

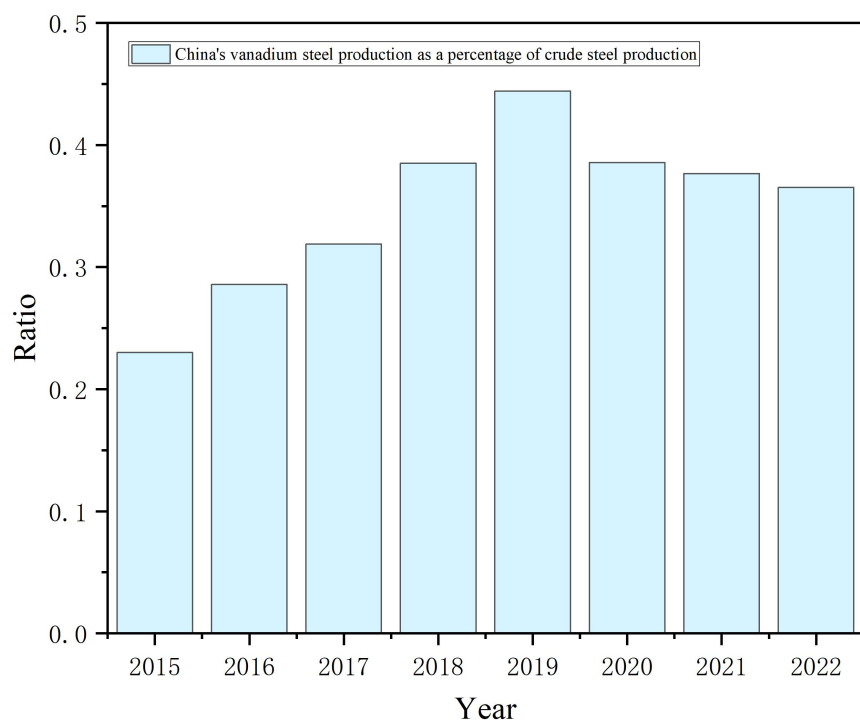


Fig. S1. China's vanadium steel production as a percentage of crude steel production over time

