Supplementary Information

Techno-economic optimisation of steel supply chains in the clean energy transition: A case study of post-war Ukraine

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S1. Supplementary Results

S1.1 Renewable power, hydrogen, and ammonia potential

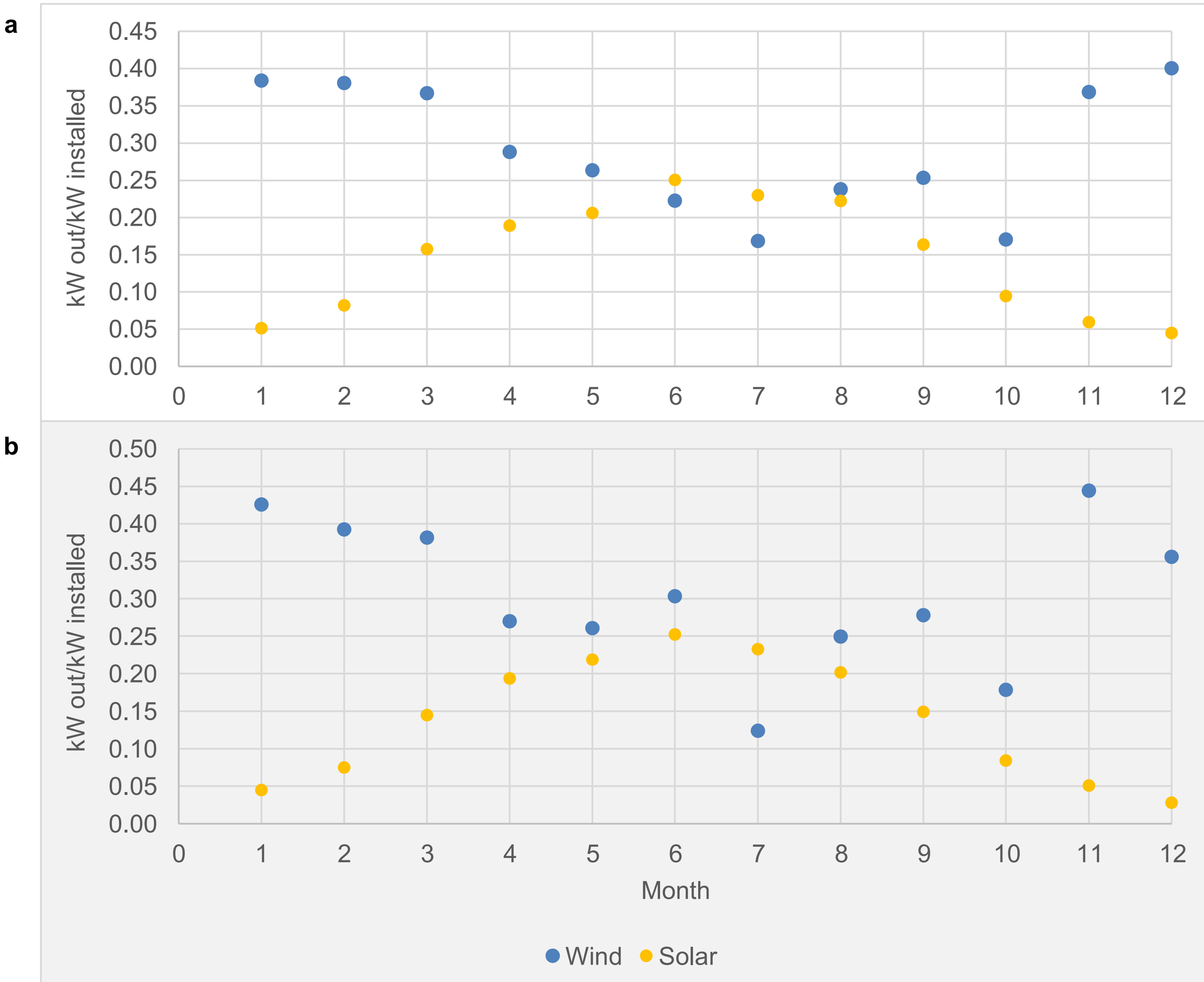


Figure S1.1. Variable renewable energy capacity profiles for each month in 2019 based on analysis of *ERA5 climatic data, displayed for two locations – (a) Odesa oblast with coordinates 46°, 29° (grid #s01), (b) Dnipropetrovsk oblast with coordinates 48°. 34° (grid #s18).*

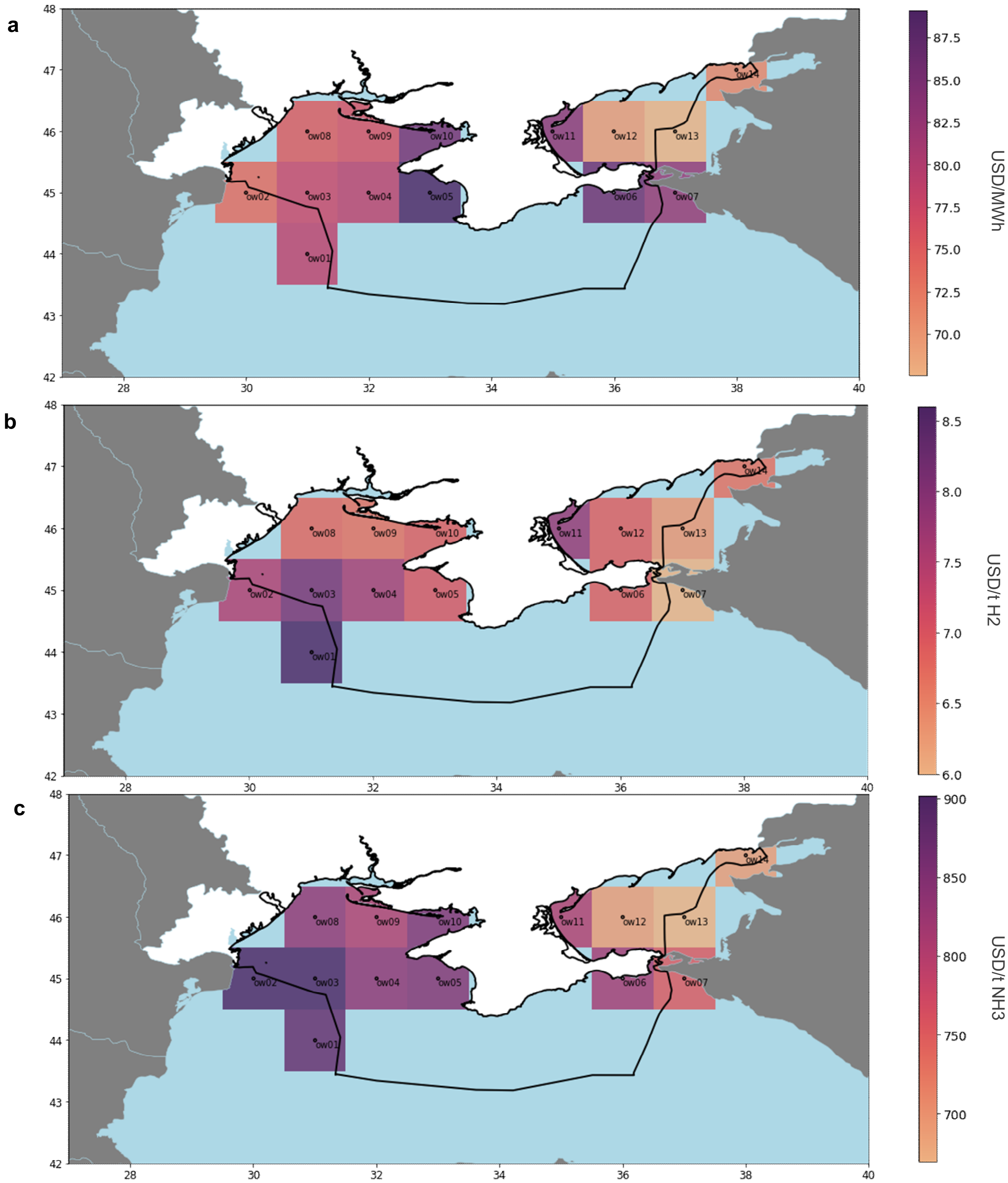


Figure S1.2. Cost-minimised results of offshore wind plant energy products in 2050, at 1° x 1° grid spatial resolution (about 111 km (latitude) x 73 km (longitude), projected on equal axes so that longitude and latitudes are equidistant - (a) Levelised cost of firm electricity (in USD/MWh). (b) Levelised cost of continually supplied hydrogen (in USD/t H_2). (c) Levelised cost of continually supplied ammonia (in USD/t NH_3). Locations with water depths <50m utilise fixed turbines, and <1000m floating turbines - all locations with water depth >1000m are not assessed. Fourteen grids sat at least partially within Ukraine's exclusive marine economic zone within the Black and Azov Seas, and with sea depths less than 1000m. The average levelised cost of offshore wind is $103, $89.5 and $79.4/MWh in 2030, 2040 and 2050, respectively, including substantial CGH_2, NH_3 and battery storage to assure firm power supply. Green fuel costs were similarly steep: $9.32, $8.09 and $7.20/kg H_2, and $1084, $931 and $824/t NH_3, for 2030, 2040 and 2050, respectively.

S1.2 Green HBI and green steel competitiveness

Prior to investigating optimal production and trade supply chains, steel production costs via different technological routes were assessed to understand the model's technology and fuel selection. For domestic green steel production, the BF-BOF production route is likely to be the cheapest without carbon pricing mechanisms in place, even against low-priced and continuous zero-carbon power from nuclear and/or hydropower. Favourably for industrial decarbonisation, compliance to the EU-ETS or a very similar UA-ETS is considered across all scenarios. In ascending order, the levelised cost of steel (LCOS) for the BF-BOF route was estimated at $415/t steel, scrap-EAF route at $472/t steel, NG-DRI-EAF route at $483/t steel, and H_2-DRI-EAF route at $621/t steel. Looking at H_2/NG blends for DRI, a 30/70 split led to an LCOS of $496/t steel, and a 65/35 split led to an LCOS of $542/t steel. The relative costs of production via different production routes are sensitive to the price of input commodities, especially iron ore (base case of $100/t for DR-grade, $80/t for BF-grade), metallurgical coal (base case of $200/t), natural gas (base case of $25/MWh), electricity, and hydrogen. Through a sensitivity analysis, it was deduced that a 50% increase in metallurgical coal will increase BF-BOF costs by 14%, a 50% increase in NG price will increase NG-DRI-EAF costs by 7%, a 50% increase in scrap price will increase scrap-EAF costs by 33%, and a 50% increase in RE and H_2 price will increase H_2-DRI-EAF costs by 20%. The levelised costs of steel and sensitivity analyses of various steel production routes are detailed in this section.

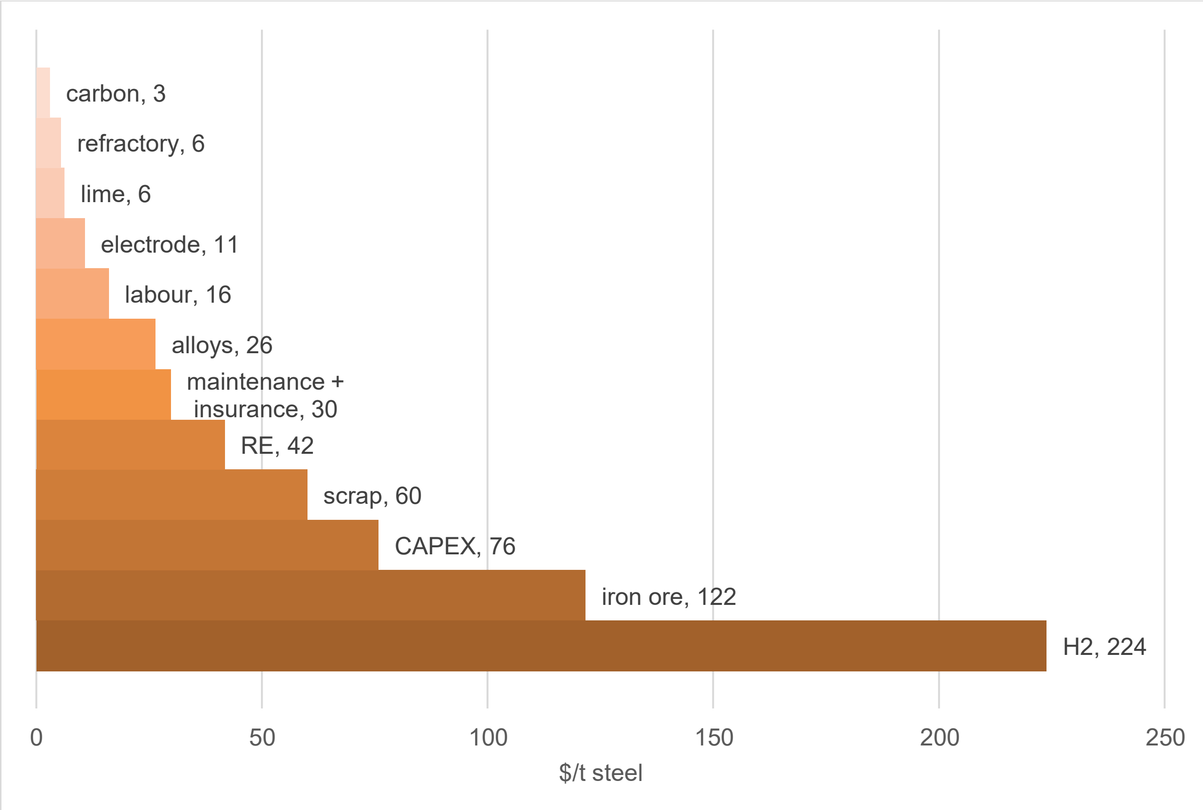


Figure S1.3. Levelised cost of steel breakdown for the H_2-DRI-EAF route, totalling $621/t steel.

Table S1.1. Sensitivity analysis of key commodities within the LCOS of the H_2-DRI-EAF route.

	Unit	**UA base**	**S.A. range**	**Favourable**	**Un-favourable**	**LCOS impact**
DR-grade ore price	$/t	100	± 30%	70	130	± 4%
RE price	$/MWh	70	± 50%	35	105	± 2%
H_2 price	$/t	3.8	± 50%	1.9	5.75	± 18%
Scrap price	$/t	300	± 50%	150	450	± 5%
Discount rate	%	8	± 50%	12	4	+4%

The co-located H_2-DRI-EAF results slightly differ our previous study (Devlin et al., 2023) due to different climatic data inputs (this study uses ERA5 instead of MERRA-2). In this study, analysis of hourly ERA5 climatic data (Hersbach et al., 2023) determined the maximum capacity factor of solar to be 14%, and wind to be 31% for the same location for the year 2019. This aligns with research by the Institute of Renewable Energy (Ukrainian Institute of Renewable Energy, 2020), which determined the capacity factor of solar to be 14% and onshore wind to be 31% (plus offshore wind to be 45%).

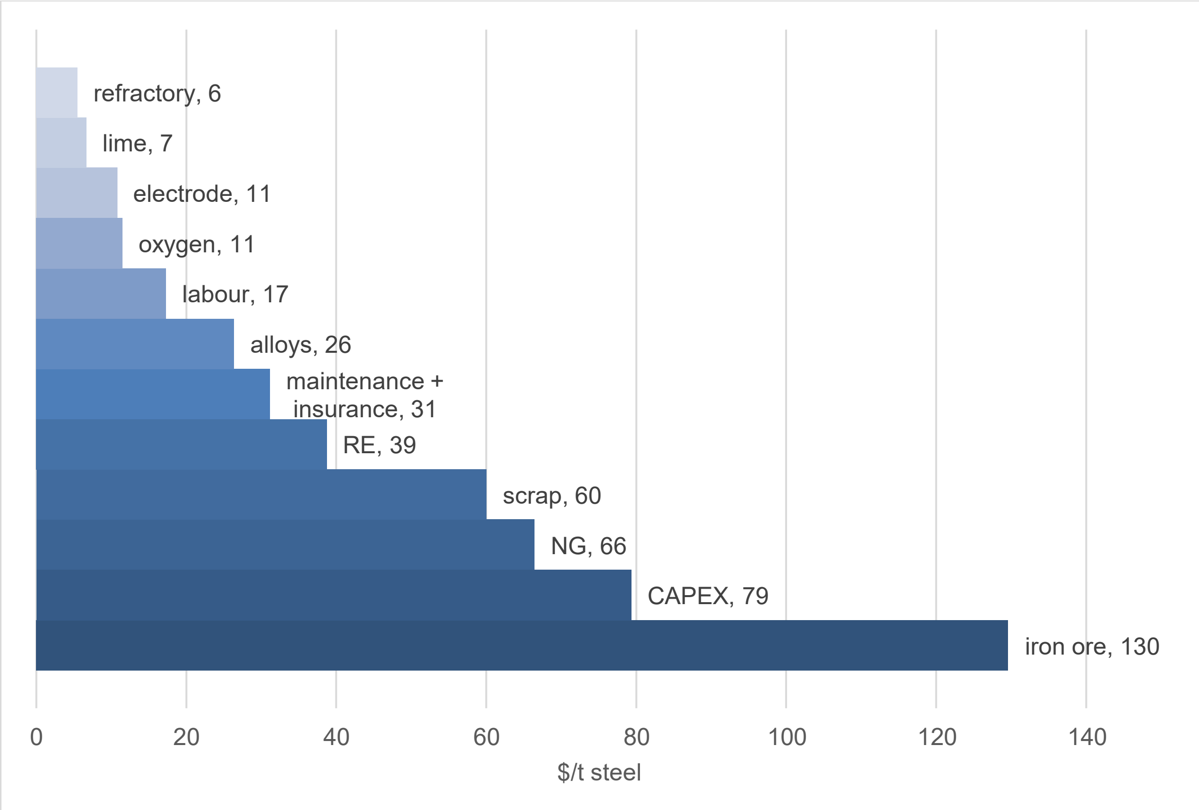


Figure S1.4. Levelised cost of steel breakdown for the NG-DRI-EAF route, totalling $483/t steel.

Table S1.2. Sensitivity analysis of key commodities within the LCOS of the NG-DRI-EAF route.

	Unit	**UA base**	**S.A. range**	**Favourable**	**Un-favourable**	**LCOS impact**
DR-grade ore price	$/t	100	± 30%	70	130	± 7%
RE price	$/MWh	70	± 50%	35	105	± 4%
NG price	$/MWh	25	± 30%	12.5	37.5	± 7%
Scrap price	$/t	300	± 50%	150	450	± 5%
Discount rate	%	8	± 50%	12	4	+4%

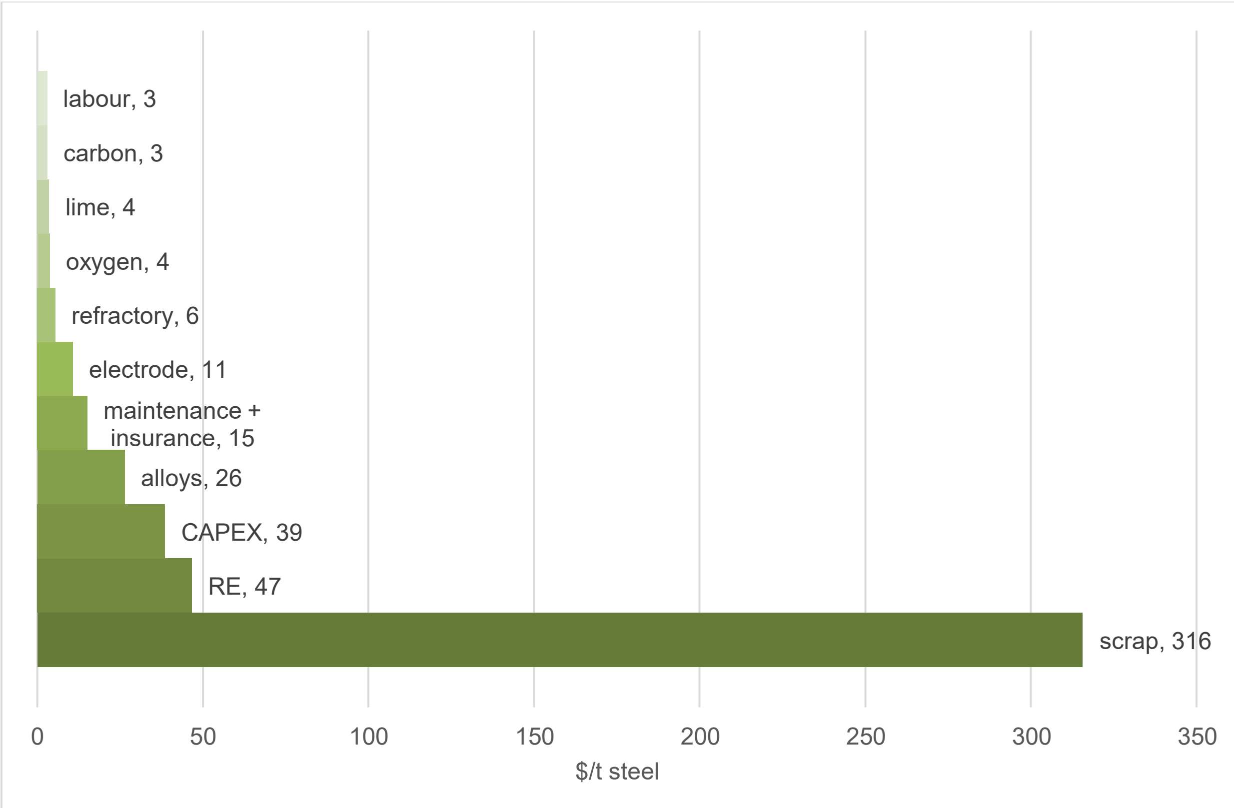


Figure S1.5. Levelised cost of steel breakdown for the scrap-based EAF route, totalling $472/t steel.

Table S1.3. Sensitivity analysis of key commodities within the LCOS of the scrap-based EAF route.

