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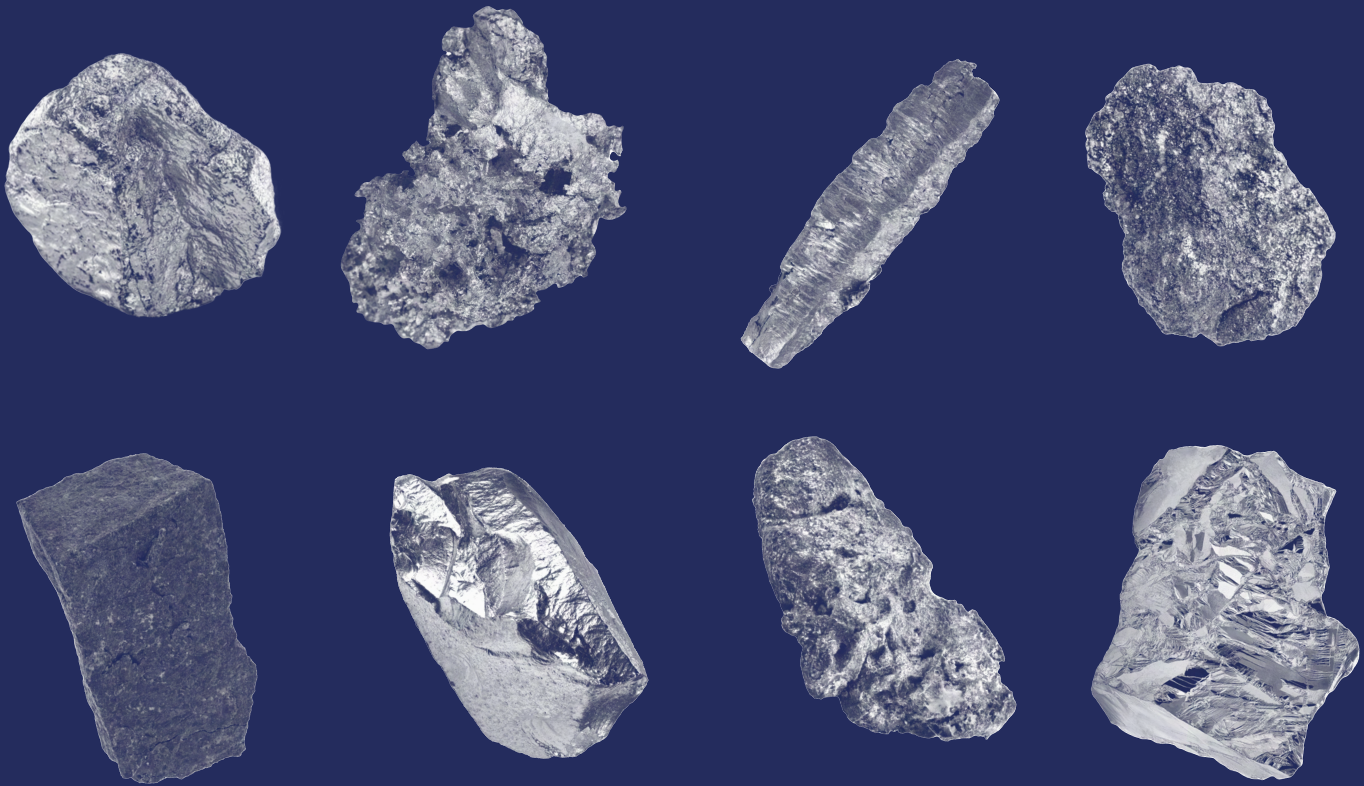
CRITICAL RAW MATERIALS FOR THE ENERGY TRANSITION IN THE EU:

HOW CIRCULAR ECONOMY APPROACHES CAN INCREASE SUPPLY SECURITY FOR CRITICAL RAW MATERIALS



FACTSHEETS ON
CRITICAL RAW MATERIALS

OCTOBER 2022

STUDY OVERVIEW

PURPOSE:

The EU is committed to the clean energy transition. This transition will require significant amounts of raw materials to create the infrastructure for electrification and clean energy production. This study highlights the importance and the opportunities for circular economy approaches to enable this transition. It demonstrates the increased resilience that can be gained in the context of ongoing geopolitical crises.

METHODOLOGY:

- Synthesis of published research on international value chain dependencies of the EU with particular focus on materials (raw and processed) that are crucial for the green energy transition. (Lithium, Nickel, Cobalt, Copper, Graphite, Silicon, Platinum Group Metals, Rare Earth Elements).
- Synthesis of published research on circular economy practices and legislative intervention points to ensure sustainable use of these raw materials and their continued stewardship in the European economy.

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KU Leuven for their 2022 milestone study "Metals for Clean Energy: Pathways to solving Europe's raw materials challenge". Besides countless other sources that were used in the making of this work, this report stands out as particularly relevant.

DATE:

June – September 2022

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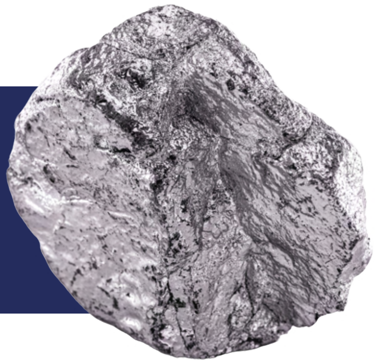
COBALT



CRITICAL METAL IN LITHIUM-ION EV BATTERIES; MOSTLY MINED IN THE DRC AND REFINED IN CHINA. ALTHOUGH DEMAND OUTLOOK IS UNCERTAIN AS BATTERY TECHNOLOGIES EVOLVE, BY 2050, 65% OF EU DEMAND COULD BE MET THROUGH RECYCLING

OVERVIEW

MATERIAL DEMAND

- **Global demand** to grow from 135kt in 2020 to 270-370kt by 2030 and up to 500-800 kt by 2050 – out of this 130-210kt in 2030, 270-600kt in 2050 are **needed for the energy turnaround.**[1]
- **EU cobalt** demand could grow from 20kt in 2020 to 30-50kt in 2030 and 80-100kt in 2050. **EU cobalt demand for the energy transition** will require 10-20kt in 2030 and 50-60kt in 2050.[1]
- **EU primary demand will rise rapidly until 2040**, when secondary sources become available from recycling of EV batteries; **By 2050 65% of the EU's overall need could be met by supply from secondary cobalt** from end-of-life (EOL) EV batteries.[2]
- However there is a **demand shift away from cobalt within EV batteries towards other technologies.**[4]

PRODUCTION

- **Mostly mined in Democratic Republic of Congo (DRC)** (74% of global supply); two other top suppliers are **Cuba and Russia** (together the three countries provide more than 80% of global supply)[1]
- **Mostly produced/refined in China** (68%), with Finland, Canada and Norway being the other top suppliers[1]
- **The EU supplies only 10% of cobalt from domestic mining activities**, which are projected to reduce output in the future[1]
- **The EU's refining operations are placed in Finland and Belgium**, supplying ~70% of current domestic demand, but no expansion planned[1]
- **tCO_2 per tonne of metal: 5 - 38**

MAIN PRODUCTS AND USE CASES

- **Application in the clean energy transition:** majority in EV batteries up to 70% [1,3,5] by 2050, limited amount in battery storage, wind turbines, solar power, bioenergy, hydrogen production and nuclear production facilities[1]
- **Application outside the clean energy transition:** superalloys (36%), carbides and diamond tools (14%), pigments and inks (13%), catalysts (12%) and magnets (7%)[3]

VALUE CHAIN CHARACTERISTICS

- **Top 3 players held almost half of total cobalt production in 2019** (Glencore 27%, Shalina Resources 10%, China Molybdenum 9%)[4]
- Cobalt is a **by-product of copper and nickel mining**[5]
- **The EU currently consumes relatively low levels of cobalt** – however building a battery value chain (esp. for cathode production) would increase demand[1]

ASSOCIATED RISKS IN THE BUSINESS AS USUAL (BAU) SCENARIO AND OPPORTUNITIES IN THE CIRCULAR ECONOMY (CE) SCENARIO

SUPPLY RISK:

- The disruptive growth in global demand due to the clean energy transition might lead to supply constraints by 2030 - 2040 due to insufficient mining projects to meet the speed of the clean energy transition (not a raw materials supply but production scaling problem)[1]
- The global energy transition requires an annual average growth rate of 4-6% of cobalt supply[1] (in the BAU scenario without CE lever reduction) - however the growth rate for its primary mined commodities copper and nickel is projected to be slower with only 3-4% per year[1]
- The EU will need to import or produce more cobalt in the next decade until secondary material becomes available – potential need for diversification of supply[1]

ENVIRONMENTAL RISKS:

- 80% of the area where cobalt is mined are at biodiversity risk[1] (DRC as primary cobalt supplier is a country with a high biodiversity risk)
- Carbon emissions from energy-intensive processing of refined cobalt (mostly in China powered by coal)

SOCIAL RISKS:

- Fundamental human rights and poor working conditions in extraction area[5]

OPPORTUNITIES:

- Creation of jobs in the recycling industry through increased need for secondary material
- Increased supply independence by strengthening domestic production capacities for cobalt-cathode material

COBALT: CIRCULAR ECONOMY LEVERS

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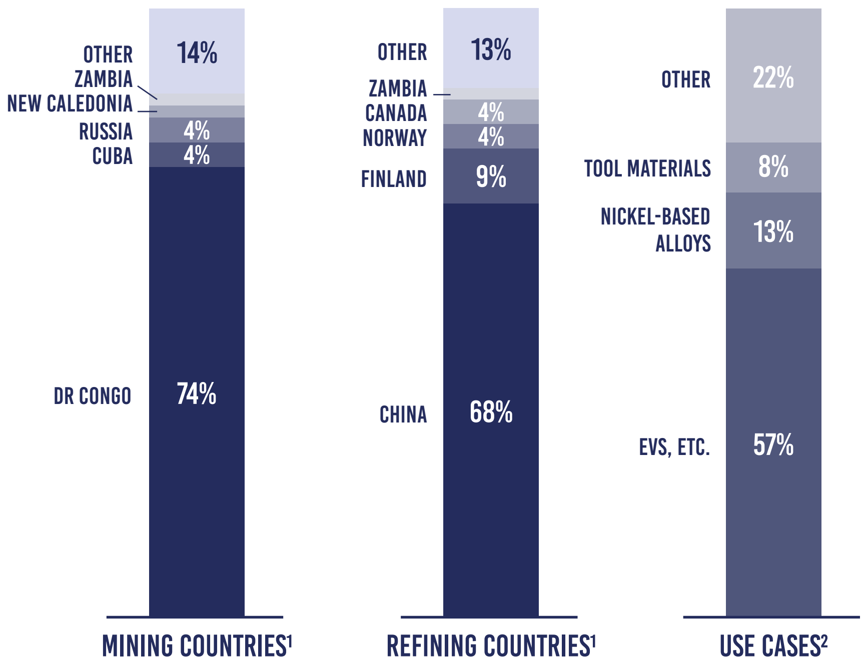
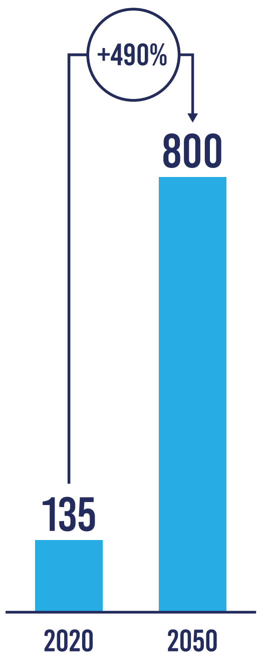
USE CASE	LEVER 1 RETHINK	LEVER 2 REDUCE	LEVER 3 REUSE	LEVER 4 RECYCLE
ELECTRIC VEHICLES (EVS) **(FOR BATTERIES)** **(3-55%)**	Improved city design and promotion of public transport can reduce need for EVs/cobalt.[1] Mobility-as-a-Service innovations and car-sharing or car-pooling can reduce car ownership.[2]	Material efficiency (e.g. reduced battery size and increased efficiency) can reduce material demand by 16%.[2] Innovation in material mix (e.g., shift to lower or no cobalt batteries) can reduce need for cobalt in EVs.[4]	Up to ~20% of end of life batteries could be re-purposed for use in stationary applications, at up to 1/3 cost savings compared to new batteries.[5]	Global recycling rates ~5% today, expected 90% by 2050; could cover 20% of global demand by 2040, 30% by 2050.[6] By 2050 65% of EU's overall need could be met by supply from secondary cobalt from EOL EV batteries.[6] Batteries have a lifetime of 10 years[7] hence the effect of recycling will only then come into effect; in 2035-2040 fast growth of recycling industries would will lead to a softening and then to a limit of further primary demand by 2040.[6]

OVERVIEW VALUE CHAIN GLOBALLY IN 2020

VALUE CHAIN CHARACTERISTICS: MINING AND REFINING COUNTRIES AS WELL AS MOST POPULAR USE CASES (2020)



GLOBAL COBALT DEMAND [KT][1]



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OVERVIEW VALUE CHAIN GLOBALLY IN 2020:

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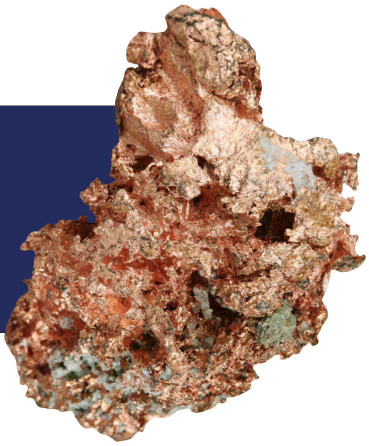
COPPER



AS A BASE METAL, COPPER IS NECESSARY FOR ALMOST ALL APPLICATIONS IN THE FIELD OF ENERGY TRANSITION. CO_2 FOOTPRINT OF SECONDARY COPPER IS 85% LESS THAN PRIMARY COPPER.

OVERVIEW

MATERIAL DEMAND

- **Global demand of copper** projected to grow from ~30Mt in 2020 to 45Mt by 2030 and up to 70Mt by 2050. This is a 51% increase in projected demand, compared with historical demand growth of 2.4% (1990-2020).[1]
- **EU copper demand** potentially grows from 4.3Mt in 2020 to 5Mt in 2030 and 6Mt in 2050. The EU's 2030 energy transition will require 1.25Mt of copper in 2030, with demand peaking in 2040.[1]

PRODUCTION

- **Global mining output:** projected to grow from 21Mt in 2020 to 23-24Mt in 2030 (Chile~30%, Peru ~10%). **Global refining capacity.** growing from 25Mt in 2020 to 31Mt in 2030 with China (~42%) being the major producer of refined copper.[1]
- **EU copper mining industry:** ~5% of global mining output, supplying up to 14% of domestic demand (0.8Mt/year); expected to decrease. **Domestic refining** covers 36% of domestic demand. Most EU imports come from Chile (19%) and Russia (19%).[1]
- **Secondary supply*:** increase from 10MT (in 2020) to 13 Mt (2030) to 25Mt (2050))[1]
- **tCO_2 per tonne of metal: 4.81**

MAIN PRODUCTS AND USE CASES

- **Biggest use cases:** electrical equipment (60%) and construction (20%); important for production of most technologies, i.e. solar PV, wind, EVs.[2]
- Current applications that are not part of the energy transition include: construction, infrastructure, industry, transport & mobility as well as consumer goods.[1]
- EU consumption of copper plateaued after a fall in 2008 financial crisis. The EU's rapid deployment of EVs etc. add to increase in demand.[1]

VALUE CHAIN CHARACTERISTICS

- Aluminum and copper are together the **most in-demand critical metals in terms of volume** – aluminum, copper, lithium, nickel and zinc add up to 80% of the critical metal demand for the global energy transition[1]
- In the EU 1Mt of copper scrap is exported each year.[1]
- **Out of the 10 biggest companies for copper production only one is in the EU** (Poland, 0,71Mt in 2020).[3]

ASSOCIATED RISKS IN THE BAU SCENARIO AND OPPORTUNITIES IN THE CE SCENARIO

SUPPLY RISK:

- Since the global energy transition is progressing faster than the mining project pipeline copper is at risk of a disruptive demand pull between now and 2050. This is because some projects either face economic or permitting challenges. There is a risk of a copper supply decline whilst demand is rising to supply the energy transition.[1]

OPPORTUNITIES:

- Educating consumers and providing infrastructure and incentives to increase recycling rate of e-waste could open up a significant "urban mine" for copper in the EU.[4]
- CO_2 footprint of secondary copper supply is 85% less than primary supply (expand recycling capacities) and 10% less if produced (mined and refined) in the EU than global.[1]

COPPER: CIRCULAR ECONOMY LEVERS

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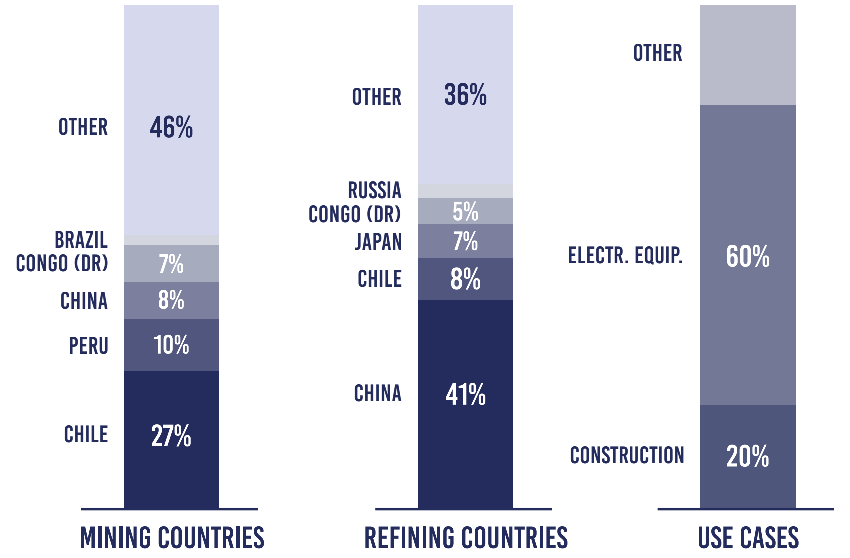
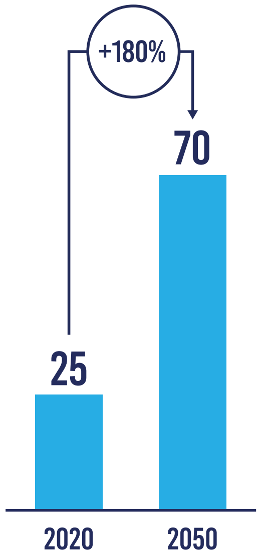
USE CASE	LEVER 1 RETHINK	LEVER 2 REDUCE	LEVER 3 REUSE	LEVER 4 RECYCLE
ELECTRICAL EQUIPMENT (60%) INCLUDING ELECTRICITY NETWORKS (EN, 6%), ELECTRIC VEHICLES (EVS, 6%) AND CONSUMER ELECTRONICS[8] (CE, ~7%), IN 2020	EVs: Autonomous and shared EV transport options can reduce need for individual car ownership[5] and dynamic road pricing can reduce traffic by over 10%.[6] CE: Extending lifetime of electrical products through consumer behaviour changes and product design shifts can decrease material demand. (1t copper ~100,000 mobile phones or 10,000 PCs).[9]	EVs: Material efficiency (e.g. reduced battery size and increased efficiency) can reduce material demand.[1] CE: Smaller and more efficient consumer electronics (i.e. smartphones) can reduce copper demand. [8]	EVs: Up to ~20% of end of life batteries could be re-purposed for use in stationary applications, at up to 1/3 cost savings compared to new batteries.[13] EC: Extending use of smartphones, TVs , washing machines and vacuum cleaners from actual to designed lifetime can extend it by almost 100.[7]	By 2050, additional recycling can reduce global primary demand for all copper use cases by 38%.[1] EVs: The End of Life Recycling Rate for EV batteries is assumed to be 70%.[1] CE: Barely 10% of smartphones get recycled better collection systems could increase this number.[8]
CONSTRUCTION (20% IN 2020)	Shared office models or virtual working reduce the demand for new construction and refits in commercial real estate. Compact living models for urban design and residential properties reduces material footprint of construction whilst retaining positive liveability.	Design improvements and efficiency gains in construction reduce material usage and wastage.	Post demolition reuse of construction materials, can be enabled through reuse marketplaces that broker buyers and sellers.	Theoretically, copper is 100% recyclable without loss in quality.[11] However, in practice it poses a problem in steel recycling.[12]

OVERVIEW VALUE CHAIN GLOBALLY IN 2020

VALUE CHAIN CHARACTERISTICS: MINING AND REFINING COUNTRIES AS WELL AS MOST POPULAR USE CASES (2020)



GLOBAL COPPER DEMAND [MT]



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RARE EARTH ELEMENTS (REE)

REE PLAY AN IMPORTANT ROLE FOR EV DRIVETRAINS AND WIND TURBINES. CHINA CONTROLS MOST OF THE PRODUCTION TODAY BUT BY 2050, GLOBAL SECONDARY SUPPLY IS EXPECTED TO SURPASS DEMAND BY OVER 200%.

OVERVIEW

MATERIAL DEMAND

- **Global REE[2] demand** is expected to be 2x higher in 2050 than today's available project pipeline; supply from recycling **exceeding demand by 208% in 2050:**
    - Dy: ~3kt today to 12-15kt by 2050
    - Nd: ~38kt today to 140-170kt by 2050
    - Pr: ~11kt today and 45-55kt by 2050
- **EU demand:**
    - Dy: <0.1kt in 2020 to 0.3-0.6kt by 2030, **decreasing by 2050 (total +2666%)**
    - Nd: ~0.2kt in 2020 to 2.5-5.0kt by 2030, **decreasing by 2050 (total +827%)**
    - Pr: ~0,1kt in 2020 to 0.7-1.4kt by 2030, **decreasing by 2050 (due to optimized intensities and secondary supply)[1]**

PRODUCTION

- **Global REE industry mining output** was 2.5kt (Dy), 35kt (Nd) and 11kt (Pr) in 2020 and is expected to reach at least 4kt (Dy), 55kt (Nd) and 15kt (Pr) in 2030
- With 62% of global supply, **China is the major extractor of REE**, followed by Burma, Australia and the USA. Even more prominently, with 87% China also holds a dominant share in the refining of REE.
- REEs can be divided into light REEs (i.e. Pr, Nd) and heavy REEs (i.e. Dy) with **China completely dominating the production for HREEs** – for LREEs there are four plants outside China.
- The EU imports appr. 80% of its REEs from China with **mining capacities currently being built up in Sweden.**[1]
- It takes 1 ton of mineral ore to extract 20kg REE.[2]
- **tCO_2 per tonne of metal: 17 (Nd), 19 (Pr), 60 (Dy).**[1]

MAIN PRODUCTS AND USE CASES

- There are **17 elements that belong to REE**; three elements (Nd, Dy, Pr) are of particular importance for the clean energy sector[3] and are used **for permanent magnets for Evs (15%), wind turbines (10%)4 and catalysts (23%).**[5]
- Only **Neodymium is used for both permanent magnets (pm) and catalysts** – with the greatest use case being for EVs, storage and wind turbines (share of Nd growing from 2% in 2020 to 20% in 2040).[6]

VALUE CHAIN CHARACTERISTICS

- Globally, **China controls ~90% of the REEs supply** with China Rare Earth Group accounting for 30% of China's total REE production.[7]
- The EU's rare earths demand is dependent on its success in **establishing a permanent magnets production industry**.[1]
- **By 2050 there will be a huge excess (208%) from secondary REE** available compared with the EUs current industrial ambitions for manufacturing permanent magnets.[1]

ASSOCIATED RISKS IN THE BAU SCENARIO AND OPPORTUNITIES IN THE CE SCENARIO

ECOLOGICAL RISKS:

- Since REEs are mined using acids, **poisoned sludge remains in the ground** // permanent **risk of radioactivity** leakage, as many rare earth ores contain radioactive substances // mining of REE leads to **2,000-20,000t waste per ton metal produced.**[1]
- REE require intense processing. The process is largely electrified, but with the majority of production taking place in China where it is coal-based the carbon footprint is very high.[8]

