

Supplementary information

Title:

Energy policy could curb Europe's overconsumption of critical material supply

Authors:

Jonathan N. Peel^{1,4}, Aysha Cotterill^{1,4}, Cyril Chelle-Michou³, Anthony Patt¹ & Tim Tröndle¹

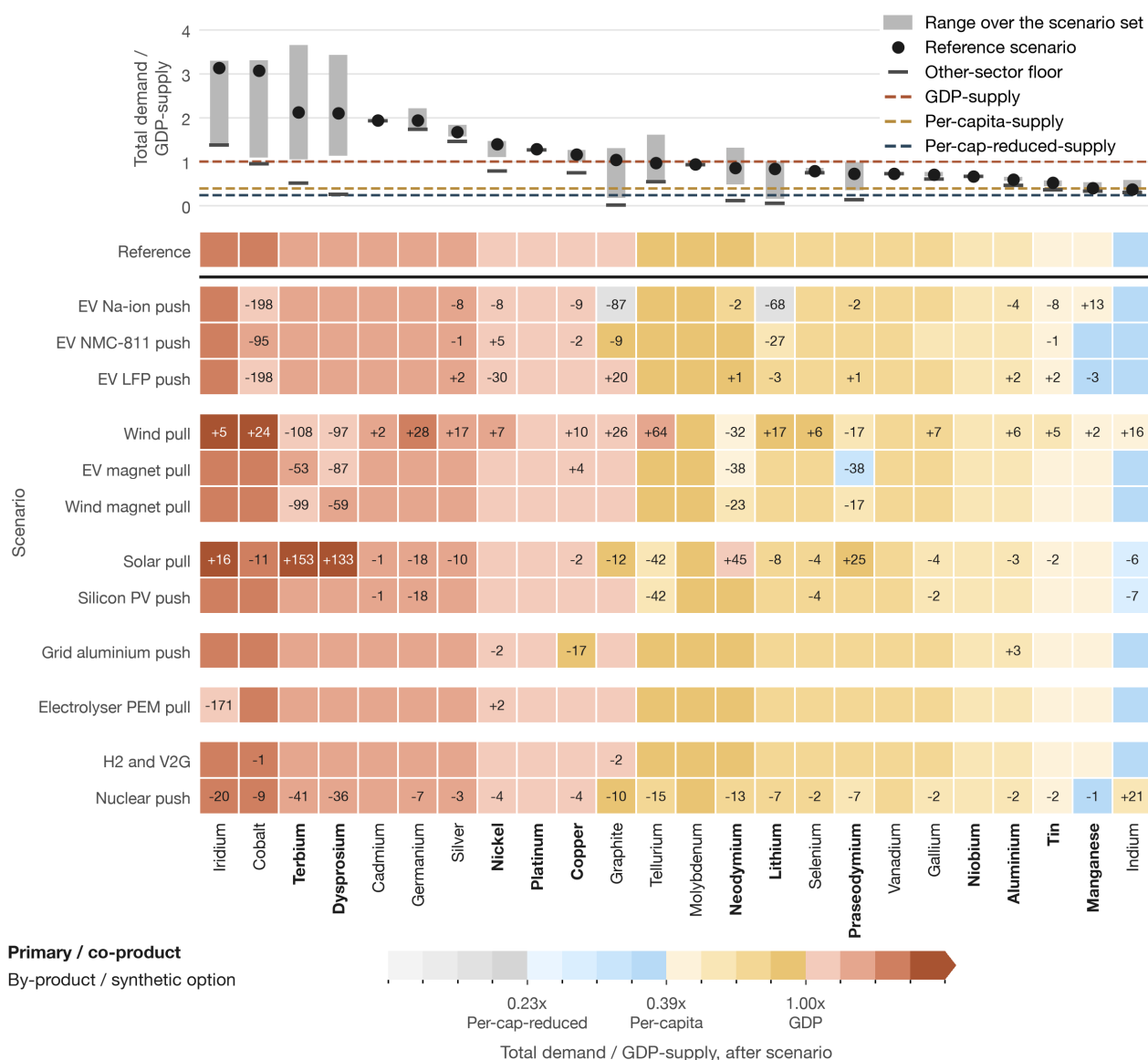
¹Institute of Environmental Decisions, ETH Zurich, Zurich, Switzerland.

³Institute for Geochemistry and Petrology, ETH Zurich, Zurich, Switzerland

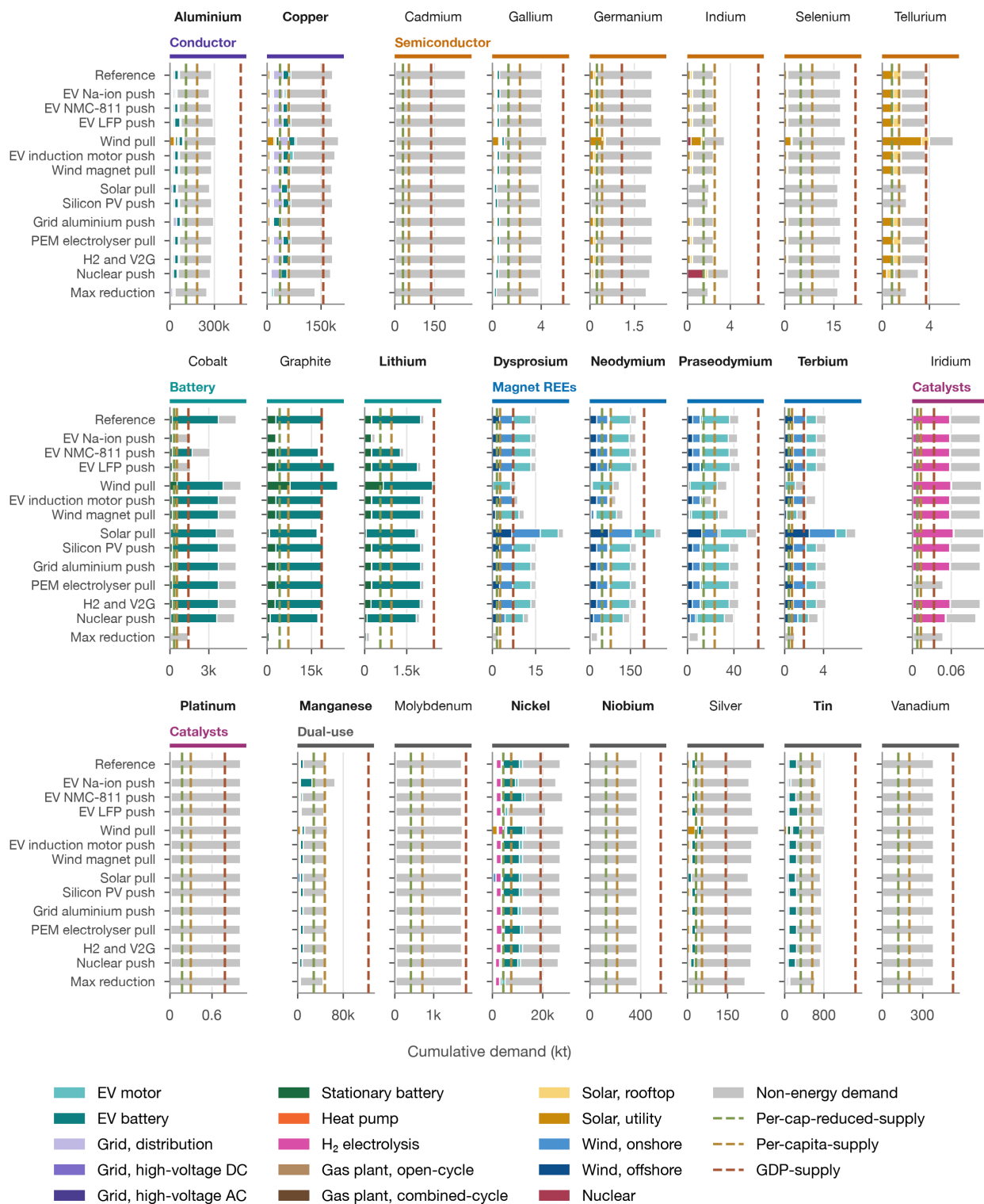
⁴These authors contributed equally: Jonathan N. Peel, Aysha Cotterill

email: jopeel@ethz.ch

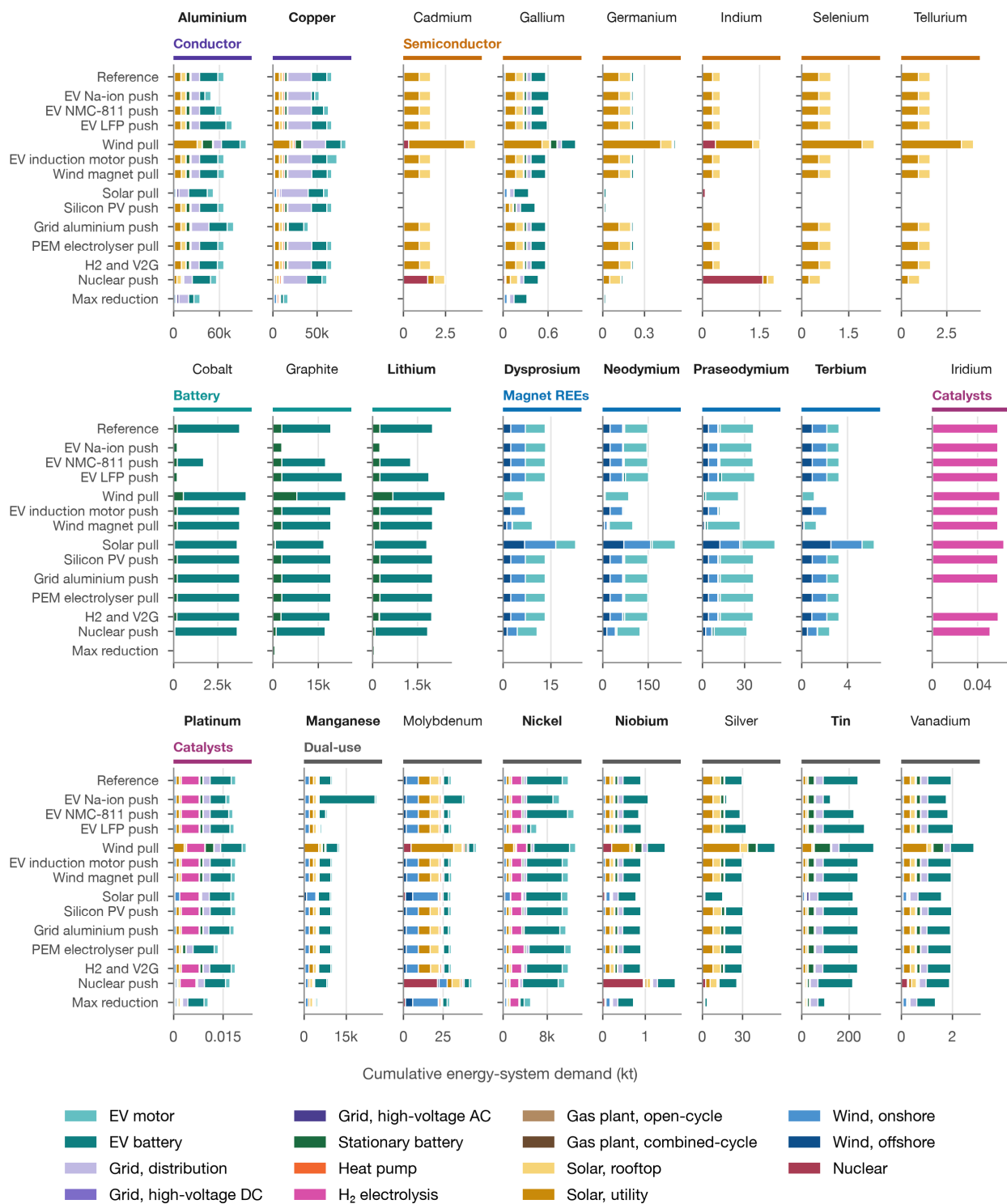
1 Additional results



Supplementary Fig. 1 | The effect of each scenario on the total demand of each critical material. Above the matrix, for each material, we show the relative demand (i.e., the demand from the energy system divided by GDP-supply). We display the value of this fraction for the reference scenario as a point and the range across scenarios as a grey band. The matrix itself has a row for each scenario and a column for each material. Each cell of the matrix is coloured to again show the relative demand after a scenario is applied. The number in each cell displays by how many percentage points the relative demand changes as a result of each scenario. To isolate the effect of each lever, we combine each system scenario with the reference market share and each market-share scenario with the reference system. This figure includes both energy system demand and non-energy demand; see Fig. 2 from the main manuscript for the equivalent figure excluding non-energy demand. Typeface indicates supply elasticity: primary materials / co-products (more inelastic) versus by-products / synthetic option (more elastic). Graphite refers to battery-grade graphite. EV, electric vehicle; Na-ion, sodium-ion; NMC, nickel manganese cobalt; LFP, lithium iron phosphate; PEM, proton-exchange membrane; H2, hydrogen; V2G, vehicle-to-grid.



Supplementary Fig. 2 | Full exploration of each scenario's material demand across all sectors.



Supplementary Fig. 3 | Full exploration of each scenario's *material* demand across all sectors, excluding non-energy demand.

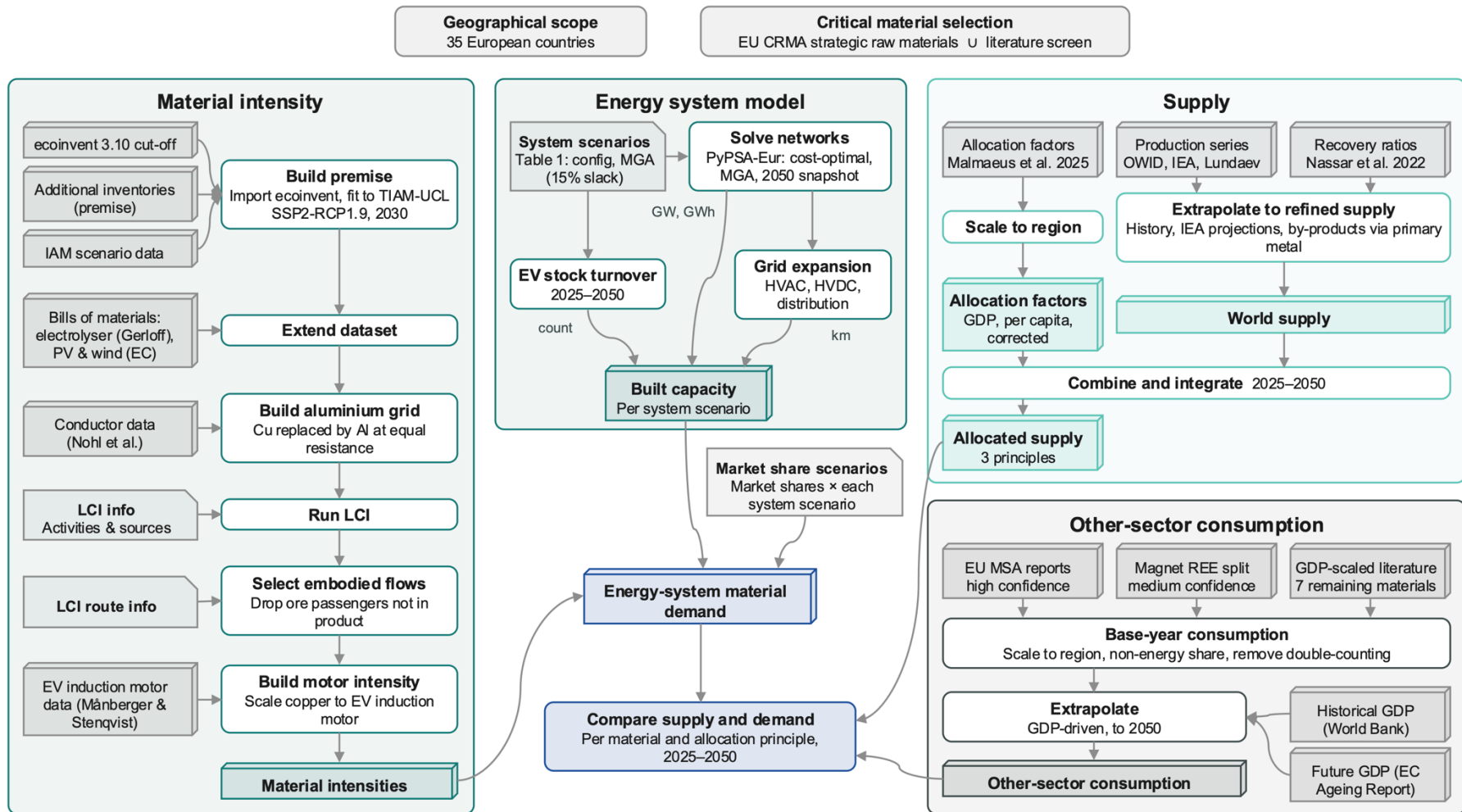
Supplementary Table 1 | Configurations of the maximum demand reduction scenario for each material.

