Outlook for battery raw materials
(literature review)

Introduction

Recognising that climate change represents an urgent threat to societies and the planet, the 2015 Paris Agreement set the goal of keeping global warming well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C (global warming has already reached 1°C).

To build on these objectives, the EU Commission has developed its long-term strategic vision[1] for a prosperous, modern, competitive and climate neutral economy in Europe, which confirms Europe's commitment to be a leader in addressing global climate change. It includes an assessment, based on several scenarios, to support the EU's strategy to reduce long-term EU GHG emissions in accordance with the Paris Agreement, starting at -80% going up to -100% by 2050 compared to 1990 levels. In all the scenarios, the electric vehicle (EV) plays an important role, creating a significant need for battery raw materials. Consequently, there are concerns about the future supply of raw materials necessary for battery production and the impact of rising prices on battery production costs.

This article is a literature review of publications from Wood Mackenzie, McKinsey & Company and Ricardo (among others), and summarises the important key messages regarding technologies, metal sources, demand, availability, prices, recycling and uncertainties/challenges of battery raw materials.

In all the scenarios defined by the EU Commission's long-term strategy to address climate change, the electric vehicle has a big role to play. The long-term supply of battery raw materials will therefore be a necessity. There are concerns regarding the future availability of raw material supply and the impact of rising prices on battery production costs. This article is a literature review which aims to summarize the important key messages regarding technologies, metal sources, demand, availability, prices, recycling, and the uncertainties and challenges associated with battery raw materials.

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Back to the future

Electric cars were a common sight in the city streets of Europe and the United States (US) more than one hundred years ago. An American, Thomas Davenport, is credited with building the first EV in 1835. When Henry Ford introduced the mass-produced gasoline-powered Model T in 1908, it symbolised the end of the age of the EV until its recent revival. This technological 'rediscovery' is already having a revolutionary impact on the automotive industry as manufacturers revise their business strategies, develop new technologies and reconfigure global supply chains while trying to secure access to battery raw materials.

Technologies

Automotive battery technology roadmaps identify lithium-ion (Li-ion) batteries as being the dominant battery type used from now to 2050. Lithium-ion is a term applied to a group of battery chemistries that contain various different materials, however they all contain lithium in the cell cathode. Currently, there are six Li-ion battery technologies, the main difference between them being the cathode composition:

- lithium cobalt oxide (LCO)
- lithium nickel manganese cobalt (NMC)
- lithium nickel cobalt aluminium (NCA)
- lithium iron phosphate (LFP)
- lithium manganese oxide (LMO)
- lithium titanate (LTO).[2]

[1] European Commission (2018). *A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy.*

[2] Mascot AS (2018).

With the exception of LCO, each of the Li-ion technologies mentioned above are used in the automotive industry today. China has been responsible for the largest growth in EV batteries, predominantly using LFP technology.

Beyond 2030 these types of Li-ion battery are expected to be superseded by next-generation battery types such as lithium-air and lithium-sulphur, which may contain very different active materials but will still require lithium, according to Ricardo (2018).

Li-ion technology has been successful for EVs because it offers a good balance of power and energy density. The key performance parameters of these battery technologies are presented in Figure 1.

Figure 1: Key performance metrics of battery technologies by chemistry

Source: Yoshio *et al.* (2009) and McKinsey & Company (2018)

strong moderate weak

Material	Description	Safety	Cost (US$/kWh)	Energy density (kWh/kg)	Cycle life[d] (times)	Ni content (kg/kWh)
LCO ($LiCoO_2$)	Mostly used in consumer electronics. Limited application for xEVs[b] (e.g. Tesla).	Low	Low	0.58	1,500–2,000	0.0
NMC[a] ($LiNi_xCo_xMn_xO_2$)	Used mainly in consumer electronics but increasingly used in xEVs.	Mid	Mid	0.60	2,000–3,000	0.69 51 wt%
LMO ($LiMn_2O_4$)	Relatively mature technology. Used in xEVs by Japanese OEMs (e.g. Nissan Leaf, Mitsubishi i-MiEV, Chevrolet Volt).	High	High	0.41	1,500–3,000	0.0
LFP ($LiFePO_4$)	Relatively new technology used in xEVs and ESS.[c] Driven by A123 Systems and Chinese manufacturers (e.g. BYD, STL).	Very high	High	0.53	5,000–10,000	0.0
NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$)	Used mostly in consumer electronics (often blended with other chemistries) and e-vehicles (e.g. Tesla)	Mid	Mid	0.72	n/a	0.68 (49 wt%)