SOCIAL RISKS:

- **Illegal mining and concerns about poor worker safety and human rights conditions** are reported about some mines in China.[1]

OPPORTUNITIES:

- Increased efforts to establish a recycling value chain in the EU could help to make use of the oversupply in 2050.[1]

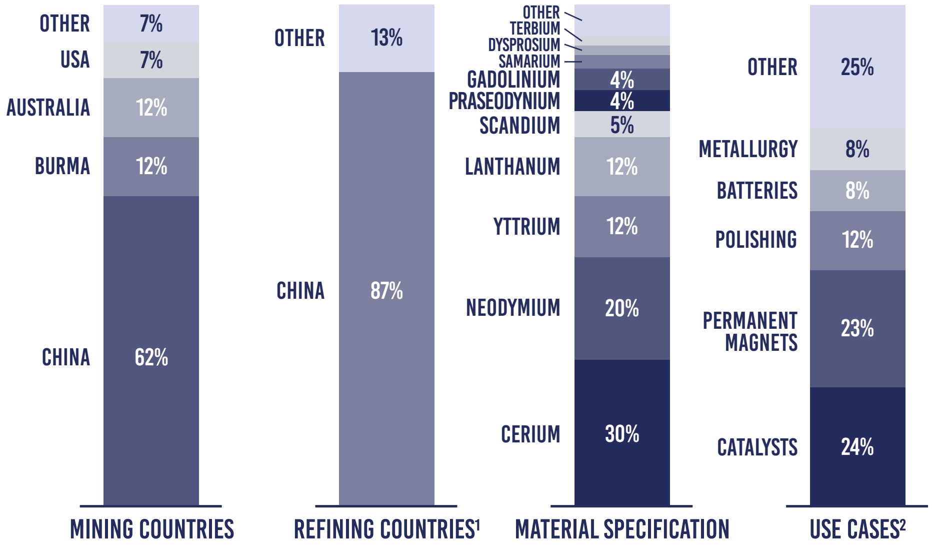
REE'S: CIRCULAR ECONOMY LEVERS

S Y S T E M I Q

USE CASE	LEVER 1 RETHINK	LEVER 2 REDUCE	LEVER 3 REUSE	LEVER 4 RECYCLE
AUTOCATALYSTS (23% IN 2020)	Not producing autocatalysts anymore will make this REE use case obsolete.	REE containing catalyst support can be substituted by aluminum oxide catalyst support, keeping the same performance.[9]	N/A	It is possible to recover more than 85% of Cerium from a spent automotive exhaust catalyst.[10] Overall recovery rate of REE is more than 90%.[11]
PERMANENT MAGNETS (EVS (15%) AND WIND TURBINES (10%) IN 2020)	Improved city design and promotion of public transport can reduce need for EVs. Change in technology consumption (e.g., shared economy) can reduce car ownership. Dynamic road pricing can reduce traffic by over 10%.[12]	EVs: Increasing efficiency can reduce material demand by up to 16%.[12] Worldwide, about 76% of all offshore wind turbines run on (REE based) permanent magnets.[13] The alternative to REE based generators are electrically excited synchronous generators that work without REEs, hence can replace them but are bigger for the same power (at least onshore).[14]	Restoring and renovating existing built environment infrastructure and reusing available materials can reduce overall demand for building materials like stainless steel.	By 2050, additional recycling can reduce global primary demand for all REE use cases by 16% (dy), 21% (nd) and 10% (pr).[1] Wind turbines: An end of life recycling rate of 90% is considered for REE permanent magnets, potentially leading to 2kt of dy, 15kt of nd and 4kt of pr for scondarey supply in 2050, covering up to 13%, 9% and 7% of 2050 demand.[1]

OVERVIEW VALUE CHAIN GLOBALLY IN 2020

VALUE CHAIN CHARACTERISTICS: MINING AND REFINING COUNTRIES AS WELL AS MOST POPULAR USE CASES (2020)



GLOBAL REE[3] DEMAND [KT]

1: refined Rare Earth Oxide supply 2018; **2:** 2017; **3:** Dy, Nd, Pr **Source:** Source: KU Leuven (2022): Metals for Clean Energy; Goodenough, K. M.; Wall, F.; Merriman, D. (2017)[16] ; Leod , C. L.; Shaulis , B. J. (2018)[17]

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GRAPHITE

CRITICAL METAL IN LITHIUM-ION EV BATTERIES AND LOW-CARBON STEELMAKING; DEMAND OUTLOOK IS UNCERTAIN AS BATTERY TECHNOLOGIES EVOLVE; MOSTLY MINED AND REFINED IN CHINA WITH POTENTIAL FOR INCREASED PRODUCTION IN THE EU.

OVERVIEW

MATERIAL DEMAND

- **Under a high-growth scenario, global graphite demand to grow 9x by 2050** (vs. 2020) - from 1000 kt to 9,300 kt in 2050).[1-4]
- **Under a high-growth scenario, EU graphite demand to grow 22x from 86 kt in 2020 to 1,940 kt in 2050.**[1-4]
- **Graphite market share as EV battery anode material to decrease post 2030**, due to silicon & lithium metal anodes.[1]

PRODUCTION

- **China dominates both natural graphite mining (ca. 80%), synthetic and natural graphite processing (ca. 65%), and battery anode production (ca. 84%).**[5] the EU imports ~47% of graphite & ~75% of battery cells from China.[6,7]
- Global natural graphite mining is increasing: Mozambique & Brazil (ca. 10% share each).[4]
- **tCO_2 per tonne of metal: 5.3.**[*8]

MAIN PRODUCTS AND USE CASES

- **Graphite demand growth driven by EV batteries.** Graphite is currently the dominant choice for Li-Ion anodes.[1]
- **Natural graphite (ore-based)** ~45% market share for Light-Duty-Electric-Vehicle (LDEV) batteries; **Synthetic graphite (from petroleum coke)** ~50% market share.[1]
- Graphite end markets: refractories (40%, as coating substances); EV batteries (25%); lubricants, carbon brushes, flame retardants, etc. (35%)[4]

VALUE CHAIN CHARACTERISTICS

- **Synthetic graphite has higher performance** & quality, but **~2x cost of natural graphite.**[7]
- Graphite abundant, but complexity of producing battery-grade (material quality, know-how required).[9,10]
- **Difficulty of securing investment for new graphite projects**, due to expected demand decline post 2030.[9,10]

ASSOCIATED RISKS IN THE BAU SCENARIO AND OPPORTUNITIES IN THE CE SCENARIO

RISKS:

- Supply **deficit of ~80kt expected in 2022.** By 2030, deficit potentially 620 kt (~37% of market). Supply dependence from China creates risks of under-supply.[1-4,9]
- Rise in low-CO_2 EAF steelmaking to further increase demand for graphite electrodes.[11]
- Social: **Human rights risks in Mozambique & China**; Environmental: Water & dust impact of natural graphite mining; **Climate change impact from synthetic graphite** production.[12,13]

OPPORTUNITIES:

- Expanding near-shore graphite production in the EU can both create jobs and reduce import risks (i.e. Humber Refinery gigafactory in the UK).[14]