Materials	System lever	Substitution levers	No. levers	Energy demand, base (kt)	Energy demand, single (kt)	Energy demand, combined (kt)	Best single scenario	Combined reduction (%)	Single reduction (%)	Additional reduction (%)
Aluminium	Solar pull	EV Na-ion push	2	66261	48837	34771	EV Na-ion push	47.5	26.3	21.2
Cadmium	Reference	Silicon PV push	1	1.62	0.0340	0.0340	Silicon PV push	97.9	97.9	0.0
Cobalt	Solar pull	EV Na-ion push	2	3098	213	56.4	EV Na-ion push	98.2	93.1	5.1
Copper	Solar pull	EV Na-ion push; Wind magnet pull; Grid aluminium push	4	65875	39308	15752	Grid aluminium push	76.1	40.3	35.8
Dysprosium	Wind pull	EV magnet pull	2	13.3	6.34	0.0690	Wind pull	99.5	52.4	47.1
Gallium	Solar pull	EV NMC-811 push	2	0.562	0.337	0.315	Solar pull	44.0	40.1	3.9
Germanium	Solar pull	EV Na-ion push	2	0.221	0.0221	0.0198	Solar pull	91.0	90.0	1.0
Graphite	Solar pull	EV Na-ion push	2	19137	2901	718	EV Na-ion push	96.2	84.8	11.4
Indium	Reference	Silicon PV push	1	0.484	0.0205	0.0205	Silicon PV push	95.8	95.8	0.0
Iridium	Reference	Electrolyser PEM pull	1	0.0586	0.00122	0.00122	Electrolyser PEM pull	97.9	97.9	0.0
Lithium	Solar pull	EV Na-ion push	2	1945	250	61.9	EV Na-ion push	96.8	87.2	9.7
Manganese	Nuclear push	EV LFP push	2	9347	6215	4756	EV LFP push	49.1	33.5	15.6
Molybdenum	Solar pull	EV NMC-811 push; Wind magnet pull;	4	30.0	29.6	28.3	Solar pull	5.7	1.4	4.3

Materials	System lever	Substitution levers	No. levers	Energy demand, base (kt)	Energy demand, single (kt)	Energy demand, combined (kt)	Best single scenario	Combined reduction (%)	Single reduction (%)	Additional reduction (%)
		Grid aluminium push								
Neodymium	Wind pull	EV Na-ion push; EV magnet pull	3	149	72.2	5.07	EV magnet pull	96.6	51.5	45.1
Nickel	Nuclear push	EV LFP push; Grid aluminium push	3	11822	6116	4957	EV LFP push	58.1	48.3	9.8
Niobium	Solar pull	EV NMC-811 push; Grid aluminium push	3	0.889	0.775	0.726	Solar pull	18.3	12.8	5.5
Platinum	Nuclear push	EV Na-ion push; Grid aluminium push; Electrolyser PEM pull	4	0.0185	0.0134	0.0104	Electrolyser PEM pull	43.9	27.8	16.1
Praseodymium	Nuclear push	EV Na-ion push; EV magnet pull; Wind magnet pull	4	36.1	12.8	0.945	EV magnet pull	97.4	64.6	32.8
Selenium	Solar pull	—	1	0.931	0.00304	0.00304	Solar pull	99.7	99.7	0.0
Silver	Solar pull	EV Na-ion push	2	29.7	15.2	3.69	Solar pull	87.6	48.9	38.7
Tellurium	Solar pull	—	1	1.61	0.0228	0.0228	Solar pull	98.6	98.6	0.0
Terbium	Wind pull	EV magnet pull	2	3.26	1.09	0.0199	Wind pull	99.4	66.5	32.9
Tin	Nuclear push	EV Na-ion push	2	240	123	100	EV Na-ion push	58.4	48.7	9.7

Materials	System lever	Substitution levers	No. levers	Energy demand, base (kt)	Energy demand, single (kt)	Energy demand, combined (kt)	Best single scenario	Combined reduction (%)	Single reduction (%)	Additional reduction (%)
Vanadium	Solar pull	EV Na-ion push; Grid aluminium push	3	1.94	1.56	1.34	Solar pull	31.2	19.9	11.3

2 Methods



Supplementary Fig. 4 | Overview of methodology.

2.1 Geographical scope

Our study's geographical scope is the default scope of PyPSA-Eur: 25 of the 27 EU member states (Austria, Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden) and nine non-member states (Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia, Norway, Serbia, Switzerland and the United Kingdom). Cyprus and Malta are not included. This is visualised in Supplementary Fig. 5.



Supplementary Fig. 5 | Countries that are included in the study region.

2.2 Material selection

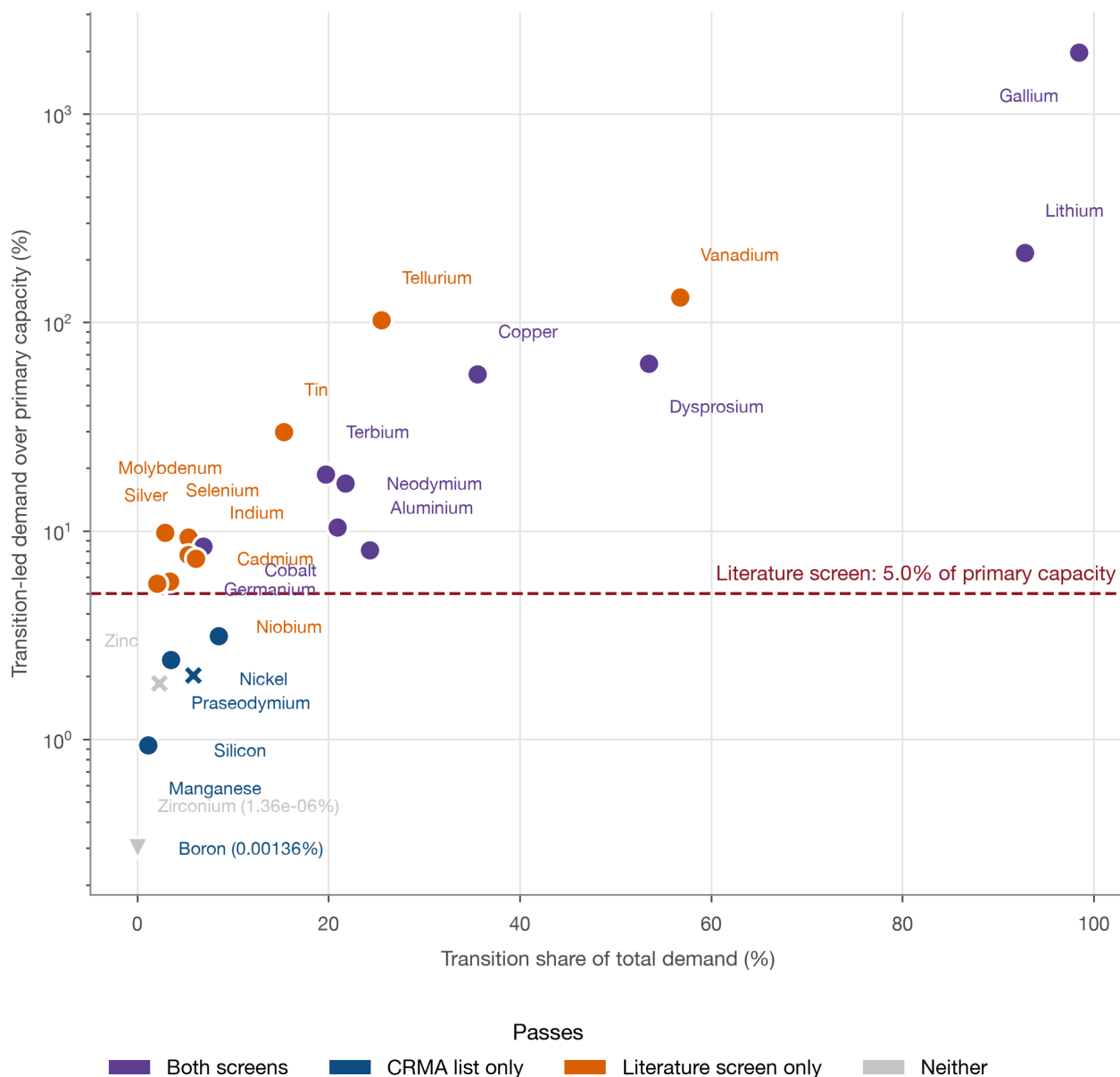
We choose materials based on a combination of a policy screen based on the EU's strategic materials list (Annex I) ¹³ and a literature screen, based on materials suffering from global overconsumption according to the literature ¹. Supplementary Table 2 shows the values we used in the literature screen, and Supplementary Table 3 lists all the materials included in our study with each screen and justification. Supplementary Fig. 6 visualises both screens. We chose 5% for the literature screen threshold as this is robust towards lower thresholds.

Supplementary Fig. 7 shows the sensitivity of the final material list to the literature screen threshold.

Supplementary Table 2 | Literature screen. Values for each *material*, extracted from Bieuville et al. ¹ for the literature screen.

Materials	Total demand (t)	Other-sector demand (t)	Transition demand (t)	Primary capacity (t)	Demand / capacity	Transition share
Gallium	9.26e+4	1,440	9.11e+4	4,630	19.7	0.984
Lithium	1.04e+6	7.55e+4	9.68e+5	4.49e+5	2.16	0.928

Materials	Total demand (t)	Other-sector demand (t)	Transition demand (t)	Primary capacity (t)	Demand / capacity	Transition share
Vanadium	8.29e+5	3.59e+5	4.71e+5	3.56e+5	1.32	0.568
Tellurium	1,930	1,430	492	480	1.03	0.255
Dysprosium	6,170	2,870	3,300	5,200	0.635	0.535
Copper	3.42e+7	2.20e+7	1.22e+7	2.15e+7	0.566	0.356
Tin	3.33e+5	2.82e+5	5.10e+4	1.71e+5	0.298	0.153
Terbium	1,140	917	225	1,210	0.187	0.197
Neodymium	1.32e+5	1.04e+5	2.88e+4	1.71e+5	0.169	0.218
Cobalt	2.76e+5	2.18e+5	5.77e+4	5.54e+5	0.104	0.209
Selenium	2.09e+4	2.03e+4	612	6,240	0.0980	0.0293
Silver	8.30e+4	7.85e+4	4,440	4.78e+4	0.0928	0.0535
Germanium	1,080	1,000	74.4	882	0.0843	0.0691
Aluminium	1.17e+8	8.85e+7	2.84e+7	3.51e+8	0.0809	0.243
Indium	2,860	2,710	153	2,000	0.0766	0.0535
Cadmium	9,560	8,970	586	7,960	0.0736	0.0613
Molybdenum	9.54e+5	9.21e+5	3.27e+4	5.71e+5	0.0572	0.0342
Niobium	2.13e+5	2.09e+5	4,420	7.93e+4	0.0557	0.0207
Nickel	3.29e+6	3.01e+6	2.81e+5	8.96e+6	0.0313	0.0852
Praseodymium	3.25e+4	3.14e+4	1,140	4.74e+4	0.0240	0.0350
Silicon	1.05e+7	9.84e+6	6.14e+5	3.02e+7	0.0203	0.0587
Iron	2.35e+9	2.19e+9	1.53e+8	7.63e+9	0.0200	0.0651
Zinc	2.84e+7	2.78e+7	6.49e+5	3.49e+7	0.0186	0.0228
Manganese	6.28e+7	6.21e+7	7.08e+5	7.57e+7	0.00935	0.0113
Chromium	1.14e+8	1.12e+8	1.51e+6	2.39e+8	0.00634	0.0133
Lead	1.02e+7	1.01e+7	2.68e+4	4.93e+6	0.00544	0.00264
Boron	1.18e+7	1.18e+7	201	1.48e+7	1.36e-5	1.70e-5
Hafnium	252	252	0.00100	603	1.66e-6	3.98e-6
Yttrium	1.96e+4	1.96e+4	0.00200	2.18e+4	9.17e-8	1.02e-7
Zirconium	1.94e+6	1.94e+6	0.0621	4.58e+6	1.36e-8	3.20e-8
Tungsten	1.04e+6	1.04e+6	0.0100	7.39e+5	1.36e-8	9.64e-9
Tantalum	4,790	4,790	0	1.31e+4	0	0



Supplementary Fig. 6 | Visualisation of literature and policy screens; axes are plotted using data from the literature.

Supplementary Table 3 | Final material selection and screens passed.

Materials	Screen passed	CRMA designation	Demand / primary capacity	Transition share of demand	Tracked	End-use group	Category
Gallium	both	strategic	19.685	0.984	Yes	Semiconductor	By-product
Lithium	both	strategic	2.155	0.928	Yes	Battery	Primary
Vanadium	literature	—	1.322	0.568	Yes	Bulk/dual-use	By-product
Tellurium	literature	—	1.026	0.255	Yes	Semiconductor	By-product
Dysprosium	both	strategic	0.635	0.535	Yes	Magnet REEs	Co-product
Copper	both	strategic	0.566	0.356	Yes	Grid/conductor	Primary
Tin	literature	—	0.298	0.153	Yes	Contacts/solder	Primary

Terbium	both	strategic	0.187	0.197	Yes	Magnet REEs	Co-product
Neodymium	both	strategic	0.169	0.218	Yes	Magnet REEs	Co-product
Cobalt	both	strategic	0.104	0.209	Yes	Battery	By-product
Selenium	literature	—	0.098	0.029	Yes	Semiconductor	By-product
Silver	literature	—	0.093	0.054	Yes	Contacts/solder	By-product
Germanium	both	strategic	0.084	0.069	Yes	Semiconductor	By-product
Aluminium	both	strategic	0.081	0.243	Yes	Grid/conductor	Primary
Indium	literature	—	0.077	0.054	Yes	Semiconductor	By-product
Cadmium	literature	—	0.074	0.061	Yes	Semiconductor	By-product
Molybdenum	literature	—	0.057	0.034	Yes	Bulk/dual-use	By-product
Niobium	literature	—	0.056	0.021	Yes	Bulk/dual-use	Primary
Nickel	policy	strategic	0.031	0.085	Yes	Bulk/dual-use	Primary
Praseodymium	policy	strategic	0.024	0.035	Yes	Magnet REEs	Co-product
Silicon	policy	strategic	0.020	0.059	No	—	—
Manganese	policy	strategic	0.009	0.011	Yes	Bulk/dual-use	Primary
Boron	policy	strategic	0.000	0.000	No	—	—
Graphite	policy	strategic	—	—	Yes	Battery	Synthetic option
Iridium	policy	strategic	—	—	Yes	H2/PGM catalysts	By-product
Platinum	policy	strategic	—	—	Yes	H2/PGM catalysts	Primary
Zinc	neither	—	0.019	0.023	No	Helper	—
Chromium	neither	—	0.006	0.013	No	—	—
Palladium	neither	—	—	—	No	—	—



Supplementary Fig. 7 | Sensitivity of literature screen threshold. The chosen threshold, 5%, is robust towards lower thresholds, but at higher percentages, cadmium, molybdenum, selenium, silver, and indium no longer pass this screen.

2.3 Technologies and sub-technologies

Supplementary Table 4 shows the sub-technologies for each technology in the reference scenario and Supplementary Table 5 summarises the source of each current market share.

Supplementary Table 4 | Technologies and sub-technologies, with their reference market shares.

