Supplementary material for a manuscript submitted to the Journal of Economic Structures

Matching global cobalt demand under different scenarios for co-production and mining attractiveness

Supplementary material

Results and figures for all scenarios are available as ‘Supplementary_Information_2.zip’
Additional data used by the model is available as ‘Supplementary_Information_3.xlsx’

Additional supplementary materials can be provided upon request

S1-1: EXIOBASE list of products, aggregation and re-sorting into WIO structure

S1-2: EXIOBASE list of regions and regional aggregation

S1-3: Projection of future final demand for the 20 regions

S1-4: The hybrid I/O model and projection of future cobalt demand

S1-5: Linear program and dynamic stock model of cobalt, copper, and nickel reserves

S1-6: Additional results

References

In this supplementary material, we provide additional information about the model that links final demand for products and services to the depletion of cobalt resources (Figure S1).

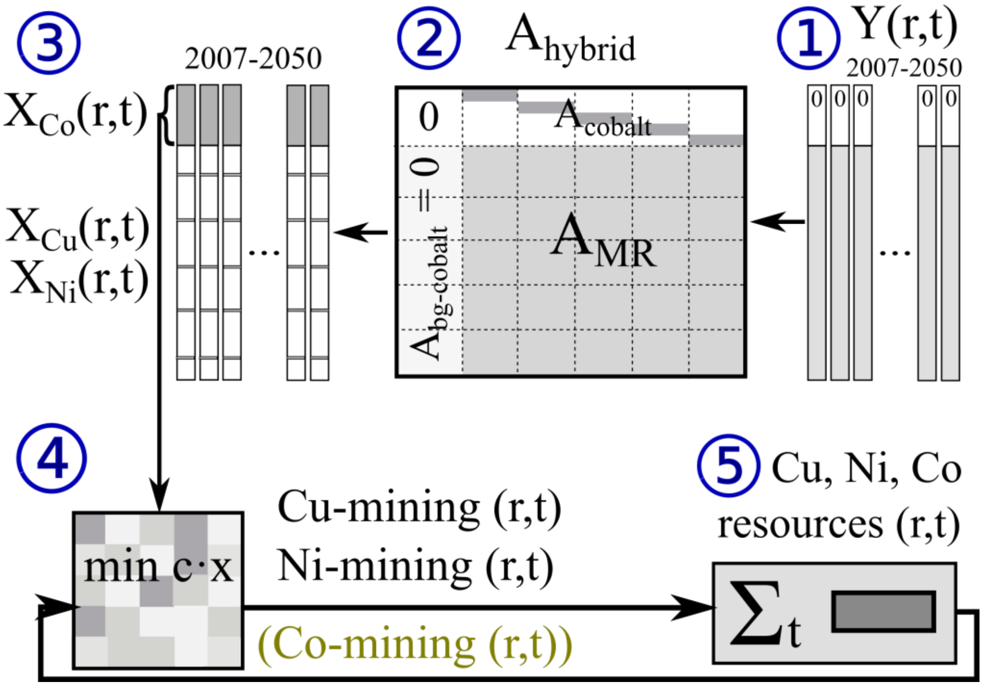

Figure S1: Model structure. (1) Estimating future final demand by using exogenous GDP projections and breaking them down into sectors using historic growth rates for the spending in different sectors. (2) Hybridizing the 20 regions MRIO model to separate cobalt demand (physical foreground matrix A_{cobalt}) from demand for non-ferrous metals. (3) Determining the total demand of cobalt by region and year using the Leontief I/O model and assuming a constant A-matrix. (4) Solving a linear program to determine extraction patterns for Cu, Ni, and Co that come with the lowest risk to investors. (5) Use a dynamic stock model of the known copper, nickel, and cobalt resources to determine their depletion over time.

Sections S1-1 and S1-2 provide general information about the product and regional classification of the model, respectively.

Section S1-3 describes the estimation of future final demand for 163 categories and 20 regions for the period 2007-2050.

In section S1-4 we describe the construction of the MRIO model and its hybridization.

In section S1-5: we present the details of the linear program and dynamic stock model of cobalt, copper, and nickel reserves.

Additional results are presented in section S1-6.

S1-1: EXIOBASE list of products, aggregation and re-sorting into WIO structure

Table S1 shows a list of the 200 product groups in the EXIOBASE classification v2.2.0, the 25 first characters of their names, the unit used, and the position to which they were re-sorted for the I/O model used in this study (Schmidt et al. 2012). If several products show the same target position, e.g., the 20 types of refinery products, which are assigned position 52, these products were aggregated into a common group at that position according to the official aggregation routine of the EU CREEA project. The 163 industries were re-sorted into production and waste treatment sectors accordingly, but not aggregated, as their number before aggregation was already 163. The products of the EXIOBASE MR-SUT were aggregated and resorted using the aggregation and resorting vector below and the aggregation and resorting routine 'pySUT.aggregate_rearrange_products' of the pySUT class (Pauliuk 2014).

Table S1: Product classification of the I/O model used. Part I, index 0-99.

Index	Code	CREEA Product List (200)	Position in I/O model	Unit	Index	Code	DESIRE Product List (200)	Position in I/O model	Unit
0	p01.a	Paddy rice	0	MEUR	50	p15.i	Food products nec	40	MEUR
1	p01.b	Wheat	1	MEUR	51	p15.j	Beverages	41	MEUR
2	p01.c	Cereal grains nec	2	MEUR	52	p15.k	Fish products	42	MEUR
3	p01.d	Vegetables, fruit, nuts	3	MEUR	53	p16	Tobacco products	43	MEUR
4	p01.e	Oil seeds	4	MEUR	54	p17	Textiles	44	MEUR
5	p01.f	Sugar cane, sugar beet	5	MEUR	55	p18	Wearing apparel; furs	45	MEUR
6	p01.g	Plant-based fibers	6	MEUR	56	p19	Leather and leather produ	46	MEUR
7	p01.h	Crops nec	7	MEUR	57	p20	Wood and products of wood	47	MEUR
8	p01.i	Cattle	8	MEUR	58	p20.w	Wood material for treatme	129	MEUR
9	p01.j	Pigs	9	MEUR	59	p21.1	Pulp	48	MEUR
10	p01.k	Poultry	10	MEUR	60	p21.w.1	Secondary paper for treat	130	MEUR
11	p01.l	Meat animals nec	11	MEUR	61	p21.2	Paper and paper products	49	MEUR
12	p01.m	Animal products nec	12	MEUR	62	p22	Printed matter and record	50	MEUR
13	p01.n	Raw milk	13	MEUR	63	p23.1.a	Coke Oven Coke	51	MEUR
14	p01.o	Wool, silk-worm cocoons	14	MEUR	64	p23.1.b	Gas Coke	52	MEUR
15	p01.w.1	Manure (conventional trea	127	MEUR	65	p23.1.c	Coal Tar	52	MEUR
16	p01.w.2	Manure (biogas treatment)	128	MEUR	66	p23.20.a	Motor Gasoline	52	MEUR
17	p02	Products of forestry, log	15	MEUR	67	p23.20.b	Aviation Gasoline	52	MEUR
18	p05	Fish and other fishing pr	16	MEUR	68	p23.20.c	Gasoline Type Jet Fuel	52	MEUR
19	p10.a	Anthracite	17	MEUR	69	p23.20.d	Kerosene Type Jet Fuel	52	MEUR
20	p10.b	Coking Coal	17	MEUR	70	p23.20.e	Kerosene	52	MEUR
21	p10.c	Other Bituminous Coal	17	MEUR	71	p23.20.f	Gas/Diesel Oil	52	MEUR
22	p10.d	Sub-Bituminous Coal	17	MEUR	72	p23.20.g	Heavy Fuel Oil	52	MEUR
23	p10.e	Patent Fuel	17	MEUR	73	p23.20.h	Refinery Gas	52	MEUR
24	p10.f	Lignite/Brown Coal	17	MEUR	74	p23.20.i	Liquefied Petroleum Gases	52	MEUR
25	p10.g	BKB/Peat Briquettes	17	MEUR	75	p23.20.j	Refinery Feedstocks	52	MEUR