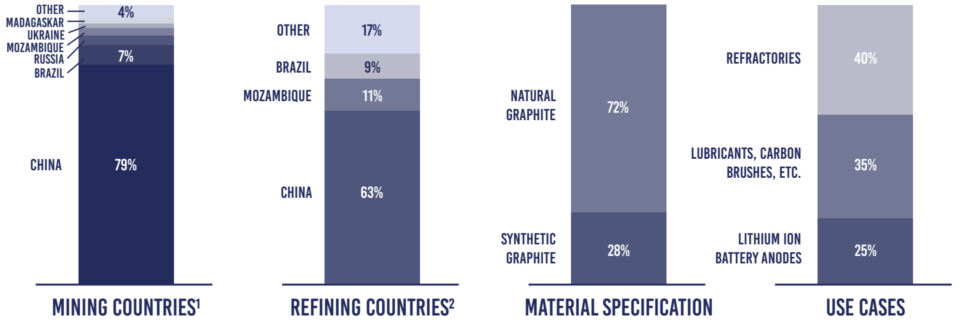
GRAPHITE: CIRCULAR ECONOMY LEVERS

SYSTEMIQ

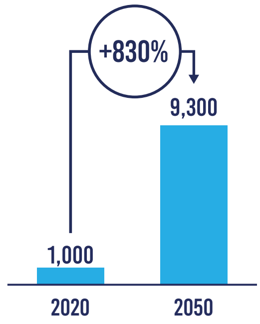
USE CASE	LEVER 1 RETHINK	LEVER 2 REDUCE	LEVER 3 REUSE	LEVER 4 RECYCLE
EVS **(FOR BATTERIES)** **(25%, IN 2020)**	Improved city design and promotion of public transport can reduce need for EVs/graphite.[15] Mobility-as-a-Service" innovations and car-sharing or car-pooling can reduce car ownership[16] Dynamic road pricing can reduce traffic by over 10%.[17]	Material efficiency (e.g. reduced battery size and increased efficiency) can reduce material demand by 16%.[5] Lithium and silicon based anode technologies can reduce graphite demand by up to 50%.[11] Lignin extracts from softwoods can be used as a substitute for graphite and thus reduce the demand.[18]	Up to ~20% of end of life batteries could be re-purposed for use in stationary applications, at up to 1/3 cost savings compared to new batteries.[19]	Graphite recycling possible, but not commercialised at scale.[20] Current methods for graphite recycling are not economically feasible for large scale industrial processes.[21] Innovations, like e.g. direct recycling can enable graphite anode recycling at scale.[22] The End of Life Recycling Rate for EV batteries is assumed to be at 70%.[23]
REFRACTORIES **(40%, IN 2020)**	Reducing metals demand would lower demand for smelting and thus refractories. Transition to low-carbon steel making lowers demand for refractories as process temperatures decrease (e.g. ~1,000 °C for Direct Reduction Iron vs. ~2,000 °C for current blast furnace)	N/A	In 2016 approximately 10% of old refractories were given a second life.[24]	Up to 20% of closed loop refractory recycling possible.[21]

OVERVIEW VALUE CHAIN GLOBALLY IN 2020

VALUE CHAIN CHARACTERISTICS: MINING AND REFINING COUNTRIES AS WELL AS MOST POPULAR USE CASES (2020)



GLOBAL GRAPHITE DEMAND [KT]



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LITHIUM

IN 2030 50% OF LITHIUM PRODUCTION WILL BE USED FOR EV BATTERIES. POTENTIAL SUPPLY SHORTAGES CAN BE AVOIDED IF INCREASED EFFORTS ARE MADE TO REDUCE DEMAND GROWTH AND INCREASE RECYCLING.

OVERVIEW

MATERIAL DEMAND

- Global lithium demand will **grow from ~350 kt Lithium Carbonate Equivalent (LCE) in 2020** to 2,000-3,000 kt by 2030 to up to **4,000-8,000 kt in 2050**.[1]
- **EU lithium demand** will grow from 23 kt in 2020 to 100-350 kt in 2030 and 700-860 kt in 2050 (**3,500% increase**).[1]
- **By 2050 77% of the EU's overall need could be met by secondary lithium** supply from end-of-life batteries.[1]

PRODUCTION

- Two ways to mine lithium: Ore mining (Australia); Salt brine extraction (Chile, Argentina, and China).[2]

  Global mining share: Australia (46%), Chile (24%), China (16%). **Refining share:** China (~60%), Chile (~20%), other.[1,2]
- Portugal is the EU's largest producer, but no battery-grade production yet (source of ~11% of EU Lithium concentrates).[1,2]
- **tCO_2 per tonne of metal:** 3.5 - 8.2 (brine), up to 22.5 (rock)

MAIN PRODUCTS AND USE CASES

- **40% of global lithium production is used for batteries.** This share will increase to ca. 50% by 2030 and then remain constant until 2050.[1]
- Other applications include ceramics and glass, lubricants, non-EV/storage Li-ion batteries, air treatment, metallurgy, polymers, construction, pharma, aluminium.[2]

VALUE CHAIN CHARACTERISTICS

- **Three companies account for 70% of lithium mining market share:** Albemarle (31%), SQM (21%), Tianqi (18%) in 2018.[3]
- **EU project pipeline** could add 130 kt mining and 155 kt refining capacity by 2030, but likelihood still uncertain.[1]
- **High energy costs a key barrier to developing EU lithium refining capacity.**[1]

ASSOCIATED RISKS IN THE BAU SCENARIO AND OPPORTUNITIES IN THE CE SCENARIO

RISKS:

- **Supply:**
  - **By 2030, global demand is expected to be 56% higher than supply.**[1]
  - Significant dependence on Chinese lithium refining capacity.[1]
- **Environmental: High water footprint** from lithium mining in South America & Australia.[4]
- **Social: Human rights concerns** in Bolivia (no production yet, but 21% of global reserves).[4]

OPPORTUNITIES:

- Developing and expanding domestic mining and processing capacities could create thousands of jobs and increase level of autonomy.[12]

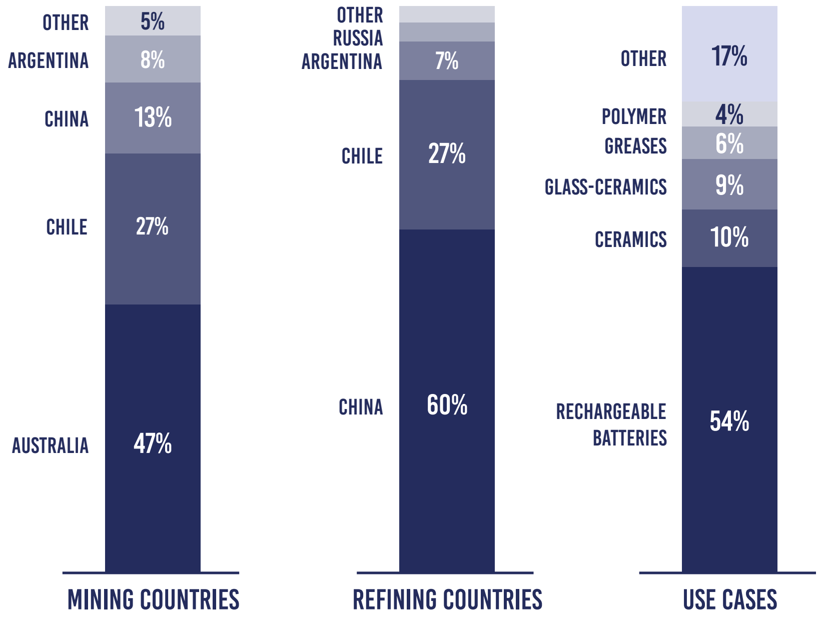
LITHIUM: CIRCULAR ECONOMY LEVERS

SYSTEMIQ

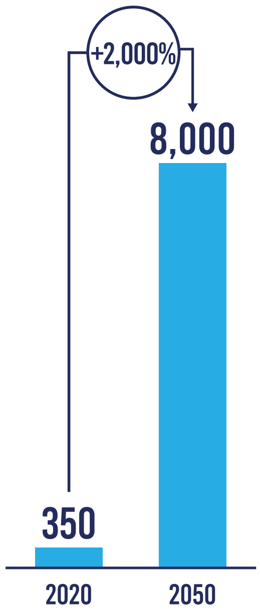
USE CASE	LEVER 1 RETHINK	LEVER 2 REDUCE	LEVER 3 REUSE	LEVER 4 RECYCLE
ELECTRIC VEHICLES (EVS) **(FOR BATTERIES)** **(CA. 40%)**	Improved city design and promotion of public transport can reduce need for EVs/lithium. Mobility-as-a-Service" innovations and car-sharing or car-pooling can reduce car ownership[5] Dynamic road pricing can reduce traffic by over 10%.[11]	Material efficiency (e.g. reduced battery size and increased efficiency) can reduce material demand by 16%.[6] Sodium-ion battery technology could reduce lithium demand for battery storage systems by ca. 10% by 2030. This corresponds to ca. 0.5% total lithium demand for EV & battery storage.[7]	Reuse batteries from EVs (as storage capacity for PVs) can reduce overall need for Lithium.[8] Up to ~20% of end of life batteries could be re-purposed for use in stationary applications, at up to 1/3 cost savings compared to new batteries.[13] Reuse EV batteries as storage batteries to balance electricity grids, particularly in connection with solar PV.	The End of Life Recycling Rate for EV batteries is assumed to be 70%.[1] By 2050 77% of the EU's overall need could be met by supply from secondary lithium from EOL EV batteries.[1] Need to close the gap on vehicles lost. About 33% of vehicles in the EU are unaccounted for at EoL, due to exports.[1] Positive economics a key barrier. Lithium not as valuable as nickel or cobalt and harder to recycle.[1]
CERAMICS AND GLASS **(CA. 20%)**	N/A	Limited potential to substitute lithium in specialty glasses and glass ceramics (e.g. cooktops).	N/A	There are currently no commercialised recycling processes to extract lithium from glass ceramics.