Technology	Sub-technology	Current market share	Functional unit	Strategic materials
Nuclear	Nuclear, PWR	100.0%	MW	Aluminium, Copper, Manganese, Nickel
Wind, offshore	Wind, GB-DFIG	5.0%	MW	Aluminium, Copper, Dysprosium, Manganese, Molybdenum, Neodymium, Nickel
	Wind, GB-PMSG	30.0%	MW	Aluminium, Copper, Dysprosium, Manganese, Molybdenum, Neodymium, Nickel, Praseodymium, Terbium
	Wind, DD-PMSG	65.0%	MW	Aluminium, Copper, Dysprosium, Manganese, Molybdenum, Neodymium, Nickel, Praseodymium, Terbium
	Wind, DD-EESG	0.0%	MW	Aluminium, Copper, Dysprosium, Manganese, Molybdenum, Neodymium, Nickel, Praseodymium, Terbium
Wind, onshore	Wind, GB-DFIG	70.0%	MW	Aluminium, Copper, Dysprosium, Manganese, Molybdenum, Neodymium, Nickel

	Wind, GB-PMSG	5.0%	MW	Aluminium, Copper, Dysprosium, Manganese, Molybdenum, Neodymium, Nickel, Praseodymium, Terbium
	Wind, DD-PMSG	20.0%	MW	Aluminium, Copper, Dysprosium, Manganese, Molybdenum, Neodymium, Nickel, Praseodymium, Terbium
	Wind, DD-EESG	5.0%	MW	Aluminium, Copper, Dysprosium, Manganese, Molybdenum, Neodymium, Nickel, Praseodymium, Terbium
Solar, utility	PV, c-Si	95.4%	MW	Aluminium, Copper, Silver
	PV, CdTe	2.4%	MW	Aluminium, Cadmium, Copper, Tellurium
	PV, CIGS	1.9%	MW	Aluminium, Copper, Gallium, Indium, Selenium
	PV, a-Si	0.3%	MW	Aluminium, Copper, Germanium
Solar, rooftop	PV, c-Si	95.4%	MW	Aluminium, Copper, Silver
	PV, CdTe	2.4%	MW	Aluminium, Cadmium, Copper, Tellurium
	PV, CIGS	1.9%	MW	Aluminium, Copper, Gallium, Indium, Selenium
	PV, a-Si	0.3%	MW	Aluminium, Copper, Germanium
Gas plant, combined-cycle	Gas power plant, CC	100.0%	MW	Aluminium, Copper, Manganese, Nickel
Gas plant, open-cycle	Gas power plant, OC	100.0%	MW	Aluminium, Copper, Manganese, Nickel
H ₂ electrolysis	H2 Electrolyzer, AEC	75.0%	MW	Aluminium, Copper, Manganese, Nickel, Silver
	H2 Electrolyzer, PEM	22.0%	MW	Aluminium, Copper, Iridium, Manganese, Nickel, Platinum
	H2 Electrolyzer, SOEC	3.0%	MW	Aluminium, Copper, Manganese, Nickel, Praseodymium
Heat pump	Heat pump	100.0%	MW	Aluminium, Copper, Manganese, Nickel
Stationary battery	Battery, NMC111, stationary	10.0%	MWh	Aluminium, Cobalt, Copper, Graphite, Lithium, Manganese, Nickel, Tin
	Battery, NMC532, stationary	10.0%	MWh	Aluminium, Cobalt, Copper, Graphite, Lithium, Manganese, Nickel, Tin
	Battery, LFP, stationary	80.0%	MWh	Aluminium, Copper, Graphite, Lithium, Nickel, Tin
Grid, high-voltage AC	Grid line, HV AC	100.0%	km	Aluminium, Copper, Manganese, Nickel, Tin
	Grid line, HV AC (Al)	0.0%	km	Aluminium, Manganese, Nickel, Tin
Grid, high-voltage DC	Grid cable, HVDC subsea	30.0%	km	Copper, Manganese, Nickel
	Grid cable, HVDC land	70.0%	km	Aluminium, Copper, Manganese, Nickel
	Grid cable, HVDC subsea (Al)	0.0%	km	Aluminium, Manganese, Nickel
	Grid cable, HVDC land (Al)	0.0%	km	Aluminium, Manganese, Nickel
Grid, distribution	Grid line, HV AC	8.0%	km	Aluminium, Copper, Manganese, Nickel, Tin
	Grid line, MV	23.0%	km	Aluminium, Copper, Nickel

	Grid line, LV	69.0%	km	Copper, Nickel
	Grid line, HV AC (Al)	0.0%	km	Aluminium, Manganese, Nickel, Tin
	Grid line, MV (Al)	0.0%	km	Aluminium, Nickel
	Grid line, LV (Al)	0.0%	km	Aluminium
EV battery	Battery, NMC111	3.0%	MWh	Aluminium, Cobalt, Copper, Graphite, Lithium, Manganese, Nickel, Tin
	Battery, NMC532	8.4%	MWh	Aluminium, Cobalt, Copper, Graphite, Lithium, Manganese, Nickel, Tin
	Battery, NMC622	35.0%	MWh	Aluminium, Cobalt, Copper, Graphite, Lithium, Manganese, Nickel, Tin
	Battery, NMC811	17.5%	MWh	Aluminium, Cobalt, Copper, Graphite, Lithium, Manganese, Nickel, Tin
	Battery, LFP	12.8%	MWh	Aluminium, Copper, Graphite, Lithium, Tin
	Battery, NCA	23.3%	MWh	Aluminium, Cobalt, Copper, Graphite, Lithium, Nickel, Tin
	Battery, Na-ion	0.0%	MWh	Aluminium, Copper, Manganese, Nickel
EV motor	EV motor, PM	90.0%	unit	Aluminium, Copper, Dysprosium, Manganese, Neodymium, Nickel, Praseodymium, Terbium
	EV motor, induction	10.0%	unit	Aluminium

Shares are within the parent technology and sum to 1. Generators: GB = gearbox, DD = direct drive, DFIG = doubly fed induction generator, PMSG = permanent-magnet synchronous generator, EESG = electrically excited synchronous generator. PV absorbers: c-Si = crystalline silicon, CdTe = cadmium telluride, CIGS = copper indium gallium diselenide, a-Si = amorphous silicon. Battery cathodes: NMC XYZ = lithium nickel manganese cobalt oxide, X:Y:Z the molar Ni:Mn:Co ratio; NCA = lithium nickel cobalt aluminium oxide; LFP = lithium iron phosphate; Na-ion = sodium-ion. The anode is graphite in every case except Na-ion (hard carbon). Other: PWR = pressurised water reactor, AEC = alkaline electrolysis cell, PEM = proton exchange membrane electrolysis cell, SOEC = solid oxide electrolysis cell, CC/OC = combined-/open-cycle, PM = permanent magnet, HV/MV/LV = high/medium/low voltage, HVDC = high-voltage direct current, (Al) = aluminium-conductor variant.

Supplementary Table 5 | Sources for each sub-technology market share.

Technology	Source	Scope
EV battery	14	EU
Wind, onshore; wind, offshore	15	Global
Solar, utility; solar, rooftop	12	Global
Grid battery	15,16	Global
EV motor	15	Global
H2 electrolysis	17	Global
Nuclear	18	Simplifying assumption
Grid, high-voltage DC	Subsea and overland split derived directly from PyPSA network	Study region
Grid, distribution	Voltage level splits calculated from ecoinvent cable distances ¹⁹ . We verify this against the market shares across the whole of Europe, 3% HV, 37% MV, and 60% LV, which gives a kg Cu/km figure within 3% of the Switzerland figure ²⁰ .	Switzerland

Gas plants; heat pumps

Technologies either with inconsequential material demand or sub-technology options. These market shares are simplified to one sub-technology.

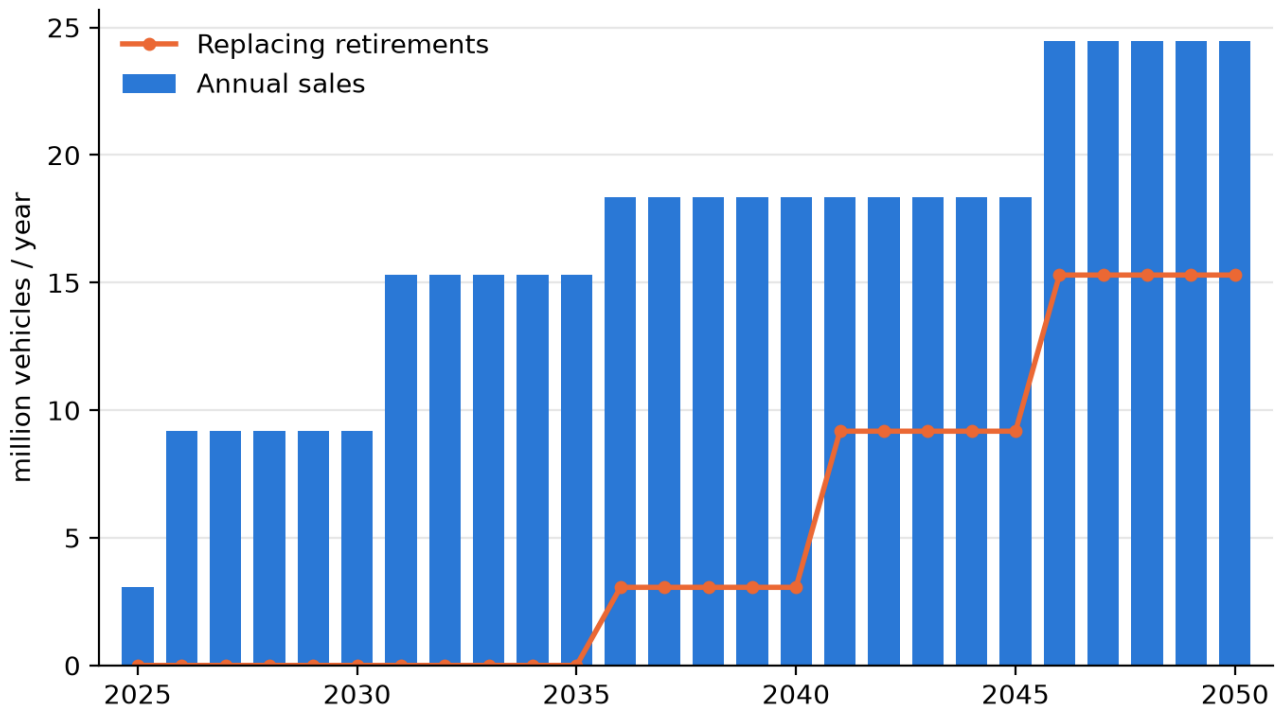
N/A



Supplementary Fig. 8 | Visualisation of market share scenarios.

2.4 Sector-coupled energy system modelling

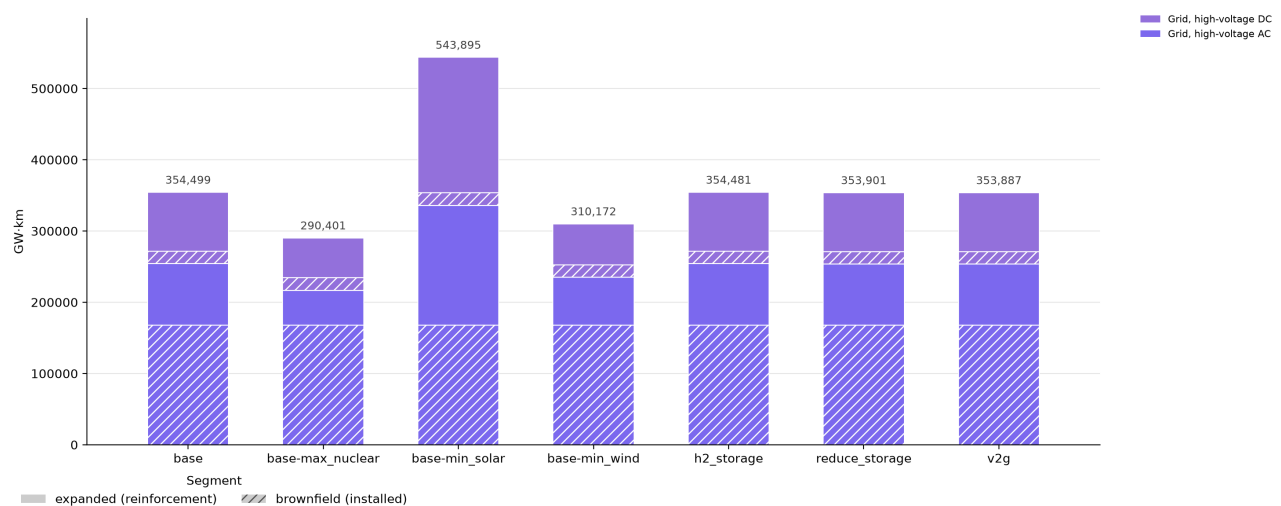
2.4.1 EV modelling



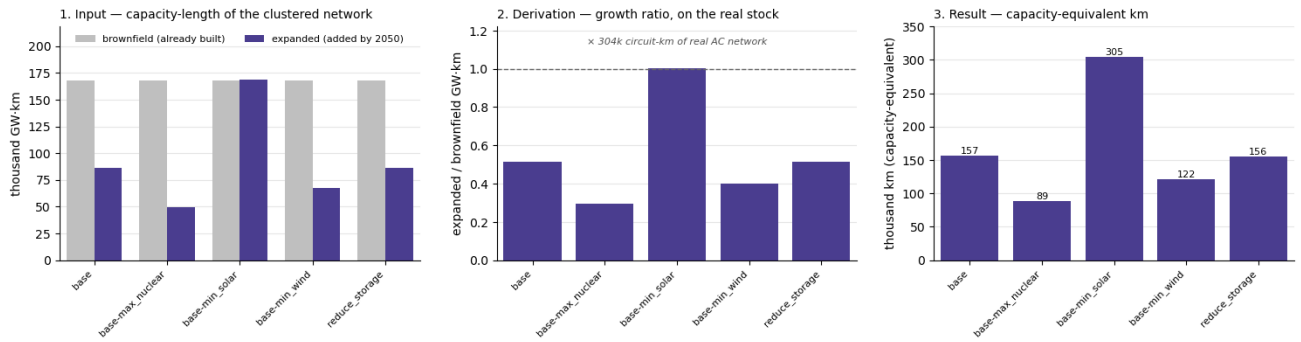
Supplementary Fig. 9 | Visualisation of forward recursive EV stock model for calculating total EV sales.

2.4.2 Grid modelling

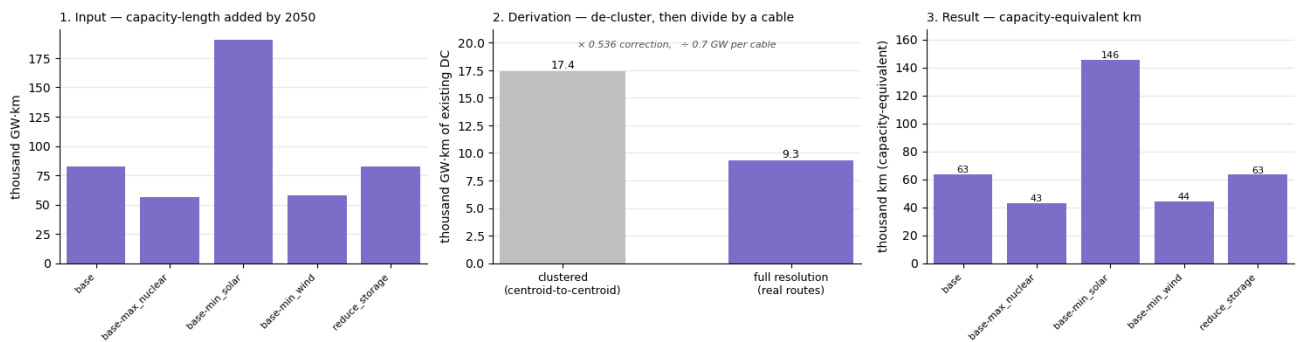
Supplementary Fig. 10 shows the final calculated circuit-length values of the high-voltage AC and DC electricity grids for each scenario. Supplementary Figs. 11–14 visualise the derivation of the circuit-length of the different parts of the electricity grid.



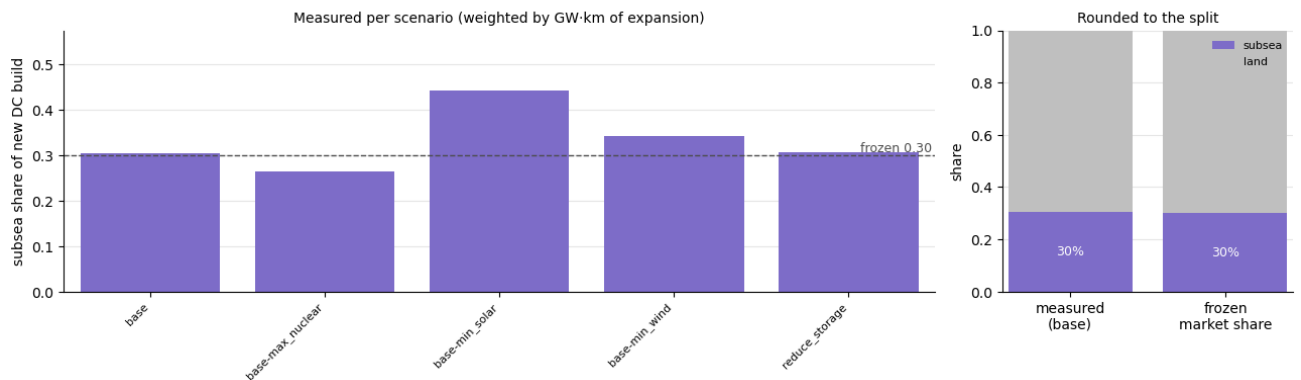
Supplementary Fig. 10 | Transmission grid circuit length for each scenario.