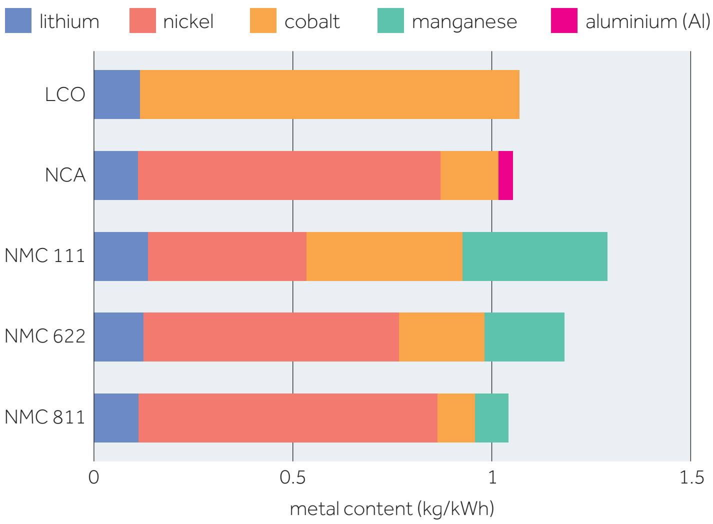
[a] For 811 configuration (i.e. cathode material is 80 percent nickel, 10 percent manganese and 10 percent cobalt, by weight).
[b] xEVs = hybrid and electric vehicles
[c] ESS = energy storage solution
[d] The cycle life is the number of complete charge/discharge cycles that the battery is able to support before its capacity falls below 80% of its original capacity.

Among all the Li-ion technologies, nickel manganese cobalt (NMC) chemistries have become the automotive OEMs' preferred technology in recent years. According to Wood Mackenzie, NMC batteries could potentially dominate by 2030 (70% of EV batteries—see Figure 2 on page 25). Other battery materials (graphene, solid-state electrolyte) are not expected to have an impact on cathode chemistry in the foreseeable future, according to McKinsey & Company.

Figure 2: Metal content of NMC (vs LCO and NCA) batteries (2017 vs 2030)

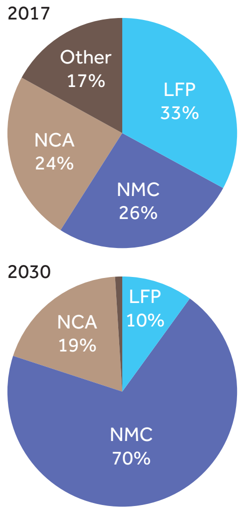
Source: Research Interfaces (2018)/Wood Mackenzie

a) Metal content of major EV battery chemistries



Note: All of the NMC lithium technologies utilise different proportions of nickel, cobalt and manganese.

b) EV battery chemistry split



China has been responsible for the largest growth in EV batteries — predominently lithium iron phosphate (LFP).

'Other' battery types include LMO and NiMH which are rapidly losing popularity.

Despite a constant flurry of 'battery breakthroughs', the industry seems to have settled on three technologies.

Nickel manganese cobalt (NMC) batteries are expected to dominate through the forecast period, although different variations exist.

Natural sources of metals

Where are these metals located around the world?

- Lithium
  - More than 95% of the world's lithium supply occurs as a primary product in the form of brines (from Argentina, Chile, Bolivia and China) or hard rock sources (from Australia and China):
    - Lithium brine deposits are found in salt lakes or salt flats (salars), and form in basins where water has leached the lithium out from the surrounding rock. The brines are captured and transferred to evaporation ponds, where they are concentrated by solar and wind evaporation, after which the lithium recovery takes place. Lithium from brines is the most suitable for battery manufacture.
    - Hard rock sources of lithium consist of granitic pegmatites, most prevalently those containing the mineral spodumene.
  - Lithium is sold and used in two main forms: lithium carbonate (19% Li), which is largely produced from brines; and lithium hydroxide (29% Li) produced from hard rock sources. Lithium hydroxide is currently the preferred form of lithium for use in longer-range EV batteries.

- Cobalt
  - Less than 10% of cobalt supply occurs as a primary product. The remainder is a by-product, primarily from copper and nickel mining. Cobalt expansion projects will therefore not only be dependent on the future demand, supply and price dynamics for cobalt, but also on future nickel and copper dynamics.
  - The total cobalt supply is split between mined cobalt and a recycle contribution.