26	p10.h	Peat	17	MEUR	76	p23.20.k	Ethane	52	MEUR
27	p11.a	Crude petroleum and servi	18	MEUR	77	p23.20.l	Naphtha	52	MEUR
28	p11.b	Natural gas and services	19	MEUR	78	p23.20.m	White Spirit & SBP	52	MEUR
29	p11.b.1	Natural Gas Liquids	19	MEUR	79	p23.20.n	Lubricants	52	MEUR
30	p11.c	Other Hydrocarbons	20	MEUR	80	p23.20.o	Bitumen	52	MEUR
31	p12	Uranium and thorium ores	21	MEUR	81	p23.20.p	Paraffin Waxes	52	MEUR
32	p13.1	Iron ores	22	MEUR	82	p23.20.q	Petroleum Coke	52	MEUR
33	p13.20.11	Copper ores and concentra	23	MEUR	83	p23.20.r	Non-specified Petroleum P	52	MEUR
34	p13.20.12	Nickel ores and concentra	24	MEUR	84	p23.3	Nuclear fuel	53	MEUR
35	p13.20.13	Aluminium ores and concen	25	MEUR	85	p24.a	Plastics, basic	54	MEUR
36	p13.20.14	Precious metal ores and c	26	MEUR	86	p24.a.w	Secondary plastic for tre	131	MEUR
37	p13.20.15	Lead, zinc and tin ores a	27	MEUR	87	p24.b	N-fertiliser	55	MEUR
38	p13.20.16	Other non-ferrous metal o	28	MEUR	88	p24.c	P- and other fertiliser	56	MEUR
39	p14.1	Stone	29	MEUR	89	p24.d	Chemicals nec	57	MEUR
40	p14.2	Sand and clay	30	MEUR	90	p24.e	Charcoal	57	MEUR
41	p14.3	Chemical and fertilizer m	31	MEUR	91	p24.f	Additives/Blending Compon	57	MEUR
42	p15.a	Products of meat cattle	32	MEUR	92	p24.g	Biogasoline	57	MEUR
43	p15.b	Products of meat pigs	33	MEUR	93	p24.h	Biodiesels	57	MEUR
44	p15.c	Products of meat poultry	34	MEUR	94	p24.i	Other Liquid Biofuels	57	MEUR
45	p15.d	Meat products nec	35	MEUR	95	p25	Rubber and plastic produc	58	MEUR
46	p15.e	products of Vegetable oil	36	MEUR	96	p26.a	Glass and glass products	59	MEUR
47	p15.f	Dairy products	37	MEUR	97	p26.w.1	Secondary glass for treat	132	MEUR
48	p15.g	Processed rice	38	MEUR	98	p26.b	Ceramic goods	60	MEUR
49	p15.h	Sugar	39	MEUR	99	p26.c	Bricks, tiles and constru	61	MEUR

Table S1 ctd: Product classification of the I/O model used. Part II, index 100-199.

Index	Code	DESIRE Product List (200)	Position in I/O model	Unit	Index	Code	DESIRE Product List (200)	Position in I/O model	Unit
100	p26.d	Cement, lime and plaster	62	MEUR	150	p45.w	Secondary construction ma	142	MEUR
101	p26.d.w	Ash for treatment, Re-pro	133	MEUR	151	p50.a	Sale, maintenance, repair	98	MEUR
102	p26.e	Other non-metallic minera	63	MEUR	152	p50.b	Retail trade services of	99	MEUR
103	p27.a	Basic iron and steel and	64	MEUR	153	p51	Wholesale trade and commi	100	MEUR
104	p27.a.w	Secondary steel for treat	134	MEUR	154	p52	Retail trade services, e	101	MEUR
105	p27.41	Precious metals	65	MEUR	155	p55	Hotel and restaurant serv	102	MEUR
106	p27.41.w	Secondary preciuos metals	135	MEUR	156	p60.1	Railway transportation se	103	MEUR
107	p27.42	Aluminium and aluminium p	66	MEUR	157	p60.2	Other land transportation	104	MEUR
108	p27.42.w	Secondary aluminium for t	136	MEUR	158	p60.3	Transportation services v	105	MEUR
109	p27.43	Lead, zinc and tin and pr	67	MEUR	159	p61.1	Sea and coastal water tra	106	MEUR
110	p27.43.w	Secondary lead for treatm	137	MEUR	160	p61.2	Inland water transportati	107	MEUR
111	p27.44	Copper products	68	MEUR	161	p62	Air transport services	108	MEUR
112	p27.44.w	Secondary copper for trea	138	MEUR	162	p63	Supporting and auxiliary	109	MEUR