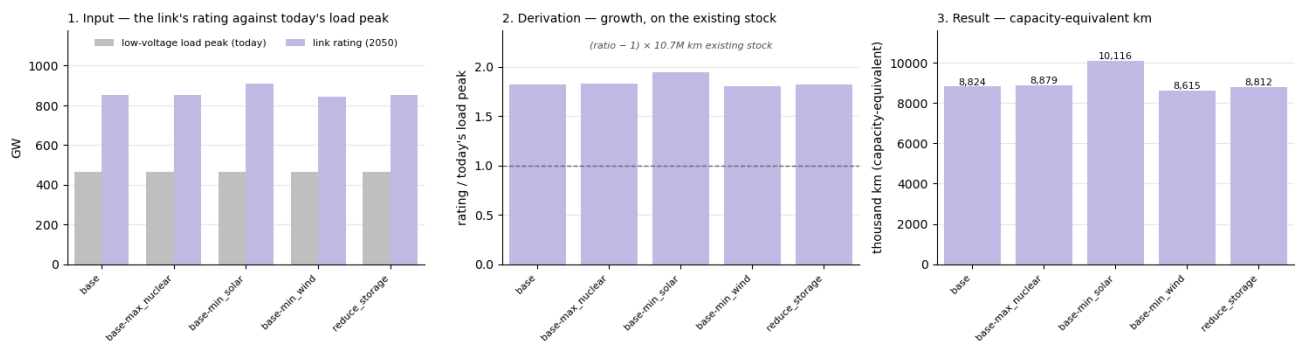
Supplementary Fig. 11 | High-voltage AC grid circuit-length derivation for each optimisation scenario.



Supplementary Fig. 12 | High-voltage DC grid circuit-length derivation for each optimisation scenario.

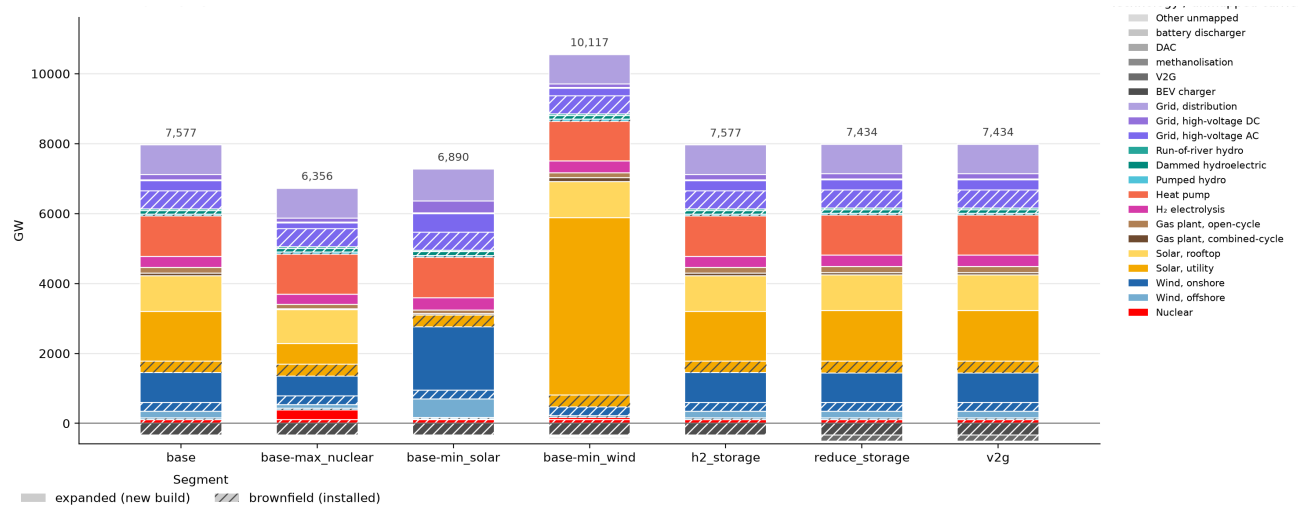


Supplementary Fig. 13 | High-voltage DC grid subsea-land split measured across optimisation scenarios (left), compared to the market shares assumed in the reference scenario (right).

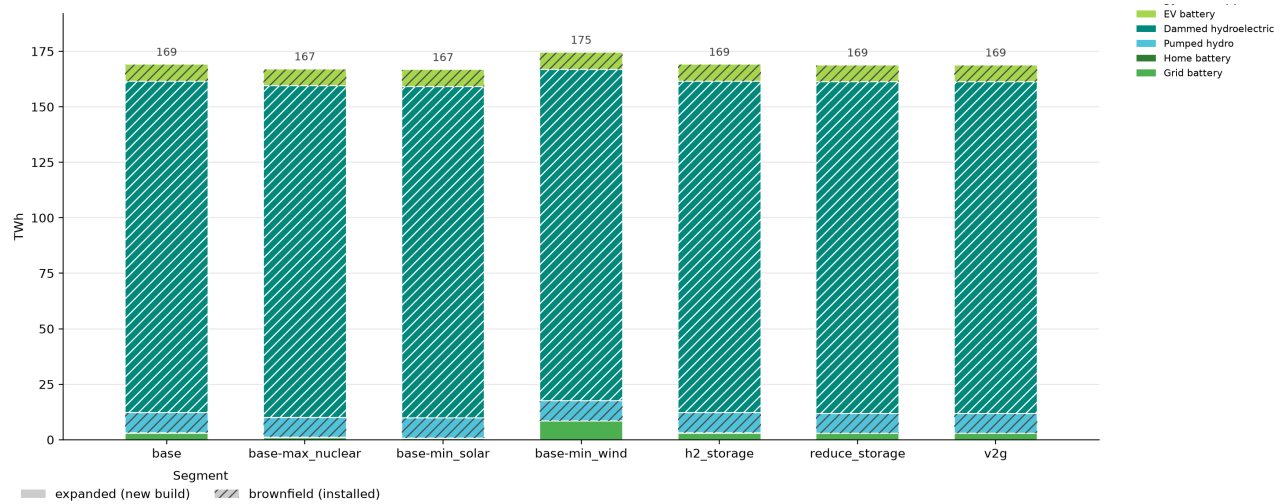


Supplementary Fig. 14 | Distribution grid circuit-length derivation for each optimisation scenario.

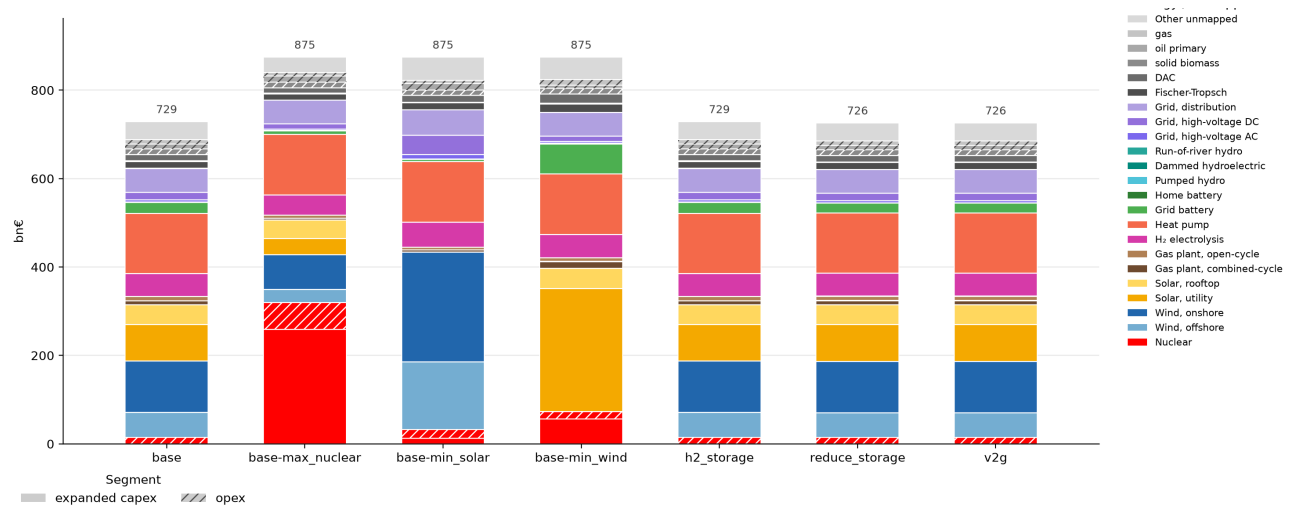
2.4.3 PyPSA-Eur networks



Supplementary Fig. 15 | Power capacities across each optimisation scenario from PyPSA-Eur.



Supplementary Fig. 16 | Storage energy capacities across each optimisation scenario from PyPSA-Eur.



Supplementary Fig. 17 | Total cost of all installed capacities across each optimisation scenario from PyPSA-Eur.

2.5 Life cycle inventories

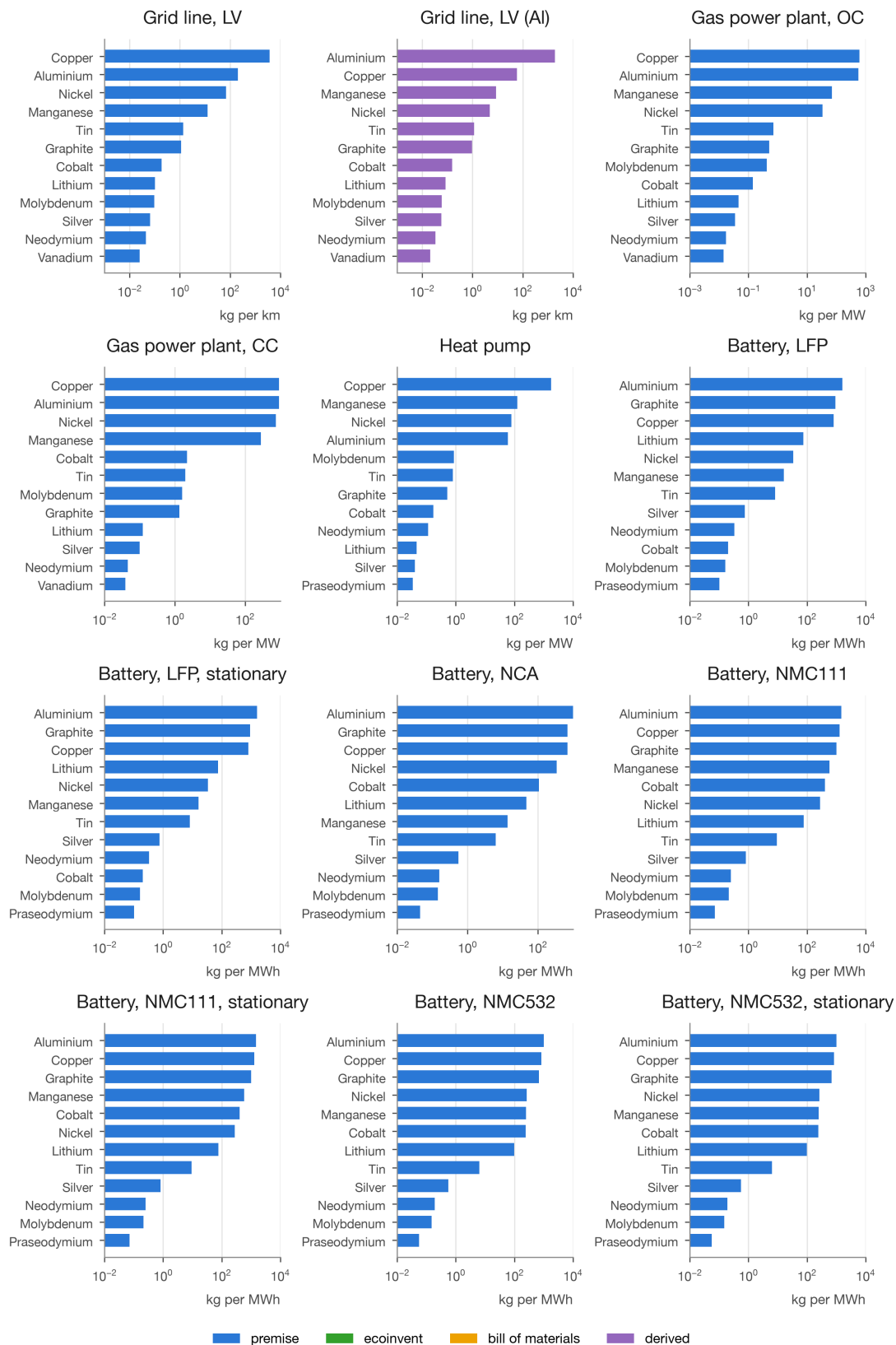
We find the life cycle inventories for the sub-technologies based on literature, life cycle assessment databases, and internal calculations, as described in Supplementary Table 6 and Supplementary Table 7.

Supplementary Table 6 | Documentation of which source supplies the material inventory of each sub-technology.

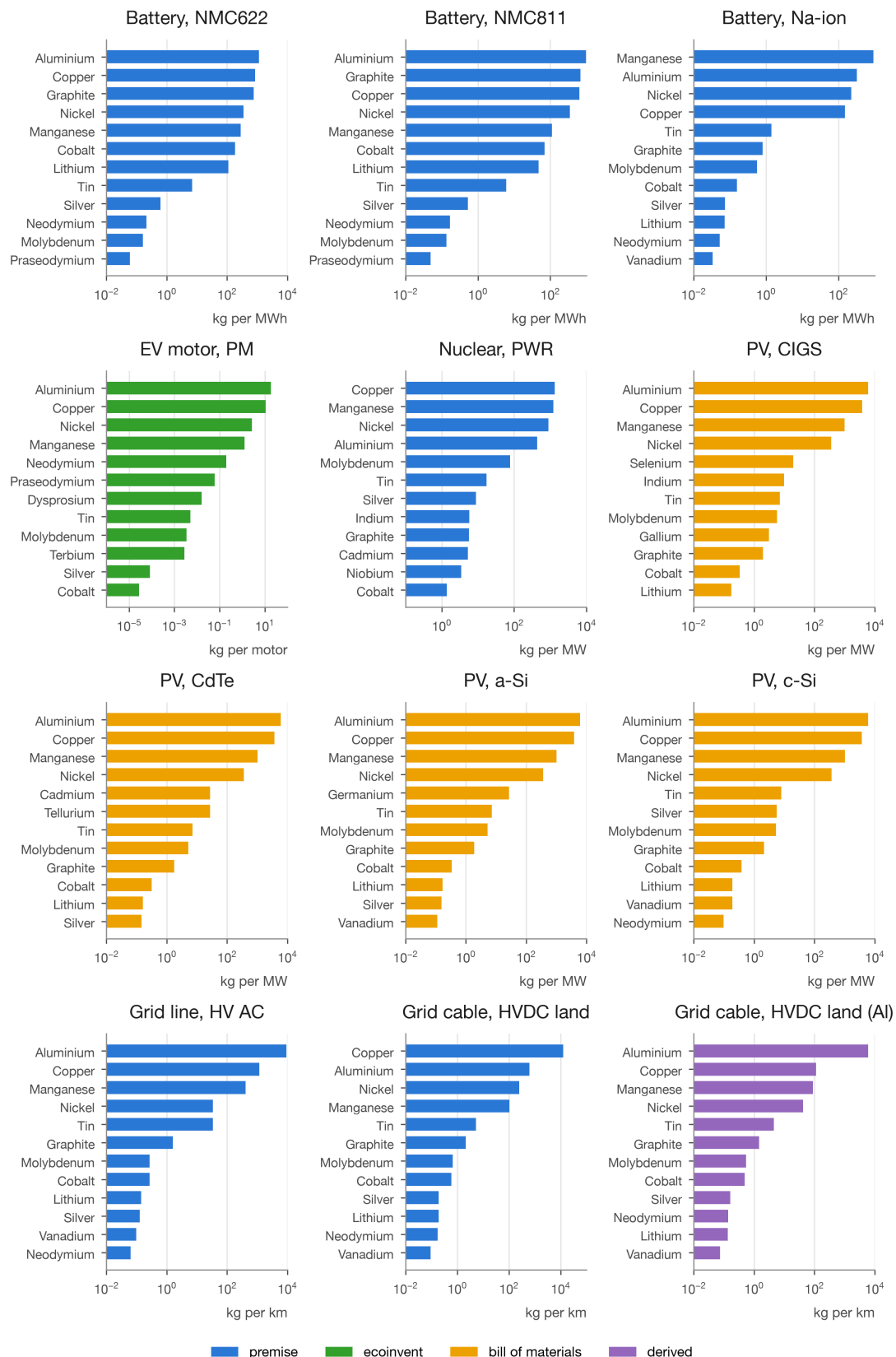
Source	Sub-technologies
premise 2.3.0 prospective database ^{21,22} ; ecoinvent 3.10, cut-off ^{19,23} , projected under the TIAM-UCL SSP2-RCP1.9 pathway for 2030	Gas power plant, CC · Gas power plant, OC · Nuclear, PWR · Heat pump · Battery, NMC111 · Battery, NMC532 · Battery, NMC622 · Battery, NMC811 · Battery, NCA · Battery, LFP · Battery, Na-ion · Battery, NMC111, stationary · Battery, NMC532, stationary · Battery, LFP, stationary · Grid line, HV AC · Grid line, MV · Grid line, LV · Grid cable, HVDC land · Grid cable, HVDC subsea
Bills of materials ¹² , each material purchased from the 2030 premise database	PV, c-Si · PV, CdTe · PV, CIGS · PV, a-Si · Wind, GB-DFIG · Wind, GB-PMSG · Wind, DD-PMSG · Wind, DD-EESG
Bills of materials ²⁴ , each material purchased from the 2030 premise database	H2 Electrolyzer, AEC · H2 Electrolyzer, PEM · H2 Electrolyzer, SOEC
Aluminium-conductor copies of the premise grid datasets, derived in this study (conductor pairing ²⁵ ; conductor shares ²⁶)	Grid line, HV AC (Al) · Grid line, MV (Al) · Grid line, LV (Al) · Grid cable, HVDC land (Al) · Grid cable, HVDC subsea (Al)
ecoinvent 3.10, cut-off ^{19,23} (not projected)	EV motor, PM
Derived from EV motor, PM ²⁷	EV motor, induction

Supplementary Table 7 | For each sub-technology, the years for which both the foreground and background inventories are built.