- Nickel
  - Pure native nickel is found in the Earth's crust only in tiny amounts, usually in ultramafic rocks and in the interiors of larger nickel-iron meteorites that were not exposed to oxygen when outside the Earth's atmosphere.
  - An important source of nickel is the iron ore limonite, which contains 1–2% nickel.
  - Major production sites include Indonesia, Canada (which is thought to be of meteoric origin), New Caledonia, Russia and Madagascar.

Demand

What is the expected demand for these metals?

The lithium and cobalt markets have historically been driven by the demand for batteries used primarily in consumer electronics, which represented 40% and 25% of lithium and cobalt demand, respectively, in 2017. In the case of nickel, the global market has traditionally been driven by stainless steel production using both high-purity class 1 and lower-purity class 2 nickel products. The growing adoption of EVs (particularly in China) and the need for EV batteries with higher energy densities (increasing battery sizes and raw material intensities) could potentially see the demand for these metals increase dramatically.

According to the McKinsey & Company analysis (see Figure 3 on page 27), the global demand for each of these metals could potentially increase as follows:

- **Lithium:** demand could increase by more than 300%, from 214 to 669 kt LCE[3] (in the base case) and to 893 kt LCE (in the aggressive case), between 2017 and 2025.
- **Cobalt:** demand could increase by 60%, from 136 to 222 kt (in the base case) and to 272 kt LCE (in the aggressive case), between 2017 and 2025.
- **Nickel:** demand could increase by 25%, from 2,000 to 2,500 kt Ni between 2016 and 2025.
  - Although stainless steel production is likely to remain the largest use of nickel, its share will decrease from 70% to 60% as the EV revolution accelerates the demand for nickel for use in battery production.
  - The demand for high-purity class 1 nickel (suitable for battery manufacturing due to its high purity and dissolvability) may increase from 33 kt in 2017 to 570 kt in 2025 (more than 10 times the current demand).

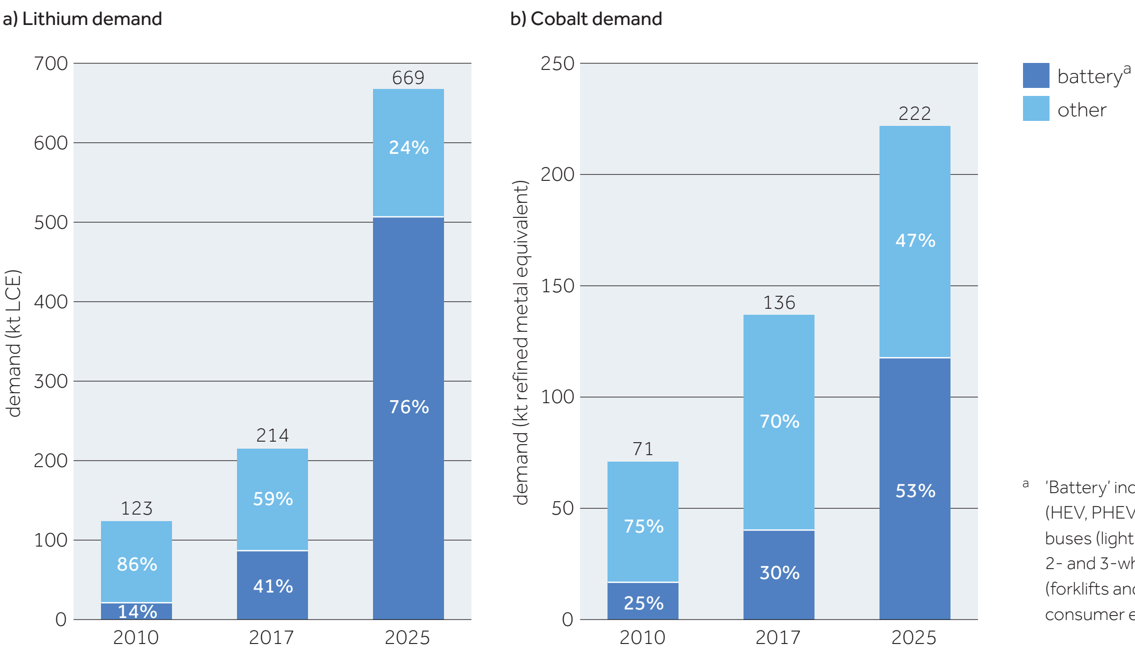
Wood Mackenzie's demand forecast aligns with the McKinsey & Company aggressive scenario (see Figure 4 on page 27). According to Wood Mackenzie, by 2030, we could potentially need at least:

- six more Greenbushes mines (the biggest lithium mine in Australia);
- three more Katanga mines (the biggest cobalt mine in the Congo); and
- six more Ambatovy mines (the biggest nickel mine in Madagascar).