113	p27.45	Other non-ferrous metal p	69	MEUR
114	p27.45.w	Secondary other non-ferro	139	MEUR
115	p27.5	Foundry work services	70	MEUR
116	p28	Fabricated metal products	71	MEUR
117	p29	Machinery and equipment n	72	MEUR
118	p30	Office machinery and comp	73	MEUR
119	p31	Electrical machinery and	74	MEUR
120	p32	Radio, television and com	75	MEUR
121	p33	Medical, precision and op	76	MEUR
122	p34	Motor vehicles, trailers	77	MEUR
123	p35	Other transport equipment	78	MEUR
124	p36	Furniture; other manufact	79	MEUR
125	p37	Secondary raw materials	140	MEUR
126	p37.w.1	Bottles for treatment, Re	141	MEUR
127	p40.11.a	Electricity by coal	80	MEUR
128	p40.11.b	Electricity by gas	81	MEUR
129	p40.11.c	Electricity by nuclear	82	MEUR
130	p40.11.d	Electricity by hydro	83	MEUR
131	p40.11.e	Electricity by wind	84	MEUR
132	p40.11.f	Electricity by petroleum	85	MEUR
133	p40.11.g	Electricity by biomass an	86	MEUR
134	p40.11.h	Electricity by solar phot	87	MEUR
135	p40.11.i	Electricity by solar ther	88	MEUR
136	p40.11.j	Electricity by tide, wave	89	MEUR
137	p40.11.k	Electricity by Geothermal	90	MEUR
138	p40.11.l	Electricity nec	91	MEUR
139	p40.12	Transmission services of	92	MEUR
140	p40.13	Distribution and trade se	93	MEUR
141	p40.2.a	Coke oven gas	94	MEUR
142	p40.2.b	Blast Furnace Gas	94	MEUR
143	p40.2.c	Oxygen Steel Furnace Gas	94	MEUR
144	p40.2.d	Gas Works Gas	94	MEUR
145	p40.2.e	Biogas	94	MEUR
146	p40.2.1	Distribution services of	94	MEUR
147	p40.3	Steam and hot water suppl	95	MEUR
148	p41	Collected and purified wa	96	MEUR
149	p45	Construction work	97	MEUR
163	p64	Post and telecommunicatio	110	MEUR
164	p65	Financial intermediation	111	MEUR
165	p66	Insurance and pension fun	112	MEUR
166	p67	Services auxiliary to fin	113	MEUR
167	p70	Real estate services	114	MEUR
168	p71	Renting services of machi	115	MEUR
169	p72	Computer and related serv	116	MEUR
170	p73	Research and development	117	MEUR
171	p74	Other business services	118	MEUR
172	p75	Public administration and	119	MEUR
173	p80	Education services	120	MEUR
174	p85	Health and social work se	121	MEUR
175	p90.1.a	Food waste for treatment:	143	MEUR
176	p90.1.b	Paper waste for treatment	144	MEUR
177	p90.1.c	Plastic waste for treatme	145	MEUR
178	p90.1.d	Intert/metal waste for tr	146	MEUR
179	p90.1.e	Textiles waste for treatm	147	MEUR
180	p90.1.f	Wood waste for treatment:	148	MEUR
181	p90.1.g	Oil/hazardous waste for t	149	MEUR
182	p90.2.a	Food waste for treatment:	150	MEUR
183	p90.2.b	Paper waste for treatment	151	MEUR
184	p90.2.c	Sewage sludge for treatme	152	MEUR
185	p90.3.a	Food waste for treatment:	153	MEUR
186	p90.3.b	Paper and wood waste for	154	MEUR
187	p90.4.a	Food waste for treatment:	155	MEUR
188	p90.4.b	Other waste for treatment	156	MEUR
189	p90.5.a	Food waste for treatment:	157	MEUR
190	p90.5.b	Paper for treatment: land	158	MEUR
191	p90.5.c	Plastic waste for treatme	159	MEUR
192	p90.5.d	Inert/metal/hazardous was	160	MEUR
193	p90.5.e	Textiles waste for treatm	161	MEUR
194	p90.5.f	Wood waste for treatment:	162	MEUR
195	p91	Membership organisation s	122	MEUR
196	p92	Recreational, cultural an	123	MEUR
197	p93	Other services	124	MEUR
198	p95	Private households with e	125	MEUR
199	p99	Extra-territorial organiz	126	MEUR

Legend:

🟦 Main product, monetary units

🟦 Main product, monetary units, aggregated

🟨 Waste treatment service, monetary units

S1-2: EXIOBASE v2.2.0 list of regions and regional aggregation

Table S2 lists the 48 countries and regions of the MR-SUT, the split of the world into 20 countries and regions used in the I/O model for this work, and the match between the two classifications. The EXIOBASE MR-SUT v2.2.0 was aggregated using the aggregation vector below and the regional aggregation routine ‘pySUT.aggregate_regions’ of the pySUT class (Pauliuk 2014).

Table S2: Regional classification of the CREEA MR-SUT and the aggregation to 20 regions.

CREEA region no	Symbol	Name	Target index
1	AT	Austria	7
2	BE	Belgium	6
3	BG	Bulgaria	7
4	CY	Cyprus	7
5	CZ	Czech Republic	7
6	DE	Germany	7
7	DK	Denmark	6
8	EE	Estonia	7
9	ES	Spain	6
10	FI	Finland	7
11	FR	France	6
12	GR	Greece	7
13	HU	Hungary	7
14	IE	Ireland	6
15	IT	Italy	6
16	LT	Lithuania	7
17	LU	Luxembourg	6
18	LV	Latvia	7
19	MT	Malta	6
20	NL	Netherlands	6
21	PL	Poland	7
22	PT	Portugal	6
23	RO	Romania	7
24	SE	Sweden	6
25	SI	Slovenia	7
26	SK	Slovakia	7
27	GB	United Kingdom	6
28	US	United States	2
29	JP	Japan	15
30	CN	China	13
31	CA	Canada	1

New region index	New region name
1	Canada
2	US
3	Mexico
4	Brazil
5	South Africa
6	W.Europe
7	C.Europe
8	Russia
9	RoW M.East
10	Turkey
11	India
12	Korea
13	China
14	Indonesia
15	Japan
16	Oceania
17	RoW America
18	Row Europe
19	Row Asia/Oc
20	Row Africa

32	KR	South Korea	12
33	BR	Brazil	4
34	IN	India	11
35	MX	Mexico	3
36	RU	Russia	8
37	AU	Australia	16
38	CH	Switzerland	6
39	TR	Turkey	10
40	TW	Taiwan	13
41	NO	Norway	6
42	ID	Indonesia	14
43	ZA	South Africa	5
44	WA	RoW Asia-Pacific	19
45	WL	RoW America	17
46	WE	RoW Europe	18
47	WF	RoW Africa	20
48	WM	RoW Middle East	9

S1-3: Projection of future final demand for the 20 regions

Regional projections for total GDP growth between 2007 and 2050 were retrieved from the OECD and the World Bank (World Bank 2015; OECD 2015), and had to be broken down into the 163 sectors. This was done by using historic sector- and region-specific growth rates as proxy for future development. The EXIOBASE v3 MR-SUT tables for years 1995 and 2011 were used to determine the relative sectoral growth (EU DESIRE Project 2013). The tables were aggregated to the 20 regions used in this study, and the ratio of the final demands (noted for a given year FD^{year}), R_n, were calculated as follows for sector n:

$$R_n = \frac{FD_n^{2011}}{FD_n^{1995}} \qquad (eq.1)$$

Ratios at the world level were used because of some inconsistencies in the 1995 SUT, which made the values of many final demand categories unreliable. Moreover, assuming that future regional economic development will follow the same trend in the future as in the limited historic period might be misleading, because of new technology but also lifestyle and 'level of development' and income level. For those reasons we kept the product-specific growth at the world average to take into account and attenuate those effects. We therefore believe that a global, world average trend in individual sectors might more correctly reflect future economic development.

Since this increase is calculated over 16 years, we assumed that the relative yearly increase was $r_n = R_n^{1/16}$. This way, an average historical growth rate for each sector was determined.

Then we combined the estimates of future total GDP growth with the historic sector specific growth data. First, The 2007 final demand vector was extrapolated into the future using the historic sectoral growth ratios (r_n), to determine $FD^{elastic}$. Then, we used the average region specific GDP growth estimates from the OECD and the World Bank to determine the average growth of each sector in each region $FD_n^{GDP,t}$. Industry sectors and waste treatment sectors were treated as two separate sub-units, but we applied the same method. From the historic data the share of growth attributed sector *n* was calculated:

$$s_n = \frac{FD_n^{elastic}}{\sum_n^{\text{industry sector}} FD_n^{elastic}} \qquad (eq.2)$$

Finally, the sector-specific estimate for final demand, FD_n^t, was calculated by distributing a certain amount of the total GDP growth to the sector, using s_n as distribution coefficient of total growth.

$$FD_n^t = FD_n^{2007} s_n \sum_n^{\text{industry sector}} FD_n^{GDP,t} \qquad (eq.3)$$

The equations 1-3 provide the model to project the final demand of the background economic sectors. We consider that there is no final demand for cobalt as cobalt is only used by industries to produce goods.