	Unit	UA base	S.A. range	Favourable	Un-favourable	LCOS impact
RE price	$/MWh	70	± 50%	35	105	± 5%
Scrap price	$/t	300	± 50%	150	450	± 33%
Discount rate	%	8	± 50%	12	4	+3%

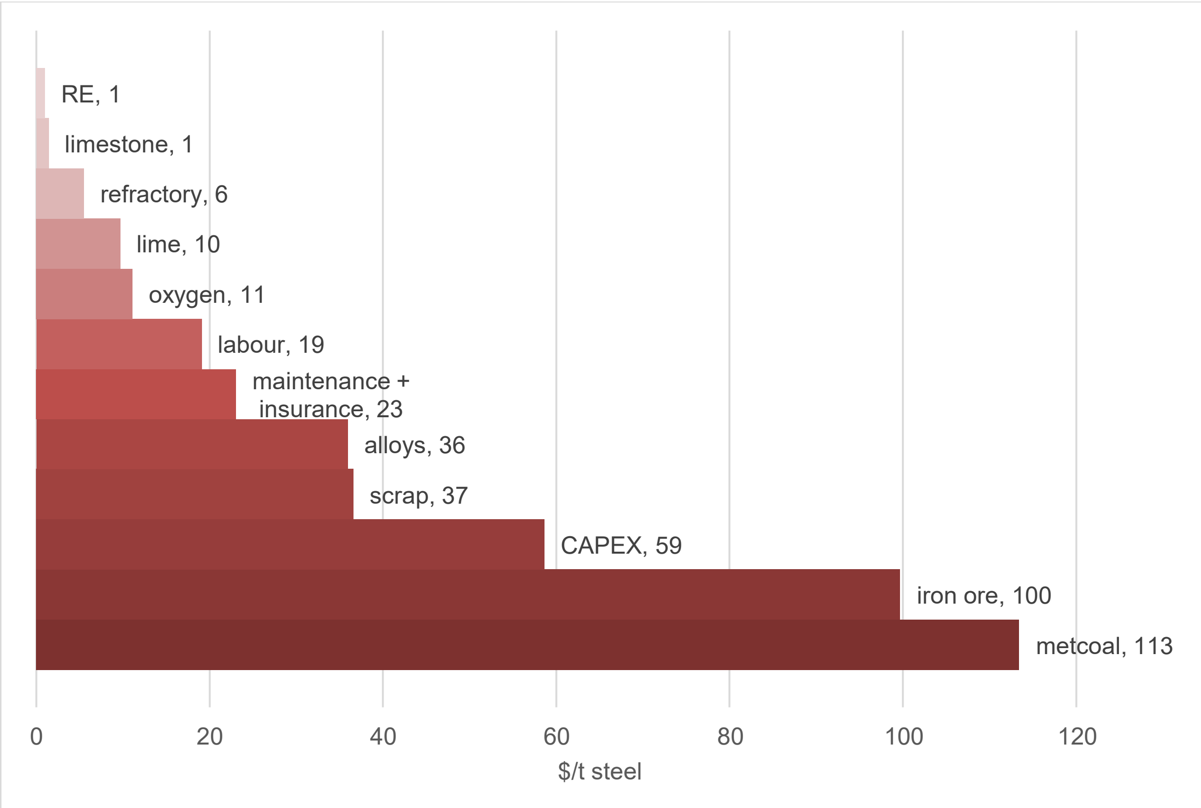


Figure S1.6. Levelised cost of steel breakdown for the BF-BOF route, totalling $415/t steel.

Table S1.4. Sensitivity analysis of key commodities within the LCOS of the BF-BOF route.

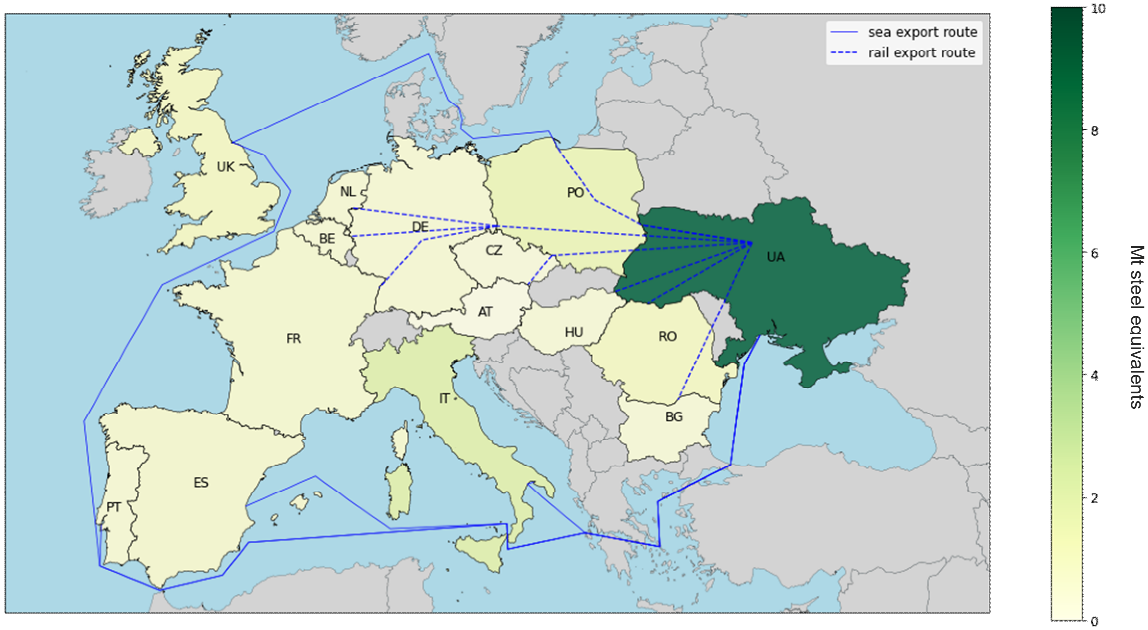
	Unit	UA base	S.A. range	Favourable	Un-favourable	LCOS impact
BF-grade ore price	$/t	80	± 20%	56	104	± 7%
Met coal price	$/t	200	± 30%	140	260	± 8%
Scrap price	$/t	300	± 50%	150	450	± 4%
Discount rate	%	8	± 50%	12	4	+4%

Table S1.5. Levelised cost of iron (LCOI) and levelised cost of steel (LCOS) breakdown for the green H2-DRI-EAF route.

				80% DRI/20% scrap			*100% DRI*		
Year	**min LCOE ($/MWh)**	**min LCOH ($/t H2)**	**LCOHBI ($/t HBI)**	**LCOS ($/t steel)**	**Δ ($/t steel)**	**HBI costs of steel (%)**	**LCOS ($/t steel)**	**Δ ($/t steel)**	**HBI costs of steel (%)**
2030	96	5.03	506	653	198	70%	719	162	77%
2040	77	4.01	458	604	192	68%	657	154	77%
2050	64	3.31	441	587	190	68%	636	151	76%

S1.3 Forecast steel demand and scrap availability

a



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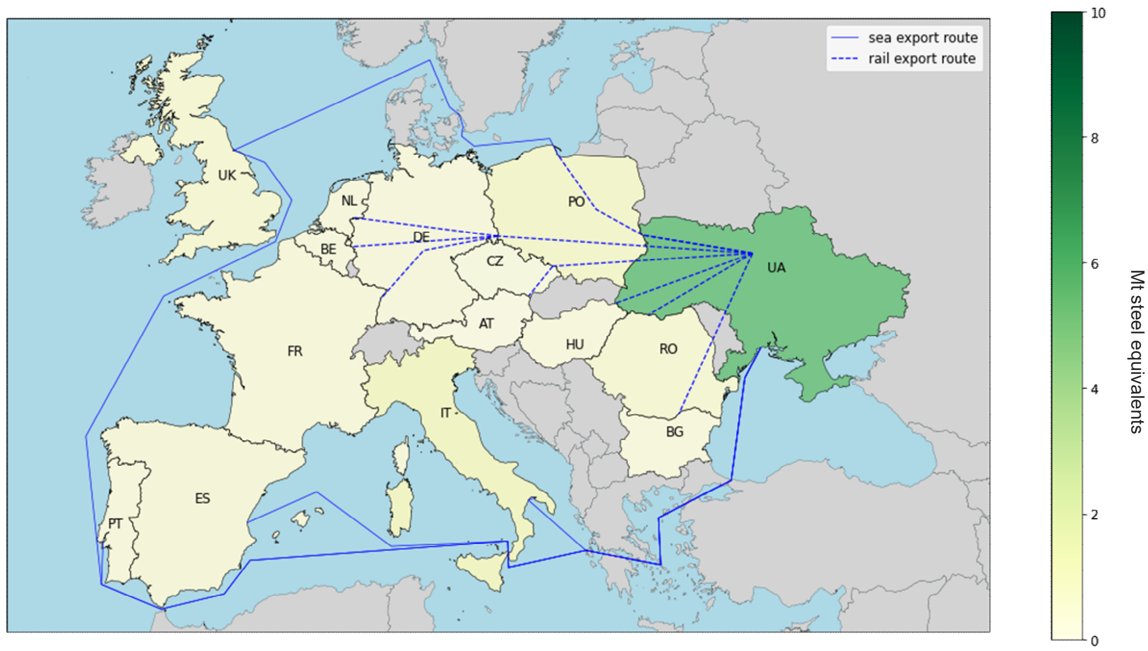

Figure S1.7. Domestic steel demand and steel/HBI export flows in 2030 for the (a) *Strong Recovery* scenario, and (b) *Slow Recovery* scenario. HBI and steel exports are compounded as steel equivalents (given 0.9 t HBI/t steel with 14% scrap charge).

a

b

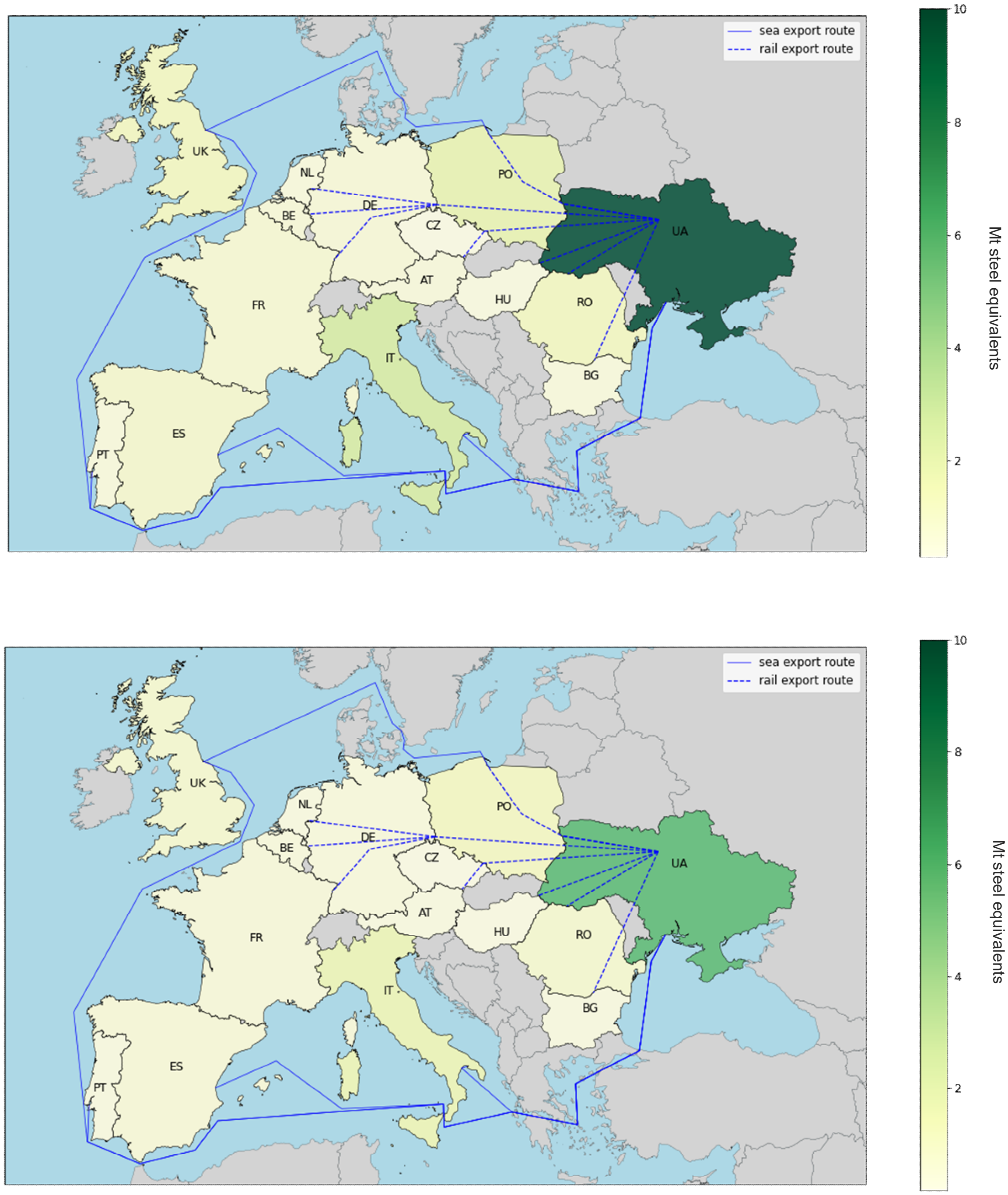

Figure S1.8. Domestic steel demand and steel/HBI export flows in 2040 for the (a) *Strong Recovery* scenario, and (b) *Slow Recovery* scenario. HBI and steel exports are compounded as steel equivalents (given 0.9 t HBI/t steel with 14% scrap charge).

a

b

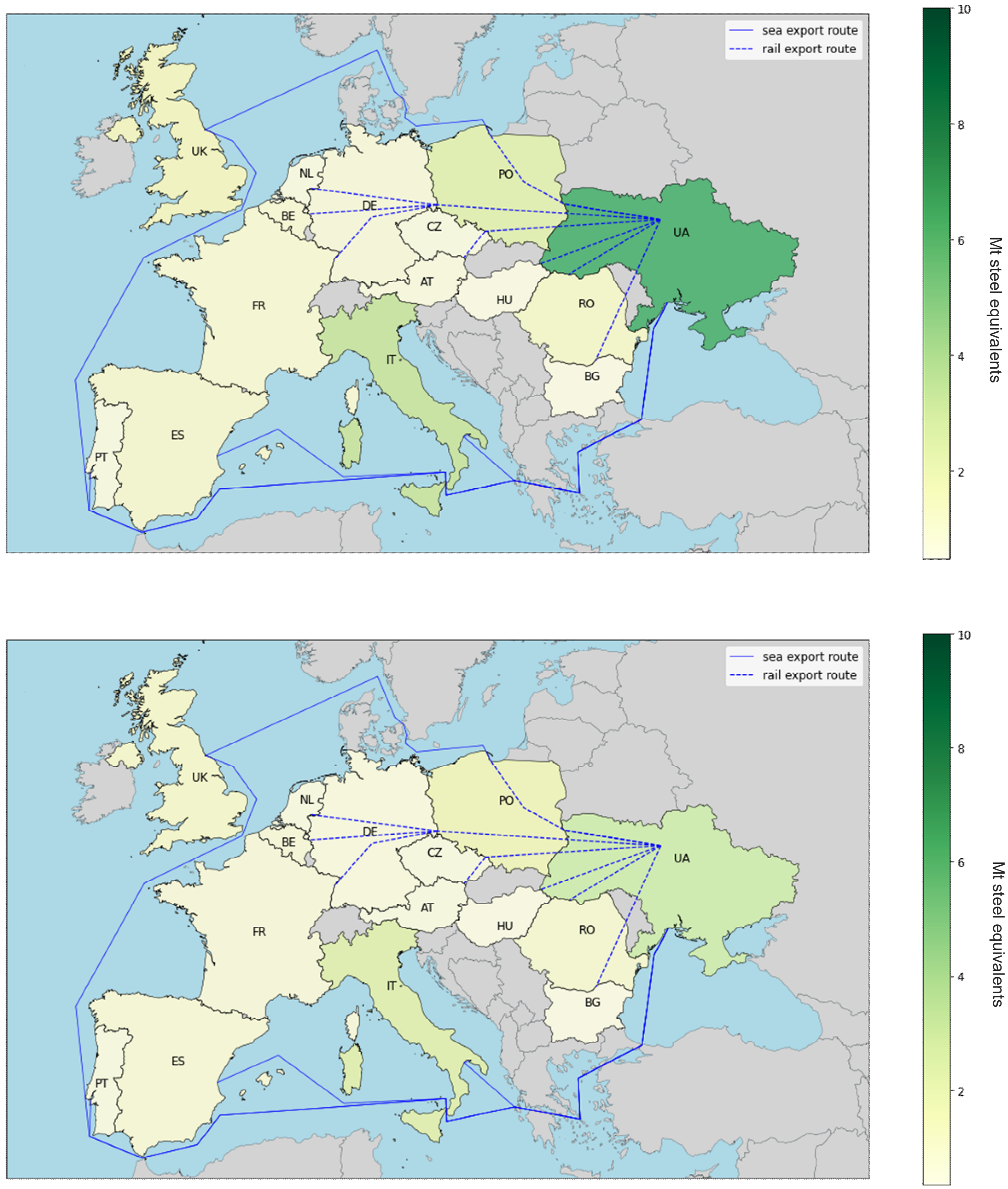

Figure S1.9. Domestic steel demand and steel/HBI export flows in 2050 for the (a) *Strong Recovery* scenario, and (b) *Slow Recovery scenario*. HBI and steel exports are compounded as steel equivalents (given 0.9 t HBI/t steel with 14% scrap charge).

S1.4 Production and trade optimisation

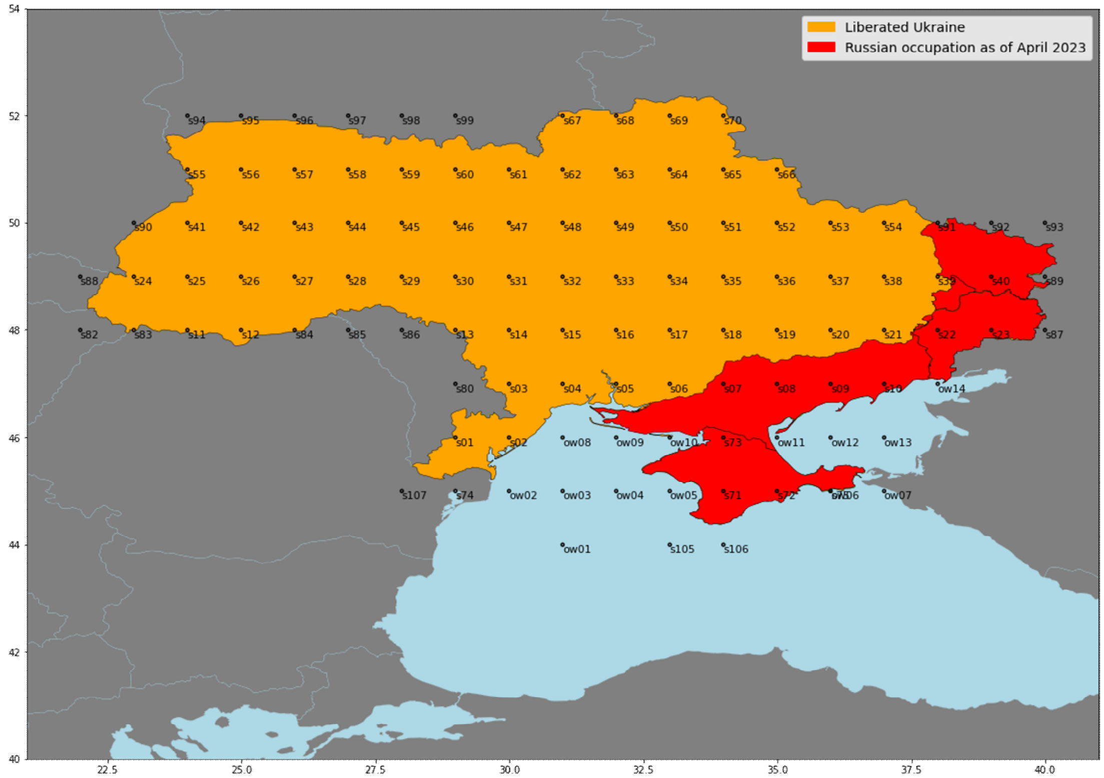

Figure S1.10. Grid identification and location for onshore energy production and manufacturing sites, and offshore wind energy production sites.

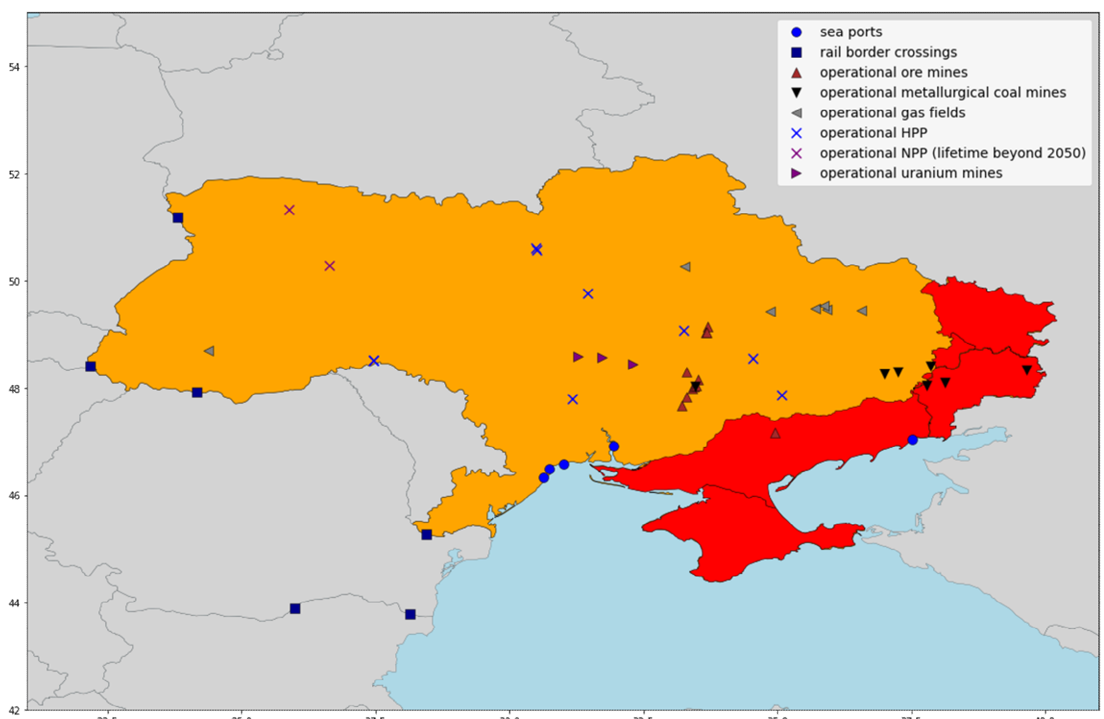

Figure S1.11. Iron and steel supply chain asset map, illustrating the location of relevant mines, established nuclear and hydropower plants, and critical transportation nodes for exports.