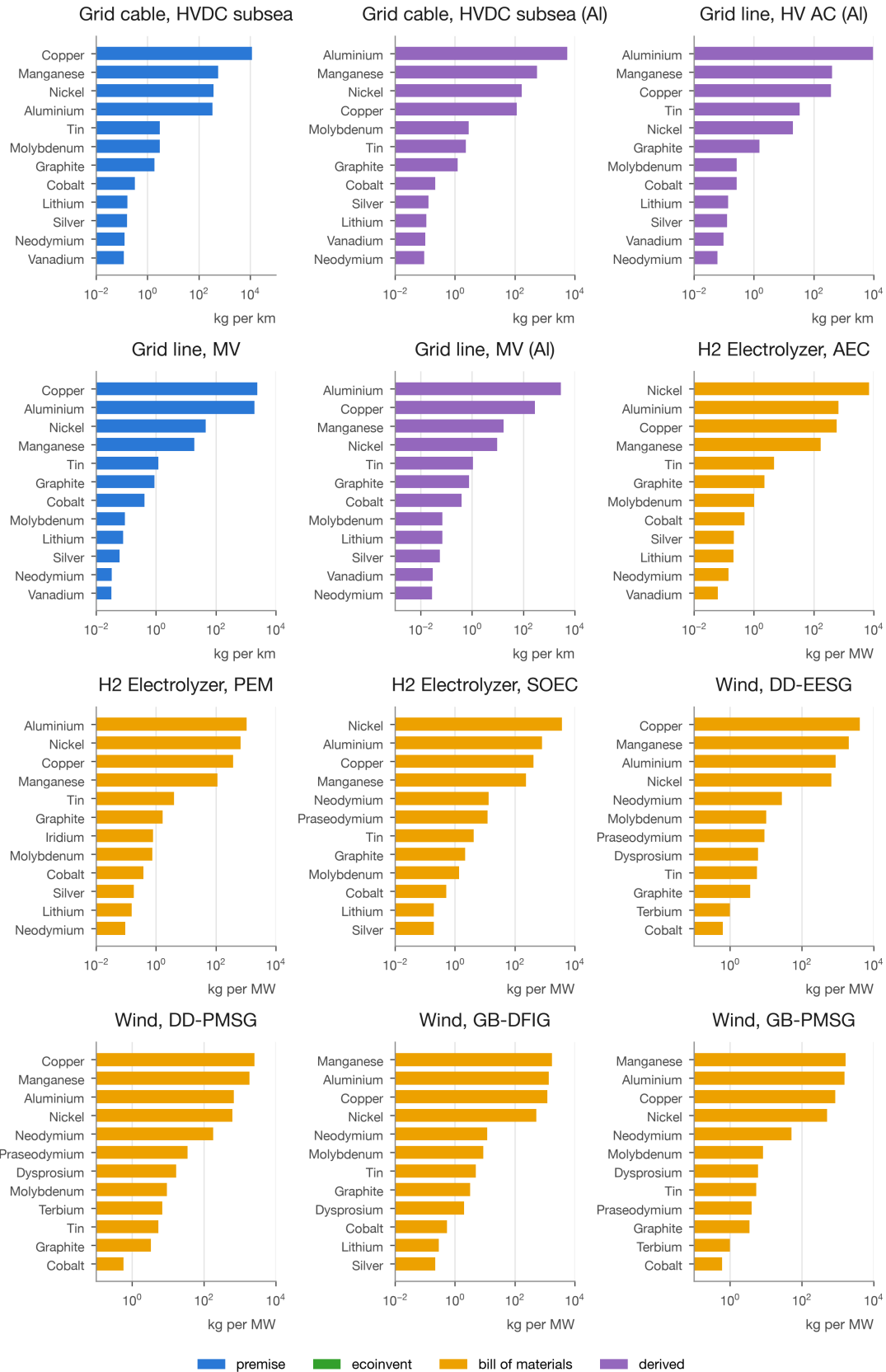
Sub-technologies	Foreground	Background
PV (bill of materials)	Carrara 2020, Table 4, MDS 2030	2030
Wind (bill of materials)	Carrara 2020, Table 2 (2018)	2030
Electrolysers (bill of materials)	Gerloff 2021 (~2019–20)	2030
Batteries, except NMC532	2030, via premise's energy-density scaling	2030
Batteries, NMC532 (EV and stationary)	premise's inventory, not scaled by year	2030
Nuclear	premise's materials-module inventory, the same in every year	2030
Gas plants, heat pump	ecoinvent's own	2030
Grid, HV AC, MV and LV, and their Al variants	ecoinvent's own (Itten 2014)	2030
Grid, HVDC land and subsea, and their Al variants	ecoinvent's own (Jorge et al. 2012)	2030
EV motor, PM	ecoinvent	ecoinvent 3.10 (not projected)
EV motor, induction	EV motor, PM, with the rotor changed following Månberger & Stenqvist 2018	ecoinvent 3.10 (not projected)



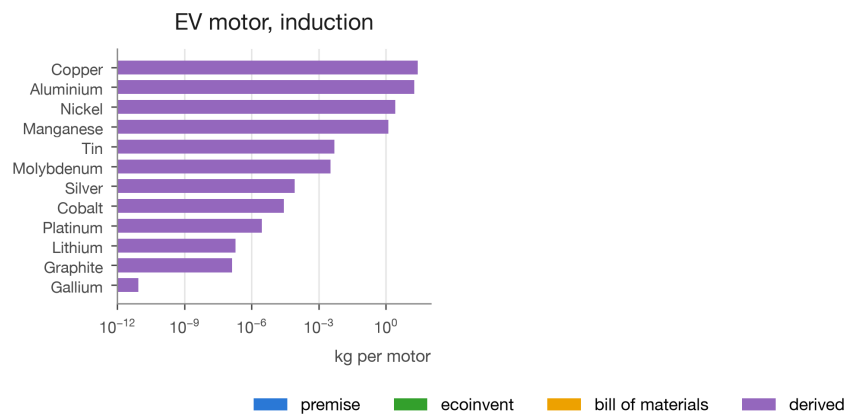
Supplementary Fig. 18 | Top material demands by technology (part 1).



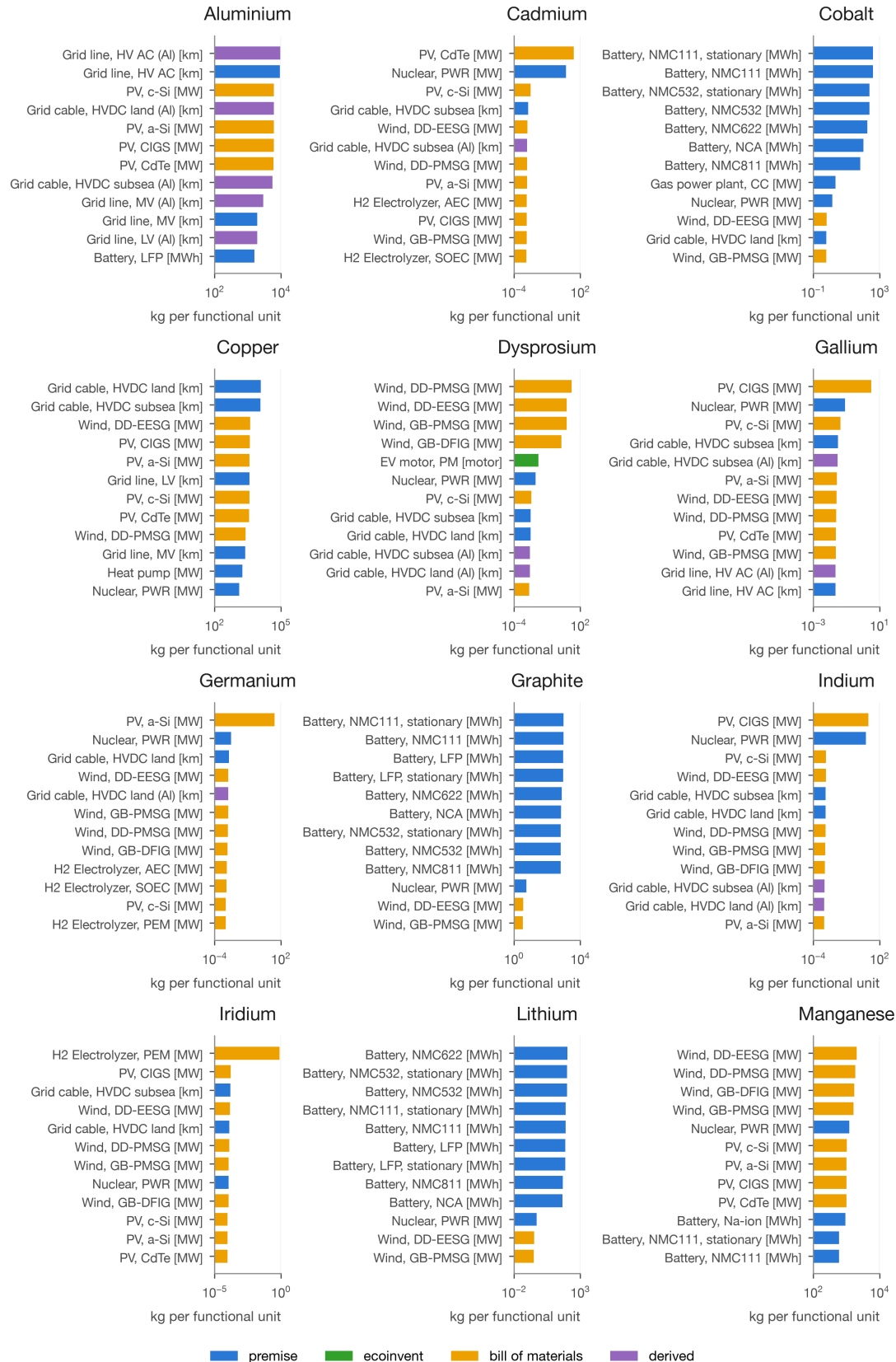
Supplementary Fig. 19 | Top material demands by technology (part 2).



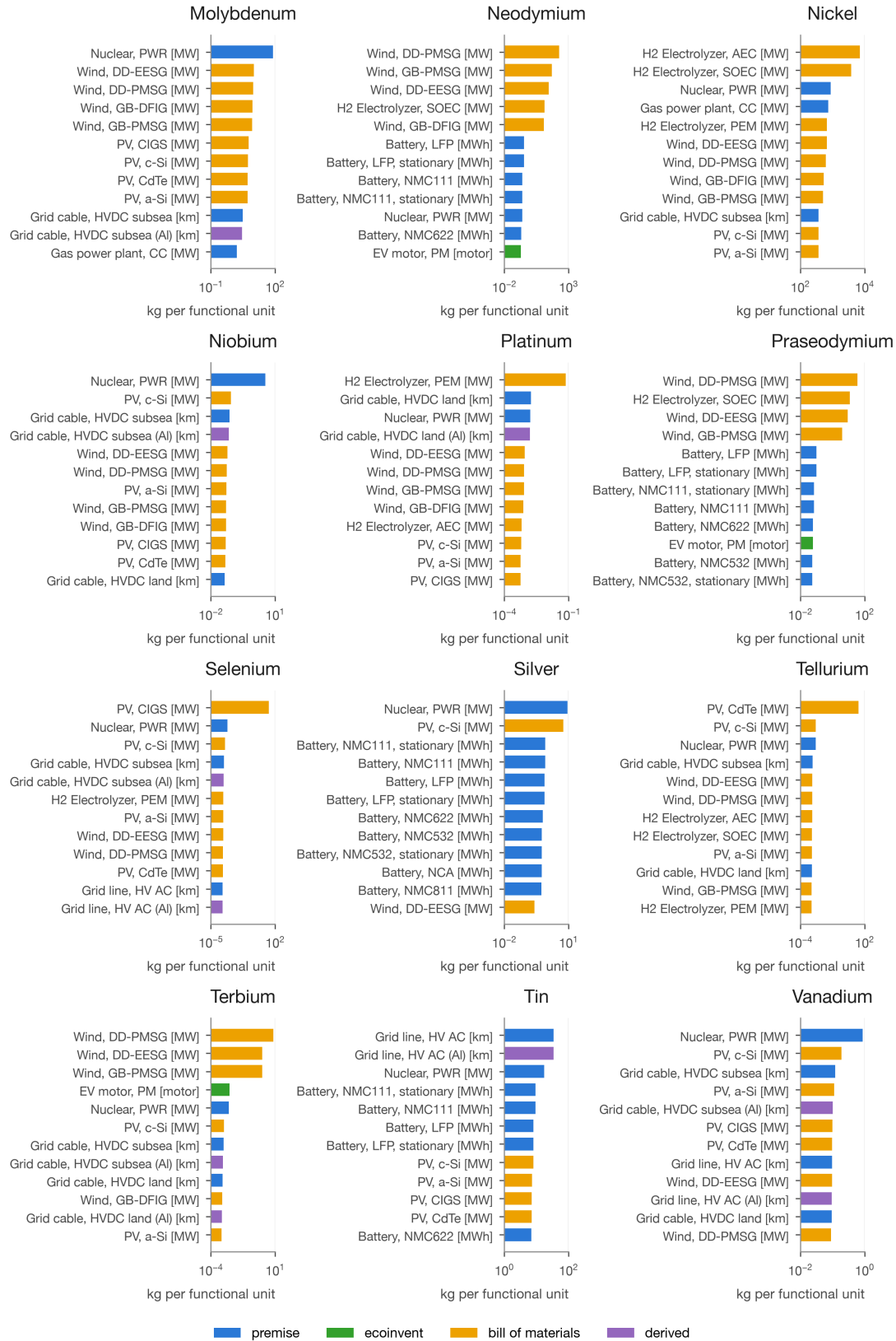
Supplementary Fig. 20 | Top material demands by technology (part 3).