S1-4: The hybrid I/O model and projection of future cobalt demand

S1-4.1: Hybridization of the MRIO model

S1-4.1.1: Regional cobalt demand:
We model cobalt demand by building a hybrid version of a multi-regional input-output model based on EXIOBASE. In the original version, cobalt supply is part of the 'Other non-ferrous metal' sector of EXIOBASE. In order to hybridize the model, cobalt demand in the different regions has to be estimated for 2007. Little data exists to estimate cobalt demand in different countries. Calculating apparent consumption of refined cobalt[1] in each region is attempted using USGS refined cobalt production data and the COMTRADE database for refined cobalt trade. However, trade data aggregates a lot of different products under code 810510 'Cobalt, unwrought, matte, waste or scrap, powders' that can have an important variation in terms of cobalt content: matte being an intermediate of metallurgy and unwrought can be thought as being almost pure cobalt (see also the report of cobalt market 2013 made by the Bureau de Recherches Géologiques et Minières (BRGM 2014) for a discussion of the COMTRADE codes for cobalt). And it is difficult to estimate an average content of cobalt in the reported trade flows to derive a meaningful apparent consumption for all regions, while matching at the same time the one reported by the USGS for the USA (USGS 2010a). The British Geological Survey also publishes data on production and imports/exports of cobalt oxide and metal (BGS 2010, 2009), but these are not available for all countries and not consistent enough to allow us to estimate meaningful apparent consumption, as according to these data, in 2007, Finland, for example, would have had an apparent consumption of cobalt of about 27 000 tons, which would have been about half of the global refined cobalt production that year.

Therefore another approach is undertaken to estimate cobalt demand by using some data provided by the Cobalt Development Institute (CDI) and some countries' report provided by USGS for 2004. Using those reports, we could even split the demand into different consuming sectors of cobalt. By assuming that the regional shares of global cobalt demand have remained roughly the same between 2004 and 2007 and by using the estimated sectoral use of cobalt in 2007, we determined 2007 demand for cobalt in the different regions and sectorsusing the RAS balancing algorithm[2].

Total demand for cobalt was estimated to around 49 100 tons by USGS in 2004 (USGS 2010a). Demand for China and Japan are taken from the USGS country reports for 2004 (USGS 2004, 2005) and are estimated to be respectively 9 500 and 12 600 tons, demand for the USA is about

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[1] Apparent consumption = Production + Imports - Exports

[2] https://en.wikipedia.org/wiki/Iterative_proportional_fitting

8 450 tons according to the USGS cobalt mineral yearbook of 2008 (USGS 2010a). Demand from Europe is taken from a CDI newsletter, which states that demand in Europe was 9 000 tons in 2004 with 80% corresponding to countries in the Western Europe region and 20% in the Central Europe region. Demand for the remaining regions is estimated using the continental share of cobalt demand provided by the CDI (The CDI 2005) shown in table S3, minus the demand that is already known for some regions. The remaining regions are attributed to the different continents as shown in table S3 and their respective demand is estimated based on the relative GDP share of the region in the continent (GDP data are taken from the World Bank).

The resulting figures are the estimated apparent consumption that may include build-up of strategic stocks or inventories, and therefore the estimated industrial usage of cobalt in 2007 by industries can be a little overestimated, which also may lead to an overestimation of the resulting projections of demand given by our model. Build-up of strategic stock or inventories is known for Japan, China, South Korea, and the USA (BRGM 2014; USGS 2005, 2010a; The CDI 2005). Even if the total size of strategic cobalt inventories is known, the amount stocked and destocked in a given year is usually not available and hence, the stock figures alone do not allow us to correct the demand (BRGM 2014).

Table S3: Apparent cobalt consumption by continent and model regions

Continent	Europe	Asia	America	Others
Share of cobalt demand	19%	61%	18%	2%
Model regions with estimation of demand	Western: 7 200 tons Central: 1 800 tons	China: 9 500 tons Japan: 12 600 tons	USA: 8 450 tons	
Model regions without estimation of demand	Turkey, RoW Europe	Russia, India, Korea, Indonesia, RoW Asia/Oceania	Canada, Mexico, Brazil, RoW America	RoW Middle East, Oceania, South Africa, RoW Africa

S1-4.1.2: Sectoral cobalt demand:

Final use data for cobalt in China, USA and Europe are available for 2004 (Table S4). The global final use is, however, unknown for 2004, and was assumed to be the same as 2005 and taken from (The CDI 2006).

Table S4: End use pattern of refined cobalt, 2004. Correspondence of IO sector number and name is below the table.

Type of applications	Attributed IO sector (cf. Table S1)	China (%)	USA (%)	Europe (%)	Global use 2005 (%)	Global use 2007 (%)
Colours Ceramics/enamels/ glass/plastics/ glazing	57	14	26,4	16,8	9	10
Tyres	57	-	-	9,1	8	6
Paint driers	57	-	-	7,9		
Catalysts	57	-	-	5,1	11	9
Plating	57	-	-	2,55	-	4
Recording materials	57	-	-	-	2	
Feedstuffs	57	-	-	1,25	-	
Others	57	10	0,7	-	-	-
Steels	69	-	8,5	7,9	-	-
Superalloy	69	-	43,2	16,8	22	22
Wear resistant/ hardfacing/ other alloys	71	-	7,4	10,2	8	6
Hard material	71	-	-	-	11	12
Cemented carbides/ cutting tools	71	11	9,1	15,1	-	
Magnets	71	8	4,7	5,5	7	6
Batteries	74	57	-	1,8	22	25
Total:		100	100	100	100	100

Sector 57: Chemicals n.e.c; Sector 69: Other nonferrous metals; Sector 71: Fabricated metal products; Sector 74: Manufacture of electrical machinery and apparatus n.e.c

It is assumed that the cobalt in form of alloys used in metallurgical purposes enters the economy through ‘Other non-ferrous metals’ (sector 69). As ‘Fabricated metal products’ (sector 71) when it is used in cutting tools and other semi-manufactured products. As ‘Chemicals n.e.c’ (sector 57) when the application requires a chemical form of cobalt, such as oxides or hydroxide (see table 6 in (The CDI 2007)). It is assumed that battery manufacturers are part of the

‘Manufacture of electrical machinery and apparatus n.e.c’ (sector 74) and that those manufacturers produce their own specific cobalt oxides that they need (for lithium batteries $LiCoO_2$ for example) and do not buy the chemicals directly from ‘Chemicals n.e.c’.
For regions where the sectoral use is not provided, an average end-use split for all other world regions is derived to meet the total global end-use of cobalt minus the amount used in the different sectors by China, the USA and Europe.
In this way the demand for cobalt per region and sector is determined for 2004. To estimate it for 2007, we assumed that the regional shares of cobalt demand were constant in between, that the global demand in 2007 equals the amount of refined cobalt produced in that year (no inventory changes), and that the end-use pattern for 2007 is as reported by the CDI (The CDI 2007). With these data, the RAS algorithm can be used to balance demand and supply for 2007, and the results are shown in table S5.

Table S5: Consumption of refined cobalt split by region and end use sector, 2007 (in tons).