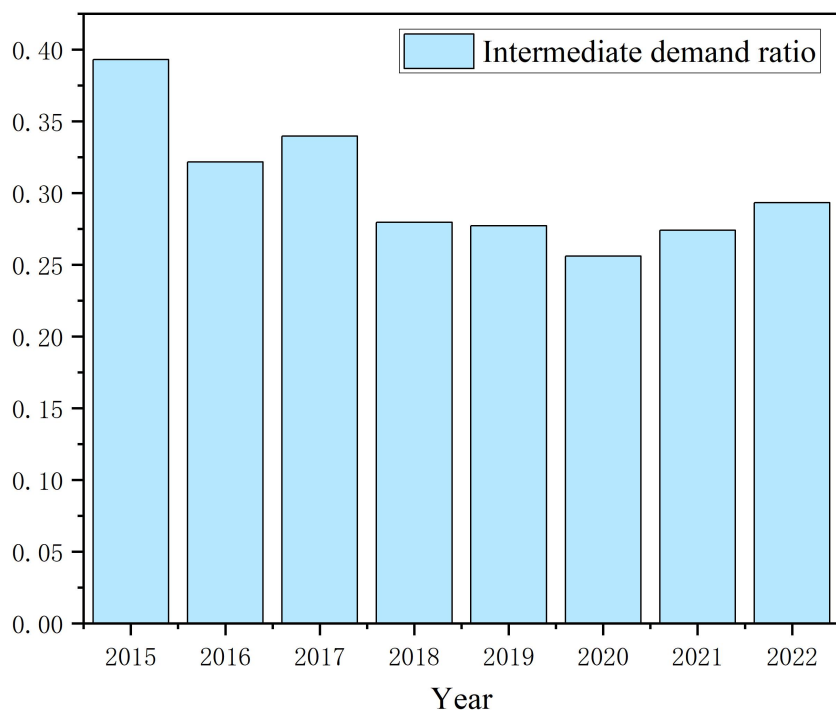


Fig. S2. Intermediate Demand Ratio from 2015 to 2022

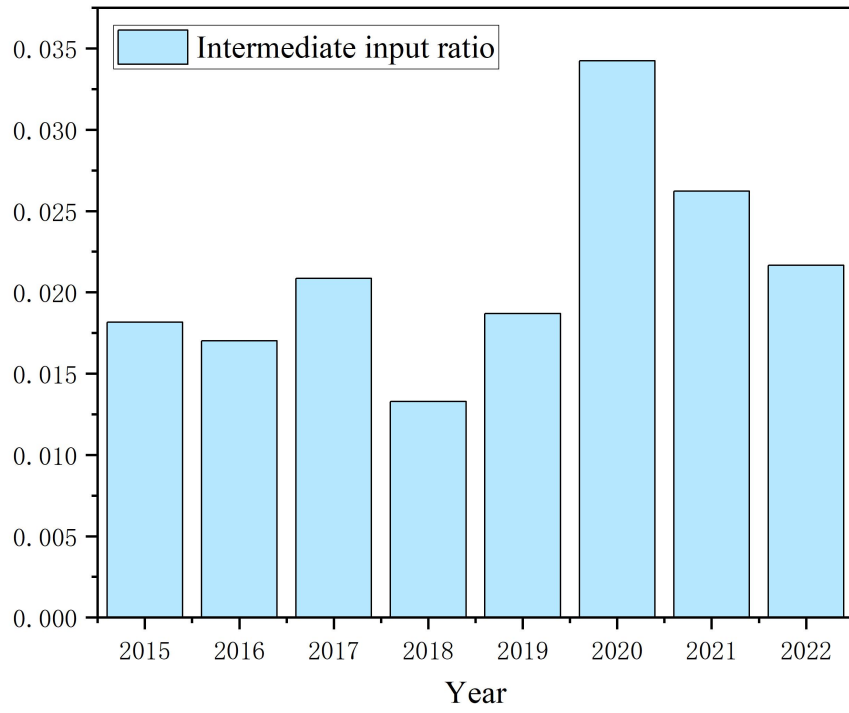


Fig. S3. Intermediate Input Ratio from 2015 to 2022

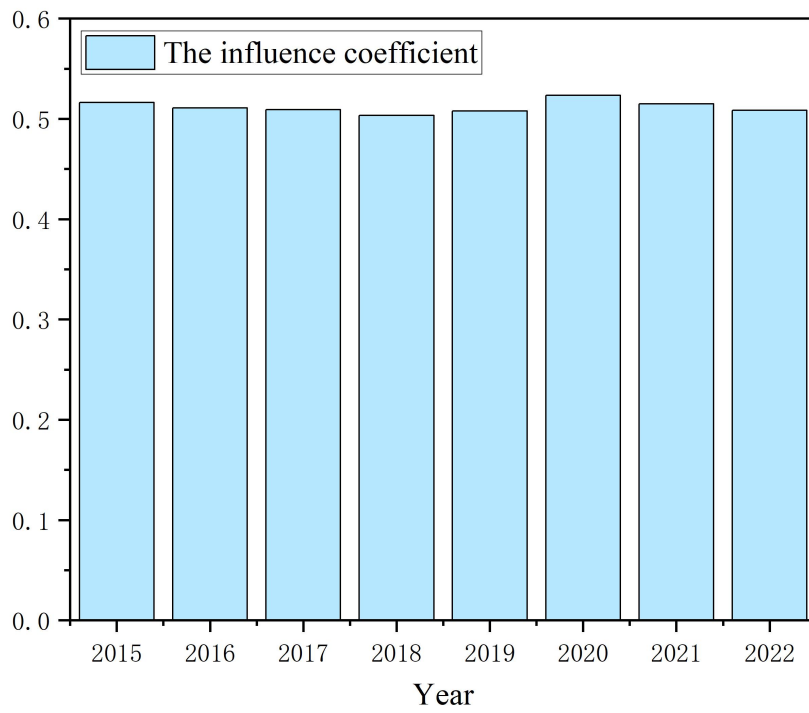


Fig. S4. Influence Coefficient from 2015 to 2022

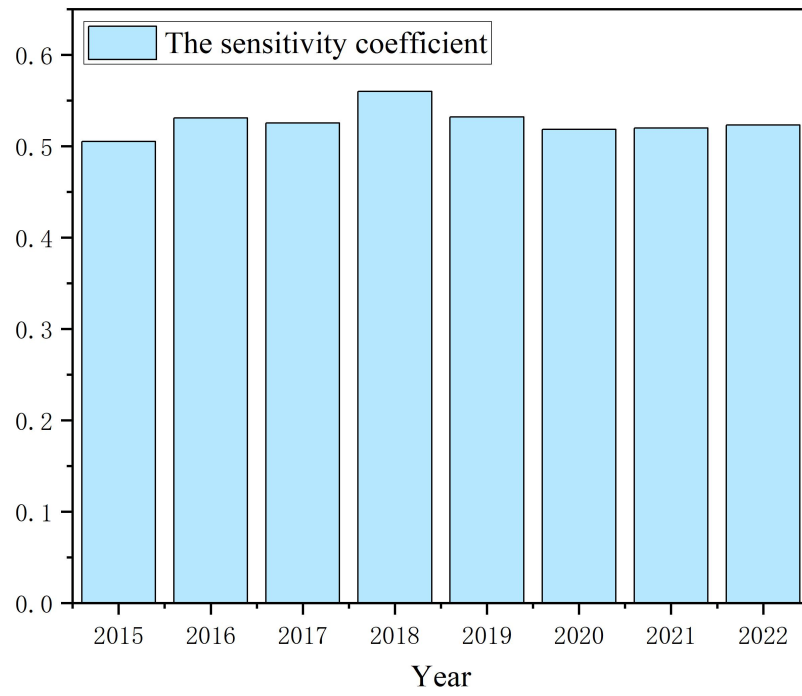


Fig. S5. Sensitivity Coefficient from 2015 to 2022

	Driving China's vanadium industry						China's vanadium industry Driving						
	Directly driving			Indirectly driving			Directly driving			Indirectly driving			
Year	Rank	Region	Industry	Value	Region	Industry	Value	Region	Industry	Value	Region	Industry	Value
2015		1 CN	Vanadium	0.008786 CN		Vanadium	0.008864 CN		Iron and st	0.288806 CN		Iron and st	0.312868
		2 CN	Transmissi	0.000274 CN		Transmissi	0.000296 CN		Chemicals	0.015868 CN		Manufactu	0.156975
		3 AU	Mining of	3.43E-05 CN		Distributio	6.92E-05 CN		Other non	0.012695 CN		Constructi	0.12456
		4 BR	Mining of	3.05E-05 CN		Productior	3.78E-05 CN		Vanadium	0.008786 CN		Manufactu	0.077037
		5 ZA	Mining of	2.79E-05 AU		Mining of i	3.55E-05 WA		Manufactu	0.006337 CN		Manufactu	0.065834
		6 WE	Mining of	2.24E-05 BR		Mining of i	3.37E-05 WM		Constructi	0.00334 CN		Chemicals	0.036198
		7 CA	Mining of	1.9E-05 CN		Productior	3.24E-05 WA		Manufactu	0.003253 CN		Manufactu	0.027978
		8 TR	Mining of	1.79E-05 ZA		Mining of i	2.85E-05 KR		Manufactu	0.003163 CN		Aluminium	0.027089
		9 WF	Mining of	1.43E-05 CN		Productior	2.44E-05 WA		Manufactu	0.002913 CN		Manufactu	0.025713
		10 RU	Mining of	1.36E-05 CN		Re-proces:	2.44E-05 WA		Constructi	0.002237 CN		Manufactu	0.02235
2016		1 CN	Vanadium	0.010204 CN		Vanadium	0.01031 CN		Iron and st	0.218392 CN		Iron and st	1.11888
		2 CN	Transmissi	0.000381 CN		Transmissi	0.000413 CN		Chemicals	0.012 WA		Constructi	0.02938
		3 BR	Mining of	2.45E-05 CN		Distributio	9.93E-05 CN		Vanadium	0.010204 WA		Manufactu	0.029199
		4 AU	Mining of	2.36E-05 CN		Productior	4.54E-05 CN		Other non	0.0096 CN		Chemicals	0.025475
		5 ZA	Mining of	1.72E-05 CN		Productior	3.72E-05 WA		Manufactu	0.00775 CN		Petroleum	0.024661
		6 WF	Mining of	1.34E-05 CN		Productior	3.11E-05 WA		Constructi	0.006267 CN		Extraction	0.02184
		7 WA	Mining of	1.3E-05 CN		Productior	3E-05 WM		Constructi	0.003344 CN		Mining of (	0.019196
		8 WE	Mining of	1.16E-05 CN		Productior	2.88E-05 WA		Manufactu	0.003328 CN		Constructi	0.017568
		9 CA	Mining of	1.05E-05 CN		Re-proces:	2.88E-05 WA		Manufactu	0.003211 WM		Constructi	0.016235
		10 NO	Mining of	1.02E-05 CN		Productior	2.88E-05 KR		Re-proces:	0.003079 WA		Manufactu	0.013391
2017		1 CN	Vanadium	0.015786 CN		Vanadium	0.016039 CN		Iron and st	0.223506 CN		Iron and st	0.4058
		2 CN	Transmissi	0.000372 CN		Transmissi	0.000404 CN		Vanadium	0.015786 CN		Constructi	0.086574
		3 AU	Mining of	2.12E-05 CN		Distributio	0.000103 CN		Chemicals	0.0149 CN		Manufactu	0.084494
		4 BR	Mining of	2.08E-05 CN		Productior	5.77E-05 CN		Other non	0.009934 CN		Manufactu	0.054955
		5 TR	Mining of	1.83E-05 CN		Productior	3.43E-05 WA		Constructi	0.006734 CN		Manufactu	0.049408
		6 AU	Mining of	1.41E-05 CN		Productior	3.38E-05 WA		Manufactu	0.006433 CN		Chemicals	0.030792
		7 ZA	Mining of	1.29E-05 CN		Productior	2.98E-05 WM		Constructi	0.002817 CN		Manufactu	0.025035
		8 WE	Mining of	1.22E-05 CN		Productior	2.94E-05 WA		Manufactu	0.002757 CN		Manufactu	0.023767
		9 JP	Mining of	1.21E-05 CN		Productior	2.92E-05 WA		Manufactu	0.002744 CN		Vanadium	0.016039
		10 BR	Mining of	1.2E-05 CN		Productior	2.83E-05 KR		Constructi	0.002656 CN		Other non	0.01368
2018		1 CN	Vanadium	0.011745 CN		Vanadium	0.011885 CN		Iron and st	0.199406 CN		Iron and st	0.287642
		2 CN	Transmissi	0.000349 CN		Transmissi	0.000389 CN		Chemicals	0.013177 CN		Constructi	0.083017
		3 AU	Mining of	2.33E-05 CN		Distributio	6.99E-05 CN		Vanadium	0.011745 CN		Manufactu	0.070573
		4 BR	Mining of	1.95E-05 CN		Productior	4.22E-05 CN		Other non	0.009224 CN		Manufactu	0.049862
		5 ZA	Mining of	1.64E-05 CN		Productior	3.6E-05 WA		Manufactu	0.004961 CN		Manufactu	0.040703
		6 CA	Mining of	1.51E-05 CN		Productior	3.48E-05 WA		Manufactu	0.002448 CN		Chemicals	0.027343
		7 GR	Mining of	9.61E-06 CN		Productior	3.4E-05 WA		Constructi	0.002018 CN		Manufactu	0.022063