[3] Lithium carbonate equivalent — the industry standard for measuring lithium volumes.

Figure 3: Expected demand for lithium and cobalt by 2025

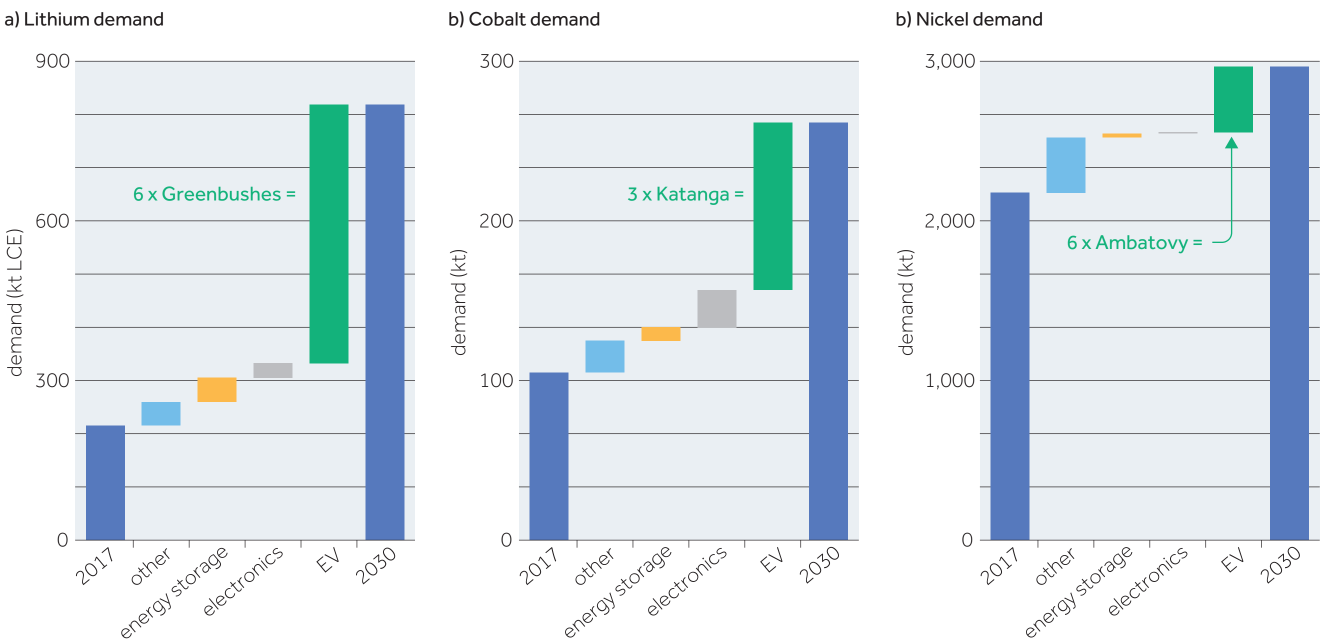
Source: McKinsey & Company (2018)



[a] 'Battery' includes automotive (HEV, PHEV, BEV), trucks and buses (light, medium, heavy), 2- and 3-wheelers, machinery (forklifts and others), grid storage, consumer electronics.