Model region	Sector 57	Sector 69	Sector 71	Sector 74	Regional demand total
Canada	25	16	23	24	88
US	2520	4879	1887	0	9286
Mexico	18	11	17	17	63
Brazil	23	15	22	23	84
South Africa	23	15	22	23	84
Western Europe	3397	1994	2345	176	7913
Central Europe	849	499	586	44	1978
Russia	510	334	482	506	1832
RoW M.East	0	121	175	184	480
Turkey	42	28	40	42	152
India	486	318	460	482	1746
Korea	440	289	417	437	1582
China	2232	0	1691	6518	10440
Indonesia	170	111	160	168	609
Japan	3854	2526	3645	3822	13847
Oceania	67	44	63	66	240
RoW America	20	13	19	20	72
RoW Europe	23	15	22	23	84
RoW Asia/ Oceania	684	448	647	678	2457
RoW Africa	73	48	69	72	261
Total per sector	15457	11726	12792	13325	53300
Share per sector	0,29	0,22	0,24	0,25	1

Sector 57: Chemicals n.e.c; Sector 69: Other nonferrous metals; Sector 71: Fabricated metal products; Sector 74: Manufacture of electrical machinery and apparatus n.e.c

S1-4.1.3: Hybrid Supply and Use tables and hybrid MRIO model:

The hybrid SUT is built as follows. The background economic data correspond to the MR-SUT provided by EXIOBASE, aggregated to the 163 product groups listed in Table S1 and the 20 regions listed in Table S2. To the thus aggregated tables, one industry was added for each region: Refined cobalt production, supplying one main product: Refined cobalt, as shown in figure S1. Use of cobalt enters the table at the intersection between the domestic refined cobalt product and the domestic cobalt using industries. And supply of cobalt is set up as each domestic refined cobalt industry supply the total amount of cobalt used domestically. We did not determine a trade pattern for cobalt, since we are at this stage only interested in the global supply-demand balance for cobalt.

The hybrid MRIO model is built starting at the supply and use table level. To avoid double counting, background economic data needs to be corrected by the amount of disaggregated production happening in the foreground using cobalt price information and inputs to cobalt production shall also be taken out from the background. Here, this is however not done for three reasons: (1) the main issue being that the SUT structure does not match perfectly the estimated use of cobalt. For example, certain industries that we know are using cobalt, do not require any ‘Other non-ferrous metal’ in the SUT, and hence the cobalt flow cannot be disaggregated. (2) Estimating the price of a single commodity flow is difficult: price information that can be found for refined cobalt comes as market price, which is different than the valuation of the SUT in basic prices. (3) The global value of refined cobalt represents only about 2.5% of the global value of the ‘Other non-ferrous metal’ sectors, and hence, the error introduced by the hybridization is very small.

Cobalt is a commodity that had a volatile price throughout 2007 and therefore margin due to financial rents might be important and lead to an overestimation of the amount to be corrected in the background SUT. When trying to disaggregate the SUT with the average price data available, negative coefficients in the background SUT and negative cobalt demand were obtained during the projections. Therefore and because of reason (3) we decided to simply add cobalt demand to the foreground. An issue with not correcting the background is that the economy would ‘need to produce more’ in order to catch up with the increase activity generated in the foreground. However, we believe that in our case this is not much because the global value of refined cobalt represents only 2.5% of the global value of the ‘Other non-ferrous metal’ sectors[3].

Once the model is built as shown in figure S1, the industries and products are resorted to have bloc-matrices of regional SUT of identical shape. Each bloc now contains 164 industries/products instead of 163, where cobalt product and industry are in the first position. This is done in order to apply the routine psc_agg from the pySUT class to build the symmetric MRIO model using Comodity Technology Construct (Pauliuk 2014).

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[3] Moreover, this share is overestimated since based on a market price of 49.2 k€ per ton given by USGS, when the SUT is in basic price (without margin and taxes) and that since cobalt price was volatile around 2007 and therefore might include a high share of financial rent. This cobalt pricing issue might, at least partly, explain why correcting the background SUT lead to negative coefficients.

S1-4.1.4: Estimation of cobalt, copper and nickel demand:

Projection of demands for the different metals are extracted from the hybrid-MRIO results. The demands are given in ktons of metal contained in ore. For cobalt the demand extracted from the MRIO are in ktons of refined cobalt. To convert it to ktons of cobalt in ore the demand is multiplied by a factor 1.22 kg of cobalt in ore per kg refined cobalt[4], which is taken from USGS cobalt mine production and refined cobalt production for 2007 (USGS 2010a).

Copper and nickel ores and concentrates are already products in the EXIOBASE classification and monetary outputs are directly taken from the MRIO results. The amount of contained metal (in physical terms) in the regional output are estimated using a regional price calculated from the supply table (regional supply of ore and concentrate in monetary terms) and the regional mine production of copper and nickel given by USGS for 2007 (regional supply of ore and concentrate in physical terms) (USGS 2010b, 2009), and assuming region-specific average prices for Cu and Ni ores and concentrates. Here we therefore assume that the mining/refining and smelting processes in the supply chains of Cu and Ni are properly separated in the SUT: all the extracted ore is going through the separate smelting process in the I/O table. Even if a company extracts and refine the ore on site, it is assumed that the flow of ore to refined metal is captured in the SUT.

S1-5: Linear program and dynamic stock model of cobalt reserves

S1-5.1: Extraction model:

A linear program is applied to determine which mines will be exploited to supply the metals. The core equations of the model are shown below.

$$\begin{array}{lll} \text{minimize:} & \sum_m C_m^T \cdot P_m & \forall m \in M \\ \text{subject to:} & \sum_m G_m \cdot P_m = D & \forall m \in M \\ & P_m > 0 & \forall m \in M \\ & P_m \le L_m & \forall m \in M \end{array} \tag{0.1}$$

Where *M* is the number of mine types. C_m is a column vector representing the mining risk of mine type *m* and its length equals the number of regions. P_m is the mine production vector determined by the linear program. It gives the amount of ore extracted in mine type *m* in the different regions and it has the same length as C. G_m is the ore grades matrix of mine type *m*. It gives the average ore grade of the different metals (cobalt, copper and nickel in our case) in the ore of mine type *m* in the different regions and has dimension number of metals studied times the number of regions. *D* represents the demand of the different metals that need to be mined.

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[4] Only from USGS data, this value can vary between 1.22 for the cobalt mineral yearbook of 2007 and 1.37 for the one from 2011. 1.22 was kept as it is hard to know if this number reflects the amount of cobalt in ore taken out from the ground or the amount of cobalt in ore entering the mine.

The last two equations set the bounds for the production vector: it has to be positive and should be lower or equal to the mining capacity L_m that is a vector of the maximum amount of ore that can be extracted from mine type m in the different regions.
We are interested in assessing the future supply of cobalt, which is mostly extracted as by-product of copper and nickel mining. To reflect this by-product nature of cobalt, the model shown in equations 1.4 is solved by only considering copper and nickel demand. The obtained output vector P is then multiplied with the cobalt grade of the different mines to determine the amount of cobalt that can be supplied. The resulting cobalt output is compared with cobalt demand. An alternative scenario would be to say that in the future, more emphasis will be put on meeting cobalt demand upfront. In that case, cobalt demand enters the linear program along with copper and nickel demand.

The cost of mining in this model is not the economic cost but the investment risk that is determined as

100 - Investment Attractiveness Index (eq. 5)

as proxy. This index is provided by the Fraser Institute; it is based on annual survey of mining companies worldwide (Cervantes et al. 2014). It takes into consideration both the mineralogical attractiveness of a country and the policy perception. This index is based on a maximal score of 100, and the higher the score the higher a country's attractiveness. Therefore in our model the complement of the index is used (eq. 5). Results from the 2012 survey were used because of better country coverage than the 2007 survey. Regional average indices were calculated from the country-specific values using USGS 2012 data for nickel and copper. For multiple metal deposits, such as copper-nickel mines, the mine was added to either copper, nickel, or cobalt mining attractiveness, in that order.