		8 WA	Mining of	9.6E-06 CN		Productior	3.35E-05 WA		Manufactu	0.002008 CN		Manufactu	0.021987
		9 TR	Mining of	9.33E-06 CN		Productior	3.34E-05 WM		Constructi	0.001739 CN		Other non	0.01218
		10 TR	Mining of	9.13E-06 CN		Productior	3.34E-05 WA		Manufactu	0.001369 CN		Vanadium	0.011885
2019		1 CN	Vanadium	0.01224 CN		Vanadium	0.012392 CN		Iron and st	0.217775 CN		Iron and st	0.318563
		2 CN	Transmissi	0.000444 CN		Transmissi	0.00048 CN		Vanadium	0.01224 CN		Constructi	0.089655
		3 AU	Mining of	0.0003 AU		Mining of i	0.000308 CN		Other non	0.009093 CN		Manufactu	0.074381
		4 BR	Mining of	0.000245 BR		Mining of i	0.000263 CN		Chemicals	0.00852 CN		Manufactu	0.05353
		5 ZA	Mining of	0.000214 ZA		Mining of i	0.000218 WA		Manufactu	0.003145 CN		Manufactu	0.043557
		6 CA	Mining of	0.000187 CA		Mining of i	0.000211 WA		Constructi	0.002459 CN		Manufactu	0.022996
		7 WA	Mining of	0.000151 WA		Mining of i	0.000155 WM		Constructi	0.001512 CN		Manufactu	0.022593
		8 TR	Mining of	0.000116 TR		Mining of i	0.00012 WA		Manufactu	0.001354 CN		Chemicals	0.020154
		9 TR	Mining of	0.000109 CN		Distributio	0.000117 WA		Manufactu	0.001292 CN		Vanadium	0.012392
		10 GR	Mining of	0.000108 TR		Mining of i	0.000111 WA		Manufactu	0.000884 CN		Other non	0.01231
2020		1 CN	Vanadium	0.011853 CN		Vanadium	0.011995 CN		Iron and st	0.204057 CN		Iron and st	0.293179
		2 AU	Mining of	0.001004 AU		Mining of i	0.001029 CN		Vanadium	0.011853 CN		Constructi	0.082247
		3 BR	Mining of	0.000809 BR		Mining of i	0.00087 CN		Chemicals	0.011496 CN		Manufactu	0.069673
		4 ZA	Mining of	0.000661 CA		Mining of i	0.000695 CN		Other non	0.004669 CN		Manufactu	0.049396
		5 CA	Mining of	0.000617 ZA		Mining of i	0.000672 WA		Constructi	0.003054 CN		Manufactu	0.040161
		6 CN	Transmissi	0.000442 WF		Mining of i	0.000501 WA		Manufactu	0.002649 CN		Chemicals	0.024771
		7 WF	Mining of	0.000436 CN		Transmissi	0.00049 WA		Manufactu	0.001132 CN		Manufactu	0.021882
		8 WA	Mining of	0.000429 WA		Mining of i	0.000439 WA		Manufactu	0.001122 CN		Manufactu	0.021861
		9 TR	Mining of	0.000384 TR		Mining of i	0.000396 WM		Constructi	0.000941 CN		Vanadium	0.011995
		10 GR	Mining of	0.000382 GR		Mining of i	0.000389 KR		Constructi	0.000664 CN		Manufactu	0.010436
2021		1 CN	Vanadium	0.015818 CN		Vanadium	0.016072 CN		Iron and st	0.212849 CN		Iron and st	0.307515
		2 CN	Transmissi	0.000439 CN		Transmissi	0.000488 CN		Vanadium	0.015818 CN		Constructi	0.087475
		3 AU	Mining of	0.000306 AU		Mining of i	0.000316 CN		Chemicals	0.013988 CN		Manufactu	0.073541
		4 BR	Mining of	0.000251 BR		Mining of i	0.000271 CN		Other non	0.004795 CN		Manufactu	0.05201
		5 ZA	Mining of	0.000231 ZA		Mining of i	0.000236 WA		Manufactu	0.003408 CN		Manufactu	0.042296
		6 CA	Mining of	0.000192 CA		Mining of i	0.000218 WA		Manufactu	0.001551 CN		Chemicals	0.028968
		7 WA	Mining of	0.000134 WA		Mining of i	0.000138 WA		Manufactu	0.001494 CN		Manufactu	0.023178
		8 FI	Mining of	0.000125 FI		Mining of i	0.000131 KR		Manufactu	0.001159 CN		Manufactu	0.023135
		9 TR	Mining of	0.00011 TR		Mining of i	0.000113 WA		Manufactu	0.001024 CN		Vanadium	0.016072
		10 GR	Mining of	0.000107 GR		Mining of i	0.00011 WM		Constructi	0.001022 CN		Manufactu	0.010932
2022		1 CN	Vanadium	0.014413 CN		Vanadium	0.014625 CN		Iron and st	0.224936 CN		Iron and st	0.359847
		2 CN	Transmissi	0.000438 CN		Transmissi	0.000478 CN		Chemicals	0.014783 CN		Constructi	0.091081
		3 AU	Mining of	0.000205 AU		Mining of i	0.000211 CN		Vanadium	0.014413 CN		Manufactu	0.081677
		4 BR	Mining of	0.000186 BR		Mining of i	0.000203 CN		Other non	0.005067 CN		Manufactu	0.049988
		5 ZA	Mining of	0.000153 ZA		Mining of i	0.000156 WA		Manufactu	0.004153 CN		Manufactu	0.047289
		6 CA	Mining of	0.000133 CA		Mining of i	0.000149 WA		Constructi	0.002764 CN		Chemicals	0.030442
		7 TR	Mining of	9.73E-05 CN		Distributio	0.000121 WA		Manufactu	0.001764 CN		Manufactu	0.025637
		8 WA	Mining of	9.04E-05 TR		Mining of i	9.97E-05 WA		Manufactu	0.001573 CN		Manufactu	0.023312
		9 GR	Mining of	8.57E-05 WA		Mining of i	9.37E-05 KR		Manufactu	0.001467 CN		Vanadium	0.014625
		10 WE	Mining of	7.48E-05 GR		Mining of i	8.78E-05 WM		Constructi	0.001328 CN		Health and	0.011163