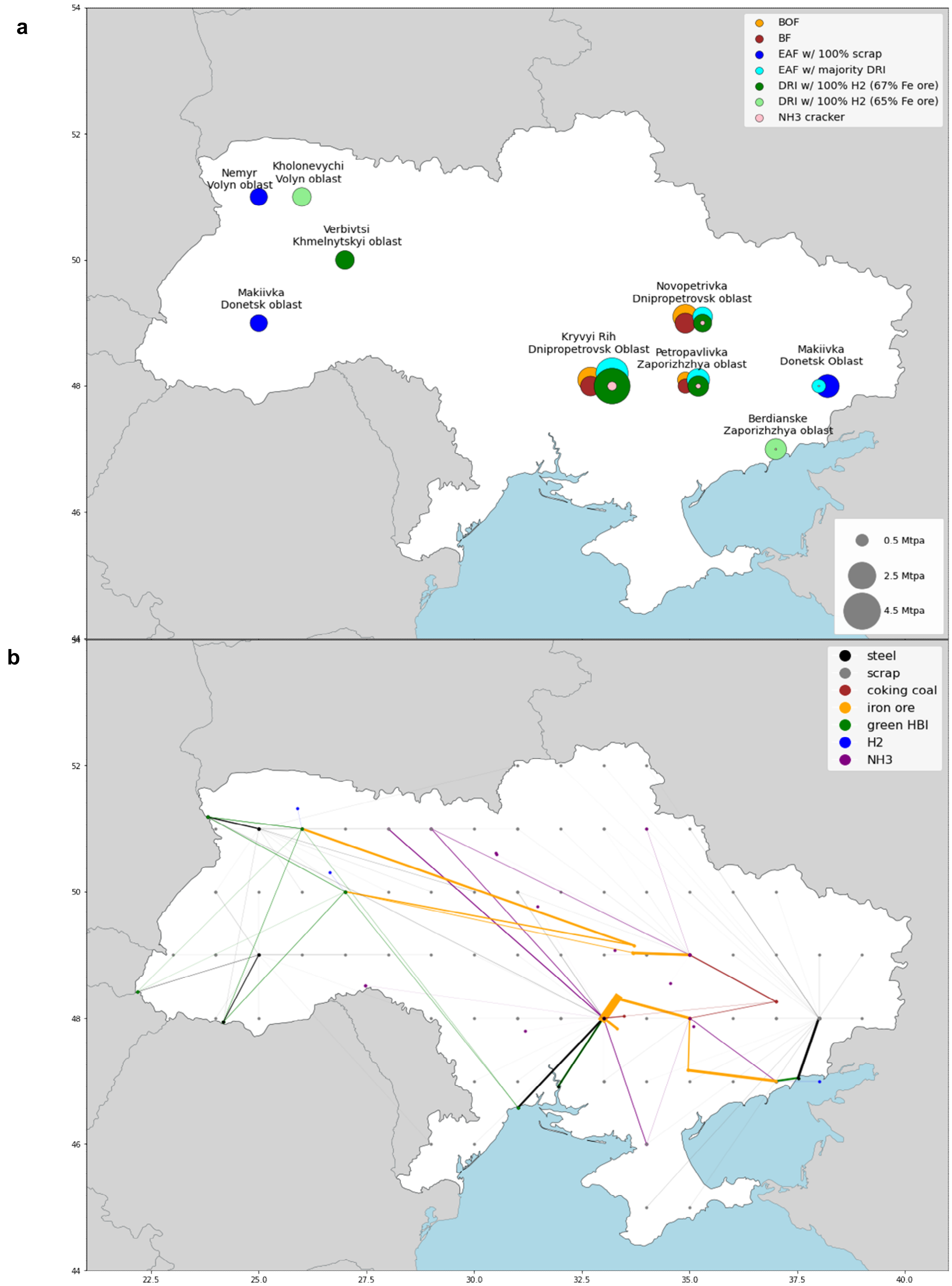

Figure S1.12. Optimised steel supply chains in 2030 under the *Strong Recovery* Scenario: (a) capacity of iron and steel production assets (marker diameter indicates rated capacity), and (b) domestic supply chain flows (straight-line distances shown, line thickness indicates trade volume).

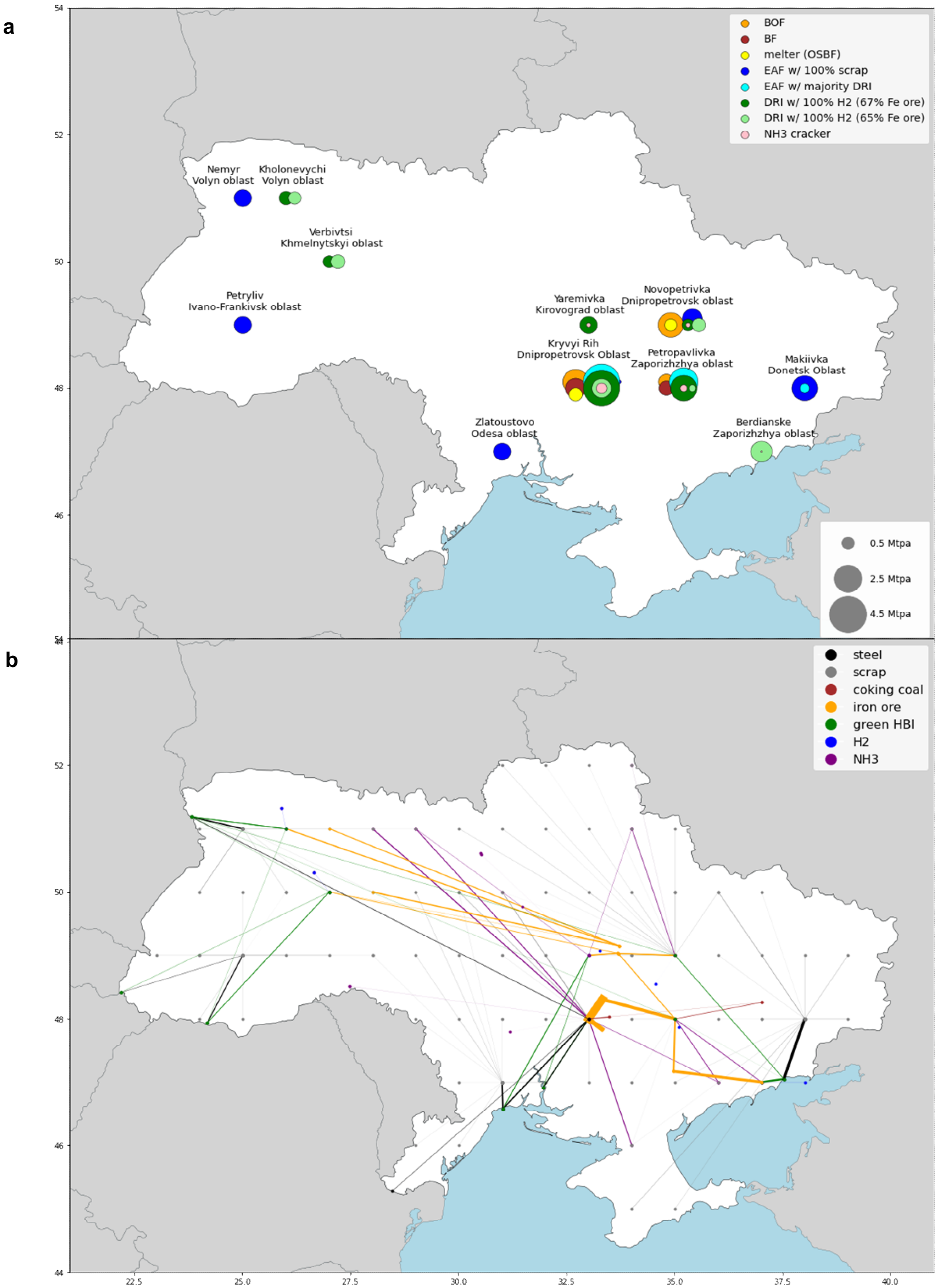

Figure S1.13. Optimised steel supply chains in 2040 under the *Strong Recovery* Scenario: (a) capacity of iron and steel production assets (marker diameter indicates rated capacity), and (b) domestic supply chain flows (straight-line distances shown, line thickness indicates trade volume).

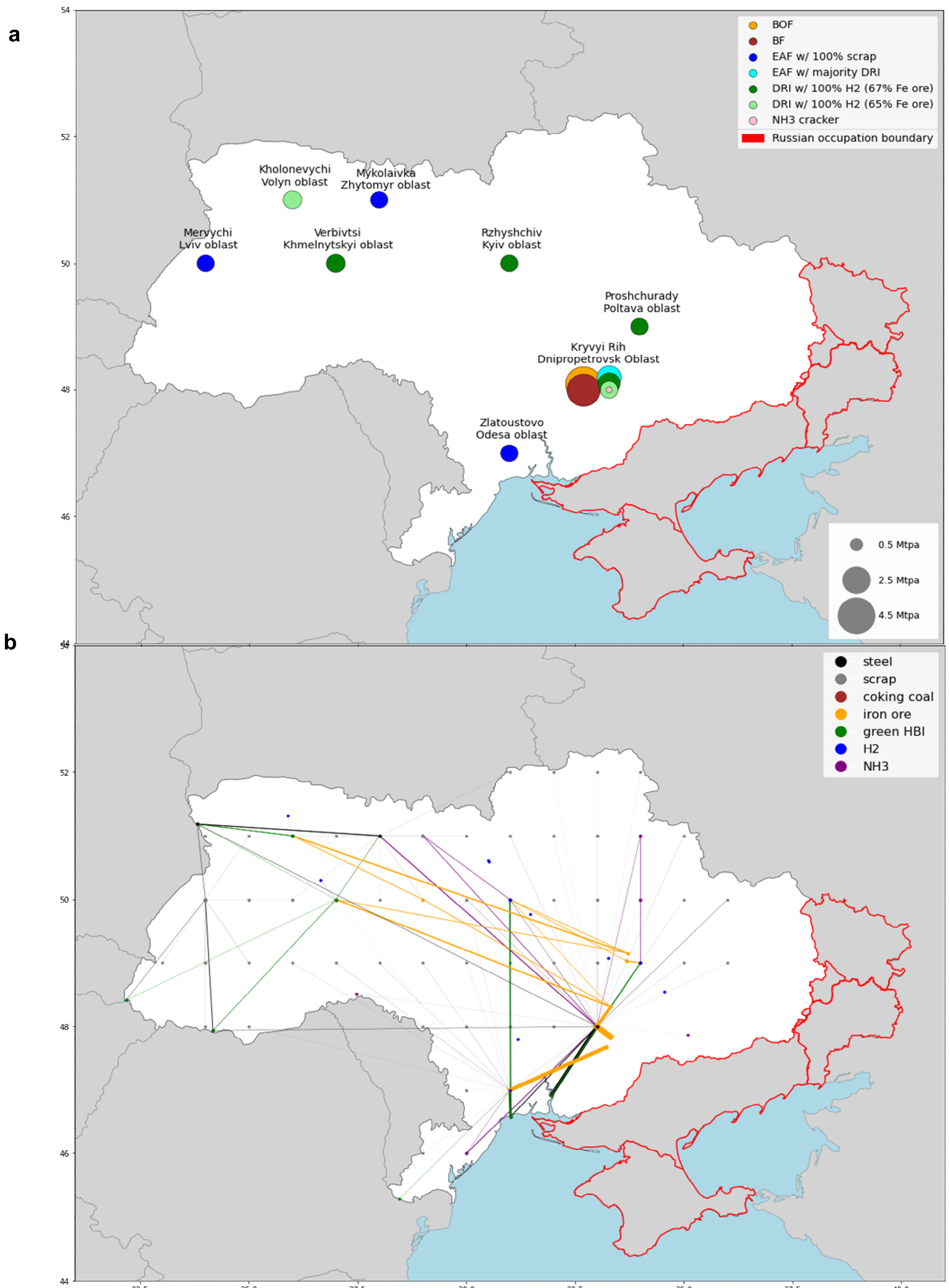

Figure S1.14. Optimised steel supply chains in 2030 under the *Slow Recovery* Scenario: (a) capacity of iron and steel production assets (marker diameter indicates rated capacity), and (b) domestic supply chain flows (straight-line distances shown, line thickness indicates trade volume). The geospatial data for Russian-occupied regions were provided by Deep State UA (2023), accurate as of April 2023.

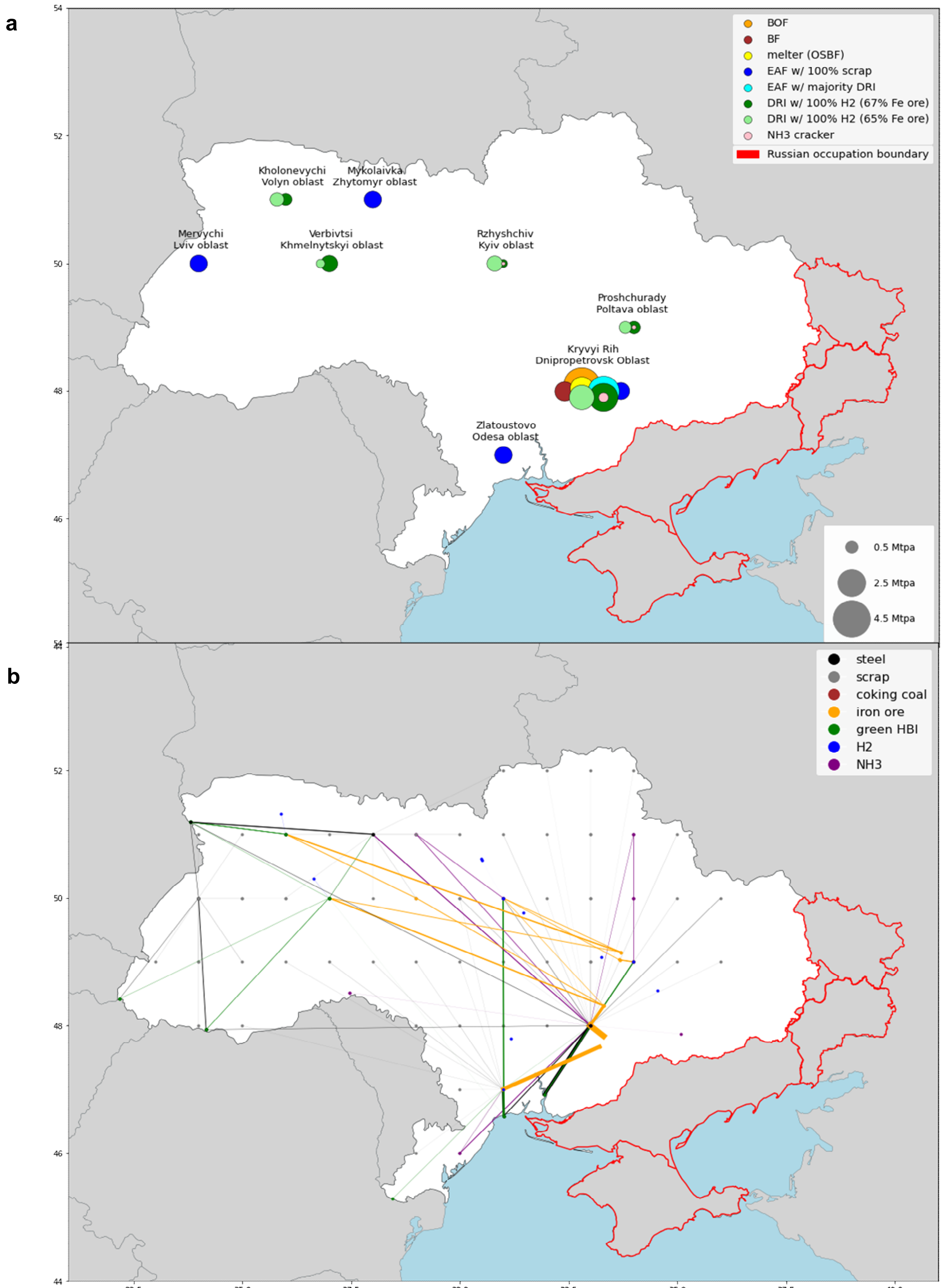

Figure S1.15. Optimised steel supply chains in 2040 under the *Slow Recovery* Scenario: (a) capacity of iron and steel production assets (marker diameter indicates rated capacity), and (b) domestic supply chain flows (straight-line distances shown, line thickness indicates trade volume). The geospatial data for Russian-occupied regions were provided by Deep State UA (2023), accurate as of April 2023.

Table S1.6. Energetic requirements for each optimised scenario.

Scenarios		**Electricity**	**H_2**	**NH_3**	**TOTAL electrical + chemical energy**	
		MWh	MWh	MWh	TWh	million GJ
Strong Recovery	2030	6,049,568	20,519,260	15,962,988	42.53	153
Strong Recovery	2040	8,712,361	26,700,622	23,267,511	58.68	211
Strong Recovery	2050	9,838,218	33,747,168	24,805,414	68.39	246
Slow Recovery	2030	2,685,120	8,118,920	4,042,818	14.85	53
Slow Recovery	2040	5,509,330	16,832,924	14,500,145	36.84	133
Slow Recovery	2050	6,091,484	21,253,312	19,728,853	47.07	169

Table S1.7. Capital requirements for energy production, by scenario.

	TOTAL		Electrolysers		Solar		Onshore wind		Offshore wind	
	MW	$ billion	MW	$ billion	MW	$ billion	MW	$ billion	MW	$ billion
Strong Recovery Scenario		**45.93**		**6.23**		**13.43**		**13.27**		**12.99**
2030 New Capacity	31896	31.96	11598	4.47	8058	5.12	7450	11.55	4790	10.83
2040 Additional Capacity	15635	8.95	3781	1.29	9413	3.77	1311	1.72	1129	2.17
2050 Additional Capacity	17989	5.02	1640	0.48	16349	4.54	0	0	0	0
Slow Recovery Scenario		**19.05**		**3.69**		**7.63**		**7.72**		
2030 New Capacity	7192	5.75	2724	1.05	2437	1.55	2031	3.15	-	-
2040 Additional Capacity	16052	9.34	4570	1.55	7998	3.21	3483	4.58	-	-
2050 Additional Capacity	14074	3.97	3693	1.09	10381	2.88	0	0	-	-

Table S1.8. Capital requirements for energy storage, by scenario.

	TOTAL		Batteries		CGH_2		NH_3	
	-	$ billion	MWh	$ billion	t H_2	$ billion	t NH_3	$ billion
Strong Recovery Scenario		**6.61**	**14840**	**2.84**	**2901**	**2.93**	**492322**	**0.85**
2030 New Capacity	-	3.05	8242	1.71	1501	1.05	195606	0.29
2040 Additional Capacity	-	2.05	3865	0.70	218	1.05	121106	0.29
2050 Additional Capacity	-	1.52	2734	0.43	1183	0.83	175611	0.26
Slow Recovery Scenario		**3.19**	**10076**	**1.85**	**1059**	**0.74**	**402639**	**0.60**
2030 New Capacity	-	0.93	3228	0.67	226	0.16	68662	0.10
2040 Additional Capacity	-	1.36	4330	0.79	578	0.40	109795	0.16
2050 Additional Capacity	-	0.91	2518	0.39	254	0.18	224182	0.34

Table S1.9. Capital requirements for iron and steel production, by scenario.

	TOTAL		DRI furnaces		EAF		OSBF		NH_3 Cracker	
	-	$ billion	Mtpa	$ billion	Mtpa	$ billion	Mtpa	$ billion	Mtpa	$ billion
Strong Recovery Scenario		**9.50**	**18.40**	**5.71**	**10.20**	**2.88**	**3.11**	**0.88**	**0.86**	**0.03**
2030 New Capacity	-	5.40	10.81	3.35	7.20	2.04	0.00	0.00	0.48	0.01
2040 Additional Capacity	-	2.18	3.26	1.01	3.00	0.85	1.11	0.31	0.22	0.01
2050 Additional Capacity	-	1.91	4.33	1.34	0.00	0.00	2.00	0.57	0.16	0.00
Slow Recovery Scenario		**6.34**	**11.20**	**3.47**	**7.17**	**2.03**	**2.92**	**0.83**	**0.59**	**0.01**
2030 New Capacity	-	3.55	6.94	2.15	4.93	1.39	0	0	0.13	0.00
2040 Additional Capacity	-	1.81	2.14	0.66	2.25	0.63	1.77	0.50	0.30	0.00
2050 Additional Capacity	-	0.99	2.12	0.66	0.00	0.00	1.15	0.32	0.16	0.00

S1.5 Economic multipliers

Table S1.10. Input-output Leontief multipliers for Ukraine's basic metals and construction industries in 2014 and 2021.

	Basic Metals				Construction			
	2014		2021		2014		2021	
	Type I	*Type II*	*Type I*	*Type II*	*Type I*	*Type II*	*Type I*	*Type II*
Output multiplier	3.24	4.38	3.34	4.28	3.23	4.38	3.60	4.65
Income multiplier	6.68	9.45	6.67	9.24	4.07	5.77	4.65	6.44
Income effect	0.53	0.75	0.41	0.57	0.53	0.75	0.46	0.64
GVA multiplier	6.56	9.75	6.38	8.80	4.26	6.32	5.15	7.37
GVA effect	0.97	1.44	0.99	1.36	0.97	1.43	0.96	1.38

Source: authors' own calculations on the basis of Input-Output Tables from State Statistics Service of Ukraine (2022). Three types of economic impacts are assessed: direct (the immediate effect on the steel sector caused by the change in final demand), indirect (throughout the supply chain, caused by the consequent changes in intermediate demand), and induced (change in compensation of employees and other incomes, causing further spending). The output multiplier is expressed as the ratio of direct and indirect (for Type I) as well as induced (for Type II) output changes to the direct output change, based on 1-unit of currency.