It is worth noting that average ore grades also influence the cost of extraction: If the ore grade of two mines mining only copper differs by a factor of ten but both mines show the same cost for extracting one ton of ore, the model will choose the one with higher grade since it can meet the copper demand 10 times 'less risky' than the low grade mine.

S1-5.2: Modelling cobalt, copper and nickel reserves:

Cobalt is rarely extracted by itself, but is a by-product of nickel and copper mining. The only operating mine with cobalt as main product is the Bou Azzer mine in Morocco. Therefore cobalt supply is highly dependent on demand for nickel and copper as they represent the main revenue for the mining company exploiting the deposit. This by-product nature constrains the amount of cobalt that can be extracted and might lead to imbalances between supply and demand. This nature of cobalt supply is to be included in the model by distinguishing cobalt extracted for itself from Co as a co-product from Cu and Ni mining and by modelling demand for all three metals. To model resources of copper, nickel, and cobalt, seven types of deposits/mines were defined: deposit that consists of only cobalt, copper or nickel, the ones that have two co-products cobalt-copper, cobalt-nickel and copper-nickel and the deposits that allow extraction of the three metals together.

The assessment of resources for those mine types is performed using the extensive data gathered by Mudd and Jowitt (2014) and Mudd, Wend and Jowitt (2013), which consists of detailed information on all deposits, being currently exploited or not, that contain nickel and copper, respectively (Mudd & Jowitt, 2014; Mudd, Weng, & Jowitt, 2013). The two databases should overlap when copper and nickel are both present, however, the names and deposit sizes do not always correspond between the two datasets. In case of conflict, we use the information from the nickel database as it contains more recent data. The mines/deposits in the databases are split into the seven groups defined above. The amount of each of the three metals in each deposit is determined by the reported amount of ore and the ore grade of the different metals in presence.

Data gathered at the deposit/mine level in each countries are aggregated under the regions defined by the MRIO model and average concentrations for each metal are calculated in each regions for each type of mine. This inventory allows us to build the grade matrices for each mine type m, G_m, which give the amount of metal that can be extracted per kg of ore mined in each region and the reserves in ore in each types of mine m in each region, R_m.

The deposit databases given by (Mudd and Jowitt 2014) and (Mudd et al. 2013) do not provide the current rate of extraction of the deposits that are currently being exploited. This information, however, is necessary for us to derive the mining capacity of each region, i.e the maximal amount of metal that can be extracted in a year in a region. The USGS provides statistics for mine production for copper and nickel (USGS 2010b, 2009). These mine production statistics per country are aggregated into regions and serve as basis for our regional mining capacity estimates. Another issue is that the USGS does not report how much of the country production happens as co-product mining. Therefore mining capacity per mine type needs to be estimated somehow. We therefore assumed that, in a given region, mine production of a given metal is split proportionally into the different mine types according to the reserves contained in this type. For example, if a region produces copper, both from copper-only mines and copper-nickel mines and these copper mines have 10 times more copper in reserves than the copper-nickel mine, then mine production from copper-only mines is assumed to be 10 times larger than copper extraction from copper-nickel mines. Since global copper production is about 10 times larger than nickel production, it is assumed that Cu, Co-Cu, Co-Cu-Ni and Cu-Ni mines have copper as their main product, since it is likely that copper represents the main source of revenue and therefore mine capacity is constrained by copper demand. The assumption is applied to mines that extract Ni (without copper), using nickel production data.

This way of splitting total mining production into different deposit types is not the most accurate, and would benefit from detailed data on which mines and deposits are currently exploited and which deposits have not been developed yet.

Each year, resource depletion is determined by subtracting the mine production of the previous year from the reserves. New mine capacity is installed following some simple rules. First, each year, each mine type in each region increases its capacity by 3%. Furthermore, if the capacity utilization rate of a mine is higher than 80% and the mine has more than 20 years of operating time left at current capacity, then this mine is allowed to increase capacity by 20%. Finally, we make sure that the mining capacity cannot be bigger than the remaining ore reserves.

S1-6: Additional results

We have defined the following five scenarios according to the parameters listed in Table S6 and we use the nomenclature in the table when present the additional results below.

Table S6: Scenario definition for cobalt supply

Number	Sub	Description
1	**a)** cobalt is only extracted as by-product (is not included in the optimisation routine)	Mining cost different in each regions
	b) cobalt needs to be supplied (is included in optimisation routine and global extraction of cobalt shall equal global cobalt demand)	
2	**a)** cobalt is only extracted as by-product (is not included in the optimisation routine)	Mining cost is the same in all regions
	b) cobalt needs to be supplied (is included in optimisation routine and global extraction of cobalt shall equal global cobalt demand)	
3	**a)** cobalt is only extracted as by-product (is not included in the optimisation routine)	Mining cost in RoW Africa is set to 100 during 2020-2035 and ramp-down of capacity from capacity 2020 to 5% of capacity 2020 over 2023 until 2029 and ramp-up back to 80% of 2020 capacity in 2035
	b) cobalt needs to be supplied (is included in optimisation routine and global extraction of cobalt shall equal global cobalt demand)	
4	**a)** Copper demand is reduced by 20% in 2050	Primary copper demand is modified in the A matrix (cobalt is considered by-product only and mining cost differs in each regions)
	b) Copper demand is increased by 20% in 2050	
5	**a)** growth rate is slowed down by 20% in 2050	GDP growth is 'slowed down' or 'speed up' (cobalt is considered by-product only and mining cost differs in each regions)
	b) growth rate is speed down by 20% in 2050	

S1-6.1: Copper and Nickel demand:

Figure S2 presents the projections of annual global copper and nickel in ore demand according to the different scenarios.

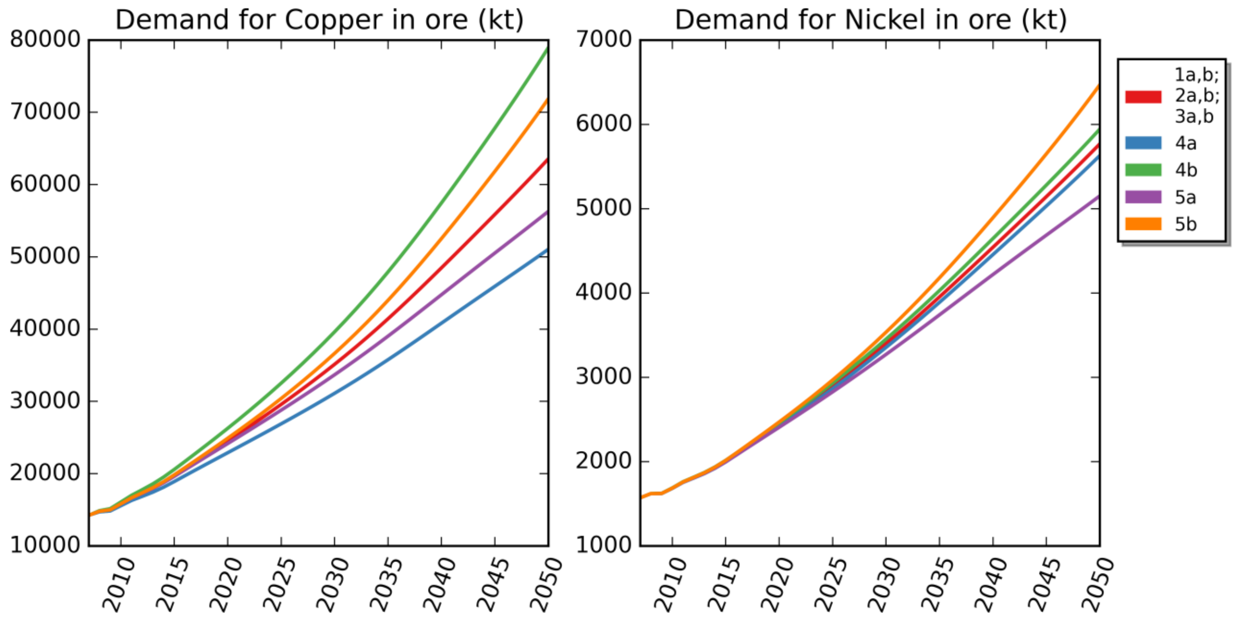

Figure S2: Annual global copper and nickel demand in kt given by the hybrid MRIO model for different scenarios (scenarios 1, 2 and 3 have the same demand shown in red)