	Pulling China's vanadium industry							China's vanadium industry Pulling								
	Directly pulling				Indirectly pulling				Directly pulling				Indirectly pulling			
Year	Rank	Region	Industry	Value	Region	Industry	Value	Region	Industry	Value	Region	Industry	Value			
2015		1 CN	Vanadium	0.008786 CN	Vanadium	Vanadium	0.008863 CN	CN	Vanadium	0.008786 CN	Vanadium	Vanadium	0.008863			
		2 CN	Iron and st	0.000642 CN	Other non	Other non	0.000259 CN	CN	Transmissi	0.006983 CN	Transmissi	Transmissi	0.007539			
		3 CN	Other non	0.000257 WA	Manufactu	Manufactu	0.000258 BR	BR	Mining of i	0.000311 CN	Productio	Productio	0.004569			
		4 WA	Manufactu	0.000208 WA	Manufactu	Manufactu	0.000127 AU	AU	Mining of i	0.000292 CN	Distributio	Distributio	0.004432			
		5 WL	Manufactu	0.000102 WM	Manufactu	Manufactu	0.000123 CN	CN	Other land	0.000113 CN	Mining of i	Mining of i	0.001697			
		6 WM	Manufactu	0.000101 WL	Manufactu	Manufactu	0.00012 JP	JP	Manufactu	7.7E-05 CN	Financial ir	Financial ir	0.000629			
		7 WA	Manufactu	9.96E-05 KR	Manufactu	Manufactu	0.0001 CN	CN	Manufactu	5.89E-05 CN	Productio	Productio	0.000504			
		8 WF	Manufactu	6.94E-05 KR	Re-proces	Re-proces	9.66E-05 DE	DE	Manufactu	5.2E-05 CN	Manufactu	Manufactu	0.00047			
		9 TR	Manufactu	6.89E-05 TR	Manufactu	Manufactu	9.15E-05 WM	WM	Mining of i	5.13E-05 CN	Other busi	Other busi	0.000379			
		10 PT	Re-proces	6.89E-05 WF	Manufactu	Manufactu	8.81E-05 AU	AU	Mining of i	4.03E-05 BR	Mining of i	Mining of i	0.000328			
2016		1 CN	Vanadium	0.010204 CN	Vanadium	Vanadium	0.01031 CN	CN	Vanadium	0.010204 CN	Vanadium	Vanadium	0.01031			
		2 CN	Iron and st	0.001412 CN	Iron and st	Iron and st	0.007233 CN	CN	Transmissi	0.005704 CN	Transmissi	Transmissi	0.006187			
		3 WA	Manufactu	0.000326 WA	Manufactu	Manufactu	0.001227 AU	AU	Mining of i	0.000206 CN	Distributio	Distributio	0.00383			
		4 CN	Other non	0.000316 KR	Re-proces	Re-proces	0.000802 BR	BR	Mining of i	0.00011 CN	Productio	Productio	0.003493			
		5 KR	Re-proces	0.000206 WM	Manufactu	Manufactu	0.000552 CN	CN	Other land	9.71E-05 CN	Mining of i	Mining of i	0.000784			
		6 WM	Manufactu	0.000152 WA	Manufactu	Manufactu	0.000552 WM	WM	Mining of i	3.11E-05 CN	Financial ir	Financial ir	0.000656			
		7 WA	Manufactu	0.000142 CN	Extraction	Extraction	0.000492 WF	WF	Mining of i	2.71E-05 CN	Productio	Productio	0.000603			
		8 WF	Manufactu	0.000121 WF	Manufactu	Manufactu	0.000464 JP	JP	Manufactu	2.57E-05 CN	Manufactu	Manufactu	0.000458			
		9 WL	Manufactu	0.000108 CN	Other non	Other non	0.000427 CN	CN	Manufactu	2.36E-05 CN	Other busi	Other busi	0.000435			
		10 TR	Manufactu	9.25E-05 WL	Manufactu	Manufactu	0.000393 CN	CN	Chemicals	2.29E-05 CN	Wholesale	Wholesale	0.000341			
2017		1 CN	Vanadium	0.015786 CN	Vanadium	Vanadium	0.016039 CN	CN	Vanadium	0.015786 CN	Vanadium	Vanadium	0.016039			
		2 CN	Iron and st	0.00088 CN	Iron and st	Iron and st	0.001599 CN	CN	Transmissi	0.004024 CN	Transmissi	Transmissi	0.004369			
		3 CN	Other non	0.000424 WA	Manufactu	Manufactu	0.000652 AU	AU	Mining of i	0.000156 CN	Distributio	Distributio	0.002694			
		4 WA	Manufactu	0.000393 CN	Other non	Other non	0.000584 BR	BR	Mining of i	0.00011 CN	Productio	Productio	0.002582			
		5 KR	Re-proces	0.000242 KR	Re-proces	Re-proces	0.000437 CN	CN	Other land	6.92E-05 CN	Financial ir	Financial ir	0.000556			
		6 WL	Manufactu	0.000205 CN	Manufactu	Manufactu	0.000348 JP	JP	Manufactu	3.41E-05 CN	Manufactu	Manufactu	0.000424			
		7 WM	Manufactu	0.000197 WA	Manufactu	Manufactu	0.000329 JP	JP	Manufactu	3.12E-05 CN	Other busi	Other busi	0.000382			
		8 WA	Manufactu	0.000186 WL	Manufactu	Manufactu	0.000318 WM	WM	Mining of i	2.64E-05 CN	Productio	Productio	0.000342			
		9 WF	Manufactu	0.000172 WM	Manufactu	Manufactu	0.000306 AU	AU	Mining of i	2.61E-05 CN	Petroleum	Petroleum	0.000206			
		10 BE	Re-proces	0.00012 WF	Manufactu	Manufactu	0.000283 DE	DE	Manufactu	2.45E-05 CN	Wholesale	Wholesale	0.000198			
2018		1 CN	Vanadium	0.011745 CN	Vanadium	Vanadium	0.011885 CN	CN	Vanadium	0.011745 CN	Vanadium	Vanadium	0.011885			
		2 CN	Iron and st	0.002144 CN	Iron and st	Iron and st	0.003093 CN	CN	Transmissi	0.001268 CN	Transmissi	Transmissi	0.00141			
		3 CN	Other non	0.001205 CN	Other non	Other non	0.001591 AU	AU	Mining of i	5.58E-05 CN	Distributio	Distributio	0.000679			
		4 WA	Manufactu	0.000974 WA	Manufactu	Manufactu	0.001532 BR	BR	Mining of i	3.26E-05 CN	Productio	Productio	0.000676			
		5 WA	Manufactu	0.000462 CN	Manufactu	Manufactu	0.00093 CN	CN	Other land	2.21E-05 CN	Financial ir	Financial ir	0.000143			
		6 KR	Re-proces	0.00045 KR	Re-proces	Re-proces	0.000779 CN	CN	Manufactu	6.9E-06 CN	Productio	Productio	0.000133			
		7 WF	Manufactu	0.000422 WA	Manufactu	Manufactu	0.00075 WM	WM	Mining of i	6.7E-06 CN	Mining of i	Mining of i	0.000125			
		8 WM	Manufactu	0.000403 CN	Manufactu	Manufactu	0.000689 JP	JP	Manufactu	5.61E-06 CN	Other busi	Other busi	9.97E-05			
		9 WL	Manufactu	0.000387 CN	Manufactu	Manufactu	0.000688 AU	AU	Mining of i	5.12E-06 CN	Manufactu	Manufactu	9.46E-05			