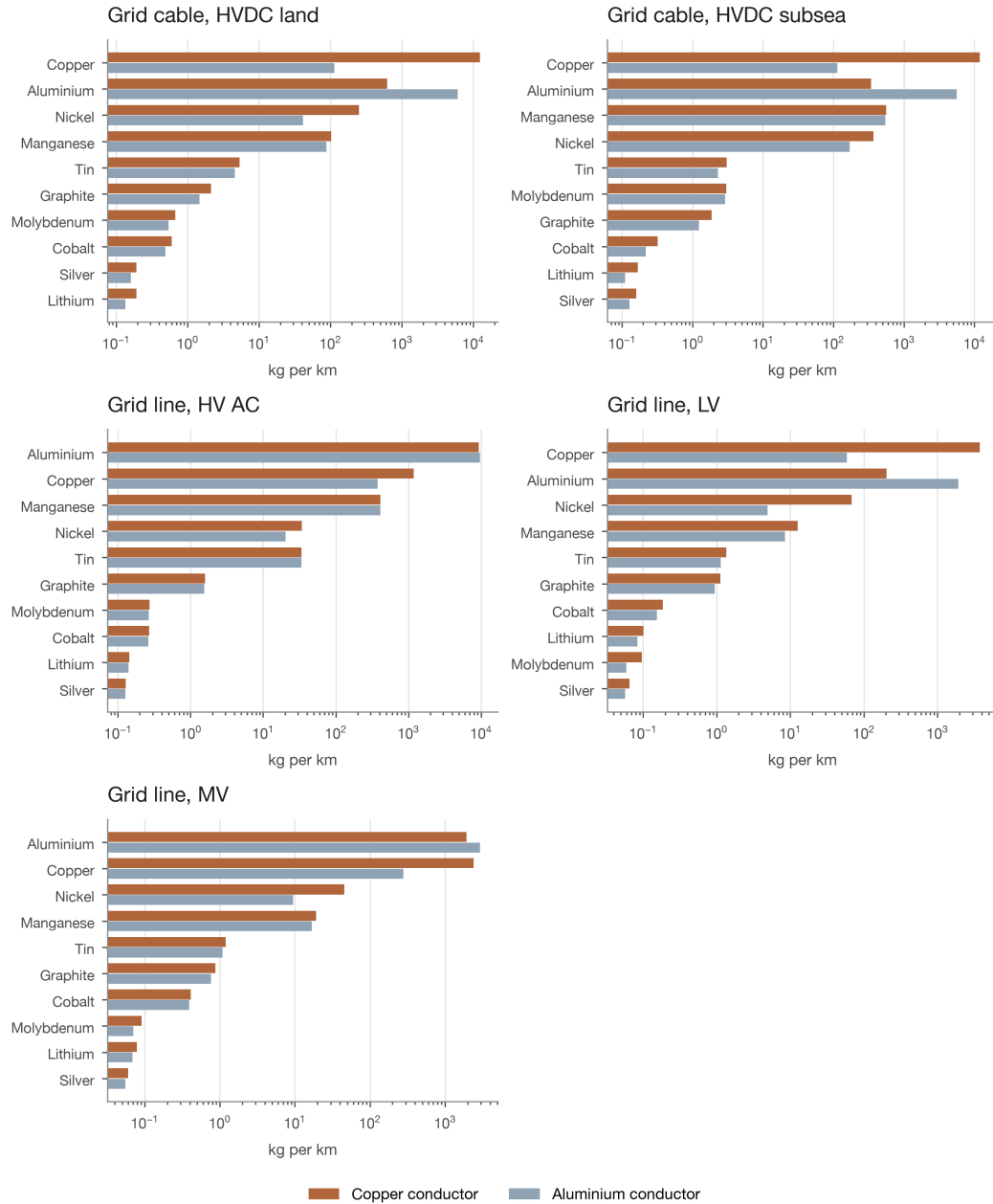
Supplementary Fig. 21 | Top material demands by technology (part 4).



Supplementary Fig. 22 | Top technology demands by materials (part 1).



Supplementary Fig. 23 | Top technology demands by materials (part 2).



Supplementary Fig. 24 | Comparison of copper grid sub-technologies with their aluminium counterparts.

2.6 Material supply

To calculate the global supply of all the materials in this study, we must be flexible regarding both method and source due to the inconsistent coverage of data. We use two methods for calculating the supply of primary materials, in order of decreasing priority.

1. **Direct.** For primary materials, we ideally have a time series for the final stage, after which the fully processed materials enter the global market (usually the “refinery” stage; exceptionally, the “smelter” stage for aluminium). We can use this directly.
2. **Mine × recovery ratio.** Where there is no time series for the final stage of production, there is usually a time series for the mining stage. We combine this with the smelting and refining recovery rate, from Nassar et al. ²⁸, to find the time series for the materials entering the global market.

For by-product materials, we use a third method, because the production of by-products depends more strongly on the trend in their host materials, rather than their own history.

3. **Host × by-product ratio.** We use time series for both the host material's mine series and the by-product ratio time series. The by-product ratio time series is the amount of the by-product that enters the market, per unit of host material output from this mine. This represents the physical process behind refining a by-product from the mine output of its host material better than directly extrapolating the output of a by-product.

We also have three sources, listed with the highest-priority source first.

1. **IEA¹⁴.** They produce forward-looking estimates for supply across a small subset of minerals key to the energy transition. The direct (refining) supply of these minerals also includes any additional output due to recycling.
2. **Our World in Data (OWID)²⁹.** OWID compiles data from the US Geological Survey³⁰, Kelly et al.³¹, and the British Geological Survey³². This provides historical direct and mine data for many materials. We predict future time-series data using a linear extrapolation of this.
3. **Lundaev et al.³³.** This provides historical mine and refinery data when OWID lacks a usable series (notably for the individual magnet REEs and iridium). We again use linear extrapolation to predict future time-series data. They also provide a projection from their research, but they did not intend this to be a realistic projection of metal supply, rather a theoretical output of academic value only; we label this “source projection”.

Supplementary Table 8 shows the final selections of the above methods and sources for each material.

Supplementary Table 8 | Final selections of method and source for each material.

Materials	Source	Method (series used)	Confidence	Secondary supply	Basis and caveats
Aluminium	OWID	Direct (smelter output)	High	No	Follows priority. Chain is refinery (alumina) then smelter; smelter output is the market-ready form.
Cadmium	OWID	Direct (refinery output)	Medium	No	Follows priority. OWID refinery series is USGS refined-cadmium output, recovered when zinc concentrate is treated.
Cobalt	IEA	Direct (refined supply outlook)	Medium	Yes	Follows priority. Host-ratio method skipped: two hosts (copper, nickel) and its own long mine + refinery series are better.
Copper	IEA	Direct (refined supply outlook)	High	Yes	Follows priority. High despite a wide method spread, because the two direct estimates (IEA, OWID) agree; the OWID refinery series is short (2020–2024).
Dysprosium	Lundaev	Mine × recovery (0.90)	Low	No	Forced single source — no individual OWID/IEA series. Level sits ~2× below the IEA magnet-REE aggregate; neodymium, praseodymium and dysprosium sanity-checked against the REE aggregate row.
Gallium	OWID	Host ratio (bauxite mine × gallium:bauxite)	Medium	No	Direct refinery series ends 2021 and misses the recent recovery buildout. Recovered from Bayer liquor; the ratio trends upward and is itself extrapolated, with no upper cap.

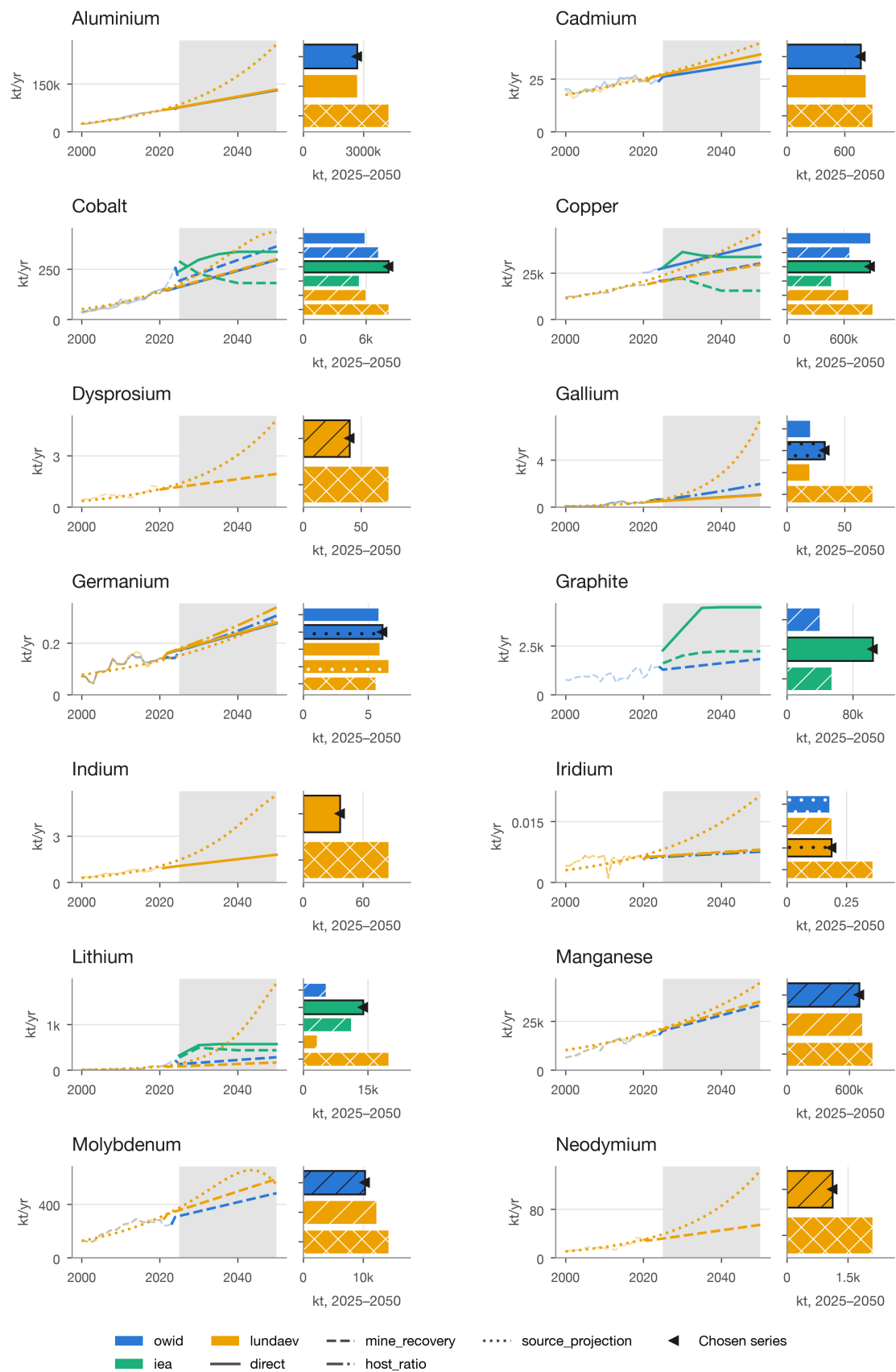
Materials	Source	Method (series used)	Confidence	Secondary supply	Basis and caveats
Germanium	OWID	Host ratio (zinc mine × germanium:zinc)	Medium	No	Follows priority; agrees closely with the direct series. Medium for small tonnage and by-product status.
Graphite	IEA	Direct (battery-grade supply outlook)	Medium	No	Only IEA covers synthetic graphite and limits to battery grade. Battery grade on both sides: natural + synthetic supply against anode demand. Refractory and electrode graphite is another commodity, out of scope.
Indium	Lundaev	Direct (refinery output)	Low	No	OWID excluded: it carries indium reserves but no production series. Lundaev's series is USGS refinery output; recovered from zinc residues.
Iridium	Lundaev	Host ratio (platinum mine × iridium:platinum)	Low	No	OWID has country rows only, no World aggregate. Tiny tonnage; host PGM output genuinely binds its expansion.
Lithium	IEA	Direct (refined lithium chemicals)	Medium	Yes	Follows priority. Medium because IEA and OWID projections disagree substantially.
Manganese	OWID	Mine × recovery (0.90)	Medium	No	Follows priority; no final-stage series exists, so mine output is converted.
Molybdenum	OWID	Mine × recovery (0.95)	Medium	No	Only a mine series exists. About half of world output is a by-product of copper porphyry and the rest primary, so no single host — its own series is extrapolated.
Neodymium	Lundaev	Mine × recovery (0.90)	Low	No	Forced single source — no individual OWID/IEA series. Level ~2× below the IEA magnet aggregate, kept as an independent cross-check rather than a fitted target.
Nickel	IEA	Direct (refined supply outlook)	High	Yes	Follows priority; long series with a corroborating OWID processing series at the final stage.
Niobium	OWID	Mine × recovery (0.90)	Medium	No	Only OWID covers niobium, and only at the mine stage. Marketed as ferroniobium; over 90% of world output is a single primary pyrochlore operation — concentrated, but not a by-product.
Platinum	Lundaev	Mine × recovery (0.96)	Low	No	OWID excluded — its World mine series is short (2020–2024). Only mostly primary.
Praseodymium	Lundaev	Mine × recovery (0.90)	Low	No	Forced single source — no individual OWID/IEA series; sanity-checked against the REE aggregate row.
Selenium	OWID	Direct (refinery output)	Medium	No	Follows priority. Recovered from the anode slimes of copper electrolytic refining.
Silver	OWID	Mine × recovery (0.95)	Medium	No	Only a mine series exists. Roughly a quarter primary and the rest a by-product of lead–zinc, copper and gold ores; no single host, so its own series is extrapolated.
Tellurium	Lundaev	Direct (refinery output)	Low	No	OWID has no tellurium series at all. Recovered from copper anode slimes; reported output is a small fraction of what the slimes contain, so supply answers to recovery investment more than to ore.

Materials	Source	Method (series used)	Confidence	Secondary supply	Basis and caveats
Terbium	Lundaev	Mine × recovery (0.90)	Low	No	Forced single source — no individual OWID/IEA series. Heavy-REE follower like dysprosium; sanity-checked against the REE aggregate row.
Tin	OWID	Mine × recovery (0.91)	Medium	No	Only OWID covers tin. Cassiterite mining; OWID gives smelter output by country but no World total, so the mine series carries it.
Vanadium	OWID	Mine × recovery (0.78)	Medium	No	Follows priority. Multi-source by-product (titanomagnetite, iron/steel slag) with no single host, so its own series is extrapolated.

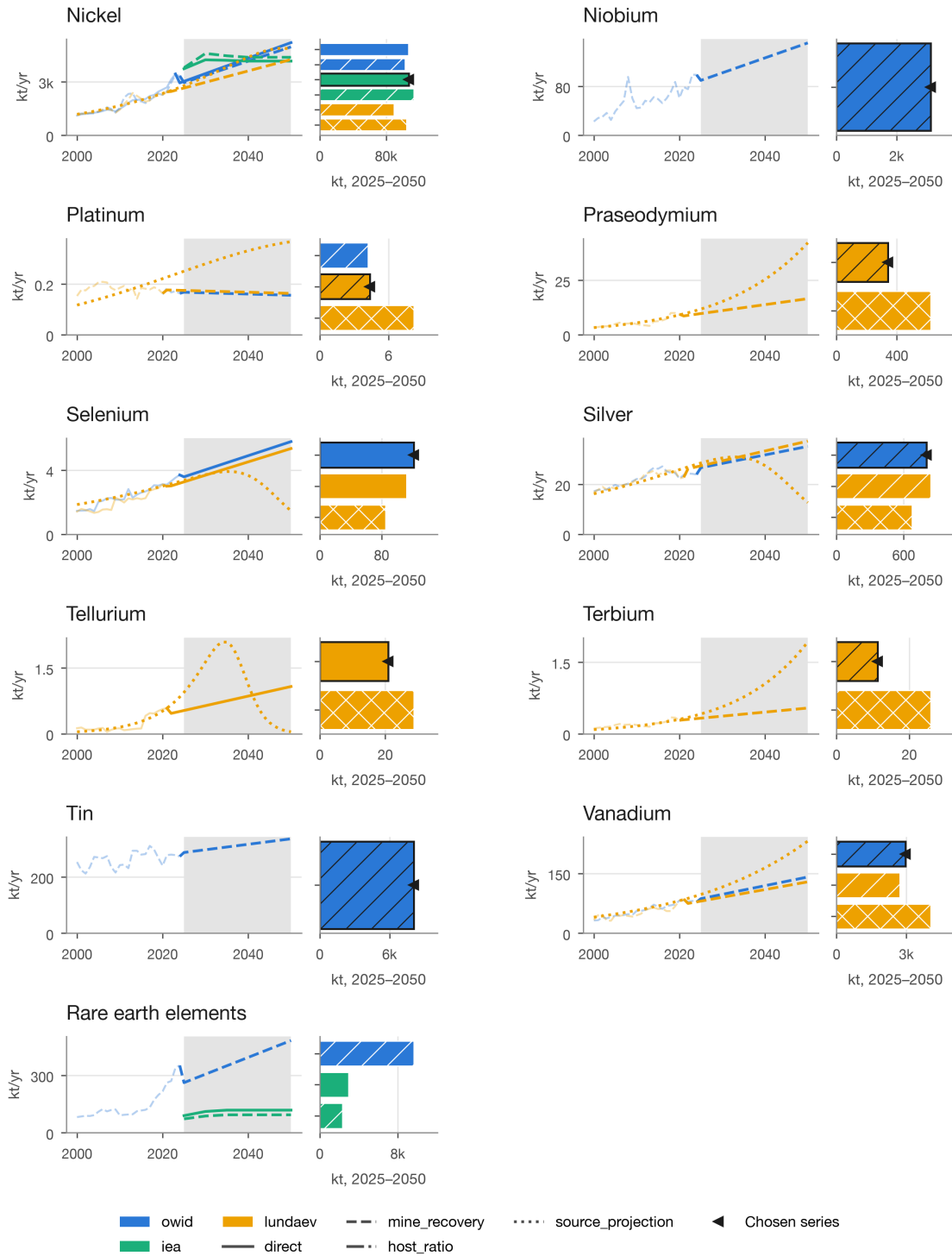
Supplementary Fig. 25 shows the possible combinations of method and source for each material, and Supplementary Fig. 26 and Supplementary Fig. 27 visualise all the available projection options for each metal. Supplementary Fig. 28 visualises the extrapolation of the by-product ratios.

source method	mineral	owid		iea			lundeav			source_projection
		direct	mine_recovery	host_ratio	direct	mine_recovery	direct	mine_recovery	host_ratio	
	Aluminium	x					x			x
	Cadmium	x					x			x
	Cobalt	x	x		x	x			x	x
	Copper	x	x		x	x			x	x
	Dysprosium								x	x
	Gallium	x		x			x			x
	Germanium	x		x			x		x	x
	Graphite		x		x	x				
	Indium						x			x
	Iridium			x					x	x
	Lithium		x		x	x			x	x
	Manganese		x						x	x
	Molybdenum		x						x	x
	Neodymium								x	x
	Nickel	x	x		x	x			x	x
	Niobium		x							
	Platinum		x						x	x
	Praseodymium								x	x
	Selenium	x					x			x
	Silver		x						x	x
	Tellurium						x			x
	Terbium								x	x
	Tin		x							
	Vanadium		x						x	x
	Rare earth elements		x		x	x				

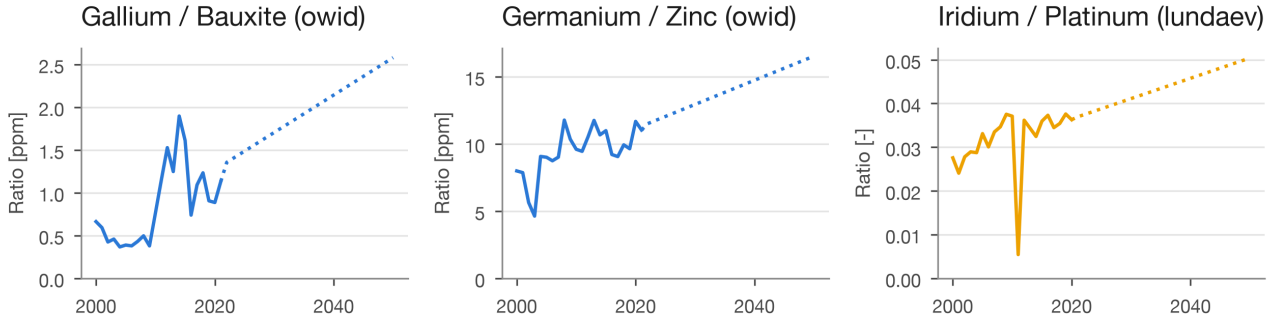
Supplementary Fig. 25 | Available sources and methods for each material.