Table S1.11. Use of domestic outputs of the '24. Basic metals' industry: aggregate combined use table (basic prices), percentage of total use, 2012-2021, and the mean (ten-year average).

NACE code	*Consumers of basic metals*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*Mean*
	I. Intermediate consumption by industries											
A01-A03	Agriculture, forestry & fishing	0.12	0.12	0.13	0.18	0.27	0.30	0.24	0.28	0.32	0.42	0.24
B05	Coal and lignite	0.38	0.32	0.12	0.07	0.10	0.12	0.14	0.13	0.06	0.14	0.16
B06	Crude petroleum and natural gas	0.12	0.10	0.10	0.16	0.47	0.12	0.33	0.37	0.10	0.00	0.19
B07-B09	Metal ores; other mining and quarrying; mining support services	0.69	0.58	0.85	0.52	0.75	0.94	0.91	0.80	1.15	2.15	0.93
C10-C12	Food products; beverages; tobacco products	0.45	0.27	0.24	0.29	0.51	0.64	0.61	1.53	0.40	0.37	0.53
C13-C15	Textiles; wearing apparel; leather and related products	0.00	0.01	0.00	0.02	0.04	0.05	0.01	0.01	0.01	0.02	0.02
C16-C18	Wood & of products of wood & cork, except furniture; articles of straw & plaiting materials; paper & paper products; printing and recording services	0.07	0.09	0.06	0.08	0.11	0.16	0.09	0.10	0.18	0.05	0.10
C19.1	Coke oven products	0.02	0.03	0.03	0.02	0.03	0.02	0.05	0.01	0.03	0.03	0.03
C19.2	Refined petroleum products	0.01	0.01	0.03	0.03	0.04	0.01	0.01	0.11	0.09	0.00	0.03
C20	Chemicals and chemical products	0.12	0.13	0.07	0.07	0.09	0.08	0.08	0.17	0.13	0.08	0.10
C21	Basic pharmaceutical products and pharmaceutical preparations	0.01	0.01	0.01	0.02	0.01	0.02	0.03	0.04	0.04	0.05	0.02
C22	Rubber & plastic products	0.07	0.11	0.12	0.11	0.24	0.36	0.32	0.32	0.18	0.50	0.23
C23	Other non-metallic mineral products	0.34	0.58	0.39	0.52	0.95	1.08	0.73	0.87	0.96	0.80	0.72
C24	Basic metals	12.50	8.93	9.42	10.65	14.00	15.40	14.58	10.98	11.71	12.13	12.03
C25	Fabricated metal products, except machinery and equipment	3.30	4.83	3.26	2.96	3.95	2.75	4.39	5.57	6.58	5.34	4.29
C26	Computer, electronic & optical products	0.11	0.11	0.12	0.09	0.12	0.09	0.12	0.13	0.12	0.07	0.11
C27	Electrical equipment	0.39	1.75	1.21	0.87	0.96	0.86	0.91	1.41	1.08	0.95	1.04
C28	Machinery and equipment n.e.c.	2.49	2.76	1.76	1.66	1.45	1.67	1.28	2.05	1.66	1.73	1.85
C29	Motor vehicles, trailers and semi-trailers	0.58	0.37	0.12	0.01	0.13	0.20	0.19	0.40	0.00	0.17	0.22
C30	Other transport equipment	4.91	3.15	1.21	0.47	0.58	0.66	0.81	1.34	1.18	0.66	1.50
C31-C33	Furniture; other manufactured goods; repair & installation of machinery and equipment	1.05	0.73	0.59	0.68	0.70	1.26	0.89	1.56	1.39	1.72	1.06
D35	Electricity, gas, steam and air conditioning supply	2.24	2.69	3.04	2.86	2.93	3.82	3.10	3.89	5.61	3.58	3.38
E36-E39	Water supply; sewerage; waste management and remediation	0.63	0.93	1.92	1.08	1.48	1.34	1.11	1.42	1.15	0.74	1.18

F41-F43	Construction	4.85	4.94	3.89	2.72	2.59	2.93	3.33	4.93	5.30	3.83	3.93
G45-G47	Wholesale and retail trade; repair of motor vehicles and motorcycles	0.23	0.39	0.51	0.30	0.86	1.17	1.00	1.20	1.06	1.38	0.81
H49-H52	Land transport; water transport; air transport; warehousing & transport support	0.22	0.15	0.32	0.19	0.16	0.14	0.11	0.27	0.44	0.19	0.22
H53	Postal & courier services	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I55-I56	Accommodation; food & beverage services	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.01
J58-J60	Publishing; motion picture, video & TV programme production; sound recording, programming and broadcasting services	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
J61	Telecommunications	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.01
J62-J63	Computer programming & consultancy services; information services	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00
K64-K66	Financial services; insurance, reinsurance and pension funding, excl. compulsory social security; activities auxiliary to financial services	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
L68	Real estate activities	0.08	0.06	0.15	0.05	0.00	0.10	0.10	0.19	0.20	0.21	0.11
M69-M71	Legal and accounting services; activities of head offices; management consultancy activities; architectural & engineering services; technical testing & analysis	0.09	0.07	0.07	0.10	0.22	0.19	0.24	0.11	0.14	0.11	0.13
M72	Scientific research & development	0.08	0.11	0.05	0.04	0.04	0.04	0.03	0.05	0.09	0.04	0.06
M73-M75	Advertising & market research; other professional, scientific and technical services; veterinary services	0.01	0.02	0.01	0.00	0.06	0.05	0.04	0.14	0.17	0.19	0.07
N77-N82	Administrative and support service activities	0.02	0.03	0.02	0.02	0.03	0.05	0.02	0.06	0.06	0.05	0.04
O84	Public administration and defence; compulsory social security	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P85	Education	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.01
Q86-Q88	Human health and Social Work activities	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.00
R90-R93	Arts, Entertainment and recreation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S94-S96, T97	Other service activities; activities of households	0.00	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01
	Total intermediate demand	**36.09**	**34.39**	**29.87**	**26.86**	**33.94**	**36.67**	**35.86**	**40.51**	**41.62**	**37.75**	**35.36**
	II. Final consumption expenditure											

P.3	**Total**	**0.05**	**0.01**	**0.04**	**0.06**	**0.06**	**0.05**	**0.05**	**0.06**	**0.05**	**0.04**	**0.05**
P.31; S.14	Households	0.05	0.01	0.04	0.06	0.05	0.04	0.05	0.06	0.05	0.04	0.05
P.31; S.15	Non-profit institutions serving households	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P.31, P.32; S.13	General government	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	III. Gross capital formation											
P.5g	**Total**	**-0.34**	**-1.10**	**-1.30**	**0.28**	**2.85**	**0.08**	**0.52**	**0.36**	**-2.66**	**-1.64**	**-0.30**
P.51g	Gross fixed capital formation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P.52	Changes in inventories	-0.34	-1.10	-1.30	0.28	2.85	0.08	0.52	0.36	-2.66	-1.64	-0.30
P.53	Net acquisitions of valuables	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	IV. Exports											
P.6	**Exports of goods and services**	**64.20**	**66.70**	**71.38**	**72.80**	**63.15**	**63.21**	**63.57**	**59.06**	**60.99**	**63.85**	**64.89**
	Total use of domestic production at basic prices	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

Source: authors' own calculations using data from National Accounts of Ukraine (State Statistics Service of Ukraine, 1990-2021).

Table S1.12. Applying the multiplier - economic impact of the additional $12.63bn of post-war reconstruction demand, US$ in current prices, average per year**.**

NACE Code	*Industry group*	*Initial effect*	*Type I multipliers*	*Type II multipliers*	*Type I multipliers*	*Type II multipliers*	*Type I multipliers*	*Type II multipliers*
			Output		**Income**		**GVA**	
A01-A03	Agriculture, forestry & fishing	0.00	0.11	1.38	0.01	0.14	0.05	0.58
B05	Coal and lignite	0.00	0.75	0.97	0.16	0.20	0.33	0.42
B06	Crude petroleum and natural gas	0.00	1.21	1.78	0.11	0.16	0.88	1.29
B07-B09	Metal ores; other mining and quarrying; mining support services	0.00	1.73	1.86	0.19	0.21	0.76	0.82
C10-C12	Food products; beverages; tobacco products	0.00	0.01	1.33	0.00	0.13	0.00	0.26
C13-C15	Textiles; wearing apparel; leather and related products	0.00	0.03	0.27	0.01	0.07	0.01	0.13
C16-C18	Wood & of products of wood & cork, except furniture; articles of straw & plaiting materials; paper & paper products; printing and recording services	0.00	0.31	0.50	0.03	0.05	0.07	0.11
C19.1	Coke oven products	0.00	0.42	0.48	0.02	0.02	0.04	0.05
C19.2	Refined petroleum products	0.00	0.82	1.11	0.05	0.07	0.11	0.15
C20	Chemicals and chemical products	0.00	0.84	1.32	0.08	0.12	0.09	0.15
C21	Basic pharmaceutical products and pharmaceutical preparations	0.00	0.03	0.26	0.00	0.05	0.01	0.08
C22	Rubber & plastic products	0.00	0.90	1.11	0.08	0.10	0.12	0.15
C23	Other non-metallic mineral products	0.00	3.13	3.31	0.29	0.31	0.50	0.53
C24	Basic metals	0.00	2.45	2.77	0.15	0.17	0.38	0.43
C25	Fabricated metal products, except machinery and equipment	0.00	1.28	1.43	0.18	0.20	0.25	0.28
C26	Computer, electronic & optical products	0.00	0.21	0.35	0.05	0.08	0.05	0.09
C27	Electrical equipment	0.00	0.40	0.48	0.08	0.09	0.11	0.13
C28	Machinery and equipment n.e.c.	0.00	0.53	0.69	0.13	0.17	0.16	0.21
C29	Motor vehicles, trailers and semi-trailers	0.00	0.34	0.63	0.11	0.20	0.07	0.14
C30	Other transport equipment	0.00	0.08	0.11	0.02	0.03	0.03	0.04
C31-C33	Furniture; other manufactured goods; repair & installation of machinery and equipment	0.00	0.22	0.39	0.05	0.09	0.08	0.14
D35	Electricity, gas, steam and air conditioning supply	0.00	1.82	2.62	0.26	0.38	0.54	0.78
E36-E39	Water supply; sewerage; waste management and remediation	0.00	0.10	0.17	0.03	0.05	0.03	0.05

F41-F43	**Construction**	**12.63**	**20.55**	**20.87**	**2.04**	**2.07**	**3.85**	**3.91**
G45-G47	Wholesale and retail trade; repair of motor vehicles and motorcycles	0.00	3.41	5.62	0.71	1.17	1.67	2.76
H49-H52	Land transport; water transport; air transport; warehousing & transport support	0.00	1.52	2.20	0.40	0.58	0.66	0.96
H53	Postal & courier services	0.00	0.01	0.03	0.01	0.01	0.01	0.02
I55-I56	Accommodation; food & beverage services	0.00	0.03	0.22	0.00	0.03	0.02	0.12
J58-J60	Publishing; motion picture, video & TV programme production; sound recording, programming and broadcasting services	0.00	0.11	0.18	0.02	0.04	0.04	0.07
J61	Telecommunications	0.00	0.04	0.18	0.01	0.04	0.02	0.10
J62-J63	Computer programming & consultancy services; information services	0.00	0.16	0.27	0.02	0.04	0.09	0.15
K64-K66	Financial services; insurance, reinsurance and pension funding, excl. compulsory social security; activities auxiliary to financial services	0.00	0.53	0.88	0.15	0.25	0.35	0.58
L68	Real estate activities	0.00	0.26	0.92	0.02	0.09	0.19	0.68
M69-M71	Legal and accounting services; activities of head offices; management consultancy activities; architectural & engineering services; technical testing & analysis	0.00	0.45	0.63	0.11	0.15	0.20	0.28
M72	Scientific research & development	0.00	0.02	0.03	0.01	0.01	0.01	0.02
M73-M75	Advertising & market research; other professional, scientific and technical services; veterinary services	0.00	0.18	0.35	0.03	0.06	0.10	0.19
N77-N82	Administrative and support service activities	0.00	0.31	0.50	0.10	0.17	0.16	0.26
O84	Public administration and defence; compulsory social security	0.00	0.12	0.17	0.08	0.12	0.09	0.13
P85	Education	0.00	0.01	0.09	0.01	0.06	0.01	0.06
Q86-Q88	Human health and Social Work activities	0.00	0.01	0.11	0.00	0.05	0.00	0.05
R90-R93	Arts, Entertainment and recreation	0.00	0.01	0.05	0.00	0.02	0.00	0.03
S94-S96, T97	Other service activities; activities of households	0.00	0.01	0.08	0.00	0.02	0.01	0.05
	Total	**12.63**	**45.46**	**58.70**	**5.83**	**8.08**	**12.18**	**17.44**

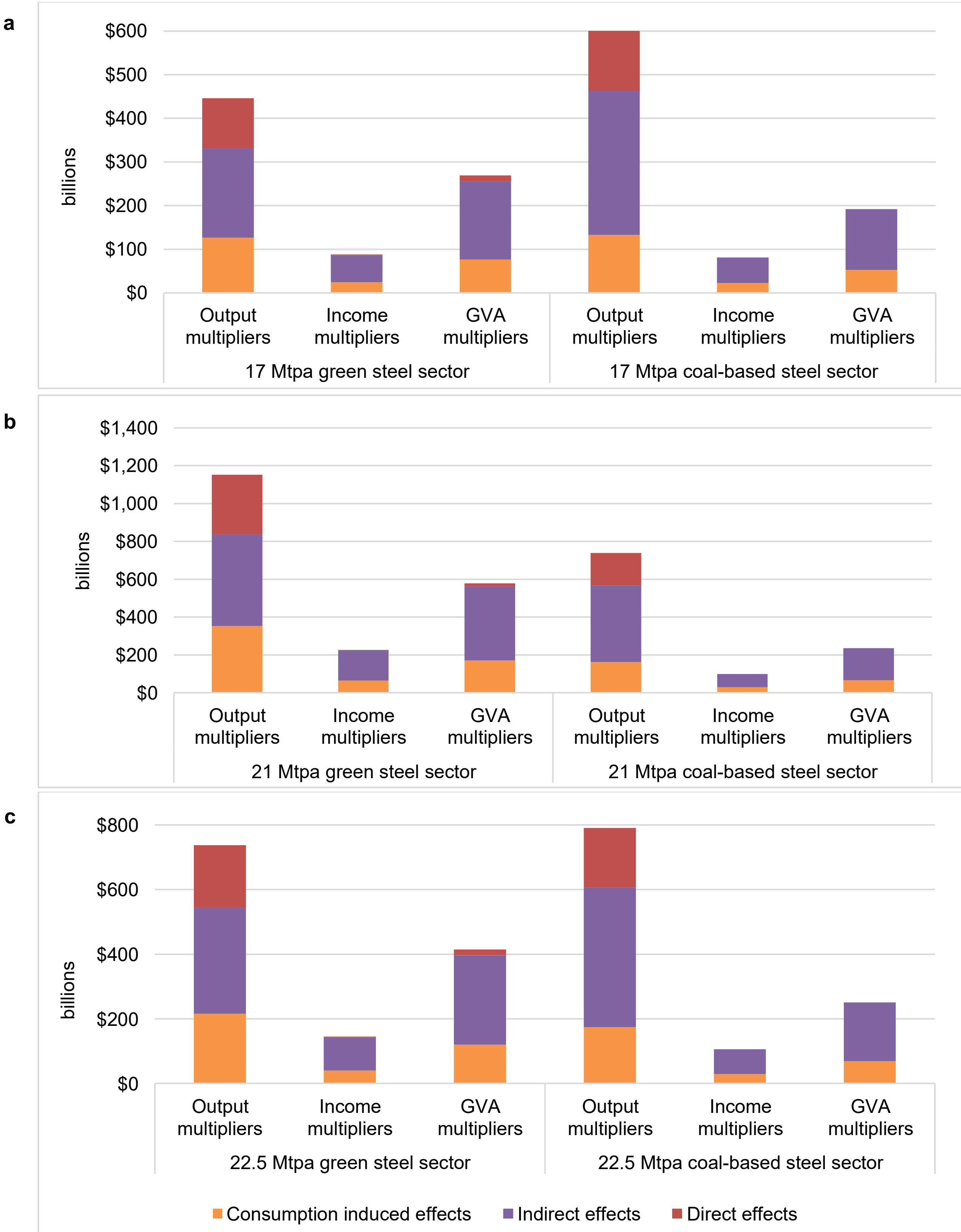

Figure S1.16. The macroeconomic effects of steel production, quantified in terms of output, income and GVA multipliers over a 20-year project lifetime, and compared across two distinct sectorial pathways: (i) the green steel sector (based on the *Strong Recovery* scenario), and (ii) the coal-based steel sector (based on pre-war 2021 economic multipliers). Demonstrated for (a) steel output of 17.2 Mtpa, equivalent to the 2030 *Strong Recovery* scenario, (b) steel output of 21.1 Mtpa, equivalent to the 2040 *Strong Recovery* scenario, and (c) steel output of 22.5 Mtpa, equivalent to the 2050 *Strong Recovery.*

S2. Supplementary Experimental Procedures

S2.1 Near zero-carbon electricity, hydrogen, and ammonia production

The challenge of using renewable energy to produce green hydrogen and ammonia is the variability of the renewable energy resource. If downstream equipment, like the electrolyser (which is the biggest consumer of energy), is equal in size to the renewable energy farm, then it will sit idle whenever renewable energy is not available. On the flipside, if the electrolyser is much smaller than the renewable energy farm, then energy will be curtailed whenever the farm generates at its maximum rate. Optimisation tools are needed to strike a balance between these requirements to prevent wastage of electricity or low utilisation of downstream equipment. These tools also enable other considerations to be included: (i) whether only wind, only solar, or a hybrid of both, achieves the lowest costs; (ii) whether production of chemical fuels should be smoothed out using buffer storage downstream (which in the case of hydrogen is very expensive), or by oversizing of renewables upstream (which will increase curtailment); (iii) the constraints introduced by equipment with limited flexibility, like the Haber-Bosch plant, which cannot be turned off entirely and must always operate at or above a minimum fraction of its design rate (a number of values are used for this minimum design rate in the literature – a conservative value of 30% is adopted here).

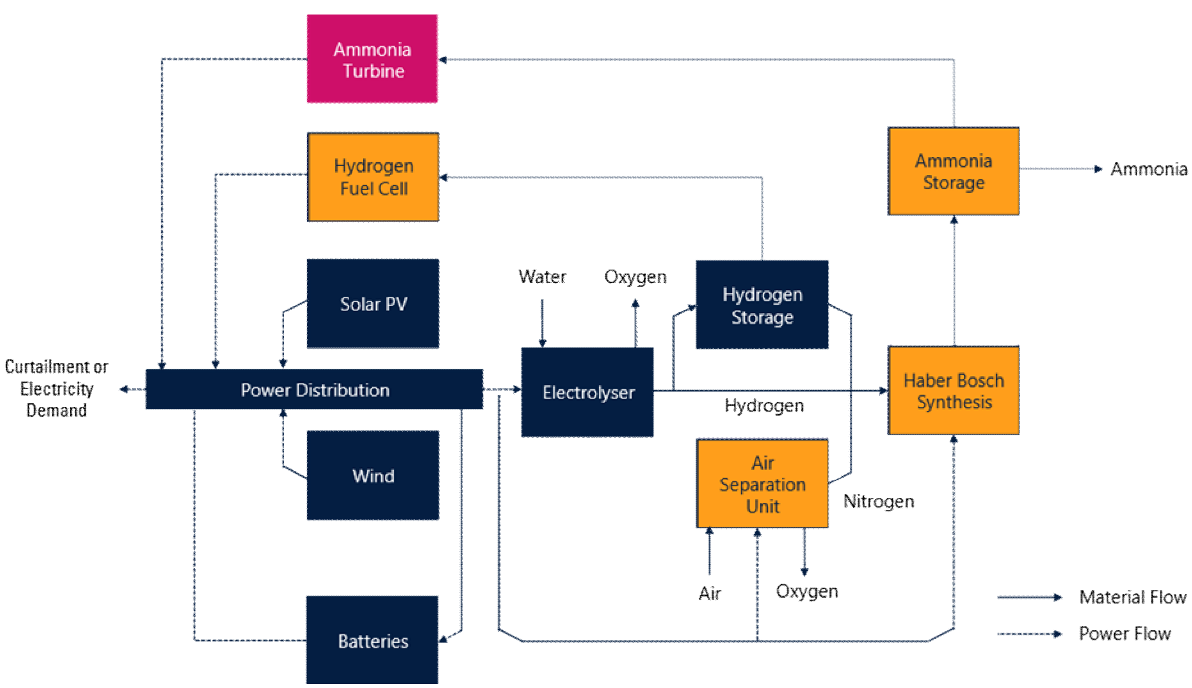

Figure S2.1. System for the production of hydrogen, ammonia, and electricity. The size of each unit is determined by an optimisation model, which minimises the net present value of the system, using the capital cost of each unit, and weather data, which determines the output of electricity in each hour from the installed wind and solar plants. In the hydrogen case, a constant load of hydrogen must be produced using only the units in dark blue (Solar PV, wind, power distribution, electrolysis, hydrogen storage and batteries); for the ammonia case, a constant ammonia stream must be produced, using the same units as for hydrogen and the units in orange (Air separation unit, Haber-Bosch synthesis, a hydrogen fuel cell and ammonia storage); for the electricity case, a near constant electricity demand must be met – any unit can be used.

The land area available to install RE infrastructure (solar PV panels and onshore wind turbines) for green steel production was assessed for all 73 land-based grids. Factors were applied to determine the land available for renewables, which depended on the land type classification ($f\_RE_{land\_class}$). Land classifications were defined by the MODIS5 dataset (Friedl & Sulla-Menashe, 2019) and RE reduction factors are shown in Table S2.1. An additional reduction factor of 0.2 was applied to account for the portion of total RE land availability that the steel sector may consume (f_steel), which matches the pre-war energy consumption of the steel sector as portion of Ukrainian final energy consumption.

$$Land\_Available\_SteelRE^{grid} = \sum_{land\_class} T\_land^{grid}_{land\_class} * f\_RE_{land\_class} * f\_steel \qquad \forall\, grid$$

The sea area available to install RE infrastructure (offshore wind turbines) for green steel production was similarly assessed; however, a single RE reduction factor was applied for all locations.

$$Sea\_Available\_SteelRE^{grid} = T\_sea^{grid} * f\_RE_{sea} * f\_steel \qquad \forall\, grid$$

Table S2.1. Fraction of land available for renewables according to land classification (Salmon & Bañares-Alcántara, 2022).