		10 WA	Manufactu	0.000262 WF	Manufactu	Manufactu	0.000666 CN	CN	Chemicals	4.97E-06 CN	Retail trade	Retail trade	8.52E-05			
2019		1 CN	Vanadium	0.01224 CN	Vanadium	Vanadium	0.012392 CN	CN	Vanadium	0.01224 CN	Vanadium	Vanadium	0.012392			
		2 CN	Iron and st	0.001556 CN	Iron and st	Iron and st	0.002276 CN	CN	Transmissi	0.002309 CN	Transmissi	Transmissi	0.002495			
		3 CN	Other non	0.00087 CN	Other non	Other non	0.001177 AU	AU	Mining of i	0.001046 CN	Productio	Productio	0.001521			
		4 WA	Manufactu	0.000381 WA	Manufactu	Manufactu	0.0007 BR	BR	Mining of i	0.00066 CN	Distributio	Distributio	0.001489			
		5 KR	Re-proces	0.000191 CN	Manufactu	Manufactu	0.000657 AU	AU	Mining of i	0.000125 AU	Mining of i	Mining of i	0.001076			
		6 WA	Manufactu	0.000186 CN	Manufactu	Manufactu	0.000476 JP	JP	Manufactu	0.000125 BR	Mining of i	Mining of i	0.000711			
		7 WF	Manufactu	0.000185 CN	Manufactu	Manufactu	0.000465 WM	WM	Mining of i	0.000118 CN	Mining of i	Mining of i	0.000506			
		8 WL	Manufactu	0.000166 CN	Manufactu	Manufactu	0.000405 JP	JP	Manufactu	0.000112 JP	Manufactu	Manufactu	0.000293			
		9 WM	Manufactu	0.000144 KR	Re-proces	Re-proces	0.000387 DE	DE	Manufactu	8.99E-05 CN	Financial ir	Financial ir	0.000283			
		10 WF	Manufactu	0.000102 WA	Manufactu	Manufactu	0.00037 KR	KR	Manufactu	6.52E-05 AU	Mining of i	Mining of i	0.000218			
2020		1 CN	Vanadium	0.011853 CN	Vanadium	Vanadium	0.011995 CN	CN	Vanadium	0.011853 CN	Vanadium	Vanadium	0.011995			
		2 CN	Iron and st	0.000969 CN	Iron and st	Iron and st	0.001393 AU	AU	Mining of i	0.004981 AU	Mining of i	Mining of i	0.005107			
		3 CN	Other non	0.000272 WA	Manufactu	Manufactu	0.00045 CN	CN	Transmissi	0.00346 CN	Transmissi	Transmissi	0.003839			
		4 WA	Manufactu	0.000234 CN	Manufactu	Manufactu	0.000405 BR	BR	Mining of i	0.003083 BR	Mining of i	Mining of i	0.003312			
		5 WF	Manufactu	0.000112 CN	Other non	Other non	0.000393 WM	WM	Mining of i	0.000572 CN	Productio	Productio	0.00179			
		6 WA	Manufactu	0.00011 CN	Manufactu	Manufactu	0.000304 JP	JP	Manufactu	0.000489 CN	Distributio	Distributio	0.001731			
		7 KR	Re-proces	0.000105 CN	Manufactu	Manufactu	0.000301 AU	AU	Mining of i	0.000465 JP	Manufactu	Manufactu	0.001231			
		8 WL	Manufactu	9.96E-05 CN	Manufactu	Manufactu	0.000267 JP	JP	Manufactu	0.000314 AU	Constructio	Constructio	0.000703			
		9 WM	Manufactu	8.85E-05 CN	Casting of	Casting of	0.000243 WF	WF	Mining of i	0.000302 AU	Mining of i	Mining of i	0.000688			
		10 CN	Chemicals	6.11E-05 WA	Manufactu	Manufactu	0.000228 AU	AU	Mining of i	0.000257 WM	Mining of i	Mining of i	0.000626			
2021		1 CN	Vanadium	0.015818 CN	Vanadium	Vanadium	0.016072 CN	CN	Vanadium	0.015818 CN	Vanadium	Vanadium	0.016072			
		2 CN	Iron and st	0.000889 CN	Iron and st	Iron and st	0.001285 CN	CN	Transmissi	0.00394 CN	Transmissi	Transmissi	0.004388			
		3 WA	Manufactu	0.000253 WA	Manufactu	Manufactu	0.000462 AU	AU	Mining of i	0.001566 CN	Distributio	Distributio	0.002099			
		4 CN	Other non	0.000246 CN	Manufactu	Manufactu	0.000377 BR	BR	Mining of i	0.001056 CN	Productio	Productio	0.002078			
		5 WA	Manufactu	0.000123 CN	Other non	Other non	0.00036 WM	WM	Mining of i	0.000197 AU	Mining of i	Mining of i	0.001617			
		6 WL	Manufactu	9.84E-05 CN	Manufactu	Manufactu	0.000281 JP	JP	Manufactu	0.000164 BR	Mining of i	Mining of i	0.00114			
		7 WF	Manufactu	9.74E-05 CN	Manufactu	Manufactu	0.00028 AU	AU	Mining of i	0.00016 JP	Manufactu	Manufactu	0.000492			
		8 WM	Manufactu	8.84E-05 CN	Manufactu	Manufactu	0.000249 JP	JP	Manufactu	0.000105 CN	Financial ir	Financial ir	0.000458			
		9 CN	Chemicals	6.56E-05 WA	Manufactu	Manufactu	0.000239 WF	WF	Mining of i	9.43E-05 CN	Productio	Productio	0.000403			
		10 WA	Casting of	6.22E-05 CN	Casting of	Casting of	0.000227 WA	WA	Mining of i	9.03E-05 CN	Mining of i	Mining of i	0.000398			
2022		1 CN	Vanadium	0.014413 CN	Vanadium	Vanadium	0.014625 CN	CN	Vanadium	0.014413 CN	Vanadium	Vanadium	0.014625			
		2 CN	Iron and st	0.001175 CN	Iron and st	Iron and st	0.001879 CN	CN	Transmissi	0.003278 CN	Transmissi	Transmissi	0.003573			
		3 CN	Other non	0.000367 WA	Manufactu	Manufactu	0.000614 AU	AU	Mining of i	0.000945 CN	Distributio	Distributio	0.002268			
		4 WA	Manufactu	0.000335 CN	Other non	Other non	0.000565 BR	BR	Mining of i	0.000624 CN	Productio	Productio	0.002055			
		5 WA	Manufactu	0.000161 CN	Manufactu	Manufactu	0.000479 AU	AU	Mining of i	0.000136 AU	Mining of i	Mining of i	0.000976			
		6 WF	Manufactu	0.000143 CN	Manufactu	Manufactu	0.000354 JP	JP	Manufactu	0.000124 BR	Mining of i	Mining of i	0.000682			
		7 WL	Manufactu	0.000143 CN	Manufactu	Manufactu	0.000323 WM	WM	Mining of i	0.000117 CN	Financial ir	Financial ir	0.000442			
		8 WM	Manufactu	0.000121 WA	Manufactu	Manufactu	0.000317 WA	WA	Mining of i	6.63E-05 CN	Manufactu	Manufactu	0.000397			
		9 KR	Manufactu	8.47E-05 CN	Manufactu	Manufactu	0.000302 WA	WA	Mining of i	5.84E-05 JP	Manufactu	Manufactu	0.000359			
		10 KR	Re-proces	8.11E-05 CN	Casting of	Casting of	0.000294 AU	AU	Mining of i	5.81E-05 CN	Other busi	Other busi	0.000314			