Supplementary Fig. 26 | Available and chosen supply projection for each material (part 1).



Supplementary Fig. 27 | Available and chosen supply projection for each material (part 2).



Supplementary Fig. 28 | Extrapolation of by-product ratios.

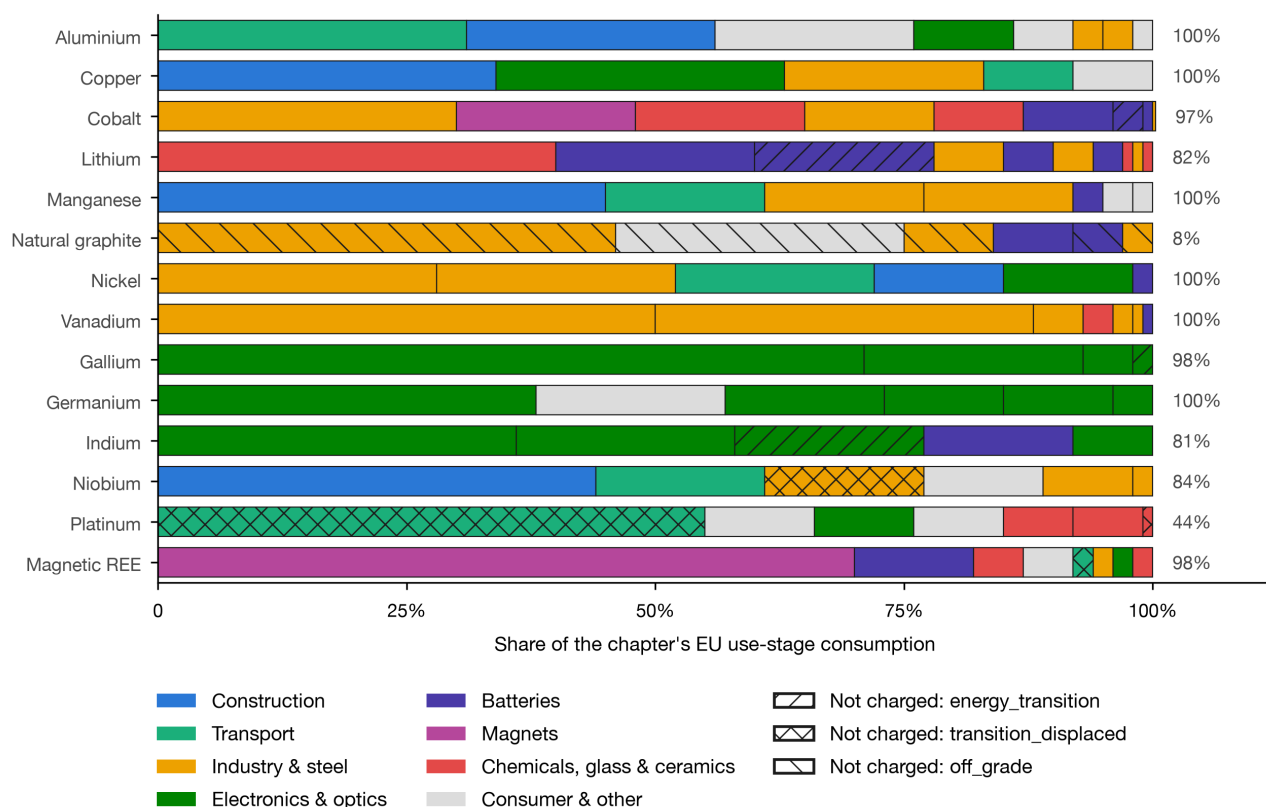
2.7 Non-energy demand

The calculation of the non-energy consumption, $C^{non-energy}$, for a material, m , and base year of that material's MSA report, t_0 is shown in the main manuscript, and reproduced in Supplementary Equation 1, below.

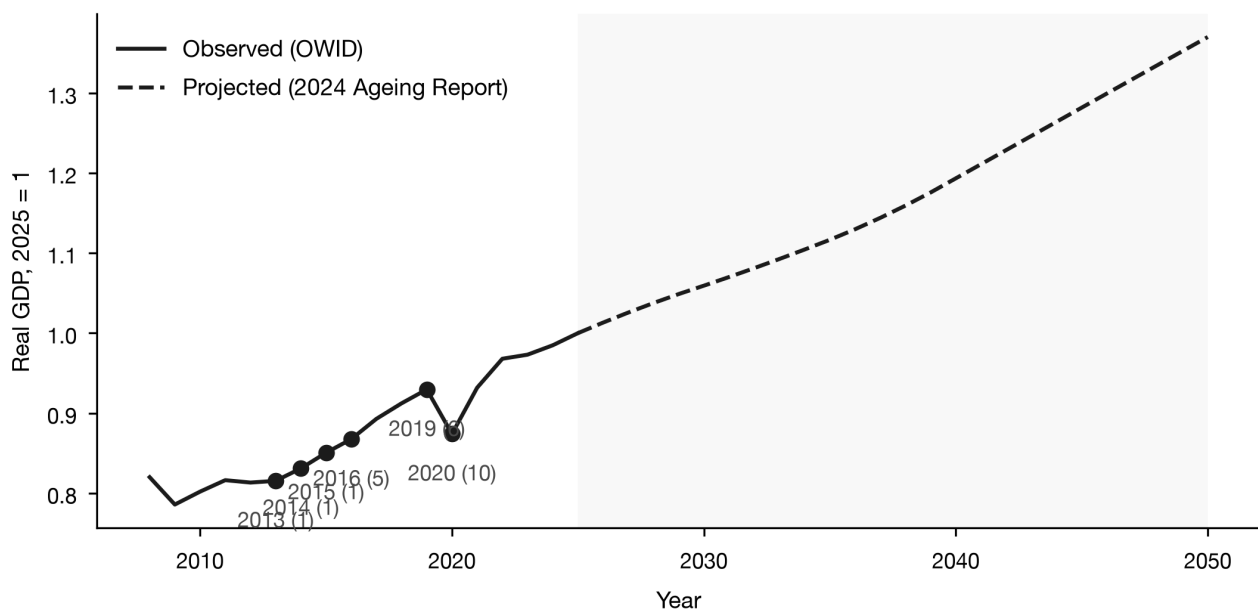
$$C_{m,t_0}^{non-energy} = C_{m,t_0}^{total} \times f_{m,t_0}^{charged} \times f_{m,t_0}^{region}, t_0 = t_0(m) \quad [1]$$

Where $t_0(m)$ is the base year as a function of which year's report a material appears in, C^{total} is the total EU economy consumption, $f^{charged}$ is the fraction of the total economy's demand charged to non-energy demand, and f^{region} is a scaling factor to scale the EU-27 or EU-28 region to our study's country set.

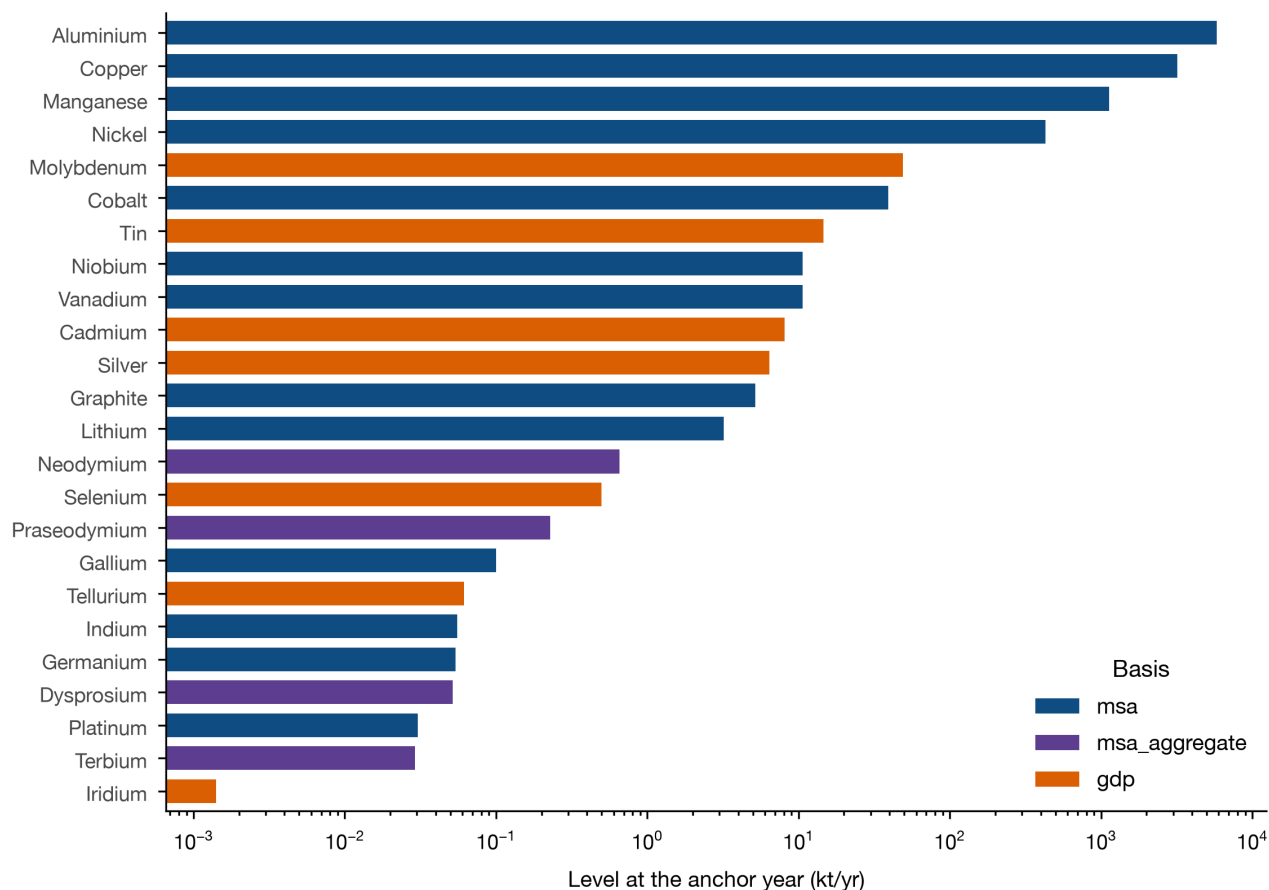
$f^{charged}$ often quantifies a judgement call as to which parts of demand we should charge to non-energy, and which are already included in the transition. This is visualised in Supplementary Fig. 29 and written in full in Supplementary Table 9. We do not charge (1) applications that we also cover directly in our modelling of the energy transition, to avoid double counting, (2) demands displaced by the transition itself, such as the platinum used in internal combustion engine catalytic converters, and (3) off-grade graphite that refers to a different material from the one our supply series measures. (2) is a simplification, as demands displaced by the transition will be replaced slowly from now until 2050; this results in the non-energy demand being an underestimate for platinum and niobium.



Supplementary Fig. 29 | Visualisation of which segments of material system analysis^{34–37} are attributed to non-energy demand.



Supplementary Fig. 30 | EU GDP historical and projected.



Supplementary Fig. 31 | Resulting material non-energy demands for the anchor year, i.e., the year a metal's other-sector demand level is measured at.

Supplementary Table 9 | Attribution of each material system analysis end-use application to a sector and an end-use class, with the reasoning and source page behind each call.

Materials	MSA report	Application	Representative product	Share	Sector	End-use class	Reason	Page
Aluminium	MSA_2018	Transportation		0.31	transport	other	2013 vehicle fleet; electric drivetrains are a rounding error in it, and the ones this study builds come from the EV stock model	17
Aluminium	MSA_2018	Building and construction		0.25	construction	other	construction	17
Aluminium	MSA_2018	Industrial machinery and equipment		0.03	industry_steel	other	industry	17
Aluminium	MSA_2018	Consumer durables		0.06	other	other	consumer goods	17
Aluminium	MSA_2018	Electrical engineering		0.10	electronics_optics	other	contains the transmission and distribution conductor this study models, alongside motors, transformers and appliances; MSA_2018 gives no representative product to resolve it, so the slice stays other and aluminium's non-energy fraction is an upper bound	17
Aluminium	MSA_2018	Packaging and cans		0.20	other	other	packaging	17
Aluminium	MSA_2018	Others		0.02	other	other	miscellaneous	17
Aluminium	MSA_2018	Dissipative uses		0.03	industry_steel	other	deoxidation in steelmaking	17
Copper	MSA_2018	Electrical and electronic products		0.29	electronics_optics	other	power utilities, telecoms, lighting and wiring devices; contains the grid conductor this study models but is not resolved further, so copper's non-energy fraction is an upper bound	22
Copper	MSA_2018	Building and construction		0.34	construction	other	plumbing and building wire	22
Copper	MSA_2018	Industrial machinery and equipment		0.20	industry_steel	other	industry	22
Copper	MSA_2018	Transportation equipment		0.09	transport	other	2014 vehicle fleet; see the aluminium transportation row	22

Materials	MSA report	Application	Representative product	Share	Sector	End-use class	Reason	Page
Copper	MSA_2018	Consumer and general goods		0.08	other	other	consumer goods	22
Cobalt	MSA_2020_batteries	Superalloys		0.30	industry_steel	other	turbine and aerospace alloys	13
Cobalt	MSA_2020_batteries	Magnets		0.18	magnets	other	SmCo and AlNiCo industrial magnets; the NdFeB traction and generator magnets this study models are accounted through their rare-earth content, not their cobalt	13
Cobalt	MSA_2020_batteries	Intentionally dissipative uses (IDU)		0.17	chemicals_glass	other	tyre adhesives, paint dryers, ceramics and pigments	13
Cobalt	MSA_2020_batteries	Hard metals		0.13	industry_steel	other	cemented carbide tooling	13
Cobalt	MSA_2020_batteries	Catalysts		0.09	chemicals_glass	other	chemical and refining catalysts	13
Cobalt	MSA_2020_batteries	Portable batteries		0.09	batteries	other	consumer electronics	13
Cobalt	MSA_2020_batteries	Mobility batteries (including e-bikes)		0.03	batteries	energy_transition	EV traction batteries; this study builds that demand from the EV stock model and would double count it here	13
Cobalt	MSA_2020_batteries	Industrial batteries		0.01	batteries	other	standby and traction batteries; grid-scale storage was negligible in the 2016 reference year	13
Cobalt	MSA_2020_batteries	Other metallic uses (OMU)		0.003	industry_steel	other	miscellaneous metallurgy	13
Lithium	MSA_2020_batteries	Glass and ceramics		0.40	chemicals_glass	other	glass-ceramics	18
Lithium	MSA_2020_batteries	Batteries - Portable		0.20	batteries	other	consumer electronics	18
Lithium	MSA_2020_batteries	Batteries - Mobility		0.18	batteries	energy_transition	EV traction batteries; see the cobalt mobility-battery row	18
Lithium	MSA_2020_batteries	Lubricants and greases		0.07	industry_steel	other	lithium greases	18
Lithium	MSA_2020_batteries	Batteries - Industrial		0.05	batteries	other	standby and traction batteries; grid-scale storage was negligible in the 2016 reference year	18
Lithium	MSA_2020_batteries	Continuous casting		0.04	industry_steel	other	casting fluxes	18

