1.6
nonOECD	DRI_SAF_BOF_BECCS	2.1	2.2	2.2	2.2
nonOECD	DRI_SAF_BOF_H2	3.9	4.1	4.0	4.1
nonOECD	DRI_SAF_BOF_NG	32.9	34.0	32.7	33.9
nonOECD	EAF_scrap_bio_NG_finish	62.8	57.6	57.4	56.3
nonOECD	EAF_scrap_fossil_NG_finish	357.8	326.9	325.9	319.1
nonOECD	SR_BOF	22.3	21.3	20.4	21.3
nonOECD	SR_BOF_CCS	20.3	21.4	20.8	21.4
2050					
OECD	AEL_EAF	0.4	0.4	0.4	0.6
OECD	BF_BOF	36.0	36.3	40.6	33.9
OECD	BF_BOF_BECCSmax	10.4	10.4	10.4	12.4
OECD	BF_BOF_BECCSmin	10.9	10.9	10.9	13.0
OECD	BF_BOF_CCS_73%	14.5	14.6	14.9	13.2
OECD	BF_BOF_CCS_86%	8.4	8.4	8.4	11.8
OECD	DRI_EAF_BECCS	4.8	4.8	4.8	6.1
OECD	DRI_EAF_H2	3.2	3.3	3.3	3.8
OECD	DRI_EAF_NG	31.7	32.0	32.7	28.9
OECD	DRI_EAF_NG_CCS	11.8	11.9	11.9	15.4
OECD	DRI_EAF_coal_CCS	2.0	2.0	2.0	2.4
OECD	DRI_SAF_BOF_BECCS	4.4	4.4	4.4	6.1
OECD	DRI_SAF_BOF_H2	4.6	4.6	4.6	6.0
OECD	DRI_SAF_BOF_NG	28.4	28.7	29.2	25.9
OECD	EAF_scrap_bio_NG_finish	76.9	77.3	77.4	79.9
OECD	EAF_scrap_bio_elec_finish	34.2	34.4	34.4	35.2
OECD	EAF_scrap_fossil_NG_finish	138.9	139.6	139.8	144.6
OECD	EAF_scrap_fossil_elec_finish	36.8	37.0	37.0	37.9
OECD	MOE	1.0	1.0	1.0	1.2
OECD	SR_BOF	20.4	20.6	23.0	19.2
OECD	SR_BOF_CCS	21.6	21.7	21.6	28.9
nonOECD	AEL_EAF	3.7	3.7	3.7	3.7
nonOECD	BF_BOF	118.5	116.8	115.5	114.8
nonOECD	BF_BOF_BECCSmax	101.9	102.1	101.6	101.4
nonOECD	BF_BOF_BECCSmin	108.9	109.1	108.5	108.4
nonOECD	BF_BOF_CCS_73%	102.2	102.1	101.5	101.3
nonOECD	BF_BOF_CCS_86%	92.2	92.2	91.7	91.6
nonOECD	DRI_EAF_BECCS	18.7	18.8	18.7	18.6
nonOECD	DRI_EAF_H2	13.1	13.1	13.1	13.0
nonOECD	DRI_EAF_NG	101.1	101.1	100.3	99.7
nonOECD	DRI_EAF_NG_CCS	57.7	57.8	57.5	57.4
nonOECD	DRI_EAF_coal	17.9	17.9	17.8	17.8
nonOECD	DRI_EAF_coal_CCS	7.9	7.9	7.9	7.8
nonOECD	DRI_SAF_BOF_BECCS	20.5	20.5	20.4	20.4
nonOECD	DRI_SAF_BOF_H2	22.4	22.4	22.3	22.2
nonOECD	DRI_SAF_BOF_NG	107.8	107.8	107.0	106.4
nonOECD	EAF_scrap_bio_NG_finish	214.1	213.8	213.7	211.3
nonOECD	EAF_scrap_bio_elec_finish	96.2	96.0	95.9	94.9
nonOECD	EAF_scrap_fossil_NG_finish	389.0	388.4	388.2	383.7
nonOECD	EAF_scrap_fossil_elec_finish	103.8	103.6	103.5	102.4
nonOECD	MOE	8.8	8.9	8.8	8.8
nonOECD	SR_BOF	69.9	68.9	68.2	67.8
nonOECD	SR_BOF_CCS	224.8	225.0	223.8	223.5

SI Table 4: Steel production by technology and region, for scenarios with free emissions allowances

		Free Emissions Allowances				
		FA-All	FA-nonOECD			
region	sector	NoCBAM	NoCBAM	CBAM-OECD	CBAM-OECD_Reb	CBAM-OECD_Subs
2015						
OECD	BF_BOF	272.2	272.2	272.2	272.2	272.2
OECD	DRI_EAF_NG	31.5	31.5	31.5	31.5	31.5
OECD	EAF_scrap_fossil_NG_finish	194.7	194.7	194.7	194.7	194.7
nonOECD	BF_BOF	898.8	898.8	898.8	898.8	898.8
nonOECD	DRI_EAF_NG	52.2	52.2	52.2	52.2	52.2
nonOECD	DRI_EAF_coal	21.8	21.8	21.8	21.8	21.8
nonOECD	EAF_scrap_fossil_NG_finish	150.3	150.3	150.3	150.3	150.3