Spatial Correlation Index

Year	Rank	Region	Industry	Value
2015	1	WA	Manufactu	0.005377
	2	WM	Constructi	0.004253
	3	KR	Manufactu	0.004188
	4	WA	Manufactu	0.003171
	5	WA	Constructi	0.002819
	6	WA	Manufactu	0.002625
	7	WL	Constructi	0.0026
	8	WA	Manufactu	0.00189
	9	IN	Constructi	0.001841
	10	WL	Manufactu	0.001712
2016	1	WA	Manufactu	0.015213
	2	WA	Constructi	0.014779
	3	WM	Constructi	0.008168
	4	WA	Manufactu	0.006851
	5	WA	Manufactu	0.006768
	6	KR	Re-proces	0.006406
	7	WA	Manufactu	0.004835
	8	KR	Manufactu	0.004177
	9	WM	Manufactu	0.003813
	10	WF	Constructi	0.003801
2017	1	WA	Constructi	0.00624
	2	WA	Manufactu	0.005666
	3	WM	Constructi	0.00327
	4	WA	Manufactu	0.002867
	5	KR	Constructi	0.00278
	6	WA	Manufactu	0.002601
	7	WL	Constructi	0.002461
	8	KR	Re-proces	0.002367
	9	WA	Manufactu	0.002158
	10	WF	Constructi	0.002002
2018	1	WA	Manufactu	0.00467
	2	WA	Manufactu	0.002363
	3	WM	Constructi	0.002082
	4	WA	Manufactu	0.001983
	5	WA	Constructi	0.001905
	6	KR	Re-proces	0.001521
	7	WF	Constructi	0.001521
	8	WA	Manufactu	0.001476
	9	KR	Constructi	0.00143
	10	JP	Manufactu	0.001389
2019	1	WA	Constructi	0.000975
	2	WA	Manufactu	0.000998
	3	WM	Constructi	0.001033
	4	WA	Manufactu	0.001099
	5	WA	Manufactu	0.001222
	6	WA	Manufactu	0.001529
	7	WF	Constructi	0.001629
	8	KR	Constructi	0.001921
	9	JP	Manufactu	0.00324
	10	KR	Re-proces	0.003479
2020	1	WA	Constructi	0.003479
	2	AU	Mining of i	0.003068
	3	WA	Manufactu	0.002769
	4	BR	Mining of i	0.002091
	5	WA	Manufactu	0.001415
	6	WM	Constructi	0.001408
	7	WA	Manufactu	0.001281
	8	WF	Constructi	0.000917
	9	KR	Constructi	0.000853
	10	JP	Manufactu	0.00079
2021	1	WA	Manufactu	0.003347
	2	KR	Manufactu	0.001818
	3	WA	Manufactu	0.001812
	4	WA	Manufactu	0.001577
	5	WM	Constructi	0.00148
	6	WA	Manufactu	0.001311
	7	WA	Constructi	0.001311
	8	JP	Manufactu	0.000971
	9	AU	Mining of i	0.000966
	10	WF	Constructi	0.00092
2022	1	WA	Manufactu	0.00411
	2	WA	Constructi	0.003861
	3	KR	Manufactu	0.002326
	4	WA	Manufactu	0.001943
	5	WA	Manufactu	0.001897
	6	WM	Constructi	0.001869
	7	WA	Manufactu	0.001445
	8	JP	Manufactu	0.001182
	9	WF	Constructi	0.001175
	10	WA	Manufactu	0.001052