Materials	MSA report	Application	Representative product	Share	Sector	End-use class	Reason	Page
Lithium	MSA_2020_batteries	Batteries - E-bikes		0.03	batteries	other	e-bikes are not in the modelled transport system; the EV stock model covers cars	18
Lithium	MSA_2020_batteries	Pharmaceuticals		0.01	chemicals_glass	other	lithium salts	18
Lithium	MSA_2020_batteries	Al-Li alloys		0.01	industry_steel	other	aerospace alloys	18
Lithium	MSA_2020_batteries	Polymers		0.01	chemicals_glass	other	polymerisation initiators	18
Lithium	MSA_2020_batteries	Air treatment		0.00	chemicals_glass	other	desiccants and air conditioning	18
Manganese	MSA_2020_batteries	Building & Construction		0.45	construction	other	construction steel	21
Manganese	MSA_2020_batteries	Transportation		0.16	transport	other	vehicle steel; see the aluminium transportation row	21
Manganese	MSA_2020_batteries	Engineering		0.16	industry_steel	other	engineering steel	21
Manganese	MSA_2020_batteries	Metalware		0.15	industry_steel	other	metal goods	21
Manganese	MSA_2020_batteries	Batteries (portable/mobility/e-bikes/industrial)		0.03	batteries	other	MSA lumps the four battery types; the mobility share of manufactured battery manganese was 2 of 21.5 kt Mn, so the slice is predominantly portable alkaline cells	21
Manganese	MSA_2020_batteries	Domestic Appliances		0.03	other	other	appliances	21
Manganese	MSA_2020_batteries	Miscellaneous		0.02	other	other	miscellaneous metallurgy	21
Natural graphite	MSA_2020_batteries	Refractories		0.46	industry_steel	off_grade	steelmaking refractories	25
Natural graphite	MSA_2020_batteries	Miscellaneous		0.29	other	off_grade	foundry, pencils, seals and other uses	25
Natural graphite	MSA_2020_batteries	Friction materials		0.09	industry_steel	off_grade	brake linings	25
Natural graphite	MSA_2020_batteries	Batteries (portable/mobility/e-bikes/industrial)		0.08	batteries	other	MSA lumps the four types of Li-ion battery; the EU mobility share was 2 kt C of 62 kt C manufactured in 2016, so the slice is predominantly portable	25

Materials	MSA report	Application	Representative product	Share	Sector	End-use class	Reason	Page
Natural graphite	MSA_2020_batteries	Other batteries		0.05	batteries	off_grade	non-lithium cells	25
Natural graphite	MSA_2020_batteries	Lubricants		0.03	industry_steel	off_grade	graphite lubricants	25
Nickel	MSA_2020_batteries	Metal goods		0.28	industry_steel	other	stainless metal goods	28
Nickel	MSA_2020_batteries	Engineering		0.24	industry_steel	other	engineering stainless steel	28
Nickel	MSA_2020_batteries	Transportation		0.20	transport	other	vehicle steel; see the aluminium transportation row	28
Nickel	MSA_2020_batteries	Building & Construction		0.13	construction	other	construction stainless steel	28
Nickel	MSA_2020_batteries	Electro and Electronics		0.13	electronics_optics	other	electronics	28
Nickel	MSA_2020_batteries	Batteries (portable/mobility/e-bikes/industrial)		0.02	batteries	other	MSA lumps the four battery types; the mobility share of manufactured battery nickel was 3 of 3.9 kt Ni, but the slice is 2% of EU use either way	28
Vanadium	MSA_2021_nine	HSLA		0.50	industry_steel	other	high-strength low-alloy structural steel	51
Vanadium	MSA_2021_nine	Special steel		0.38	industry_steel	other	tool and crankshaft steel	51
Vanadium	MSA_2021_nine	Super alloys for high-end uses		0.05	industry_steel	other	jet engine superalloys	51
Vanadium	MSA_2021_nine	Chemicals		0.03	chemicals_glass	other	sulphuric acid and maleic anhydride catalysts	51
Vanadium	MSA_2021_nine	Cast Iron for rigid structures		0.02	industry_steel	other	cast iron	51
Vanadium	MSA_2021_nine	Stainless steel		0.01	industry_steel	other	stainless steel	51
Vanadium	MSA_2021_nine	Energy storage		0.01	batteries	energy_transition	vanadium redox-flow batteries; a grid-scale storage this study neglects	51
Gallium	MSA_2023	Electronic devices with Ga-based integrated circuits	Smartphones	0.71	electronics_optics	other	consumer electronics	63

Materials	MSA report	Application	Representative product	Share	Sector	End-use class	Reason	Page
Gallium	MSA_2023	Ga-based LEDs and lighting	Flat panel displays	0.22	electronics_optics	other	lighting and displays are outside the modelled energy system	63
Gallium	MSA_2023	Military/medical/wireless applications with Ga-based integrated circuits	Military radars & sensors	0.05	electronics_optics	other	defence and medical electronics	63
Gallium	MSA_2023	Photovoltaics	CIGS PV panels	0.02	electronics_optics	energy_transition	thin-film PV is a modelled sub-technology	63
Germanium	MSA_2023	Infrared optics	Infrared cameras	0.38	electronics_optics	other	optics	69
Germanium	MSA_2023	Others	Transistors	0.19	other	other	PET production and microelectronics	69
Germanium	MSA_2023	Fibre optics	Fibre optic cable	0.16	electronics_optics	other	telecoms	69
Germanium	MSA_2023	Gamma ray detection	Gamma ray detector	0.12	electronics_optics	other	detectors	69
Germanium	MSA_2023	Satellite solar cells	Wafers	0.11	electronics_optics	other	space power; the label reads solar, but the representative product is a satellite wafer and no modelled technology uses one	69
Germanium	MSA_2023	LEDs	LED	0.04	electronics_optics	other	lighting	69
Indium	MSA_2023	Solders + thermal interface materials	Car windshield solders	0.36	electronics_optics	other	solders	76
Indium	MSA_2023	Alloys/compounds/semiconductors + other	Glass lenses	0.22	electronics_optics	other	alloys and optics	76
Indium	MSA_2023	Photovoltaics	Copper indium gallium diselenide solar cells (CIGS)	0.19	electronics_optics	energy_transition	thin-film PV is a modelled sub-technology	76
Indium	MSA_2023	Batteries	Primary button cells	0.15	batteries	other	button cells, not storage; the label alone would mislead	76
Indium	MSA_2023	Flat panel displays	Indicator panels incorporating liquid crystal display (LCD)	0.08	electronics_optics	other	displays	76
Niobium	MSA_2023	Construction (Steel)	Steel bridges	0.44	construction	other	construction steel	94
Niobium	MSA_2023	Automotive (Steel)	Passenger vehicles	0.17	transport	other	vehicle steel; see the aluminium transportation row	94

Materials	MSA report	Application	Representative product	Share	Sector	End-use class	Reason	Page
Niobium	MSA_2023	Oil & Gas	Oil or gas tubes	0.16	industry_steel	transition_displaced	fossil extraction and transport infrastructure, which the modelled transition removes	94
Niobium	MSA_2023	Other	Superconductors in MRIs	0.12	other	other	medical superconductors	94
Niobium	MSA_2023	Stainless Steel	Stainless steel in passenger vehicles	0.09	industry_steel	other	vehicle stainless steel	94
Niobium	MSA_2023	Special Steel	Aerospace parts	0.02	industry_steel	other	aerospace	94
Platinum	MSA_2023	Autocatalyst	Autocatalysts	0.55	transport	transition_displaced	internal-combustion aftertreatment; the modelled transition retires the ICE fleet this demand rides on, so it is not charged to the region	104
Platinum	MSA_2023	Other	Pollution control catalysts	0.11	other	other	industrial emission control	104
Platinum	MSA_2023	Electronics	Hard drives	0.10	electronics_optics	other	electronics	104
Platinum	MSA_2023	Jewellery	Jewellery	0.09	other	other	jewellery	104
Platinum	MSA_2023	Chemicals	Catalysts	0.07	chemicals_glass	other	chemical industry catalysts	104
Platinum	MSA_2023	Medical and biomedical	Pacemakers	0.07	chemicals_glass	other	medical devices	104
Platinum	MSA_2023	Petroleum	Naphtha reforming catalysts	0.01	chemicals_glass	transition_displaced	petroleum refining; not part of the modelled energy system and removed by it, so it is not charged to the region	104
Platinum	MSA_2023	Glass	Glass fibre extruding nozzles	0.00	chemicals_glass	other	glass fibre	104
Magnetic REE	MSA_2023	Magnets	Magnets in cars; magnets in industrial robots	0.70	magnets	other	We are forced to assume, since the reference offers no further resolution. In 2020, EVs sold were largely not electric, so we assume that magnets are not part of the transition. This will overestimate the non-energy demand for magnet REEs slightly.	116

Materials	MSA report	Application	Representative product	Share	Sector	End-use class	Reason	Page
Magnetic REE	MSA_2023	Batteries	NiMH batteries (in portable devices)	0.12	batteries	other	NiMH cells in portable devices, not traction batteries; the label alone would mislead	116
Magnetic REE	MSA_2023	Glass and ceramics	Pigments in glass tableware; pigments in ceramic tiles	0.05	chemicals_glass	other	pigments	116
Magnetic REE	MSA_2023	Other uses		0.05	other	other	laser dopants, radiography and the nuclear industry	116
Magnetic REE	MSA_2023	Autocatalysts	Cars	0.02	transport	transition_displaced	internal-combustion aftertreatment; see the platinum autocatalyst row	116
Magnetic REE	MSA_2023	Metal excl. batteries	Iron and steel production; jet plane engines	0.02	industry_steel	other	metallurgical additions	116
Magnetic REE	MSA_2023	Phosphors	Fluorescent lamps	0.02	electronics_optics	other	lighting	116
Magnetic REE	MSA_2023	Magnetic resonance imaging	Contrast agent for MRI	0.02	chemicals_glass	other	medical imaging	116

3 References

1. Bieuville, P., Majeau-Bettez, G. & de Bortoli, A. Technology flexibility and sobriety to address shortage of energy-transition metals. *Nat. Sustain.* 1–12 (2026) doi:10.1038/s41893-025-01762-y.
2. Dong, H. et al. Sub-technology market share strongly affects critical material constraints in power system transitions. *Nat. Commun.* 16, 1285 (2025).
3. Malmaeus, J. M., Alfredsson, E. C. & Lindblom, E. On the allocation of critical metals between nations for a green and just transition. *Environ. Dev.* 54, 101157 (2025).
4. Wei, Y.-M. et al. Navigating energy transition solutions for climate targets with minerals constraint. *Nat. Clim. Change* 15, 833–841 (2025).
5. Shi, H. et al. Critical mineral constraints pressure energy transition and trade toward the Paris Agreement climate goals. *Nat. Commun.* 16, 4496 (2025).
6. García-Gusano, D. et al. The future need for critical raw materials associated with long-term energy and climate strategies: The illustrative case study of power generation in Spain. *Energy* 314, 134266 (2025).
7. Wang, S. et al. Future demand for electricity generation materials under different climate mitigation scenarios. *Joule* 7, 309–332 (2023).
8. Ushie, O. J. et al. Resilient strategies to mitigate the volatility of copper and aluminium critical mineral demand for net-zero electricity network production. *Sustain. Energy Res.* 12, 56 (2025).
9. Mutke, J., Finke, J., Esser, K. & Heinrichs, H. Materealistic? How European energy system models exceed raw material reserves. Preprint at <https://doi.org/10.48550/arXiv.2606.12201> (2026).
10. Teixeira, B., Brito, M. C. & Mateus, A. Critical metal supply risks for EU electric vehicle batteries: supply-demand misalignments under production and recycling scenarios. *Miner. Econ.* <https://doi.org/10.1007/s13563-026-00700-4> (2026) doi:10.1007/s13563-026-00700-4.
11. Morfeldt, J., Johansson, D. J. A. & Davidsson Kurland, S. A combination of measures limits demand for critical materials in Sweden’s electric car transition. *Commun. Earth Environ.* 6, 163 (2025).
12. Carrara, S., Alves Dias, P., Plazzotta, B. & Pavel, C. Raw Materials Demand for Wind and Solar PV Technologies in the Transition towards a Decarbonised Energy System. <https://publications.jrc.ec.europa.eu/repository/handle/JRC119941> (2020) doi:10.2760/160859.
13. European Parliament and Council of the European Union. Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020. *OJ L*, 2024/1252 vol. 2024/1252 (2024).
14. International Energy Agency. Global Critical Minerals Outlook 2026. <https://www.iea.org/reports/global-critical-minerals-outlook-2026> (2026).

15. International Energy Agency. The Role of Critical Minerals in Clean Energy Transitions. <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions> (2022).
16. International Energy Agency. Batteries and Secure Energy Transitions. <https://www.iea.org/reports/batteries-and-secure-energy-transitions> (2024).
17. Observatorio Tecnológico del Hidrógeno. Renewable Hydrogen Production via Electrolysis: State-of-the-Art and Future Prospects. (2025).
18. World Nuclear Association. World Nuclear Performance Report 2025. <https://world-nuclear.org/our-association/publications/global-trends-reports/world-nuclear-performance-report> (2025).
19. ecoinvent Association. ecoinvent database v3.10, cut-off system model. ecoinvent Association (2023).
20. Eurelectric. Distribution Grids in Europe: Facts and Figures 2020. (2020).
21. Sacchi, R. et al. premise: PProspective EnvironMental Impact asSEment. (2025).
22. Sacchi, R. et al. PProspective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renew. Sustain. Energy Rev.* 160, 112311 (2022).
23. Wernet, G. et al. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 21, 1218–1230 (2016).
24. Gerloff, N. Comparative Life-Cycle-Assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production. *J. Energy Storage* 43, 102759 (2021).
25. Nohl, L. et al. Material Requirements for Electricity Grids. <https://publications.jrc.ec.europa.eu/repository/handle/JRC143190> (2025).
26. Itten, R., Frischknecht, R. & Stucki, M. Life Cycle Inventories of Electricity Mixes and Grid. <https://www.lc-inventories.ch> (2014).
27. Månberger, A. & Stenqvist, B. Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development. *Energy Policy* 119, 226–241 (2018).
28. Nassar, N. T., Lederer, G. W., Brainard, J. L., Padilla, A. J. & Lessard, J. D. Rock-to-Metal Ratio: A Foundational Metric for Understanding Mine Wastes. *Environ. Sci. Technol.* 56, 6710–6721 (2022).
29. Our World in Data. Minerals. Our World in Data (2025).
30. U.S. Geological Survey, National Minerals Information Center. U.S. Geological Survey Mineral Commodity Summaries 2025 Data Release (ver. 2.0, April 2025). U.S. Geological Survey <https://doi.org/10.5066/P13XCP3R> (2025).
31. Kelly, T. D. & Matos, G. R. Historical Statistics for Mineral and Material Commodities in the United States (2016 Version). <https://doi.org/10.3133/ds140> (2014) doi:10.3133/ds140.
32. British Geological Survey. World Mineral Statistics, 1970 onwards. British Geological Survey (2024).

33. Lundaev, V., Solomon, A. A., Le, T., Lohrmann, A. & Breyer, C. Review of critical materials for the energy transition, an analysis of global resources and production databases and the state of material circularity. *Miner. Eng.* 203, 108282 (2023).
34. Passarini, F., Ciacci, L., Nuss, P. & Manfredi, S. Material Flow Analysis of Aluminium, Copper, and Iron in the EU-28. (2018) doi:10.2760/1079.
35. Matos, C. T. et al. Material System Analysis of Five Battery-Related Raw Materials: Cobalt, Lithium, Manganese, Natural Graphite, Nickel. (2020) doi:10.2760/519827.
36. Matos, C. T. et al. Material System Analysis of Nine Raw Materials: Barytes, Bismuth, Hafnium, Helium, Natural Rubber, Phosphorus, Scandium, Tantalum and Vanadium. (2021) doi:10.2760/677981.
37. European Commission. Update of the 2015 Material System Analyses. (2024) doi:10.2873/440874.