Figure 4: Lithium, cobalt and nickel expected demand by 2030

Source: Wood Mackenzie



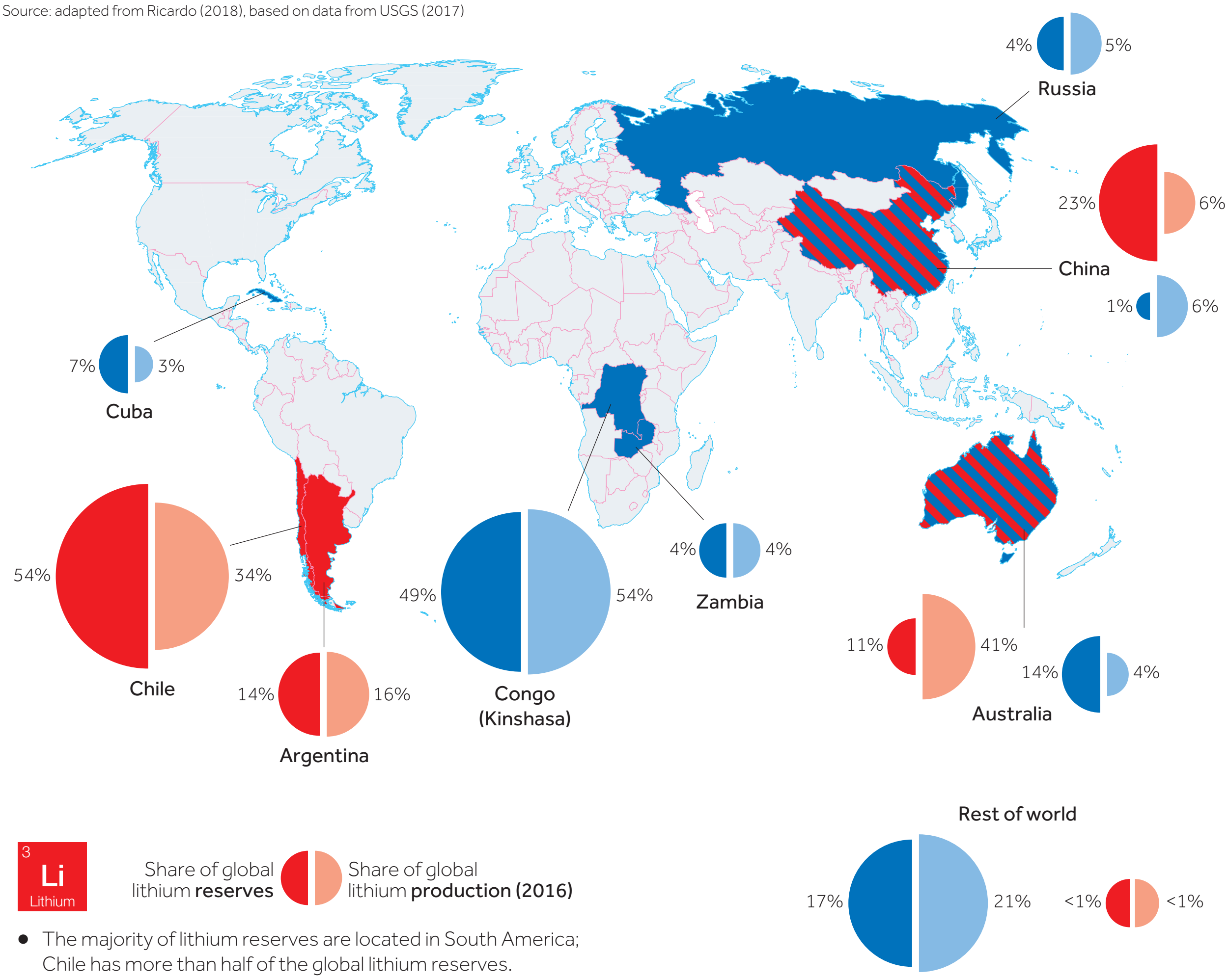
Availability

Is there sufficient availability to cover the expected demand?

The majority of these metals are located in a few countries around the world (see Figure 5).

Figure 5: Worldwide availability of lithium and cobalt

Source: adapted from Ricardo (2018), based on data from USGS (2017)



- The majority of lithium reserves are located in South America; Chile has more than half of the global lithium reserves.
- Lithium production and prices could depend heavily on the policies of the Chilean government.