Countries and regions		
AT		Austria
BE		Belgium
BG		Bulgaria
CY		Cyprus
CZ		Czech Republic
DE		Czechoslovakia
DK		Denmark
EE		Estonia
ES		Spain
FI		Finland
FR		France
GR		Greece
HR		Croatia
HU		Hungary
IE		Ireland
IT		Italy
LT		Lithuania
LU		Luxembourg
LV		Latvia
MT		Malta
NL		Netherlands
PL		Poland
PT		Portugal
RO		Romania
SE		Sweden
SI		Slovenia
SK		Slovakia
GB		United Kingdom
US		United States of America
JP		Japan
CN		China
CA		Canada
KR		South Korea
BR		Brazil
IN		India
MX		Mexico
RU		Russia
AU		Australia
CH		Switzerland
TR		Turkey
TW		Taiwan
NO		Norway
ID		Indonesia
ZA		South Africa
WA		Other Asia & Pacific
WL		Other Americas
WE		Other Europe
WF		Other Africa
WM		Other Middle East

Scenario analysis

Final demand constraint:

$$Q_{\{5,t\}} = D_t \quad (s1)$$

where D_t is the final demand in year t.

Production balance (No Rec):

$$Q_{\{1,t\}} = \{D_t\} / \{y_{\{12\}} \cdot y_{\{23\}} \cdot y_{\{34\}}\} \quad (s2)$$

where $Q_{\{1,t\}}$ is input from stage 1 (mining), $y_{\{ij\}}$ is yield (conversion efficiency) from stage $i \rightarrow j$.

Production balance (With Rec):

$$Q_{\{1,t\}} = \{D_t - y_{\{52\}} \cdot Q_{\{5,t-1\}}\} / \{y_{\{12\}} \cdot y_{\{23\}} \cdot y_{\{34\}}\} \quad (s3)$$

Carbon emissions:

$$C_t = e_1 Q_{\{1,t\}} + e_2 Q_{\{2,t\}} + e_3 Q_{\{3,t\}} + e_4 Q_{\{4,t\}} + e_5 Q_{\{5,t\}} \quad (s4)$$

where e_i is the carbon intensity of stage i.

Profit:

$$\Pi_t = p \cdot D_t - (c_1 Q_{\{1,t\}} + c_2 Q_{\{2,t\}} + c_3 Q_{\{3,t\}} + c_4 Q_{\{4,t\}} + c_5 Q_{\{5,t\}}) \quad (s5)$$

where p is the unit price of the final product, and c_i is the cost per unit in stage i.

Delivery time (average lead time):

$$T_t = \{\tau_{\{12\}} Q_{\{1,t\}} + \tau_{\{23\}} Q_{\{2,t\}} + \tau_{\{34\}} Q_{\{3,t\}} + \tau_{\{45\}} Q_{\{4,t\}} + \tau_{\{52\}} Q_{\{5,t\}}\} / \{D_t\} \quad (s6)$$

where $\tau_{\{ij\}}$ is the average processing/transportation delay from stage $i \rightarrow j$.

Based on the following results, the comparative analysis of the No Recycling

(No Rec) and With Recycling (With Rec) scenarios (2015-2022) reveals consistent advantages of incorporating recycling. The With Rec scenario reduces primary ore demand by approximately 4-5% and lowers carbon emissions by 2-3%, mainly due to decreased reliance on energy-intensive mining and processing. In addition, profitability improves by around 3-4%, and production lead times are marginally shortened. These outcomes demonstrate that recycling generates measurable environmental and economic benefits across the vanadium supply chain.

Excluding recycling systematically overestimates resource consumption, emissions, and costs in the China's vanadium industry. Incorporating recycling provides a more accurate and comprehensive representation of system dynamics, highlighting its role in resource conservation, emission reduction, and economic resilience. Therefore, recycling should be regarded as a core element of vanadium industry modeling, ensuring scientifically valid and policy-relevant insights for sustainable development.

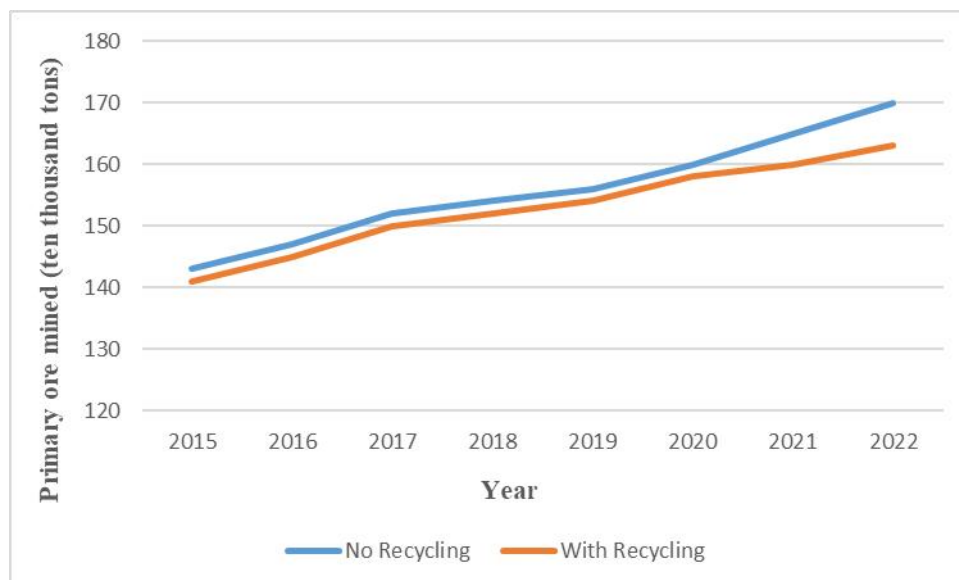


Fig. S6. Primary ore requirement under recycling and non-recycling scenarios (2015-2022)