S1-6.2: Global mining risk by 2030 for all scenarios:

Table S7 shows the minimized global mining risk in 2030. It can be seen that matching cobalt supply in the optimization routine has little effect on the global mining risk (compare scenarios 1a and 1b and 3a and 3b). However, changing copper and nickel demand has a lot of effect (scenarios 4 and 5) because the amount of ore that needs to be extracted to satisfy demand are much larger that for cobalt. It can be concluded that once mines are open the mining industry could accommodate easily the supply of cobalt, however mining risk could be an important factor to consider when opening new copper and/or nickel mines, which in return could constrain future supply of cobalt

Table S7: Minimized mining risk in 2030 for all scenarios.

	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b
Minimized global mining risk in 2030 (10^8)	2,44	2,47	0,65	0,65	2,36	2,37	2,04	2,71	2,28	2,41

Scenarios 2a and 2b show much lower global mining risk because it is set to 1 for each region and mine types.

S1-6.3: Reserves for scenarios 1a, 1b and 3a:

Figures S3 and S4 show the reserves of cobalt, copper, and nickel for scenarios 1a, 1b and 3a by region (Fig. S3) and deposit type (Fig. S4).

As it can be seen, scenario 1a will favorably extract cobalt from RoW Africa and from cobalt-copper deposits as these are the main cobalt resources in that region. In scenario 1b we can see that because we force the optimization routine to supply just the right amount of cobalt, but at a higher risk than scenario 1a, resources in RoW Africa and RoW America are depleted at a lower rate.

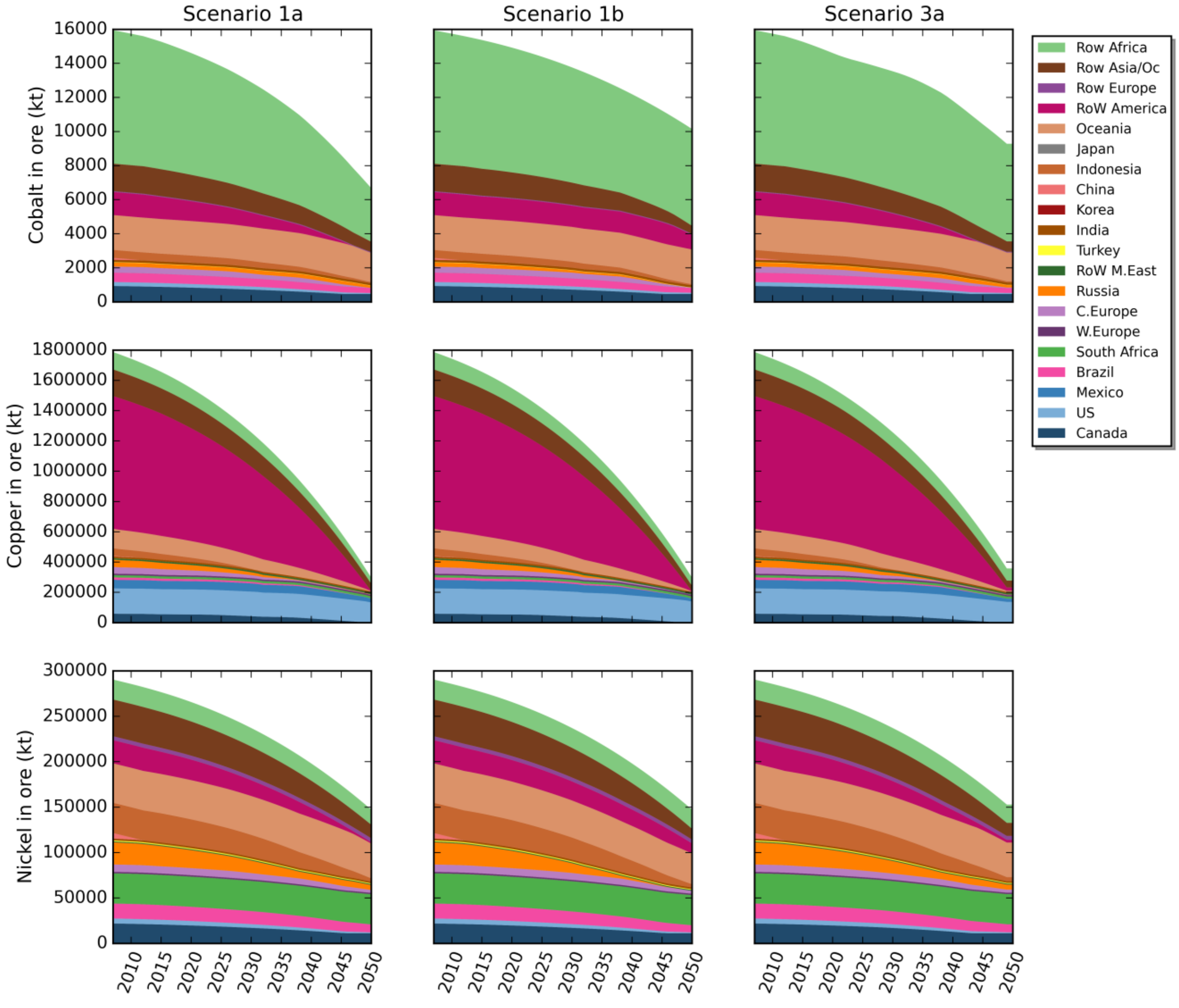

Figure S3: Reserves of cobalt, copper and nickel in ore in the different regions.