Land Cover Type	MODIS Number	Fraction of land available for renewables	
		Wind	Solar
Evergreen Needleleaf Forests	1	-	-
Evergreen Broadleaf Forests	2	-	-
Deciduous Needleleaf Forests	3	-	-
Deciduous Broadleaf Forests	4	-	-
Mixed Forests	5	-	-
Closed Shrublands	6	0.5	0.5
Open Shrublands	7	0.5	0.5
Woody Savannas	8	0.2	0.2
Savannas	9	0.2	0.2
Grasslands	10	0.2	0.2
Permanent Wetlands	11	-	-
Croplands	12	0.1	0.05
Urban and Built-up Lands	13	-	0.03
Cropland, Natural Vegetation, Mosaic	14	0.1	0.05
Permanent Snow and Ice	15	-	-
Barren	16	1	1
Water Bodies	17	-	-

Table S2.2. Solar and wind power plants commissioned in Ukraine, used as basis for learning curve projections to 2050.

Name	Location by region (oblast)	Investment	MW	Commissioning date	1MW costs (USD/MW)
Nikopol SPP	Dnipropetrovsk	€230m	246	Mar-19	1,028,455
Pokrovska SPP	Dnipropetrovsk	€200m	240	Oct-19	916,666
Kamianets-Podilskyi SPP	Khmelnytskyi	$55m	64	Mar-19	945,313
Yavoriv Solar	Lviv	€34.7m	36	Oct-18	1,069,444
Tokmak SPP	Zaporizhzhia	€45m	50	Apr-18	990,000
Botievska WPP	Zaporizhzhia	€340m	200	2014	1,870,000
Pyimorska WPP	Zaporizhzhia	€321m	200	2019	1,765,500
Orlovska WPP	Zaporizhzhia	€131m	100	2019	1,441,000
Myrnenska WPP	Kherson	€326m	164	2019	2,186,584
Overyanivska WPP	Kherson	€118m	70	2019	1,854,285

Table S2.3. Time-variable cost parameters for renewable energy and hydrogen production and storage.

	UA / global prices	Unit (million)	2022	2030	2040	2050	Source/notes
Onshore wind turbine	UA	$/MW	1.823	1.550	1.314	1.151	2022 value from actual installed projects in Ukraine; then learning curves applied
Offshore fixed bottom wind turbine	Global	$/MW	2.660	2.260	1.920	1.680	Salmon and Bañares-Alcántara (2022)
Offshore floating bottom wind turbine	Global	$/MW	2.990	2.540	2.150	1.890	Salmon and Bañares-Alcántara (2022)
Land-based solar panel	UA	$/MW	0.990	0.635	0.401	0.277	2022 value from actual installed projects in Ukraine; then learning curves applied
Electrolysers (low-temperature)	Global	$/MW	-	0.385	0.340	0.295	IEA (2021)
Lithium-ion batteries	Global	$/MWh	-	0.207	0.182	0.156	Cole and Frazier (2020)
Hydrogen fuel cell	Global	$/MW	-	0.457	0.267	0.218	Whiston et al. (2019)
CGH_2 storage vessel (200 bar)	Global	$/MW	-	0.700	0.700	0.700	Abdin et al. (2021)

Table S2.4. Time-variable efficiency of electrolysis and fuel cells.

	UA / global data	Unit	2022	2030	2040	2050	Source
Electrolyser efficiency	Global	% (LHV)	-	68%	72%	75%	IEA (2019)
FC efficiency	Global	% (LHV)	-	60%	62%	64%	IEA (2015)

Table S2.5. Energy and cost parameters for ammonia production.

	UA / global data	Unit	Value	Source
Haber Bosch Electricity Consumption	Global	MWh/t NH_3	1	IRENA (2022)
Haber Bosch Plant	Global	USD/tpa NH_3 (rated capacity)	700	
Liquefied NH_3 storage vessel	Global	USD/t NH_3 (peak capacity)	1500	

S2.2 Dynamic material flow analysis

To determine post-consumer steel outflows, the lifetime probability distribution function was applied to inflows, according to the steel product category (assuming continuous distribution):

$$Outflow(t,c) = \frac{stock(t'_0)}{(t - t'_0)} + \sum_{t'<t} Inflow(t',c) * f(t,t',\tau(c),\sigma(c))$$

$$f(t,t',\tau(c),\sigma(c)) = \frac{1}{\sigma\sqrt{2\pi}} * \exp\left(\frac{-(t - t' - \tau)^2}{2\sigma^2}\right)$$

Where f(t,t',τ,σ) is the lifetime probability distribution function, t is the model year (2030, 2040, 2050), t' is the cohort of steel product (1900-2070), τ is the lifetime of the product category and σ is the standard deviation of the lifetime, as defined in the table below.

Table S2.6. Ukrainian in-use steel stocks in 1900, lifetime and standard deviation by steel product category, based on per capita stock estimates from Pauliuk et al. (2013) for the former USSR region.

	Ukraine in use stocks, 1900	***Lifetime***	***Standard deviation of the lifetime***
Product category (c)	(kt)	τ (years)	σ (years)
Transportation	1872	20	6.00
Machinery	839	30	9.00
Construction	5279	75	22.50
Appliances/packaging	740	15	4.50

S2.3 Iron and steel production and trade

S2.3.1 Establishing the model

Energy can be drawn from fossil fuels (metallurgical coal, natural gas), renewables (hybrid onshore solar and wind, offshore wind, hydropower), or near-zero carbon alternatives (nuclear power). Newly installed solar and wind plants and existing hydro and nuclear power plants could produce electricity, hydrogen, and/or ammonia for use in steel production. Electricity could be transmitted and distributed via the network, hydrogen transported in compressed gaseous form within freight trucks or pipelines, and ammonia transported in liquid form within pipelines.

Process flexibility and energy storage are critical in managing renewable energy sources (RES) for cost-effective industrial operations. Whilst oversizing of renewable energy production infrastructure (i.e., solar panels and wind turbines) is essential, since the wind does not always blow nor the sun always shine, it becomes an operational choice to make hydrogen and/or steel production flexible (thereby oversizing electrolyser and furnace capacities, respectively, and providing relevant energy/material storage facilities). The broad requirement for continuous DRI operations to ensure a uniform oxidation front was shown in previous work (Devlin et al., 2023) to limit the benefits of EAF flexibility. Hence, at the facility-level, this study focuses on optimising upstream electricity and hydrogen production.

The following supply chain network features framed the model:

(1) Within a country, commodities can be moved between (production) sites and ports;
(2) Internationally, commodities can be moved between ports or rail border crossings;
(3) Raw materials into iron and steelmaking (called "RawMat") must be supplied locally at a site, or transported from suppliers in the case of electricity, H_2, NH_3, metallurgical coal, iron ore and natural gas;
(4) On each site, any production activities can happen, and any raw materials can be supplied;
(5) A production activity will consume feeds;
(6) H_2 can be supplied as a primary resource or as a product from NH_3 cracking (which is a production activity);
(7) Any site or port can provide a product to directly contribute to meeting the national demand; transporting products to a demand centre in a country is not modelled (steel demand can be met at any grid/port as we do not know where finishing processes will occur);
(8) Commodities produced by offshore, HPP, or NPP can only be moved from their origin to a site, not between sites; they can effectively be exchanged between sites, not directly but after they have become part of RawMatSupply at a site for electricity, H_2 or NH_3.

S2.3.2 Steel production routes

In addition to the conventional integrated BF-BOF and scrap-based EAF routes, the following possible low- and near-zero emissions ironmaking routes were modelled:

- DRI with 100% H_2 feedstock (67%-Fe or 65%-Fe ore);

- DRI with 65% H_2 feedstock (minimum amount of NG to maintain DRI of 3.5%-carbon(C); 67%-Fe ore);
- DRI with 70% NG feedstock (maximum amount of H_2 without altering NG-DRI infrastructure; 67%-Fe ore); and
- DRI with 100% NG feedstock (67%-Fe or 65%-Fe ore).

Iron was fed into the following possible steelmaking routes (OHF excluded as an outdated and inefficient technology):

- EAF charged with 86% DRI (of 0%-C or 3.5%-C, produced using 67%-Fe ore), 14% scrap; and
- BOF charged with 89% DRI (of 0%-C or 3.5%-C, produced using 65%-Fe ore), 11% scrap, combined with pre-BOF melter unit (OSBF).

Hence, there are eight possible iron and steelmaking routes considered, with semi-finished steel as the final product:

- BF-BOF;
- scrap-EAF;
- 100% H_2-DRI-EAF;
- 100% NG-DRI-EAF;
- 70% NG-DRI-EAF;
- 65% H_2-DRI-EAF;
- 100% NG-DRI-OSBF-BOF; and
- 100% H_2-DRI-OSBF-BOF.

Insufficient iron quality is a major concern for upscaling production using DR shaft furnaces. Due to the production of sponge iron in DRI operations (rather than molten iron as in BF operations with slag production), ore gangue is preserved. Hence, ore of higher quality must be fed into the furnace, of around 67%-Fe content (Barrington, 2018). The average global in-situ Fe-content of iron ore deposits is 47%, and for Ukraine, this is 35%; both far less than the extracted ore Fe-content due to the preferential extraction of higher quality ores (U.S. Geological Survey, 2022). Significant beneficiation will be required to deliver direct reduction (DR)-grade ore. Alternatively, BF-grade ore can be used, so long as DRI is followed by an extra electric smelting unit (similar to the EAF) before BOF steelmaking, to melt the sponge iron into molten iron and remove impurities. This process is advantageous in using existing assets and lower quality ore (Cavaliere et al., 2022b; Zulli, 2022). Therefore, this study investigates both the DRI-EAF route, which demands higher-quality 67%-Fe ore, and the DRI-melter-BOF route, which requires 65%-Fe ore.

The continuation of any OHF assets is not considered for any scenario as it is an outdated and inefficient technology. In 2008, the BF-OHF route represented 2.2% of global production, but 41.3% of Ukraine's production (worldsteel, 2010). Within the next decade to 2018, BF-OHF production dropped to 0.4% of global production, yet persisted in Ukraine with 22.9% of production; Russia is the only other country where OHFs still exist (World Steel Association, 2020). OHF is outdated technology of the early 1900s (Basil Turner, 1900); in comparison to the BF-OHF route, the BF-BOF route consumes 25% less energy (Morfeldt et al., 2015), and emits 8% less CO_2 due to the reduction in the use of fossil fuel firing (e.g., natural gas, fuel oil, coal or tar) across the surface of the steel bath for heating and carbon reduction (IPCC, 2019).

S2.3.3 Key sets

Key sets were processes, products (output of processes), commodities (which can be transported), and locations.

Table S2.7. Commodity sets and subsets.

Set Declaration	Elements
Commodity	ore67pel (67%-Fe ore pellets), ore65pel, ore65lump, ore65fines, ore65sinter, HBI-C0-67o (HBI with 0%-C content and produced using 67%-Fe ore), HBI-C4-67o, HBI-C0-65o, HBI-C4-65o, pigi (pig iron), SFS (semi-finished steel), elec (electricity), RE (onshore renewable energy), offRE (offshore renewable energy), HP (hydropower), NP (nuclear power), H_2 (hydrogen), greenH_2 (electrolytic H_2 produced using onshore hybrid solar/wind), offgreenH_2 (electrolytic H_2 produced using offshore wind), pinkH_2 (electrolytic H_2 produced using nuclear power), hydroH_2 (electrolytic H_2 produced using hydropower), NH_3, greenNH_3, offgreenNH_3, pinkNH_3, hydroNH_3, NG (natural gas), coke, metcoal (metallurgical coal), scrap, lime, limestone, alloys, oxygen, carbon, electrode, refractory, labour
DemandCom (Commodity)	SFS, HBI-C0-67o, HBI-C0-65º
Electricity (Commodity)	RE, offRE, NP, HP
Hydrogen (Commodity)	greenH_2, offgreenH_2, pinkH_2, hydroH_2
Ammonia (Commodity)	greenNH_3, offgreenNH_3, pinkNH_3, hydroNH_3
SpecialCommodity (Commodity)	RE, offRE, NP, HP, greenH_2, offgreenH_2, pinkH_2, hydroH_2, greenNH_3, offgreenNH_3, pinkNH_3, hydroNH_3
Product (Commodity)	ore65sinter, coke, HBI-C0-67o, HBI-C4-67o, HBI-C0-65o, HBI-C4-65o, pigi, SFS, H_2
Feed (Commodity)	ore67pel, ore65pel, ore65lump, ore65fines, ore65sinter, elec, H_2, NH_3, NG, metcoal, coke, scrap, HBI-C0-67o, HBI-C4-67o, HBI-C0-65o, HBI-C4-65o, pigi, lime, limestone, alloys, oxygen, carbon, electrode, refractory, labour
RawMat (Commodity)	elec, H_2, NH_3, scrap, lime, limestone, alloys, oxygen, carbon, electrode, refractory, labour
TransportableCommodity* (Commodity)	elec, H_2, NH_3, ore67pel, ore65pel, ore65lump, ore65fines, HBI-C0-67o, HBI-C4-67o, HBI-C0-65o, HBI-C4-65o, SFS, RE, offRE, HP, NP, greenH_2, offgreenH_2, pinkH_2, hydroH_2, greenNH_3, offgreenNH_3, pinkNH_3, hydroNH_3, NG, metcoal, scrap
Bulk (Commodity)	ore67pel, ore65pel, ore65lump, ore65fines, HBI-C0-67o, HBI-C4-67o, HBI-C0-65o, HBI-C4-65o, SFS, metcoal, scrap

*transport of lime, limestone, alloys, oxygen, carbon, electrodes, and refractories are ignored because there are no constraints on availability.

Table S2.8. Process-related sets and subsets.

Set Declaration	Elements
Process	sintering, coking, BF, BOF, DRIwH_2-67o, DRIwNG-67o, DRIw65H_2-67o, DRIw70NG-67o, DRIwH_2-65o, DRIwNG-65o, OSBFwDRI-C0, OSBFwDRI-C4, EAFwDRI-C0, EAFwDRI-C4, EAFwscrap, cracking
ExFurnace	exDRP, exEAF, exBF, exBOF
Brownfield (ExFurnace,Process)	exDRP.(DRIwH_2-65o, DRIwH_2-67o, DRIwNG-65o, DRIwNG-67o, DRIw70NG-67o, DRIw65H_2-67o), exEAF.(EAFwDRI-C0, EAFwDRI-C4, EAFwscrap), exBF.BF, exBOF.BOF

Table S2.9. Location sets and subsets.

Set Declaration	Definition	Elements
Location	All locations	s01*s73, ow01*ow14, p01*p18, r01*r12, o01*o11, m01*m07, n01*n07, NPP1*NPP2, HPP1*HPP9
Site (Location)	Manufacturing sites	s01*s73
OffshoreSite (Location)	Offshore wind energy production sites	ow01*ow14
Port (Location)	Sea port capable of handling dry bulk commodities	p01*p18
RailX (Location)	railway crossings capable of handling dry bulk commodities	r01*r12
OreMine (Location)	iron ore mines	o01*o11
CoalMine (Location)	metallurgical coal mines	m01*m07
GasField (Location)	natural gas field or processing plant	n01*n07
NPP (Location)	nuclear power plant	NPP1*NPP2
HPP (Location)	hydro power plant	HPP1*HPP9

Table S2.10. Sets to group country with supply chain elements.

Set Declaration	Elements
Country	UA (Ukraine), IT (Italy), ES (Spain), PO (Poland), RO (Romania), BG (Bulgaria), UK (United Kingdom), DE (Germany), FR (France), BE (Belgium), NL (Netherlands), PT (Portugal), CZ (Czech Republic), AT (Austria), HU (Hungary)
CountrySite (Country, Site)	UA.(s01*s73)
CountryOffshoreSite (Country, OffshoreSite)	UA.(ow01*ow14)
CountryPort (Country, Port)	UA.(p01*p05), IT.(p06*p07), ES.(p08*p09), UK.p10, DE.(p11*p12), FR.(p13*p14), BE.p15, NL.p16, PT.p17, PO.p18
CountryRailX (Country, RailX) *railX must be associated with both countries either side of crossing*	PO.r01, RO.(r02*r03), BG.(r04*r05), DE.r06, FR.r07, BE.r08, CZ.r09, NL.r10, AT.r11, HU.r12/
CountryOreMine (Country, OreMine)	UA.(o01*o11)
CountryCoalMine (Country, CoalMine)	UA.(m01*m07)
CountryGasField (Country, GasField)	UA.(n01*n07)
CountryNPP (Country,NPP)	UA.NPP1*NPP2
CountryHPP (Country,HPP)	UA.(HPP1*HPP2)

S2.3.4 Overall mass and energy balances

Process Balance - Feed consumption (FC) is equal to specific consumption (SC) of the feed in each process, multiplied by the manufactured product output (ProdOut):

$$FC^{site,feed} = \sum_{process} SC_{process}^{feed} * ProdOut_{process}^{site} \qquad \forall\ site, feed$$

Specific consumption rates collected from a range of sources, most of which were used in a previous study (Devlin et al., 2023), with additional data from Müller et al. (2021) and Jacobasch et al. (2021) for H_2/NG blends in DRI, Cavaliere et al. (2022b) for the DRI-OSBF-EAF route, and IEAGHG (2013) for the conventional BF-BOF, among others. Specific consumption rates are detailed in Table S2.12.

Site Balance – The site's incoming commodities, accounted for as local raw material supply (RawMatSup), manufactured product output and/or received freight by national transportation (NatTrans), must equal the site's outgoing commodities, accounted for as feed consumption, national demand contributions (NatDemCont) and/or dispatched freight by national transportation:

$$RawMatSup_{cmdty}^{site} + \sum_{process} ProdOut_{process}^{site} + \sum_{location'} NatTrans_{cmdty}^{location',site} = FC_{cmdty}^{site} + NatDemCont_{cmdty}^{site} + \sum_{location'} NatTrans_{cmdty}^{site,location'}$$

Repeated for all sites and transportable commodities:

$$\forall\ site, cmdty$$

Port Balance - The port's incoming commodities, which include received freight by national or international (imports) transportation, must equal the site's outgoing commodities, accounted for as national demand contributions and/or dispatched freight by national or international (exports) transportation:

$$\sum_{site'} NatTrans_{cmdty}^{site',port} + \sum_{port'} Imports_{cmdty}^{port',port} = NatDemCont_{cmdty}^{port} + \sum_{site'} NatTrans_{cmdty}^{port,site'} + \sum_{port'} Exports_{cmdty}^{port,port'}$$

Repeated for all ports and transportable commodities:

$$\forall\ port, cmdty$$

Rail Border Crossing Balance – similarly to ports, rail border crossing is a key transportation node in the supply chain to deliver exports. Railway freight is only received by national transportation (although technically this is international transportation), since national transport is associated with railway movements, and international transport is associated with shipping vessel movements:

$$\sum_{site'} NatTrans_{cmdty}^{site',railX} = NatDemCont_{cmdty}^{railX} + \sum_{site'} NatTrans_{cmdty}^{railX,site'}$$

National Demand Balance – National demand for a commodity is met by national demand contributions from any port or site. We predominantly investigate steel demand; our model stops after continuous casting to produce semi-finished steel, which would require further downstream processing into the final products. The location of these processing plants is undefined, hence transportation to final steel consumption demand centres is not considered:

$$NatDemand_{cmdty}^{country} = NatDemCont_{cmdty}^{port} + NatDemCont_{cmdty}^{site} + NatDemCont_{cmdty}^{railX}$$

Repeated for all countries (Ukraine and trading partners) and commodities:

$$\forall\ country, cmdty$$

S2.3.5 Zero-carbon electricity, hydrogen, and ammonia supply

Electricity, H_2 and NH_3 can be supplied from four different sources:

a. onshore hybrid solar + wind (RE, greenH_2, greenNH_3 - produced at Site);
b. offshore wind (offRE, offgreenH_2, offgreenNH_3 - produced at OffshoreSite);
c. hydropower (HP, hydroH_2, hydroNH_3 - produced at HPP (hydropower plant)); and
d. nuclear power (NP, pinkH_2, pinkNH_3 - produced at NPP (nuclear power plant)).

$$RawMatSup_{"elec"}^{site} = Supply\_RE^{site} + Supply\_offRE^{site} + Supply\_NP^{site} + Supply\_HP^{site}$$

$$Supply\_offRE^{site} = \sum_{OffSite} NatTrans_{"offRE"}^{OffSite,Site}$$
$$Supply\_NP^{site} = \sum_{NPP} NatTrans_{"NP"}^{NPP,Site}$$
$$Supply\_HP^{site} = \sum_{HPP} NatTrans_{"HP"}^{HPP,Site}$$

The same equations are repeated for H_2 and NH_3.

S2.3.6 Production facilities and existing assets

Existing assets are integrated into the model with two binary variables: (i) to control the investment decision to continue/discontinue the use of existing furnaces (on_or_off), and (ii) to enable minimum capacity determination for any process (install_or_not). Production demand was met by a combination of active existing assets and new assets (NewCap), comprising the total production capacity (TotCap). If existing assets were not utilised, the corresponding furnaces were retired. A distinction is made between furnaces and capacities, to ensure that both binary conditions are met and total production capacity is observed:

$$TotCap_{process}^{site} * f_{util} \geq ProdOut_{process}^{site}$$

The furnace capacity utilisation factor (f_{util}) of 85% was assumed for all furnaces which was the upper end of observed capacity utilizations over the last 20 years, considered necessary for the industry to undertake new investment (Vogl et al., 2021). Although this observation was based on BF-BOF plants, it is considered state-of-the-art for steelmaking and the same assumption will be made for direct reduction and electric furnaces:

$$ActiveExFurnace_{numf,ExFur}^{site} = ExFurnace_{numf,ExFur}^{site} - RetiredFurnace_{numf,ExFur}^{site}$$

Numf denotes the furnace unit (i.e. furnace number) and *ExFur* dneotes the technology of the existing furnace:

$$ActiveExCap_{process}^{site} = \sum_{numf} \sum_{ExFur} (ExFurnace_{numf,ExFur}^{site} - RetiredFurnace_{numf,ExFur}^{site})$$

$$NewCap_{process}^{site} = TotCap_{process}^{site} - ActiveExCap_{process}^{site}$$

$$\sum_{numf} \sum_{ExFur} ActiveExFurnace_{numf,ExFur}^{site} = \sum_{process} ActiveExCap_{process}^{site}$$

Retired furnace capacity must be equal to: (i) existing furnace capacity, or (ii) zero (i.e., retire entire facility, not just a fraction of - many inefficiencies occur at partial loads and should be avoided):

$$RetiredFurnace_{numf,ExFur}^{site} = ExFurnace_{numf,ExFur}^{site} * on\_or\_off\ _{numf,ExFur}^{site}$$

New capacity must be equal to: (i) minimum furnace capacity requirement, or (ii) zero. Minimum capacity for processes is 1 Mtpa, excluding EAFs and OSBFs which is set at 0.5 Mtpa:

$$NewCap_{process}^{site} > MinCap_{process} * install\_or\_not\ _{process}^{site}$$

Existing iron and steel production asset data was gathered from the *Global Energy Monitor*'s Steel Plant Tracker (GEM, 2022) and *GEM* Blast Furnace Tracker (GEM, 2023a), including the process capacity, furnace capacities, age of assets, and the latest BF relining year.