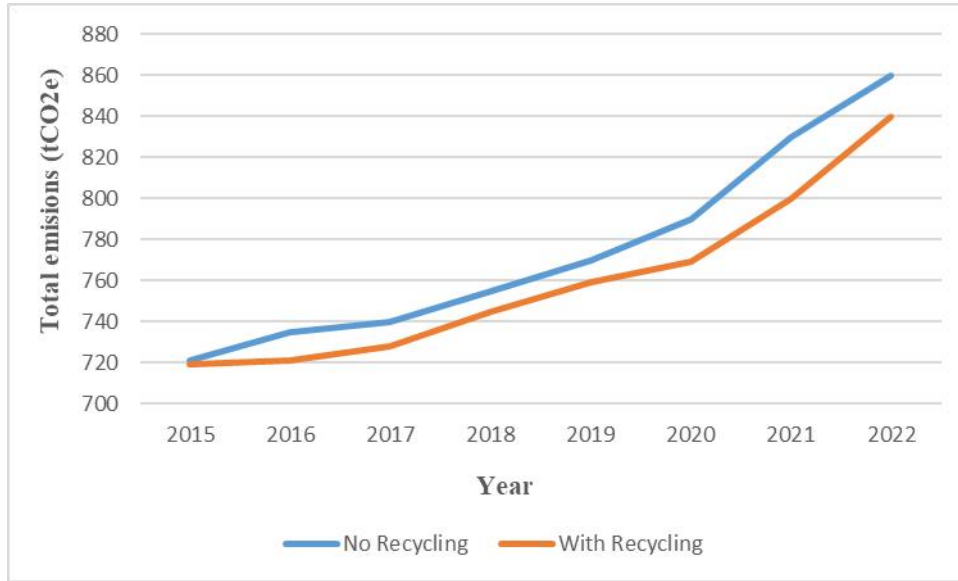


Fig. S7. Total Emissions under recycling and non-recycling scenarios (2015-2022)

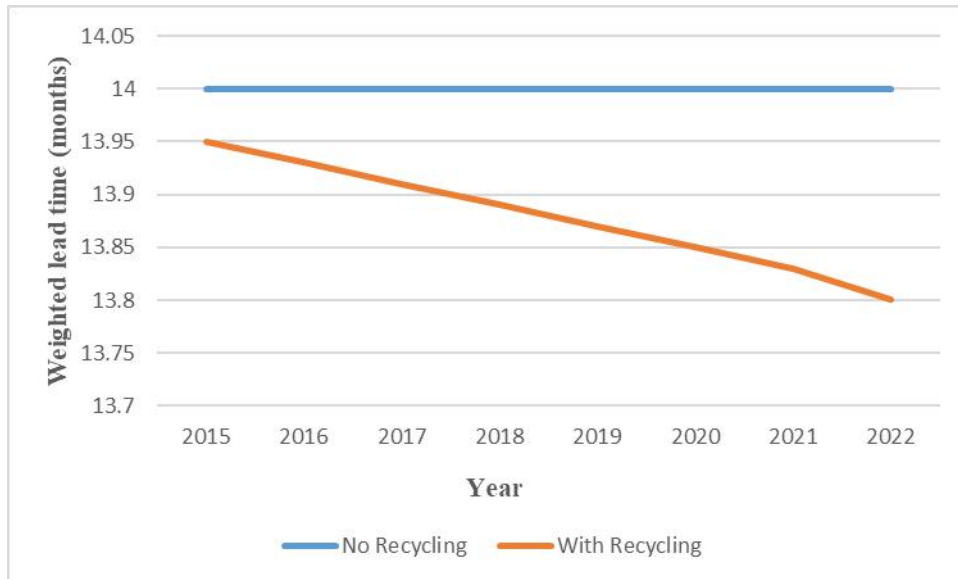


Fig. S8. Supply lead time under recycling and non-recycling scenarios (2015-2022)

Uncertainty Analysis

Methods

To ensure the robustness of the nested input-output (IO) model, a probabilistic uncertainty analysis was conducted. Key parameters subject to variability include the technical coefficients of the A matrix, final demand vectors, recycling participation rates (r_t), stage-specific yields (y_{ij}), carbon intensities (e_i), and cost factors (c_i). Probability distributions were assigned to each parameter based on empirical data, literature sources, and expert judgment. Specifically, Beta distributions were adopted

for rate-type parameters (e.g., recycling rates), lognormal distributions for strictly positive parameters (e.g., costs and emission intensities), and triangular distributions for parameters with limited data availability.

Sampling was performed using Latin Hypercube Sampling (LHS) with 5,000 iterations to efficiently explore the uncertainty space. For each sample, the Leontief inverse $(I - A)^{-1}$ was recalculated, the nested IO model (including the recycling feedback loop) was solved, and outcome variables were recorded: primary ore demand, cumulative carbon emissions, total production cost, and system profitability.

To further assess the contribution of parameter uncertainty, a variance-based global sensitivity analysis (Sobol indices) was conducted. This method decomposes the variance of each output into first-order and total effects attributable to individual parameters, providing insights into both direct and interaction effects.

Uncertainty Outcomes

To ensure the robustness of the nested input-output (IO) framework, we implemented a probabilistic uncertainty analysis. Key parameters subject to variability included the technical coefficients of the A matrix, final demand vectors, recycling participation rates (r_t), stage-specific yields (y_{ij}), carbon intensities (e_i), and cost factors (c_i). Probability distributions were assigned to each parameter following their characteristics: Beta distributions for rate-type parameters (e.g., recycling rates), lognormal distributions for strictly positive parameters (e.g., costs and emission intensities), and triangular distributions for parameters with limited empirical evidence. Sampling was conducted using Latin Hypercube Sampling (LHS) with 5,000 iterations, and for each draw the Leontief inverse $(I - A)^{-1}$ was recalculated, the nested IO model (including the recycling feedback loop) was solved, and outcome variables were recorded, namely: primary ore demand, cumulative carbon emissions, total production cost, and system profitability.

The results show that the extended IO model including the vanadium sector and its recycling stage consistently produces narrower uncertainty bands and greater alignment with observed industrial statistics compared with the baseline IO model

without the vanadium sector. In particular, excluding the vanadium sector leads to systematic underestimation of system profitability and output (3-7%) and overestimation of carbon emissions (5-7%), reflecting structural bias. By contrast, inclusion of the vanadium sector allows the model to capture resource feedback loops, yielding more stable estimates and a scientifically rigorous representation of closed-loop production.

To further attribute variability, a variance-based global sensitivity analysis (Sobol indices) was conducted. The analysis revealed that recycling participation rates (r_t) and carbon intensities (e_i) dominate the variance contribution in output indicators, underscoring the centrality of explicitly modeling the vanadium recycling stage. The absence of this stage not only reduces explanatory power but also overlooks critical parameter interactions that shape the system's environmental and economic performance.

In conclusion, the findings confirm that explicitly incorporating the vanadium sector-particularly the recycling stage-into IO models is both scientifically justified and practically indispensable. Models omitting this sector yield biased and unstable results, whereas those including it better capture resource efficiency, carbon reduction, and profitability dynamics. This validates the scientific rationale for treating the vanadium sector as an essential structural component of IO-based sustainability assessments, reinforcing the importance of closed-loop modeling approaches for strategic and critical minerals.