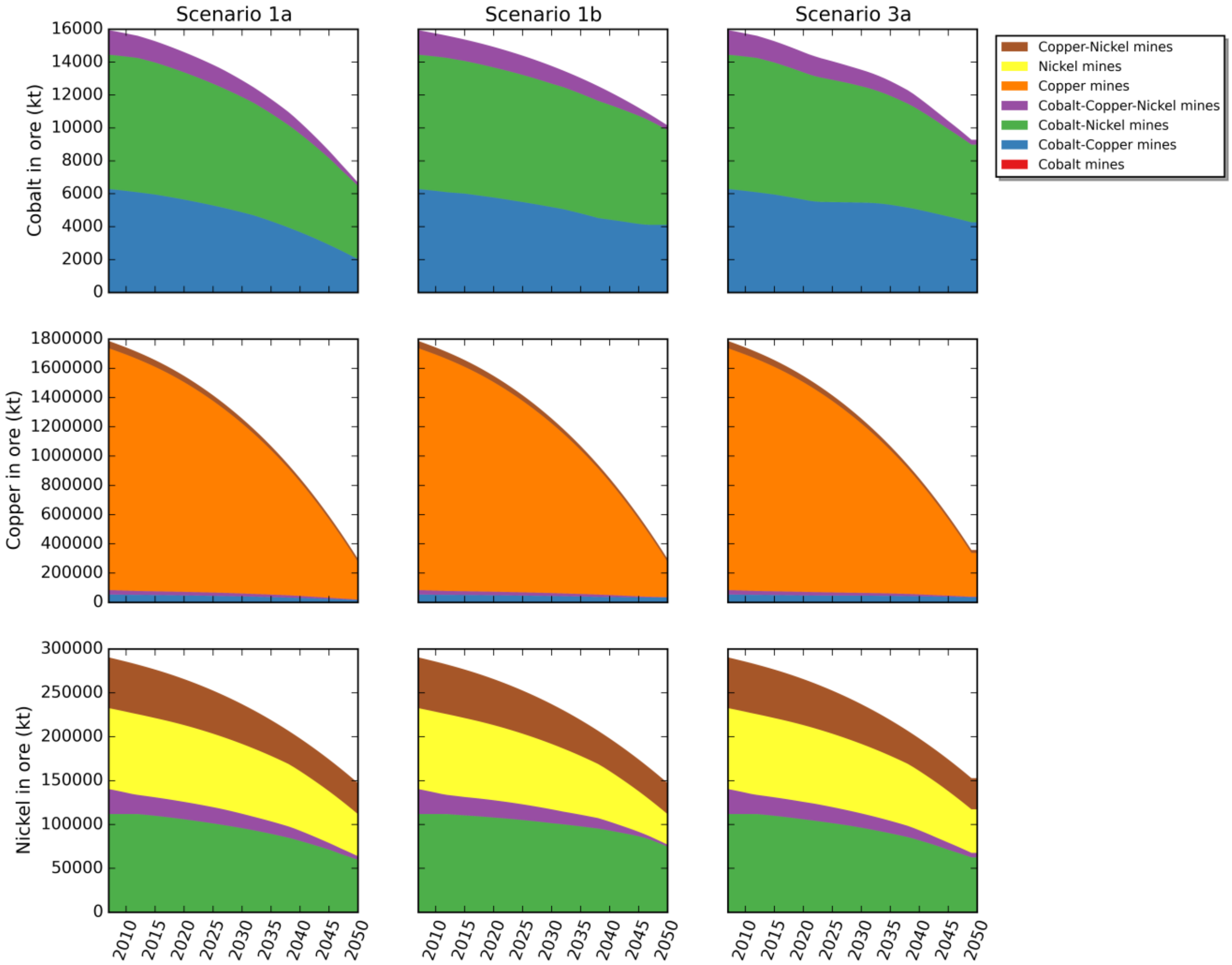

Figure S4: Reserves of cobalt, copper and nickel in ore in the different mine types.

S1-6.4: Mining capacity of scenario 3a (supply dropout in Africa 2020-2035):

As it can be seen from figure S5, which shows the mining capacity of the different regions and mine types, there is enough mining capacity installed throughout the shock period of 2020-2035 to supply cobalt, copper and nickel, even though shortages of cobalt supply could occur during that period because not all available cobalt can be economically extracted from the by-products of copper and nickel mining. That means that redistributing the mining output of RoW Africa onto the other world regions would be possible but come with a higher investment risk than in the base scenario 1.

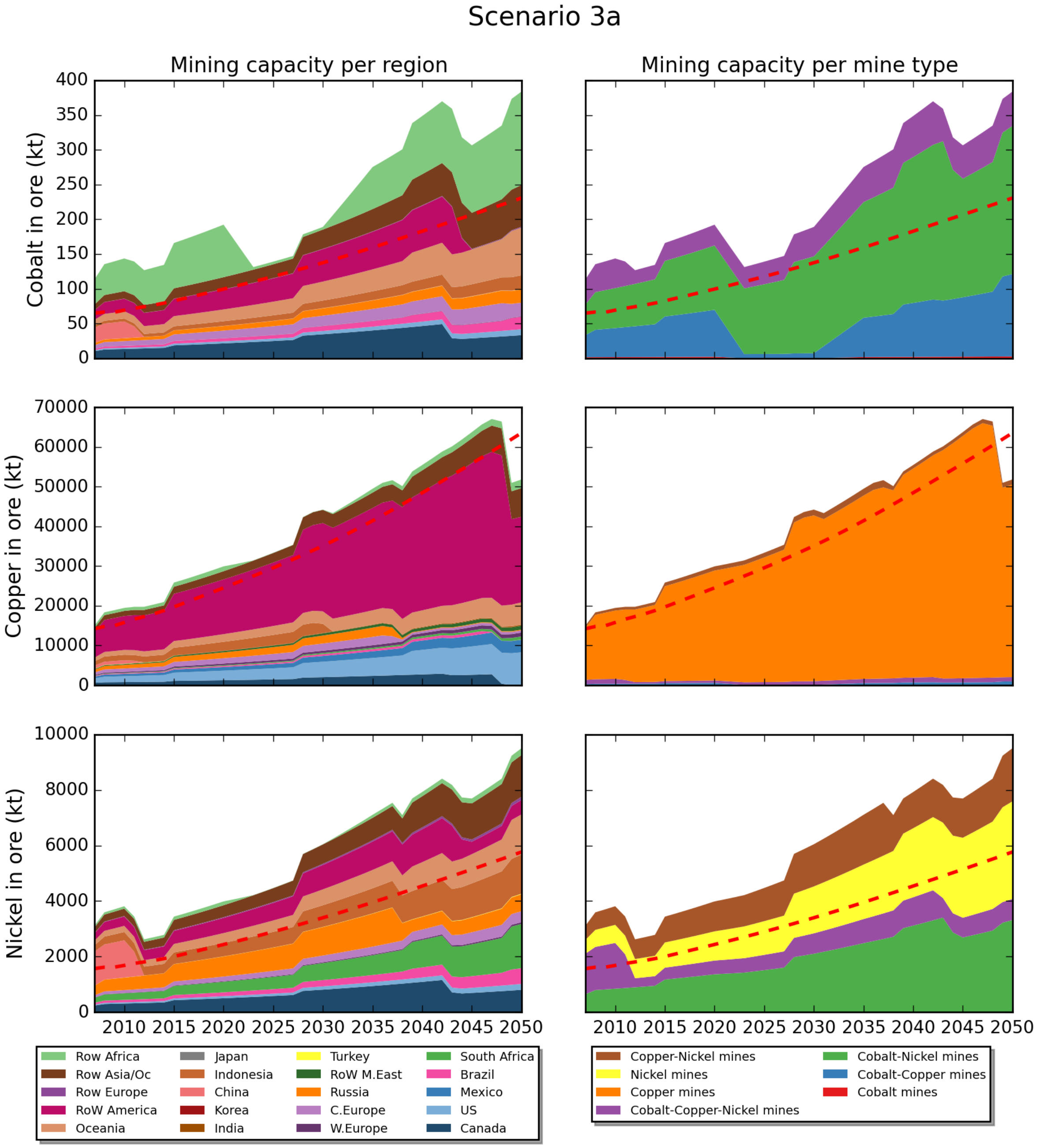

Figure S5: Mining capacity of cobalt, copper and nickel for scenario 3a, split across regions and mine types.

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