OVERVIEW VALUE CHAIN GLOBALLY IN 2020

VALUE CHAIN CHARACTERISTICS: MINING AND REFINING COUNTRIES AS WELL AS MOST POPULAR USE CASES (2020)



GLOBAL LITHIUM DEMAND [KT LCE]



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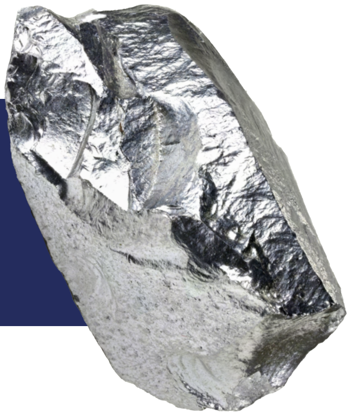
SILICON



GROWING DEMAND FROM THE ELECTRIC VEHICLE AND SOLAR POWER INDUSTRIES. DESIGN AND SYSTEM IMPROVEMENTS CAN IMPROVE MATERIAL EFFIENCY AND INCREASE RECYCLING.

OVERVIEW

MATERIAL DEMAND

- **Global demand for silicon** is expected to grow from ~ 2,800kt in 2020 to 3,500-4,500kt by 2030 up to 5,000-6,000kt by 2050. Of this, the **energy transition** will require 650-1,250kt in 2030 to 1,000-1,700kt in 2050. Historical demand growth lies at 5.5% (2007-2020).[1]
- **EU silicon demand** is expected to grow from 435kt in 2020 to 600-700 kt by 2030 and up to 650-900kt by 2050; thus, **a total increase of 62%** with 46% for the transition towards clean energy.[2]
- **The EU's 2030 energy transition goals** will require 50-170kt of silicon, rising to 70-230 kt by 2040 and then stabilizing (with the increase being equivalent to 50% of the EU's silicon consumption today).[1]

PRODUCTION

- **77% of silicon metal is produced in China**, followed by Brazil, Norway and France. While the world's current refined silicon output amounts to ~3,000kt the industry is burdened by a huge Chinese overcapacity of additional 4,000kt.[1]
- **The EU silicon industry supplies up to ~70% of domestic demand.** EU silicon is produced in Spain, Iceland, Norway, France, and Germany with no further silicon refining capacities being planned.[1]
- **What is not domestically produced in the EU is imported from Brazil** (~40%), followed by China (~30%) and Malaysia (~7%).[1]
- Silicon production is **highly electricity-intensive and due to impurities, needs intensive refining** to produce solar grade silicon metal.[1]
- **tCO_2 per tonne of metal: 11.**[1]

MAIN PRODUCTS AND USE CASES

- **Silicon is mostly used in Aluminium alloys** (45%), followed by silicones and silanes (35%), solar cells (12%; necessary growth rate 24%3)) and semiconductors (3%) It is mostly used alloyed with aluminium to make dynamo and transformer plates, engine blocks, cylinder heads, machine tools and to deoxidise steel.[4]
- Silicon is also **used in silicon based anodes** as an addition to graphite in EVs.[1]

VALUE CHAIN CHARACTERISTICS

- Today, silicon is **only recycled alloyed together with Aluminium**, pure silicon is not typically recycled.[1]
- **Expected oversupply of Chinese silicon production may cause price drops that would negatively affect EU markets.**[1]
- Top six companies for anode production are Chinese, accounting for two-thirds of global production capacity.[5]

ASSOCIATED RISKS IN THE BAU SCENARIO AND OPPORTUNITIES IN THE CE SCENARIO

ECONOMIC RISK:

- Expected oversupply of Chinese silicon production could cause price drops that would negatively affect EU markets.[1]

SOCIAL RISK:

- 77% of silicon metal is produced in China, with associated human rights and worker safety risks such as reported for the Xinjiang Uyghur Autonomous Region.[1]

OPPORTUNITIES:

- If produced in the EU, the CO_2 footprint for silicon lies at 3.4 tons per ton primary metal – this is 69% less than when producing outside the EU (at 11 tons).[1]
- Creation of jobs through recycling of solar PVs and EV batteries.[1]

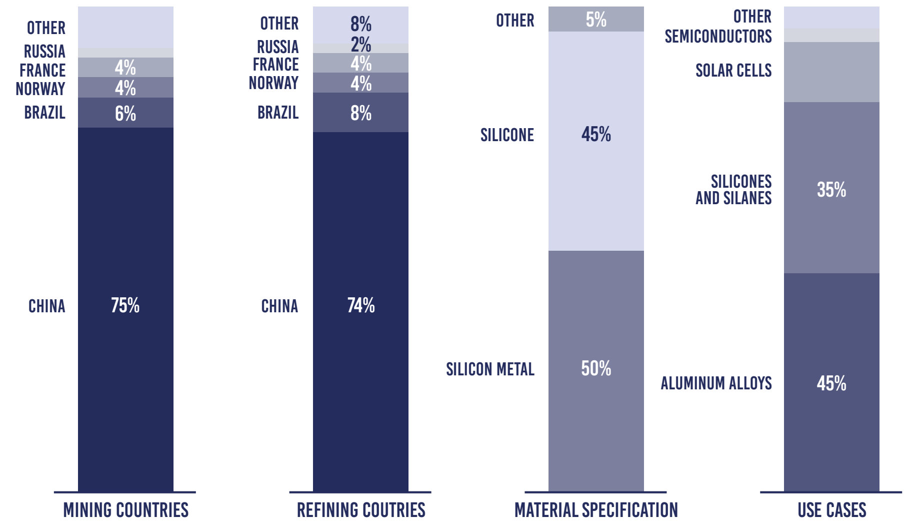
SILICON: CIRCULAR ECONOMY LEVERS

SYSTEMIQ

USE CASE	LEVER 1 RETHINK	LEVER 2 REDUCE	LEVER 3 REUSE	LEVER 4 RECYCLE
SOLAR PVS (12% IN 2020)	Reducing the demand for electricity can lower the demand for Solar PVs and therefore reduce material demand.	Thinner silicon wafers can decrease material demand by up to 75%.[8] Combining silicon with perovskite materials in tandem solar cells offers the opportunity to greatly increase solar PV efficiencies, generating more electricity with fewer material requirements[9, 10]	Solar PVs can be reused in grid-tied and off-grid applications.[11] Silicon from Solar PVs can be reused as nano-silicon for lithium-ion batteries for i.e. EV batteries.[12] A projected 40% of all Solar PVs could be reused, possibly enabling a circular Solar PV system by 2032.[13]	By 2050, module recycling of solar PV material can contribute 34% to material demand.[14] It is possible to make PVs out of 100% recycled silicon from manufacturing powder.[15] Due to nationwide policies the end of life recovery rate of Solar PVs in the EU is as high as 95%.[11]
ALUMINIUM-ALLOYS (45% IN 2020)	Since Aluminium-alloys are widely used in electronic technology, consumption patterns need to be rethought to decrease material demand.[16]	N/A	Increasing lifetime of consumer electronics could decrease resource use by 11-25%	Currently Silicon is recycled in aluminium alloys with ~45% recycling rate.[1]

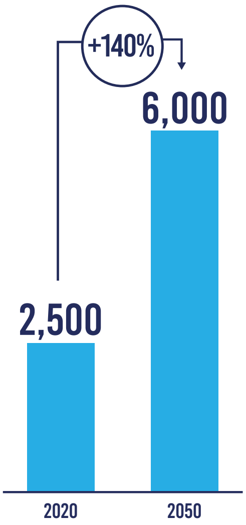
OVERVIEW VALUE CHAIN GLOBALLY IN 2020

VALUE CHAIN CHARACTERISTICS: MINING AND REFINING COUNTRIES AS WELL AS MOST POPULAR USE CASES (2020)



Source: Source: KU Leuven (2022): Metals for Clean Energy; ANSA Silicon LLP (2021): Silicon Metal

GLOBAL SILICON DEMAND [KT]



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SYSTEMIQ

PLATINUM GROUP METALS (PGM'S)

PGM'S WILL BECOME INCREASINGLY IMPORTANT FOR HYDROGEN ELECTROLYSERS AND FUEL CELLS. PGMS ARE HIGHLY RECYCLABLE AND SECONDARY SUPPLY CAN HELP TO MEET DEMAND.