2030						
OECD	BF_BOF	293.0	16.4	28.4	94.8	25.4
OECD	DRI_EAF_H2	0.2	1.1	1.8	1.8	2.3
OECD	DRI_EAF_NG	18.6	14.7	24.8	26.1	21.7
OECD	DRI_SAF_BOF_H2	0.2	1.6	2.6	2.6	3.7
OECD	DRI_SAF_BOF_NG	5.0	4.0	6.8	7.2	6.0
OECD	EAF_scrap_bio_NG_finish	15.6	24.7	40.8	40.8	42.5
OECD	EAF_scrap_fossil_NG_finish	87.5	136.0	224.8	224.9	234.7
OECD	SR_BOF	2.4	0.6	1.1	3.7	1.0
OECD	BF_BOF_BECCSmax	0.0	1.5	2.4	2.4	3.0
OECD	BF_BOF_BECCSmin	0.0	1.6	2.5	2.5	3.1
OECD	BF_BOF_CCS_73%	0.0	1.4	2.3	2.5	2.0
OECD	BF_BOF_CCS_86%	0.0	1.1	1.7	1.7	2.5
OECD	DRI_EAF_BECCS	0.0	0.9	1.5	1.5	2.1
OECD	DRI_EAF_NG_CCS	0.0	1.7	2.8	2.8	3.7
OECD	DRI_EAF_coal_CCS	0.0	0.3	0.5	0.5	0.7
OECD	DRI_SAF_BOF_BECCS	0.0	0.8	1.3	1.3	2.0
OECD	SR_BOF_CCS	0.0	1.1	1.7	1.7	2.3
nonOECD	BF_BOF	1472.7	1650.4	1473.3	1412.4	1469.9
nonOECD	DRI_EAF_H2	0.8	0.8	0.9	0.9	0.9
nonOECD	DRI_EAF_NG	42.3	45.1	46.1	45.1	45.6
nonOECD	DRI_EAF_coal	34.2	36.3	34.3	33.8	34.3
nonOECD	DRI_SAF_BOF_H2	1.4	1.5	1.6	1.6	1.6
nonOECD	DRI_SAF_BOF_NG	15.1	15.9	16.2	16.0	16.1
nonOECD	EAF_scrap_bio_NG_finish	35.2	38.6	43.2	42.1	42.4
nonOECD	EAF_scrap_fossil_NG_finish	206.8	226.8	254.0	247.4	249.5
nonOECD	SR_BOF	14.4	16.1	14.3	13.7	14.3
2050						
OECD	AEL_EAF	0.0	0.1	0.2	0.2	0.3
OECD	BF_BOF	220.2	7.1	12.0	109.4	10.8
OECD	DRI_EAF_H2	0.1	1.2	2.0	2.0	2.3
OECD	DRI_EAF_NG	203.4	8.5	14.0	16.1	12.1
OECD	DRI_SAF_BOF_H2	0.3	1.7	2.8	2.8	3.6
OECD	DRI_SAF_BOF_NG	219.1	7.6	12.5	14.4	10.8
OECD	EAF_scrap_bio_NG_finish	42.8	43.9	71.0	70.9	72.8
OECD	EAF_scrap_bio_elec_finish	5.6	18.6	29.9	29.8	30.2
OECD	EAF_scrap_fossil_NG_finish	66.5	80.3	130.1	129.7	133.7
OECD	EAF_scrap_fossil_elec_finish	5.3	20.2	32.6	32.5	33.0
OECD	MOE	0.1	0.3	0.5	0.5	0.6
OECD	SR_BOF	28.3	4.0	6.8	62.1	6.1
OECD	BF_BOF_BECCSmax	0.0	3.5	5.5	5.4	6.3
OECD	BF_BOF_BECCSmin	0.0	3.6	5.8	5.7	6.7
OECD	BF_BOF_CCS_73%	0.0	3.9	6.3	7.2	5.5
OECD	BF_BOF_CCS_86%	0.0	2.9	4.6	4.5	6.3
OECD	DRI_EAF_BECCS	0.0	1.8	2.8	2.8	3.6
OECD	DRI_EAF_NG_CCS	0.0	4.8	7.6	7.6	9.8
OECD	DRI_EAF_coal_CCS	0.0	0.8	1.3	1.3	1.5
OECD	DRI_SAF_BOF_BECCS	0.0	1.6	2.6	2.6	3.6
OECD	SR_BOF_CCS	0.0	7.3	11.6	11.5	15.2
nonOECD	AEL_EAF	0.8	0.9	0.9	0.9	0.9
nonOECD	BF_BOF	1176.8	1591.1	1435.8	1318.7	1431.5
nonOECD	DRI_EAF_H2	1.5	1.7	1.8	1.8	1.8
nonOECD	DRI_EAF_NG	43.1	48.8	48.9	46.9	48.6
nonOECD	DRI_EAF_coal	35.5	41.9	39.8	38.2	39.7
nonOECD	DRI_SAF_BOF_H2	3.2	3.8	3.9	3.8	3.9
nonOECD	DRI_SAF_BOF_NG	49.5	54.8	54.8	52.8	54.5
nonOECD	EAF_scrap_bio_NG_finish	110.3	130.6	139.5	133.9	137.8
nonOECD	EAF_scrap_bio_elec_finish	35.8	43.3	46.2	44.3	45.6
nonOECD	EAF_scrap_fossil_NG_finish	192.8	226.8	242.3	232.6	239.4
nonOECD	EAF_scrap_fossil_elec_finish	37.0	44.5	47.5	45.6	46.9
nonOECD	MOE	1.7	2.0	2.1	2.0	2.1
nonOECD	SR_BOF	147.4	196.9	176.5	161.9	176.0