S2.3.7 Production Economics

The overall objective is to minimise the net present value (NPV) of total production, transport, and carbon costs. Production costs are separated into the NPV of OPEX (of all facilities), CAPEX of new assets, CAPEX of active existing capacity that has not yet fully depreciated (i.e., construction year < 20 years ago), and debt incurred due to retirement of assets that have not yet fully depreciated. Transport costs are separated into land transport costs (via railway, pipeline, electricity grid), sea transport costs (via dry bulk carriers and liquefied gas tankers), and the additional processing demands for transporting HBI (briquetting and heating pre-DRI). The price of carbon is also calculated according to the anticipated domestic UA-ETS policy and CBAM on exports to the EU:

Minimise: $NPV^{sector} = NPV^{OPEX} + CAPEX^{NewAssets} + CAPEX^{ActiveExCap} + CAPEX^{BFreline} + Debt^{RetiredAssets} + NPV^{LandTrans} + NPV^{SeaTrans} + NPV^{HBIburden} + NPV^{CTax}$

The NPV is a sum of all costs over the 20-year project lifetime. The time variable (Y) is introduced for cost parameters that will change over time – renewable electricity, green H_2 and green NH_3 costs, commodity prices, carbon prices, carbon-intensity benchmarks, and reduction factors for free allowances.

A discount factor is applied to calculate the present value of future incurred costs. 2030, 2040, and 2050 are the model start year (Year 0) and the 20 subsequent years are the operation years:

$$df_{OpYear} = \frac{1}{(1+r)^Y}$$

The NPV for operational expenditures is defined as:

$$NPV^{OPEX} = \sum_{site}\sum_{cmdty}\sum_{Y=1}^{20}(((RawMatSup_{cmdty}^{site} * ComPrice_{cmdty}^{Y}) + (CAPEX^{TotAssets} * f_{M\&I})) * df_Y)$$

Where:

$$CAPEX^{TotAssets} = \sum_{site}\sum_{process}(TotCap_{process}^{site} * upCAPEX_{process} * \left(1 + f_{greenfield}{}^{site}\right))$$

Labour was treated as a commodity. The price of commodities (ComPrice) is detailed in Table S2.13, and unit prices of capital assets (upCAPEX) in Table S2.14. The cost factor for maintenance and insurance of assets ($f_{M\&I}$) was 4% (Garcia & Berghout, 2019; Wijayanta et al., 2019). An additional 10% economic burden was applied to new sites ($f_{greenfield}$) to account for the cost-benefits of utilising existing human and physical capital in existing (brownfield) sites; for example, a skilled workforce and railway connections to nearby ports. These effects are softened in the context of war, where a portion of critical infrastructure has been destroyed and skilled workers have been dislocated; in a non-war context, a 25% capital premium for greenfield projects would be more appropriate.

Logic for existing capacity:

- If utilising existing capacity, pay for any remaining capital payments;
- If utilising existing BF capacity, also must account for BF relining; and
- If not utilising existing capacity, still must pay for any remaining capital payments (debt).

To determine the present value of partly depreciated capital:

$$CAPEX^{ActiveExCap} = \sum_{site}\sum_{numf}\sum_{ExFur}\left(ActiveExFurnace_{numf,ExFur}^{site} * upCAPEXex_{ExFur} * \frac{f_{CR}}{adj\_f_{CR}{}_{numf}^{site}}\right)$$

$$f_{CR} = \frac{r(1+r)^n}{(1+r)^n - 1}$$

Where f_{CR} denotes the capital recovery factor, r denotes the real discount rate (8%; 0.08) and n the project lifetime (20 years).

And adj_f_{CR} denotes the adjusted capital recovery factor, which is similarly calculated to f_{CR} yet with n_{adj} which is the remaining payment period related to existing furnaces, where capital has not yet fully depreciated (i.e., the furnace was constructed less than 20 years ago). $Y_{construct}$ refers to the year of asset construction in years (ago) and Y_{reline} refers to the year of BF reline in years (ago), both in reference to the model year (2030, 2040, or 2050):

$$n_{adj}{}_{numf}^{site} = n - Y_{construct}$$

or, $$n_{adj}{}_{numf}^{site} = n - Y_{reline}$$

All BFs will require one relining in the 20-year project lifetime; the median historic BF campaign life is 17 years, and capital is approximately 40% of the original BF investment (Vogl et al., 2021). To determine the present value of future BF relining costs (capital and labour), we multiply costs by an adjusted discount factor:

$$NPV^{BFreline} = \sum_{site}\sum_{numf}\sum_{ExFur}\sum_{Y=1}^{20}\left(ActiveExFurnace_{numf,ExFur}^{site} * \frac{upBFreline + (labourBFreline * ComPrice_{labour}^{Y})}{(1+r)^{n_{adj}{}_{numf}^{site}}}\right)$$

$$\forall\ ExBF$$

For debt of required assets, we calculate the present value of partly depreciated capital:

$$Debt^{RetiredAssets} = \sum_{site}\sum_{numf}\sum_{ExFur}\left(RetiredFurnace_{numf,ExFur}^{site} * upCAPEX_{ExFur} * \frac{f_{CR}}{adj\_f_{CR}{}_{numf}^{site}}\right)$$

S2.3.8 Natural resource and circularity constraints

Land availability for renewable energy infrastructure (hybrid onshore solar and wind) must be more than the combined land consumption of RE, H_2 and NH_3. Land consumption is determined by the quantity of commodity supplied and land intensity factor of each commodity. The steel sector can only consume 20% of total land availability for solar panels and wind turbines:

$$RELandAvlb^{site} * 20\% > \sum_{RE,H2,NH3} (RawMatSupply_{cmdty}^{site} * LandInt\ _{cmdty}^{site})$$

Sea area availability for offshore wind infrastructure must be more than the combined sea area consumption of RE, H_2 and NH_3. Sea consumption is determined by the quantity of commodity supplied and sea area intensity factor for each commodity. The steel sector can only consume 20% of available sea area for wind turbine installation:

$$owSeaAvlb^{site} * 20\% > \sum_{RE,H2,NH3} (RawMatSupply_{cmdty}^{OffshoreSite} * SeaInt\ _{cmdty}^{OffshoreSite})$$

Ore reserves and supply

We know the historical output of ore from a mine, characterised by Fe% and the form of the final product (e.g., 65% Fe pellets). However, there is a noticeable lack of information regarding the Fe content at a more granular spatial resolution and the relationship between in-situ ore type and Fe-content, and beneficiation costs. Hence, simplification of ore product costs is employed (BF-grade ore \$80/t and DR-grade ore \$100/t) with constraints on BF-grade and DR-grade ore production capacity.

Ore supply is constrained by annual ore output at a particular mine (AnnualOreOut):

$$AnnualOreOut_{grade}^{mine} > \sum_{site\prime} NatTrans_{ore_{grade}}^{mine,site\prime}$$

Where *n* is project lifetime (20 years) and mass efficiency considers the mass conversion rate from reserve (extracted material quantity) to final product (65% or 67%-Fe grade ore), therefore taking into consideration the amount of gangue lost in crushing, screening, communition and beneficiation processes.

No transport of anything other than ore from mines to sites:

$$0 = NatTrans_{cmdty}^{mine,site} \quad \forall\ cmdty\ not \in ore$$

No transport of anything to mines:

$$0 = NatTrans_{cmdty}^{site,mine} \quad \forall\ cmdty$$

Metallurgical coal and natural gas reserves and supply
The equations for ore mines were adjusted to satisfy metallurgical coal mines (CoalMine) and natural gas refineries (NGRefinery). Strip ratio is not relevant for NG, but refinery efficiency is, which is used to determine an eqv mass ratio; approximately 90% refinery efficiency (Forman et al., 2014).

Scrap steel availability
National scrap steel availability was determined by dynamic material flow analysis, then distributed across sites as a function of population density:

$$ScrapAvlb^{site} > ScrapSupply^{site}$$

S2.3.9 Emissions and imposed carbon prices

Emissions were firstly calculated at site-level using set emission facto*rs (EF)* given in Table S.2.11, then aggregated by steel class – primary (ore-based) and secondary (scrap-based). CO_2 emissions are referred to rather than GHG emissions, since CO_2 is the primary emission source. Scope 2 emissions were zero, since all energy was derived from renewables:

$$TotScope1^{class} = \sum_{site,process} (ProdOut_{process}^{site} * EF_{process}) \qquad \forall\, process \in class$$

Table S2.11. Scope 1 emission factors for iron and steelmaking processes.

	Process	Product	Scope 1 emissions (t CO_2/t product)	Reference
Traditional CO_2-intensive technology	Integrated BF-BOF	LS (total route)	2.400	Metinvest (2020); Koolen (2022)
	coking	coke	0.113	Case with zero emissions electricity, escalated to 2.410 total emissions (Fan & Friedmann, 2021)
	sintering	ore65sinter	0.304	“ “
	BF	pigi	1.931	“ “
	BOF	LS	0.050	Reduced relative BOF emissions (transferring to BF) to align with DRI-OSBF-BOF route emission-intensities (MPP, 2022)
Transitional technology	DRI-EAF with 100% NG	LS (total route)	0.560	
	DRIwNG-67o	HBI-C4-67o	0.435	Fig. 14 from Müller et al. (2021)
	EAFwDRI-C4	LS	0.146	Vogl et al. (2018); Jacobasch et al. (2021)
	DRI-OSBF-BOF with 100% NG	LS (total route)	0.681	
	DRIwNG-65o	HBI-C4-65o	0.435	Fig. 14 from Müller et al. (2021)
	OSBFwDRI-C4	pigi	0.146	Assumed same as EAFwDRI-C4
	BOF	LS	0.050	
	DRI-OSBF-BOF with 70% NG/30% H_2	LS (total route)	0.496	
	DRIw70NG-67o	HBI-C4-67o	0.367	Fig. 14 from Müller et al. (2021)
	EAFwDRI-C4	LS	0.146	
	DRI-OSBF-BOF with 65% H_2/35% NG	LS (total route)	0.361	
	DRIw65H_2-67o	HBI-C4-67o	0.226	Fig. 14 from Müller et al. (2021)
	EAFwDRI-C4	LS	0.146	
Near-zero carbon technology	EAFwscrap	LS	0.099	assuming oxidation of carbon within scrap (~1-2%-C) is approx. average of DRI with 4%-C and O%-C content; Burchart-Korol (2013) calculated 0.26t CO_2/t steel for scrap-based steelmaking in Poland which represents emission-intensive technology rather than BAT
	H_2-DRI-EAF	LS (total route)	0.053	
	DRIwH_2-67o	HBI-C0-67o	0.000	Vogl et al. (2018)
	EAFwDRI-C0	LS	0.053	Vogl et al. (2018)
	H_2-DRI-OSBF-BOF	LS (total route)	0.103	
	DRIwH_2-65o	HBI-C0-65o	0.000	Vogl et al. (2018)
	OSBFwDRI-C0	pigi	0.053	Assumed same as EAFwDRI-C0
	BOF	LS	0.050	

There were two separate calculations for carbon prices: domestic carbon tax and the Carbon Border Adjustment Mechanism (CBAM). Only for the 2030 *Slow Recovery* scenario did Ukraine not have EU membership and, therefore, CBAM for EU/UK exports was relevant; otherwise, Ukraine's domestic carbon tax was given by the EU-ETS. f_{reduc} denotes the reduction factors for free allowances, which under the EU-ETS, are allocated to trade-exposed industries to prevent carbon leakage:

$$AllowableCO2_Y^{class} = BenchCO2int_Y^{class} * PrimarySFS^{class}$$

$$TaxableCO2_Y^{class} = \min\left(TotScope1^{class} - AllowableCO2_Y^{class}, 0\right)$$

$$DomesticCTax2_Y^{class} = TaxableCO2_Y^{class} * Cprice_Y^{UA} * (1 - {f_{reduc}}_Y^{UA})$$

$$CBAM_Y^{class} = {f_{exp}}_Y^{class} * TaxableCO2_Y^{class} * ((Cprice_Y^{EU} * (1 - {f_{reduc}}_Y^{EU}))) - (Cprice^{UA} * \left(1 - {f_{reduc}}_Y^{UA}\right)))$$

$$NPV^{CTax} = \sum_{class} \sum_{Y=1}^{20} (df_Y * (DomesticCTax2_Y^{class} + CBAM_Y^{class}))$$

S2.3.10 Transport economics

Commodities can be transported nationally using railway freight (dry bulk goods), pipeline (liquefied NH_3, NG) or grids (electricity). The unit cost of dry bulk railway freight in Ukraine is approximately \$0.025 per tonne per km (Forbes, 2022), equivalent to \$0.043/t/km (one-way distance) when the return journey is considered with a 30% fuel consumption reduction on the return leg. Pipeline costs for liquefied NH_3 were taken to be \$0.05/t/km (Nayak-Luke et al., 2021), and NG to be \$0.08/t/km (DeSantis et al., 2021). The Ukrainian National Commission for State Regulation of Energy and Public Utilities (Verkhovna Rada of Ukraine, 2022) resolved the electricity transmission tariff for green metallurgical enterprises to be \$5.67/MWh/km, a 57% reduction on the generic tariff, which is applied for electricity transportation. A cost uplift of 55% is applied to offshore electricity transmission and liquefied NH_3 pipeline, proportional to the uplift on offshore wind power plants compared to onshore. CGH_2 pipeline for offshore wind plants is costed at \$2/t H_2/km, constrained to a maximum 500km transported distance (Graf, 2021), and CGH_2 by truck freight is costed at \$12.5/t H_2/km (mean of 50km and 300km transmission costs (\$1.875/kg H_2), divided by the transport distance (150km) and expressed in tonnes; data from Yang and Ogden (2007)) and constrained to maximum 150km transported distance – so expensive it is not expected to be utilised. The straight-line distance plus a land margin of 30% was applied to determine the overall transported distance:

$$CostTransLand_{cmdty} = \sum_{loc,loc'} (NatTrans_{cmdty}^{loc,loc'} * LandDist^{loc,loc'}) * (1 + LandMargin) * ucLandTrans_{cmdty}$$

$$NPV^{LandTrans} = \sum_{cmdty} \sum_{Y=1}^{20} (CostTransLand_{cmdty} * df_Y)$$

International transportation to facilitate exports from Ukraine to the EU was enabled by dry bulk carriers (DBC) to ship dry bulk goods (SFS, HBI) and liquefied gas tankers (LGT) to ship NH_3 at -33°C. Both vessel categories pertain various sizes and payload capacities; selection is based on importing/exporting port draft and length, and cost-minimisation of vessel journeys considering charter fees, berthing fees, and fuel consumption (cost parameters from Devlin and Yang (2022) and Salmon et al. (2021)). All vessels are assumed to use green NH_3, with the cost determined by the average cost across all sites in the modelled year:

$$TransTonnageDBC_{DBC}^{port,port'} = \sum_{bulk} NatTrans_{DBC,bulk}^{port,port'}$$
$$\forall\ DBC, \quad if: CarrierDraft_{DBC} < PortDraft^{port,port'}$$
$$and: CarrierLength_{DBC} < PortLength^{port,port'}$$

Since charter fees are a daily rate, calculate the number of journeys for each vessel:

$$NumJourneysDBC_{DBC}^{port,port'} = \frac{TransTonnageDBC_{DBC}^{port,port'}}{CarrierPayload_{DBC}}$$

$$CostTransSeaBulk_{DBC,Y}^{port,port'} = NumJourneysDBC_{DBC}^{port,port'} * CarrierCharterFee_{DBC} * \frac{SeaDist_{DBC} * SeaMargin * 2}{CarrierSpeed * 24} + (CarrierBerthFee_{DBC} * 2) + (CarrierFuelCons_{DBC} * SeaDist_{DBC} * SeaMargin * 2 * ucNH3_Y) + (CarrierPayload_{DBC} * TurkeyFee)$$

Where a sea margin of 15% is applied according to standard shipping provision for increased distance travelled due to factors including high winds, currents, and shallow water (Wärtsilä, 2023). *TurkeyFee* is the additional fee of $4/t cargo applied to all routes that pass by Turkey's Bosporus and Dardanelles (GMK, 2023) .

A very similar set of equations was utilised to calculate international transportation costs using LGTs, then NPV determined for total sea transportation costs:

$$NPV^{SeaTrans} = \sum_{port}\sum_{port'}\sum_{DBC}\sum_{Y=1}^{20}((CostTransSeaBulk_{DBC}^{port,port'} + CostTransSeaLiq_{LGT}^{port,port'}) * df_Y)$$

To calculate the additional cost burdens for HBI briquetting and HBI heating pre-DRI, that would not be incurred if iron and steelmaking were co-located, we use the following equations:

$$CostHBIbriq_Y^{loc,loc'} = NatTrans_{'HBI'}^{loc,loc'} * ElecPrice_Y^{loc} * ElecCons\_Briq$$
$$CostHBIheat_Y^{loc,loc'} = NatTrans_{'HBI'}^{loc,loc'} * ElecPrice_Y^{loc'} * ElecCons\_HBIheat$$

$$\forall\ not\ Colocation(loc, loc')$$

$$NPV^{HBIburden} = \sum_{loc}\sum_{loc'}\sum_{Y=1}^{20}((CostHBIbriq_Y^{loc,loc'} + CostHBIheat_Y^{loc,loc'}) * df_Y)$$

For the cost of HBI heating pre-DRI the electricity price of the importing site/country is applied, whereas for HBI briquetting the electricity price of the exporting country is applied.

S2.4 Economic multiplier analysis

S2.4.1 Input-Output analysis

Input-Output (I-O) analysis, originating from the Nobel Prize winning work of Leontief (1966), is based on a systems approach to the economy – whether regional, national, or global – which stresses inter-industrial or sectorial interdependence, whereby the output of one sector is often the input of another. This study employed the I-O based economic analysis (Richardson, 1972; Miller and Blair, 2009; Raa, 2005) to (i) examine the impact of the Ukrainian steel industry on production, income, and growth; and (ii) model the effects of post-war reconstruction on the domestic steel demand, and on the wider economy in the long-term. Through a detailed disaggregation of economic activities, Leontief inverse matrices were developed to provide quantitative transaction relationships between industrial components of a given economic system (Leontief, 2008). Manipulation of I-O analytical tables by applying matrix algebra allows one to model the impact of the initial expenditure change experienced by one sector on output (i.e., expenditure, income, and GVA) of all the other sectors, and on the economy as a whole. The I-O multiplier analysis is the most analytically rigorous approach to regional modelling, in comparison with the two alternatives – the Keynesian income multiplier and economic base models (McCann, 2013: Ch. 5).

Three types of economic relationships were assessed: direct, indirect, and induced. *Direct* is the immediate effect caused directly by the change in final demand (e.g., for steel). *Indirect* is the subsequent effect caused by the consequent changes in intermediate demand within supply chains (i.e., iron ore mining, freight transportation services). *Induced* is the effect attributable to the ensuing change in compensation of employees and other incomes, which may cause further spending, and hence further changes in final demand on domestic products. Specifically, if there is an increase in the final demand for a particular industry's product, we can assume that there will be an equivalent increase in the output of that industry, as producers react to meet the increased demand; this is the direct effect. As these producers expand their output, there will also be an increase in demand on their domestic suppliers and so on down the supply chain; this is the indirect effect. Driven by these direct and indirect effects, the level of household income throughout the domestic economy will increase, as a result of increased employment. A proportion of this increased income will be re-spent on domestically produced products; this is the induced effect.

- Direct: This is the immediate effect caused directly by the change in final demand;
- Indirect: This is the subsequent effect caused by the consequent changes in intermediate demand;
- Induced: This is the effect attributable to the ensuing change in compensation of employees and other incomes, which may cause further spending and hence further changes in final demand.

Supplier linkage effects or **Type I multipliers** cover direct and indirect effects only. Type I multipliers may potentially underestimate the effect on the economy as they do not estimate induced effects. In addition to direct and indirect effects, **Type II multipliers** also cover induced effects. It should be stressed that the multipliers derived from the detailed I-O tables are constructed to reflect the transactions within a given, in our case, national economy. Any imported products which are required to meet the change in final demand have been removed, and are not included in the calculation of the multiplier. The I-O multipliers, thus, estimate the economic activity within the domestic economy.

The economic analysis was conducted on the historical 'basic metals' industry, based on data published by the Ukraine State Statistics Service from 2005 to 2021, which provided complete flows of products (goods and services) in the economy for a given year. Since 2015, these data have been produced to cover the total use of domestic production at basic prices, disaggregated into intermediate consumption by 42 industries/product groups (NACE Rev. 2; see Table S1.11), and by 7 final demand sectors, including final consumption expenditure (of households; non-profit institutions servicing households; general government), gross capital formation (including gross fixed capital formation; changes in inventories; and net acquisition of valuables), and exports of goods and services. These I-O Tables denote the relationship between producers and consumers and the interdependencies of domestic industries.