OVERVIEW

MATERIAL DEMAND

- Global demand for PGMs is expected **increase by 64% between 2020 and 2050** overall use. Total demand (2020): 224t (Pt), 310t (Pd), 32t (Rh), 32t (Ru), 7t (Ir).[1]
- **EU 2020 demand is about a quarter of global demand:** ~53t (Pt), ~62t (Pd).[2]
- Future demand projections strongly depend on chosen clean energy pathways. **Demand for Pt is driven strongly by increased number of fuel cells** - but improvements in fuel cell technology could abate that increase. Likewise, **fewer internal combustion engine (ICE) sales will reduce demand** for Pt and Pd in autocatalysts.[9]

PRODUCTION

- **Most PGM are mined by South Africa** (~70% Pt, ~40% Pd, ~93% Ru), followed by Russia (~8% Pt, ~20% Pd) and Zimbabwe (~5% Pt, 3% Pd). In 2020 the total estimated world production of PGM was 443 metric tons (154t Pt, 192t Pd).[3] 95% of known world resources are located in South Africa.[10]
- Secondary supply (2020): ~53t (Pt) ~98t (Pd), ~11t (Rh).[4]
- 71% of the EU's supplies for Pt come from South Africa, with an even higher share for Rh, Ir and Ru.[5]
- **tCO_2 per tonne of metal: 20,600***

MAIN PRODUCTS AND USE CASES

- **There are six platinum group metals:** platinum (Pt), palladium (Pd), rhodium (Rh), osmium (Os), iridium (Ir) and ruthenium (Ru) out of which Pt and Pd are the most important ones due to their economic values and high quantities and the other four being by-products of Pt and Pd.
- **PGMs are mainly used for autocatalysts** (72%), followed by chemical industry (9%) electronics (8%) and glass (3%).[5] In the future, PGMs will see increased use in hydrogen electrolysers and fuel cells, while use in autocatalysts will decline.

VALUE CHAIN CHARACTERISTICS

- PGMs are highly recyclable, but actual recycling rates depend on recovery rates of components (autocatalysts) in which they are used.
- **Extraction, concentration and refining of PGMs is comparatively complex** and cost-intensive creating large incentives for recycling.[8] **Actual recycling rates for Pt and Pd are at 60%.**[9] The contribution of secondary materials to total demand is at ~30%.[7]
- In South Africa, ores generally have a low PGM content; **it takes up to six months and between 10 and 40 tonnes of ore to produce one ounce (28g) of platinum.**[8]

ASSOCIATED RISKS IN THE BAU SCENARIO AND OPPORTUNITIES IN THE CE SCENARIO

RISKS:

- Social: **PGM mines in SA operate at a depth below 0.5 to 2 kms. Mining is labour intense**, requires hand-held pneumatic drills and **the working area has to be refrigerated** due to the high thermal gradient of the metal.[8]
- Economic: **Prices for PGMs have become highly volatile**, in part due to reliance on individual processing plants in global value chains. During 2020/2021, prices for PGMs increased up to fourfold within 6 months.[4]

OPPORTUNITIES:

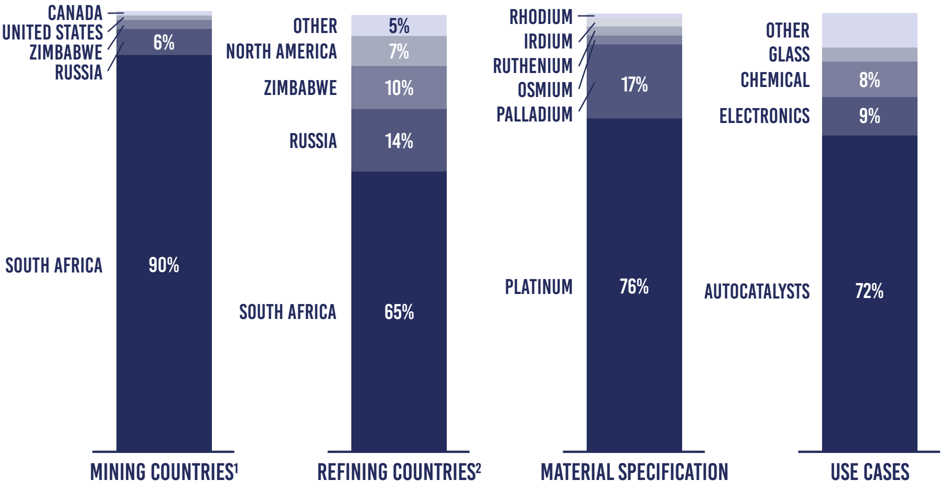
- Electricity consumption during the production processes for PGMs is the main source of GHG emissions from primary production. **Improvements to the power production (from fossil to renewable) in SA would drastically improve PGM GHG emissions.**[10]
- PGMs used in hydrogen production are easy to recover and recycle at the end of their useful life, which makes them particularly suitable for innovative leasing models or "metal as a service".

PGM'S: CIRCULAR ECONOMY LEVERS

USE CASE	LEVER 1 RETHINK	LEVER 2 REDUCE	LEVER 3 REUSE	LEVER 4 RECYCLE
HYDROGEN ELECTROLYSER AND FUEL CELLS (FUTURE USE)	N/A	Use of Pt in fuel cells for cars and trucks is subject to positive innovation, decreasing the amount needed. For example, alkaline electrolizers avoid Pt use and research shows that Pt could be substituted with iron.[11]	N/A	PGM used in electrolysers does not degrade and can be fully recycled. But lifetime of electrolysers is 20 30 years, meaning that substantial secondary supply will only begin to materialise after 2050.
AUTOCATALYSTS (72% IN 2020)	Shifting from ICE vehicles to BEVs means removal of that share of platinum demand so far caused by autocatalysts.	Speeding up the end of ICE sales will decrease the corresponding need for autocatalysts and PGMs. PGMs can also be partially substituted with copper, reducing PGM demand.[12]	N/A	95% of the PGM content of spent automotive catalysts can be recovered.[13] However, 50% of catalysts are not recovered due to leaks in the reverse supply chain.[16]
CONSUMER ELECTRONICS (8% IN 2020)	Globally 1.4 billion phones are sold annually and thrown away before reaching end of life.[14] New XaaS business models could reduce number of new consumer electronics, but the potential is tbd.	N/A	Extending the use of consumer electronics through refurbishment and resales would reduce demand for Pt in use. Increasing actual lifetime of consumer electronics to the lifetime a product is capable of would decrease resource use by 11-25%.	Improving collection and recycling rates of consumer electronics would increase recycling rate.[15]

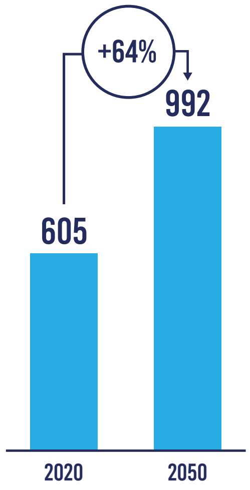
OVERVIEW VALUE CHAIN GLOBALLY IN 2020

VALUE CHAIN CHARACTERISTICS: MINING AND REFINING COUNTRIES AS WELL AS MOST POPULAR USE CASES (2020)



1: 2021; **2:** numbers refer to Platinum only. **Source:** KU Leuven (2022): Metals for Clean Energy; Statista (2021)[17]

GLOBAL PGM DEMAND 2020 [T]



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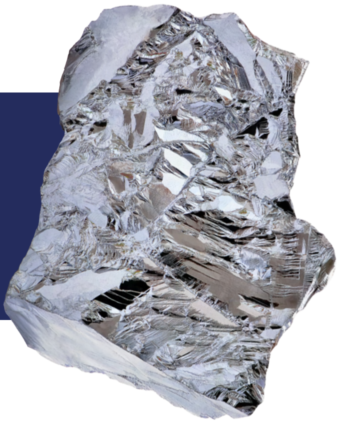
SYSTEMIQ

NICKEL



NICKEL MAKES UP 50-80% OF THE METAL IN A LITHIUM-ION BATTERY AND IS ALSO KEY FOR RENEWABLE ENERGY; ENSURING OLD EV BATTERIES GET RECOVERED AND RECYCLED IS CRUCIAL FOR NICKEL SUPPLY.