S2.4.2 Definition of 'standard' multipliers and 'effect' multipliers

The basic Ukraine State Statistics Service-produced I-O tables were used to create a Leontief inverse matrix, and generate output multipliers, following the standard algebraic formulations and guidance from key practitioners (Eurostat, 2008; Office for National Statistics, 2022). The initial monetary values in the transaction matrices were converted into ratios called technical coefficients, by dividing each cell of the domestic intermediate matrix by its column total (output at basic prices). These technical coefficients can be used directly to access the added value of a given sector. Consequently, to calculate the output multipliers, Leontief Inverse matrices were derived, which show for each industry the direct and indirect (Type I), and direct, indirect, and induced (Type II) effects upon total output of an additional 1-unit of currency (e.g., Ukrainian hryvnia / UAH) of final demand. Income and GVA multipliers were subsequently derived using the standard matrix algebraic formulas (see Table S1.10).

For the step-by-step derivation of Leontief inverse matrices (Type I and Type II), we have followed the approach advocated by d'Hernoncourt et al. (2011), McLennan (1995), and the Scottish Government I-O team (2022). The Leontief Inverse Matrices were derived from the published Ukraine I-O Tables to generate the output multipliers; all the other multipliers (income and GVA) were derived using known industry ratios: for example, wages and salaries (compensation of employees) per UAH 1m of industry output, or gross value added per UAH 1m of industry output. We have not produced employment multipliers because employment numbers coherent with the Ukrainian balanced compensation of employees' data have never been published by the Ukraine State Statistics Service.

The Ukrainian 'standard' multipliers calculated for this study for 2014 and 2021 (see Table S1.10) estimate the indirect (Type I) and indirect plus induced (Type II) impacts as a result of a direct, final demand-driven change in industry output, income or GVA. The output multiplier is expressed as the ratio of direct and indirect (and induced, if Type II multipliers are used) output changes to the direct output change due to 1 unit (in currency) increase in final demand. Using 2014 figures, for example, for an increase in final demand of UAH 100m for the '24 Basic Metals' Industry, the direct impact on this industry will be a requirement to increase its total output by UAH 100m, to meet the additional final demand. A change in final demand will always equal the change in direct output, as products must be made in order to be sold. To estimate the subsequent indirect effects on the industry's suppliers, we multiply the direct impact (UAH 100m) by the Type I industry output multiplier for this industry grouping (3.24), giving a total direct plus indirect impact on national output of UAH 324m. Using the Type II industry output multiplier for this industry grouping (4.38), we can then estimate the total of the direct, indirect, and induced impacts on output by multiplying it by the direct impact (UAH 100m) to give UAH 438m. Subsequently, we can work out the induced impact on output by subtracting the direct plus indirect impact worked out using the Type I multiplier above (UAH 324m) from the total of the direct (UAH 100m), indirect (UAH 224m), and induced impacts using the Type II multiplier (UAH 438m), resulting in an induced impact on output of UAH 114m.

The GVA multiplier is expressed as the ratio of the direct and indirect (and induced, if Type II multipliers are used) GVA changes to the direct GVA change. Thus, if you have the change in GVA for the industry, the GVA multiplier can be used to calculate the change in GVA for the economy as a whole. A hypothetical change in demand for the '24 Basic Metals' Industry group that leads to a UAH 100m increase in GVA for that industry, therefore, has a direct impact of UAH 100m. Using 2014 figures, to estimate the subsequent indirect effect on this industry's suppliers given the increase in GVA, we multiply the direct GVA impact (UAH 100m) by the Type I GVA multiplier for this industry grouping (6.56), giving a total direct plus indirect impact on national GVA of UAH 656m. Using the Type II industry GVA multiplier for this industry grouping (9.75), we can estimate the total of the direct, indirect, and induced impacts on GVA by multiplying it by the direct impact (UAH 100m) to give UAH 975m. To work out the induced impact on GVA, we can subtract the direct (100m) plus indirect (656m – 100m = 556m) impacts established by using the Type I multiplier above (UAH 656m) from the direct, indirect, and induced impacts using the Type II multiplier (UAH 975m), resulting in an induced impact on national GVA of UAH 319m.

The income (or compensation of employees) multiplier is the ratio of direct plus indirect (plus induced, if Type II multipliers are used) income changes to the direct income change: if you have the change in compensation of employees (i.e., wages and salaries) for the industry, the income multiplier can be used to calculate the change in compensation of employees for the economy as a whole. Using the Type I and Type II multipliers for this industry grouping, we can easily work out the direct, indirect, and induced impacts of a hypothetical increase in demand for the '24 Basic Metals' Industry, following the steps outlined above.

In turn, the Ukrainian 'effect' multipliers calculated for this study for 2014 and 2021 estimate the indirect (Type I) and indirect plus induced (Type II) impacts as a result of a direct, final demand-driven change in output. This is expressed in terms of a change in income or GVA. There are no output 'effect' multipliers for these will be the same as the output multiplier itself. The income (or compensation of employees) 'effect' multiplier estimates the indirect (and induced, if Type II multipliers are used) income change, as a result of a direct change of UAH 100m of output generated by the final demand sector. Using 2014 figures for the '24 Basic Metals' industry', a UAH 100m increase in output for this industry grouping is estimated to support UAH 53m of income (wages and salaries) using Type I effects (direct & indirect), and UAH 75m of income using Type II effects (direct, indirect & induced). Similarly, an increase in UAH 100m of final demand for '24 Basic Metals' Industry that year is estimated to support UAH 97m of GVA using Type I effects (direct & indirect), and UAH 144m of GVA using Type II effects (direct, indirect & induced). Again, by subtracting Type I GVA effects from Type II GVA effects, we can work out the induced effect of UAH 47m in this scenario.

S2.4.3 Economic impact assessment of Ukraine's post-war reconstruction and domestic steel demand

The I-O Leontief multipliers produced for this study shows a very high level of supplier linkage effects of Ukraine's steel sector and, even more so, of its extremely high income and GVA growth effects on the broader economy. In 2021, the '24 Basic metals' industry's Type I output multiplier (3.34) was ranked as the sixth highest out of 42 industry groupings, whilst its Type II output multiplier (4.28) was ranked at #11/42; both of the industry's Type I and Type II income multipliers (6.67 and 9.24 respectively) were ranked as the second highest, whilst its Type I and Type II GVA multipliers (6.38 and 8.80) were both ranked as the fifth highest across the domestic economy. For comparison, the impact of the European steel industry on the EU economy, similarly taking into account the direct effect, concerned with the industry's own activity, the indirect effect, related to activity in its supply chain, and the induced effect, resulting from the wage-funded spending of both industry and supply chain workers, is about one-third smaller, on average: the latest EU steel sector's multipliers for GVA stand at 4.4 (Type I) and 5.8 (Type II), respectively.

In terms of final demand, by far the largest consumers of Ukrainian steel are located overseas, with 65% of all domestic production, on average, being destined for exports (see Table S1.11). At home, in addition to the '24 Basic metals' industry grouping itself, the largest steel consumers include the following eight industry groupings, in order of importance: '25 Fabricated metal products, except machinery and equipment', '41-43 Construction', '35 Electricity, gas, steam and air conditioning supply', '28 Machinery and equipment n.e.c.', '30 Other transport equipment', '36-39 Water supply; sewerage; waste management and remediation', '31-33 Furniture; other manufactured goods; repair & installation of machinery and equipment', and '27 Electrical equipment'. These data were used in the paper's material flows analysis.

To forecast the domestic steel demand during Ukraine's post-war reconstruction, we have applied the latest pre-war I-O multipliers for the construction sector. Indeed, the '41-43 Construction' industry grouping's income and GVA multipliers in 2021, the last year before the full-scale Russian invasion, were just behind the steel sector's, coming at the top sixth and seventh places amongst 42 domestic industry groupings. Most importantly, the construction sector's output multiplier in 2021 (4.65) was the Ukrainian economy's third highest. According to the *Updated Ukraine Recovery and Reconstruction Needs Assessment* by the Government of Ukraine, the World Bank Group, the European Commission, and the United Nations (World Bank, 2023), the cost of reconstruction and recovery in Ukraine has grown to US $410.6bn (equivalent of €383bn). In particular, the report has found total direct **damage** to buildings and infrastructure coming to $134.7bn, with aggregate economic, social, and other monetary **loss** resulting from the war adding another $289.1bn. These estimates cover only the first year period from Russia's invasion of Ukraine on 24 February 2022, with the cost of reconstruction and recovery expected to stretch over 10 years, at least. The detailed breakdown of the $411bn worth of Ukraine recovery and reconstruction needs (= damage + loss) provided by the World Bank is sectoral and geographical. However, it conflates production, income, and expenditure-based cost estimates, making the total figure inappropriate for a straightforward I-O analysis. At the same time, the $134.7bn figure, which quantifies direct physical damage to infrastructure and buildings, is directly applicable as an increase in the final demand for the construction industry's products over a ten-year period.

If we assume Ukrainian construction industry companies have won a contract worth $134.7bn to repair and build infrastructure and buildings in Ukraine over the next ten years 2025 to 2035, it is valid to apply an I-O multiplier: this will be capital spending and, regardless of the funding source, this is valid final demand. The *Updated Ukraine Recovery and Reconstruction Needs Assessment* assumes relatively equal splits across all ten projected years and is calculated in the prices for the year of the spend, so there is no need to adjust for inflation. This level of spending represents a huge economic shock, however, raising a question about the existence of spare capacity within the construction industry to meet this demand. The size of this reconstruction contract amounts to 4.6 years' worth of Ukraine's pre-war 2021 construction output, whereas the time period for this spending is estimated to take place over 10 years, at least; hence, the reconstruction needs will only be utilising less than ½ of the pre-war capacity. Given that the construction work will take place in Ukraine, and assuming that the companies receiving the money are based in Ukraine, there is no need to adjust for final demand imports.

It is unclear whether Ukraine's recovery funds and the projects financed from them would be taxed in Ukraine. The US government, for example, has protested against the taxation of its contractors by the Afghan government during the post-Taliban reconstruction in the 2010s (SIGAR, 2013). At the same time, we expect that domestic building firms would be winning the Ukraine reconstruction contracts; hence, it is prudent to adjust the $134.7bn sum for taxes less subsidies on products, using the Gross Fixed Capital Formation column in the industry by industry I-O Tables. For 2021, this shows UAH 44.393bn for a total GFCF of UAH 719.771bn, which is 6.2%. Subtracting this from $134.7bn = $126.3bn. Therefore, for output, income, and GVA effects we will use $126.3bn spent over 10 years in equal shares of $12.63 per year:

- Construction industry's Type I output multiplier: 3.60, Type II: 4.65
    - Multiplied by $12.63bn = $45.46bn and $58.70bn;
- Construction industry's Type I income **effect**: 0.46, Type II: 0.64
    - Multiplied by $12.63bn = $5.83bn and $8.08bn;
- Construction industry's Type I GVA **effect**: 0.96, Type II: 1.38
    - Multiplied by $12.63bn = $12.18bn and $17.44bn.

Noting that Type I multipliers sum together direct and indirect effects, whilst Type II multipliers also include induced effects, the following final results are arrived at:

- Direct Output effects: $12.63bn;
- Indirect Output effects: $45.46 - $12.63 = $32.83bn; and
- Induced Output effects: $58.70 - $45.46 = $13.24bn.

The same calculation can be done to separate direct, indirect, and induced for income and GVA.

Amongst the construction sector's five supplier industries most enabled by this increase in final demand on annual basis over 10 years, are '23 Other non-metallic mineral products' (Type I multiplier increase: $3.13bn, Type II: $3.31bn), '24 Basic metals' ($2.45bn and $2.77bn), '35 Electricity, gas, steam and air conditioning supply' ($1.82bn and $2.62bn), '49-52 Land transport; water transport; air transport;

warehousing & transport support' ($1.52bn and $2.20bn), and '07-09 Metal ores; other mining and quarrying; mining support services' ($1.73bn and $1.86bn).

In the final result, using the latest Ukrainian I-O model of the economy, it is estimated that $12.63bn of construction demand annually during Ukraine's post-war reconstruction supports:

- $45.5bn of economic output within the construction industry and its supply chain, plus a further $13.2bn, when the spending of wages and salaries is taken into account. This is for each year of Ukraine's post-war reconstruction period, thus, totalling $587bn over the ten years.
- $5.8bn of income is generated within the construction industry and its supply chain, plus a further $2.3bn, when the spending of wages and salaries is taken into account. This is for each year of Ukraine's post-war reconstruction period, thus, totalling $81bn over the ten years.
- $12.2bn of Gross Value-Added income is generated within the construction industry and its supply chain, plus a further $5.2bn, when the spending of wages and salaries is taken into account. This is for each year of Ukraine's post-war reconstruction period, thus, totalling $174 over the ten years.
- $2.77bn of additional steel demand generated by $12.63 of construction demand amounts to 15.5% of the 2021 annual output by the '24 Basic metals' industry, equivalent to 3.32 Mt of steel. This is for each year of Ukraine's post-war reconstruction period, thus, totalling 33.2 Mt over the ten years.
- It can be reasonably assumed that damage will increase at least two-fold in the subsequent war period, hence an additional 3.32 Mtpa of steel will be needed over 20 years, totalling 66.4 Mt of steel for post-war reconstruction needs alone. Similarly, if the post-war reconstruction period extends to 20 years, the above annualised calculations can be multiplied x 20 to arrive at the total estimates.

Note that due to the nature of I-O analysis, the final results (see Table S1.12) are rounded - these are modelled estimates, after all. Moreover, the usual I-O analytical caveats apply here: Leontief's multipliers are based on three core assumptions of proportionality, constant returns, and no substitution: (a) I-O analysis presupposes that each industry consumes inputs in stable proportions; it assumes that demand for intermediate inputs is a linear function of output, without taking into account potentially changing price-cost relations, input shortages, transportation bottlenecks, and other barriers to limitless growth; (b) the model is built on constant returns to scale, although increases in outputs do not always require proportionate increases in inputs; and (c) I-O analysis assumes no substitution between different inputs or factors of production (Munroe & Biles, 2005). Therefore, the I-O analysis undertaken in this paper should be treated with the typical model's limitations in mind.

S2.4.4 Economic impact assessment of Ukraine's post-war green steel transition

The macroeconomic impact of the optimised future green steel production on national output, income, and GVA patterns, using Type I and Type II standard multipliers and effect multipliers, was modelled. For comparison, the economic impact of the same magnitude of steel production under traditional brown coal-based steel scenarios was also assessed. (Colour denotation is used for simplification; there is diversity in production processes and, therefore, site-level carbon-intensity for both green and brown steel). The brown steel scenarios were modelled on the latest pre-war (i.e., 2021) Type II output multipliers, and the corresponding income and GVA effects, by inputting the value of steel in US$ to be produced by the basic metals industry. The expenditure of green steel scenarios was broken down, first, into the industry's key intermediate production suppliers, with relevant output multipliers used to determine output, income, and GVA impacts; then, their backward and forward linkages were determined as extra output, income, and GVA. The sum of both calculations provided an *approximate* indication of the macroeconomic effects associated with the total new green steel production function. For the green scenarios, whilst inputs and expenditure are redefined, historical I-O multipliers from 2021 must still be employed as the most recent data available.

To note, this study's green steel assessments were based on very conservative assumptions, with vigilant avoidance of double-counting of outputs generated by the industry suppliers. For examples, for GVA forecasts, the average gross operation surplus was assumed to be 8%, despite the fact that over the last decade, international steel industry's earnings before interest, taxes, depreciation, and amortisation - EBITDA margins – have averaged 8-10% (McKinsey & Co., 2023).

Thus, in addition to analysing the economic impact of increased demand for Ukraine's construction industry after the war, this study has undertaken the comparative macroeconomic assessment of carbon-intensive and decarbonised steel production processes themselves, showing that a green steel sector will benefit the economy with stronger supply chain linkages, income generation, and the gross value-added under most scenarios, modelled within the 20-year transition lifetime. According to the *Strong Recovery 2030* **green** steel scenario, the Ukrainian economy will generate $445.7bn of steel-driven output, $87.9bn of income, and $269.3bn of GVA. The corresponding *Strong Recovery 2030* **brown** steel scenario would generate more output ($604.2bn), but less income ($81.1bn), and far less GVA ($192.1bn), meaning economic growth. The *Strong Recovery 2040* **green** steel scenario appears the most impactful, generating $1.2tn of output, $226.6bn of income, and $578.3bn of GVA; by contrast, the equivalent *2040* **brown** steel scenario would result in a much smaller impact, with $739.4bn of output, $99.2bn of income, and $235.0bn of GVA. In turn, the *Strong Recovery 2050* **green** steel scenario is characterised by a smaller impact on output ($737.4bn), income ($144.6bn), and GVA ($414.8bn) than the 2040 scenario, but still beating the *Strong Recovery 2050* **brown** steel scenario in terms of income ($106.0bn) and, especially, GVA ($251.2bn). The national output projection for the *Strong Recovery* 2050 **brown** steel scenario amounts to $790.3bn, a figure little larger than under the 2050 green steel scenario. However, it is the GVA, which measures economic growth (before taxes), that serves as the most important yardstick of success, given that most of the output covers intermediate production, rather than final use. To note, the total economic impact of the three partial liberation green steel scenarios is significantly smaller than that of their full liberation counterparts: *Slow Recovery 2030* amounts to 53% of *Strong Recovery 2030*; *Slow Recovery 2040* comes at 31% of *Strong Recovery 2040*, whilst *Slow Recovery 2050* amounts to 66% of *Strong Recovery 2050*, respectively (see Figure S1.16; consult the authors for detailed calculations).

This I-O analysis of future green steel production is indicative, as it is based on historical compositions of the electricity and chemical industries, whilst growing renewables shares in the electricity sector and electrolytic processes for H_2 and NH_3 production will change how these sectors interact with the economy, and perhaps even further bolster it. Nevertheless, a strong correlation between the proposed green steel sector and economic growth is clearly determined.

Figure S2.2. Modelled Steel Production Routes. Minor inputs, including oxygen, alloys, and fluxes, are not shown for simplicity. Transportable commodities are classified into three types: (i) local (loc): transport only within same grid (1° x 1°, approx. 111km x 111km); (ii) national (nat): transport within national borders, and; (ii) exportable (exp): transport both within national borders, and exportable to other countries.

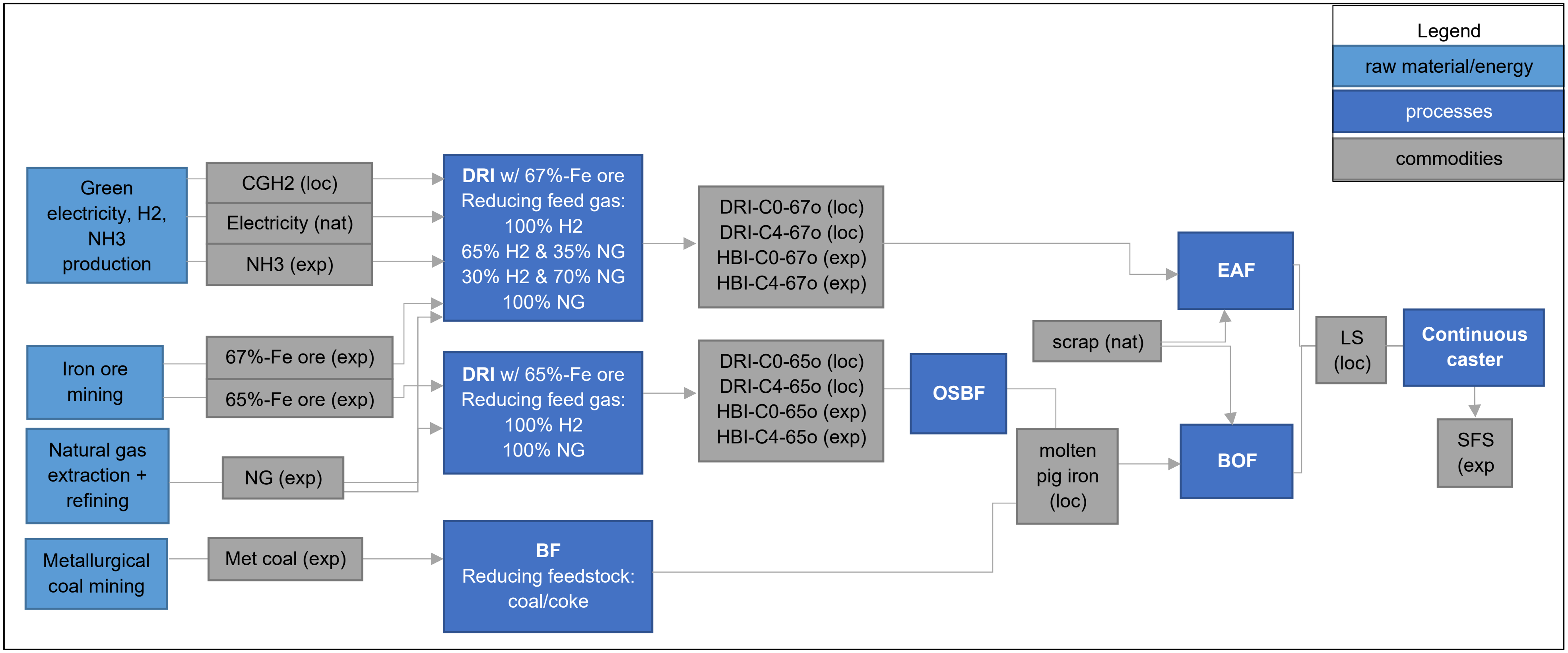

Table S2.12. Specific process consumption rates.