OVERVIEW

MATERIAL DEMAND

- Very high demand pull due to the energy transition and its use in batteries. By 2050, **global nickel demand is projected to more than triple** from ~2,400 kt today to up to 9,000 kt.[1,4]
- Global demand **for clean energy technologies will make up almost half of that demand** – up to 4,000kt in 2050.[1]
- EU demand to grow from 384kt (2020) to 800-900kt in 2050.[1]
- EU demand for Nickel for the clean energy and mobility transition is equally expected to make up almost half of that at up to 400kt in 2050.[1]

PRODUCTION

- **Indonesia and the Philippines account for 45% of global nickel extraction**, Russia additional 11%.[2]
- **China refined 35% of global nickel** in 2019. Indonesia 15%. It is expected that the market will consolidate, with Indonesia and Philippines increasing their share of total global production.[2]
- In 2020, Indonesia banned the export of nickel ore, aiming to promote a domestic downstream processing industry. China has already secured a majority of Indonesian long-term supply sources.[3]
- **The EU currently consumes about 17% of total nickel production, expected to reduce to 10% by 2050.**
- **tCO_2 per tonne of metal: 18 (class 1), 69 (class 2)**

MAIN PRODUCTS AND USE CASES

- In 2020, **73% of nickel is used to make stainless steel** (corrosion resistance), 20% alloys, 7% EV batteries.
- Nickel is also used in most clean energy technologies, mainly EV batteries, wind, solar PV, hydrogen. **The share of clean energy use cases is expected to grow from 7-8% in 2020 to 61% in 2050.**[5]

  Main demand growth driver is EV batteries, where it is used increasingly to replace cobalt. **In EV batteries, Nickel makes up 50-80%** of the total metal being used, depending on battery chemistry.

VALUE CHAIN CHARACTERISTICS

- **Two classes of nickel exist** (roughly 50-50 production split). Both are used for stainless steel-making. But EV batteries require class 1 nickel. It is likely that supply of class 1 nickel will be constrained.
- High-pressure acid leaching (HPAL) is used to produce class 1 type nickel. But HPAL production is prone to delays and cost overruns. **Alternative production methods are either cost-prohibitive or even more emissions-intensive.**[6]

ASSOCIATED RISKS IN THE BAU SCENARIO AND OPPORTUNITIES IN THE CE SCENARIO

RISKS:

- **Economic:** Indonesia and Philippines control existing and future virgin supply and have intervened in the market in the past (banning exports of ore); Class 1 nickel, needed for EV batteries is likely to be supply constrained; carbon taxes / import taxes will affect class 1 nickel due to its higher CO_2-intensity.
- **Environmental:** Class 1 nickel production emits 10 tCO_2-eq per tonne of nickel; due to degrading ores, new processes are required, which emit 19 tCO_2-eq (HPAL) and 59 tCO_2-eq (extraction from nickel pig iron) per tonne; nickel available for class 1 production is mainly found in areas where tropical rainforests grow.

OPPORTUNITIES:

- Research into EV batteries is ongoing – with the potential that improvements to battery production could extend the lifespan of batteries beyond the 15-20 years currently envisaged.

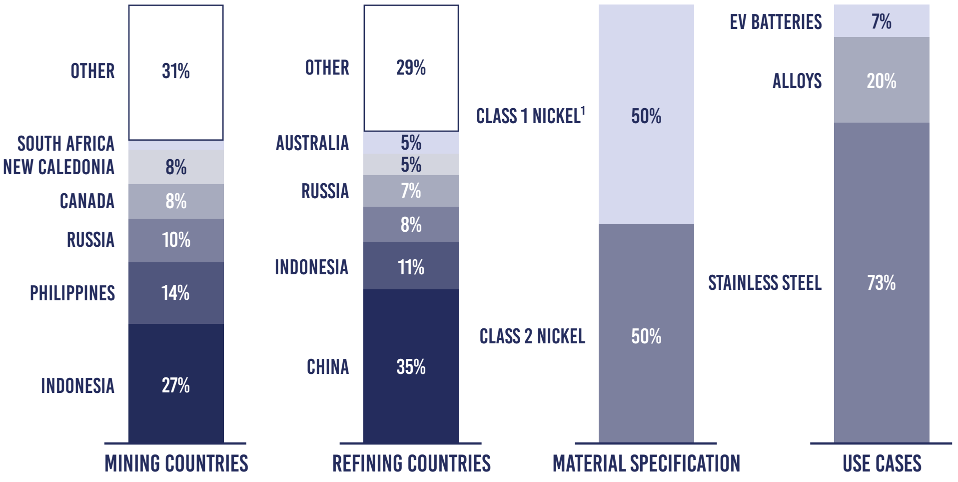
NICKEL: CIRCULAR ECONOMY LEVERS

SYSTEMIQ

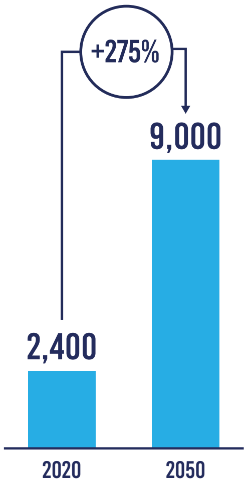
USE CASE	LEVER 1 RETHINK	LEVER 2 REDUCE	LEVER 3 REUSE	LEVER 4 RECYCLE
EVS (FOR STEEL AND BATTERIES) (7% IN 2020)	Autonomous and shared EV transport options can reduce need for individual car ownership by 16%.[8] Dynamic road pricing can reduce traffic by over 10%.[9]	Limiting the size of batteries in EVs to current sizes (e.g. through taxes or incentives) could reduce incremental battery metal demand by 16% by 2030 and beyond.[10]	Up to ~20% of end of life batteries could be re-purposed for use in stationary applications, at up to 1/3 cost savings compared to new batteries.[12] Reuse EV batteries as storage batteries to balance electricity grids, particularly in connection with solar PV.	Recycling rates of EV batteries can reach 90% or more.[13] By 2050, additional EV battery recycling can reduce global primary demand for all nickel use cases by 11%.[11]
OTHER STAINLESS STEEL (73%)	Shared office models or virtual working reduce the demand for new construction and refits in commercial real estate Compact living models for urban design and residential properties reduces material footprint of construction whilst retaining positive liveability.	Alternative building materials (such as timber) can reduce stainless steel demands in buildings. Design improvements and efficiency gains in construction reduce material usage and wastage.	Restoring and renovating existing built environment infrastructure and reusing available materials can reduce overall demand for building materials like stainless steel.	Improving recovery rate of stainless steel used in household appliances & electronics (20% lost to landfill) and buildings & infrastructure (15% lost) can reduce demand for primary steel. Digital catalogues of city and building infra-structures can enable better disassembly, deconstruction and recycling of valuable steel components.

OVERVIEW VALUE CHAIN GLOBALLY IN 2020

VALUE CHAIN CHARACTERISTICS: MINING AND REFINING COUNTRIES AS WELL AS MOST POPULAR USE CASES (2020)



GLOBAL NICKEL DEMAND [KT]



1: high-grade, required for batteries, demand expected to increase. **Source:** KU Leuven (2022): Metals for Clean Energy.

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