	Source →	(Jacobasch et al., 2021; Müller et al., 2021)				(Cavaliere et al., 2022a)				(Jacobasch et al., 2021; Müller et al., 2021)		(Kirschen et al., 2011; Vogl et al., 2018)	(Giddey et al., 2017)	(IEAGHG, 2013)			(Li et al., 2020)
Process → Input product ↓	**Unit ↓**	DRIwH_2-67o	DRIwNG-67o	DRIw65H_2-67o	DRIw70NG-67o	DRIwH_2-65o	DRIwNG-65o	OSBFwDRI-C0	OSBFwDRI-C4	EAFwDRI-C0	EAFwDRI-C4	EAFwscrap	Cracking	BF	BOF	Sintering	Coking
ore65pel	t/t product	0	0	0	0	1.437	1.4	0	0	0	0	0	0	0.358	0	0	0
ore65lump	t/t product	0	0	0	0	0	0	0	0	0	0	0	0	0.128	0	0	0
ore65fines	t/t product	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.792	0
ore65sinter	t/t product	0	0	0	0	0	0	0	0	0	0	0	0	1.142	0	0	0
ore67pel	t/t product	1.395	1.362	1.365	1.362	0	0	0	0	0	0	0	0	0	0	0	0
elec	MWh/t product	0.083	0.083	0.083	0.083	0.113	0.113	0.660	0.660	0.518	0.470	0.657	0.290	0	0.010	0	0.045
NH_3	t/t product	0	0	0	0	0	0	0	0	0	0	0	6.667	0	0	0	0
H_2	t/t product	0.067	0	0.028	0.006	0.067	0	0	0	0	0	0	0	0	0	0	0
NG	t/t product	0	0.208	0.121	0.189	0	0.208	0	0	0	0	0	0	0	0	0	0
metcoal	t/t product	0	0	0	0	0	0	0	0	0	0	0	0	0.155	0	0	1.320
coke	t/t product	0	0	0	0	0	0	0	0	0	0	0	0	0.362	0	0	0
HBI-C0-65o	t/t product	0	0	0	0	0	0	1.150	0	0	0	0	0	0	0	0	0
HBI-C0-67o	t/t product	0	0	0	0	0	0	0	0	0.846	0	0	0	0	0	0	0
HBI-C4-65o	t/t product	0	0	0	0	0	0	0	1.150	0	0	0	0	0	0	0	0
HBI-C4-67o	t/t product	0	0	0	0	0	0	0	0	0	0.924	0	0	0	0	0	0
pigi	t/t product	0	0	0	0	0	0	0	0	0	0	0	0	0	0.869	0	0
scrap	t/t product	0	0	0	0	0	0	0	0	0.194	0.194	1.020	0	0	0.118	0	0
lime	t/t product	0	0	0	0	0	0	0.011	0.011	0.053	0.053	0.029	0	0	0.068	0.010	0
limestone	t/t product	0	0	0	0	0	0	0	0	0	0	0	0	0.013	0	0.117	0
alloys	t/t product	0	0	0	0	0	0	0	0	0.011	0.011	0.011	0	0	0.015	0	0
oxygen	t/t product	0	0.086	0.057	0.076	0.079	0.079	0	0	0.004	0.056	0.045	0	0.071	0.071	0	0
carbon	t/t product	0	0	0	0	0	0	0.010	0	0.010	0	0.010	0	0	0	0	0
electrode	t/t product	0	0	0	0	0	0	0.003	0.003	0.002	0.002	0.002	0	0	0	0	0
refractory	t/t product	0	0	0	0	0	0	0	0	0.005	0.005	0.005	0	0	0.005	0	0
labour	t/t product	5	5	5	5	5	5	1	1	1	1	1	0	3	2	1	2
Output product		HBI-C0-67o	HBI-C4-67o	HBI-C4-67o	HBI-C4-67o	HBI-C0-65o	HBI-C4-65o	pigi	pigi	SFS	SFS	SFS	H_2	pigi	SFS	ore65sinter	coke

Table S2.13. Commodity prices and labour costs (excluding zero-carbon energy products).

	Value	**Unit**	**Source**
DR-grade ore	100	\$/dmt	based on costs from Black Iron (2023)
BF-grade ore	80	\$/dmt	World Bank Group (2022)
Scrap	300	\$/t	GMK (2021)
Natural gas	25	\$/MWh	Eurostat (2023)
Metallurgical coal	200	\$/t	(\$196 = 5-yr avg 2018-2022) Department of Industry (2023)
Lime	121	\$/t	Vogl et al. (2018)
Limestone	11	\$/t	Authors' estimate
Alloys	2397	\$/t	Vogl et al. (2018)
Oxygen	82	\$/t	Vogl et al. (2018)
Carbon	300	\$/t	premium for anthracite above metallurgical coal
Electrodes	5395	\$/t	Vogl et al. (2018)
Refractories	1100	\$/t	Deneen and Gross (2010)
Water	2	\$/t	Bryan Municipal Utilities
Labour	3	\$/hr	based on costs from Black Iron (2023)

Table S2.14. Unit Prices of iron and steelmaking assets.

Asset	**Value**	**Unit**	**Source**
coke plant	268	\$/tpa coke	IEAGHG (2013)
sinter plant	56	\$/tpa sinter	IEAGHG (2013)
BF	225	\$/tpa pig iron	IEAGHG (2013)
BOF	120	\$/tpa LS	IEAGHG (2013)
BF reline	100	\$/tpa pig iron	Teck (2022)
EAF	283	\$/tpa LS	Vogl et al. (2018), Facchini et al. (2021), Steel on the Net
OSBF	283	\$/tpa LS	*assume same as EAF, both electric smelting furnaces*
DRI shaft furnace	310	\$/tpa DRI	Vogl et al. (2018)
NH_3 cracker	30	\$/tpa NH_3	Cesaro et al. (2021)

S3. Supplementary Background Information

S3.1 Ukrainian steel industry emissions

Table S3.1. Breakdown of Ukrainian steel sector emissions in 2020 related to onsite processes (scope 1) and offsite electricity generation (scope 2) (Koolen & Vidovic, 2022; UNFCCC, 2022). Upstream emissions related to energy and material extraction, preparation, and transportation (scope 3), are not included.

	Production qty (kt)	**Emissions (kt CO_2)**	**Average emission factor (t CO_2/t product)**
Steel production (scope 1)	20616	2760	0.13
Iron production (scope 1)	20238	29780	1.47
Limestone/dolomite use (scope 1)	6602	2852	0.43
Electricity consumption (scope 2)	20616	12606	0.61
Total (scope 1+2)	20616	47998	2.33

S3.2 Ukraine’s mature near zero-emissions energy sources

Nuclear

Of Ukraine’s current fleet of 15 nuclear reactors across four plants (GEM, 2023c), just two nuclear reactors, built between 2005-2006, will still be operational past 2050, based on an expected lifetime of 60 years for newer units (World Nuclear Association, 2022). In 2021, 86 TWh of nuclear power was produced (BP, 2022b); therefore, operation was at a high capacity factor of 71%. Maintaining and expanding nuclear power capacity sits at the core of Ukraine’s decarbonisation strategy: the aim is for 50% of the power mix to be provided by nuclear, and the other 50% by renewables by 2035 (Enerdata, 2023). Three operational uranium (U) mines currently function with a combined capacity of 2450 tUpa, whilst two are in the pipeline, with a planned capacity of 1350 tUpa (Nuclear Energy Agency, 2023). Ukraine has an endowment of significant uranium resources: 107.2 kt U is classified as identified recoverable resources (less than $130/kg U), which is 2% of global resources (over 51% of reserves are in Australia, Kazakhstan and Canada) (Nuclear Energy Agency, 2023). Ukraine produced 134 ktU from 1944-2020 (4% of global output) and 0.71 ktU in 2020 (2% of global output) (Nuclear Energy Agency, 2023). Yet, the nation lacks processing facilities to refine and enrich the uranium concentrate into nuclear fuel. Pre-war, this was outsourced to Russia (World Nuclear Association, 2023), yet US-owned *Westinghouse Electric Company* has recently signed a contract with *Energoatom*, Ukraine’s state-owned nuclear power company, to construct and supply nine modern nuclear reactors, plus supply all nuclear fuel to the current operating fleet (European Nuclear Society, 2023).

The model assumes that the two reactors with lifetimes exceeding 2050 are upgraded to 150% of current capacity, totalling 3000 MW (22% of current capacity), which continue to operate at a capacity factor of 71%. This is a conservative approach adopted due to the location certainty; the nuclear fleet is likely to expand significantly if the government’s current energy strategies are successful. It is worth noting that the EU taxonomy (European Commission), the regional economy's classification system for sustainable activities, currently includes nuclear and fossil gas energy as transitional resources contributing to climate change mitigation, and hence the nuclear power can benefit from sustainable finance instruments and capital flows (European Parliament, 2022).

Hydro

There are ten hydropower plant (HPP) projects currently operational (excluding the recently destroyed Kakhovka Dam and Hydroelectric Power Plant), with a total capacity of 6,247 MW (32% pumped storage) (GEM, 2023b). Based on data from the International Hydropower Association's (IHA) *HydroPower Status Reports*, the average Ukrainian hydropower capacity factor was 20% in 2018 and 2019, whilst this receded to 13% in 2020, and then to just 4% in 2022. In comparison, the European average capacity factor has been about 30% for the past 5 years (Norway and Sweden both shared the peak capacity factor of 49% in 2022). Cost-effective hydropower potential (CEHP) in Ukraine is estimated at 17-18 TWh, which is minor compared to EU leaders in hydropower (i.e. Norway with 180 TWh, Sweden with 90 TWh, and France with 72 TWh of CEHP), but on-par with Germany and Finland (both about 20 TWh CEHP) (Stefanyshyn, 2018). Ukraine produced 10.4 TWh of hydropower in 2021, hence operating at 60% of potential capacity. Prospective future projects include six new HPPs on the Dniester River and rehabilitation/construction of numerous small HPPs. The model assumes an improved capacity factor of 30% (matching the European average) across the existing HPP asset fleet, and that the steel sector can consume 20% of the produced electricity.

S3.3 Ukraine's geological resources

Iron ore

Ukraine pertains 60 iron ore deposits, of which 25 are under development, with the total balance of iron ore reserves estimated at 18.065 billion tonnes (Bt) (State Research and Development Enterprise Geoinform of Ukraine, 2021). The majority of iron ore mines is located in Dnipropetrovsk oblast's Kryvyi Rih iron ore basin (8.78 Bt; 49% of total balance of reserves), Poltava oblast (5.04 Bt; 28%), and Zaporizhzhia oblast (2.76 Bt; 15%). Ukraine has 111 years remaining of current proven iron ore reserves, if extraction continues at the historical rate of 163 Mtpa. However, over half of total proven reserves are exploited, whilst substantial parts of reserves are not considered economical (Stupnik & Shatokha, 2021). Annual ore consumption is constrained to annual mine capacity across 11 sites, with only one located in the Russian-occupied territories. DR-grade ore is limited according to projected increase in beneficiation and pelletisation capacity (unique to scenario, refer to Table S.2.6). Pelletising and beneficiation capacity must grow with DRI capacity, although this study treats ore mining and preparation as an external supplier to the production system (refer to SI Section S3.2 for further details on iron ore).

Approximately 70 Mt of iron ore products were produced annually pre-war, mostly BF-grade concentrate, sinter feed, pellets and some lump (GMK, 2020). Ukraine produces about 3% of global usable iron ore (U.S. Geological Survey, 2022), and traditionally has been a net exporter of iron ore products, with 46 Mt exported in 2020 (60% of which was received by China) (EITI, 2020), equivalent to 65% of total iron ore products.

Ukraine, like most other iron ore-producing countries, is suffering from the progressive depletion of reserves, and diminishing of high-grade iron ore availability. Ore grades range from low grades (20-40% Fe, high silica content) to high grades (55-67% Fe, lower silica content) (Shnyukov et al., 2022), with the average Fe-content of historical usable ore at 62% (U.S. Geological Survey, 2022). Current challenges include inefficient processing technologies, which result in relatively low Fe-content, high gangue content (up to 10%), and high mass losses (up to 12-15%). As a general trend, mine productivity is diminishing alongside the deterioration of mining (depths increasing by 13-16m/year) and geological conditions (Stupnik & Shatokha, 2021). The growing market demand for higher grade ores, around 66-67% Fe content, suitable for direct reduction, will require significant market development and capital investment.

The two top iron ore-producing companies in Ukraine are *Metinvest* and *Ferrexpo*. Ferrexpo (2023) currently produces 65% Fe pellets, with the intention to expand to 67% Fe pellets, whilst Metinvest (2019) produces iron ore concentrate with 64-68% Fe, and pellets of 62-66% Fe content. Black Iron project is a greenfield project being developed in Central Ukraine (Shymanivske iron ore deposit in Dnipropetrovsk oblast), to produce 68% Fe content pellet feed concentrate from magnetite reserves (Black Iron, 2023). Magnetite is more amenable to beneficiation due to its magnetic properties, whilst hematite requires more energy-intensive physical separation processes to remove gangue and enhance desirable chemical (Maré et al., 2022; Xiong et al., 2022).

Metallurgical coal

Ukraine has 263 years remaining of current proven metallurgical coal reserves (1929 Mt) (EITI, 2023), if extraction continues at the historical rate of 7.33 Mtpa (2015-2018 average) (Kwilinski et al., 2020). Contrary to the opportunity presented by the large domestic reserve size, Ukraine is a net importer of metallurgical coal; total coal consumption exceeded production by 73% in 2018 (Kwilinski et al., 2020). The model constrains maximum mine production to 2015-2018 production levels (7.33 Mtpa): seven main metallurgical coal mines were assessed, four of which located in the Russian-occupied territories.

Natural gas

Natural gas reserves are estimated between 719 Bm^3 (EITI, 2020) to 1100 Bm^3 (BP, 2022a). If historical extraction rates of 20 Bm^3pa continue, approximately 35 years remain, meaning complete reserve depletion by 2056. Since current NG consumption in the Ukrainian steel industry is marginal, a minor 25% of total domestic production can be utilised by the steel industry (~5 Bm^3pa) in 2030 and 2040, reducing to zero in 2050. Seven main gas fields were assessed, none of which located in the Russian-occupied regions.

S3.4 Pre-war Ukrainian steel sector

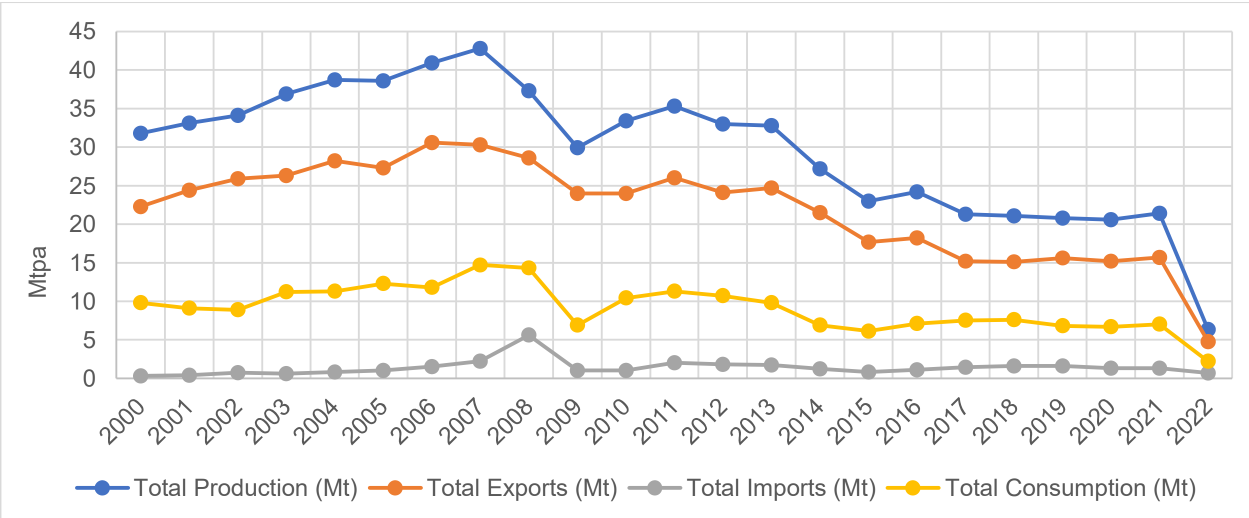

Figure S3.1. Ukraine crude steel production, trade, and consumption (2000-2022).

Table S3.2. Key state support and government aid mechanisms for Ukraine's mining and metallurgical industry, 1990s-2010s.

Government document	Category of benefits
Law of Ukraine "On Conducting Economic Experiment at Enterprises of the Mining and Metallurgical Complex of Ukraine," July 14, 1999, No. 934-XIV *(expired as of January 1, 2002).*	• Cancellation of penalties and fines accrued for late payment of taxes, fees, and other mandatory payments, which were not paid to the state budget as of July 1, 1999; • Payment of a fee to the State Innovation Fund in the amount of 50% of the rate determined by the legislation of Ukraine; • Non-withholding and non-payment of fees for the construction, reconstruction, repair, and maintenance of public roads; • Deferral of payment of taxes, fees, and other mandatory payments within their competence for a period of up to 36 months, with the application of a zero-interest rate for the use of tax credit; • Temporary establishment of corporate profit taxation in the amount of 30% of the current rate, and the difference in the funds generated from the rate change to be directed to replenish the working capital of enterprises; and • Reimbursement from the State Budget of Ukraine to the value-added tax payer, in case the value-added tax amount for the reporting period is determined as the difference between the total amount of tax liabilities and the amount of tax credit for any purchase and sale transactions (goods, works, services).

Government document	Category of benefits
Law of Ukraine “On Further Development of the Mining and Metallurgical Complex,” January 17, 2002, No. 2975-III *(expired as of January 1, 2003).*	• Allocation by enterprises of 50% of the amount of accrued corporate income tax to the General Fund of the State Budget of Ukraine. The remaining funds to be credited to a separate specia account opened in the State Treasury of Ukraine and used for the implementation of investment projects, including the restructuring of enterprises in the mining and metallurgical complex and the decommissioning of excess and inefficient capacities; and • Funds from the environmental pollution fee paid by enterprises in the mining and metallurgical complex covered by this Law to be distributed amongst local, regional, and the Autonomous Republic of Crimea budgets as well as the State Environmental Protection Fund (in proportions of 10% and 70%) to be used by enterprises for environmental protection measures.
Resolution of the Cabinet of Ministers of Ukraine “On Urgent Measures for Stabilising the Situation in the Mining and Metallurgical and Chemical Complex,” October 14, 2008, No. 925. Resolution of the Cabinet of Ministers of Ukraine “On Certain Issues Regarding the Stabilisation of Operations of Enterprises in the Chemical Industry and Mining and Metallurgical Complex,” March 24, 2010, No. 289. *(revoked in July 2010)*	• In the autumn of 2008, the Cabinet of Ministers and representatives of the mining-metallurgical and chemical industries signed a Memorandum of Understanding with the aim of normalising the situation in these industries. The objectives included stabilising prices for their products, preserving jobs, wages, and social guarantees, as well as developing the domestic market. • A moratorium was imposed on raising tariffs for freight railway transportation for mining-metallurgical and chemical enterprises, and the National Commission for Energy and Utilities Regulation suspended the increase in electricity prices from November 1, 2008. The resolution was initially adopted for the period until January 1, 2009, and its validity was extended quarterly. • According to estimates, over the course of 1 ½ years of preferential treatment, the industry received benefits in the amou of 1.9bn UAH. The Cabinet of Ministers of Ukraine did not extend these preferences further (UNIAN, 2010).
The Resolution of the Cabinet of Ministers of Ukraine “On Approval of the State Programme for the Economic Development Activation for 2013-2014,” February 27, 2013, No. 187	• Provision of state support through the mechanism of state guarantees for the implementation of modernisation projects in the mining and metallurgical complex, including the construction of the second stage of the electric steel melting complex “Interpipe Steel” of the Limited Liability Company “Metallurgical Plant “Dniprostal” in Dnipro, Ukraine.

Table S3.3. Anti-dumping measures applied to Ukraine`s base metals and articles of base metal (World Trade Organisation, 2024).

Reporting Member	Subject product	Measure in force from
United States	Silicomanganese	31.10.1994
United States	Certain cut-to-length carbon steel plate	19.11.1997
United States	Steel concrete reinforcing bar	11.04.2001
United States	Certain hot-rolled carbon steel flat products	29.11.2001
United States	Certain oil country tubular goods	18.07.2014
United States	Carbon and alloy steel wire rod	14.03.2018
United States	Prestressed concrete steel wire strand	04.06.2021
United States	Seamless carbon and alloy steel standard, line and pressure pipe	23.08.2021
United Kingdom	Hot-rolled flat products of iron, non-alloy or other alloy steel	01.01.2021
Thailand	Flat hot-rolled in coils and not in coils	26.05.2003
Russian Federation	Certain steel pipes and tubes	31.12.2005
Russian Federation	Ferrosilicon manganese	03.06.2016
Russian Federation	Seamless pipes and tubes of stainless steel	27.01.2016
Russian Federation	Hot-rolled steel angles	04.10.2017
Russian Federation	Zinc plated or coated flat-rolled steel products	06.12.2019
Mexico	Alloy and non-alloy carbon steel plate in sheets	21.09.2005
Mexico	Ferro silico manganese	24.09.2003
Mexico	Bars and rods of iron or non-alloy steel	18.09.2000
Mexico	Seamless carbon steel tubing	03.04.2018
Mexico	Hot-rolled sheet	28.03.2000
Kyrgyz Republic	Certain steel pipes and tubes	31.12.2005
Kyrgyz Republic	Ferrosilicon manganese	03.06.2016
Kyrgyz Republic	Seamless pipes and tubes of stainless steel	27.01.2016
Kyrgyz Republic	Hot-rolled steel angles	04.10.2017
Kyrgyz Republic	Zinc plated or coated flat-rolled steel products	06.12.2019
Korea, Republic of	Ferro silico manganese	29.11.2017

Kazakhstan	Certain steel pipes and tubes	31.12.2005
Kazakhstan	Ferrosilicon manganese	03.06.2016
Kazakhstan	Seamless pipes and tubes of stainless steel	27.01.2016
Kazakhstan	Hot-rolled steel angles	04.10.2017
Kazakhstan	Zinc plated or coated flat-rolled steel products	06.12.2019
Indonesia	Hot rolled plate	01.10.2012
European Union	Seamless pipes and tubes of iron or steel	29.06.2006
European Union	Hot-rolled flat products of iron, non-alloy or another alloy steel	06.10.2017
Egypt	Bars and rods of iron alloy or non-alloy steel rebar, hot rolled in wound coil or bars or rods (Steel Rebar for construction)	06.12.2017
Taiwan / Chinese Taipei	Carbon steel plate	20.02.2017
Canada	Certain steel plate	02.02.2010
Canada	Certain oil country tubular goods	02.04.2015
Brazil	Heavy plates	03.10.2013
Brazil	Seamless carbon steel line pipes for oil and gas pipelines	24.11.2014
Armenia	Certain steel pipes and tubes	31.12.2005
Armenia	Ferrosilicon manganese	03.06.2016
Armenia	Seamless pipes and tubes of stainless steel	27.01.2016
Armenia	Hot-rolled steel angles	04.10.2017
Armenia	Zinc plated or coated flat-rolled steel products	06.12.2019

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