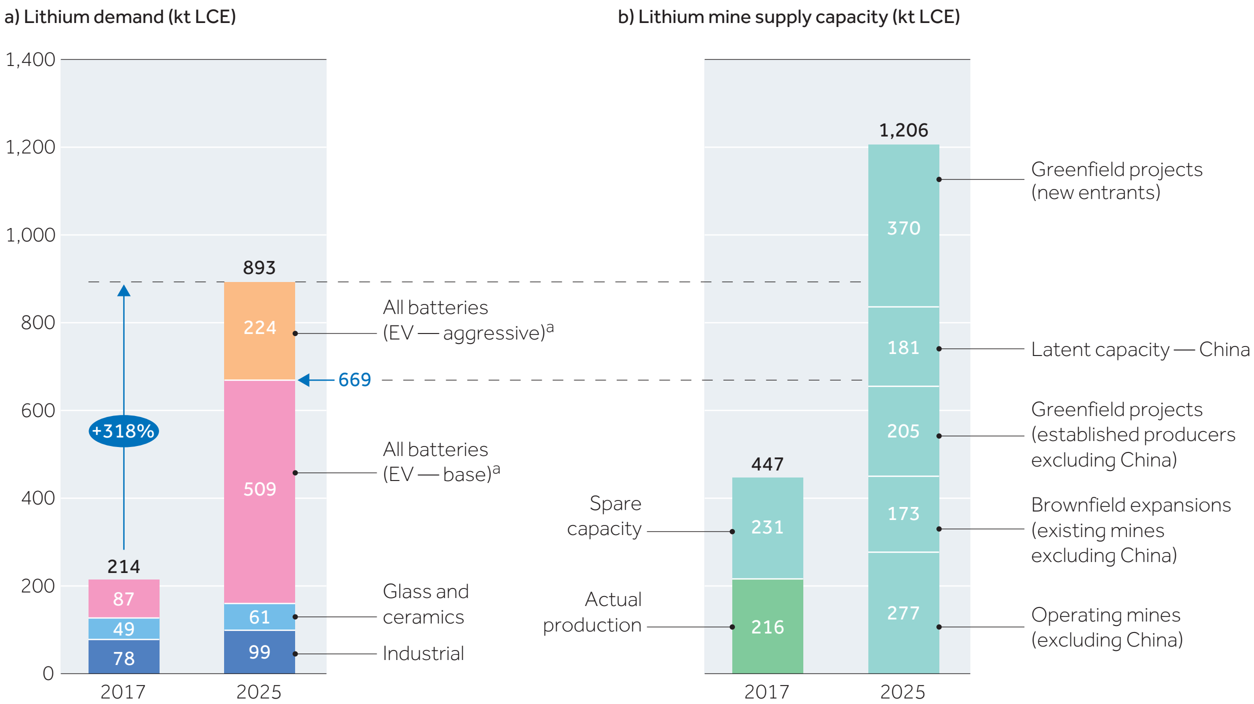
- Although cobalt reserves are present in many countries, the largest reserves and current production are located in the Congo (Kinshasa).
- Instability in this region is a factor in the 128% increase in the price of cobalt in 12 months (London Metal Exchange, September 2016–September 2017 values).

Lithium

- Only eight countries are currently producing lithium, of which three countries—Chile, Australia and China—accounted for 85% of global production (216 kt LCE) in 2017. Chile has more than half of the global lithium reserves.
- Within Europe, only Portugal has a (small) lithium industry, amounting to 0.6% and 0.4% of global production and reserves, respectively.
- Currently, four companies (Talison, SQM, Albemarle and FMC) control most of the mined product.
- Currently, there are no structural constraints on supply, with global production being well below industry capacity (450 kt LCE). For example, the world's largest miner, Talison, is operating at barely 60% of its capacity. Talison's announcement that it plans to expand its lithium production over the next few years suggests that there is ample capacity to meet the foreseen growth in demand, which is estimated to reach 669 kt LCE by 2025 (see Figure 6).

Figure 6: Lithium supply versus demand, 2017 vs 2025

Source: McKinsey & Company (2018)



[a] 'Batteries' include automotive (HEV, PHEV, BEV), trucks and buses (light, medium, heavy), 2- and 3-wheelers, machinery (forklifts and others), grid storage, consumer electronics.

- There is therefore no concern about global lithium availability, according to McKinsey & Company. However, according to Ricardo, the annual lithium demand could be the greater challenge:
  - Global lithium extraction investment is limited by the low cost of lithium from the Salar de Atacama in Chile. To supply the peak annual lithium demand for European BEVs, roughly half of the surface of the salar would need to be covered in evaporation ponds, with potential impacts on wildlife and tourism.
  - Other large lithium resources, such as the Salar de Uyuni in Bolivia — estimated to be the largest or second largest lithium resource globally — are limited in their potential annual output. In the case of the Salar de Uyuni, an extraction rate of only 10 kt/year would exceed the water replenishment rate of the basin and would have an adverse impact on local agriculture.

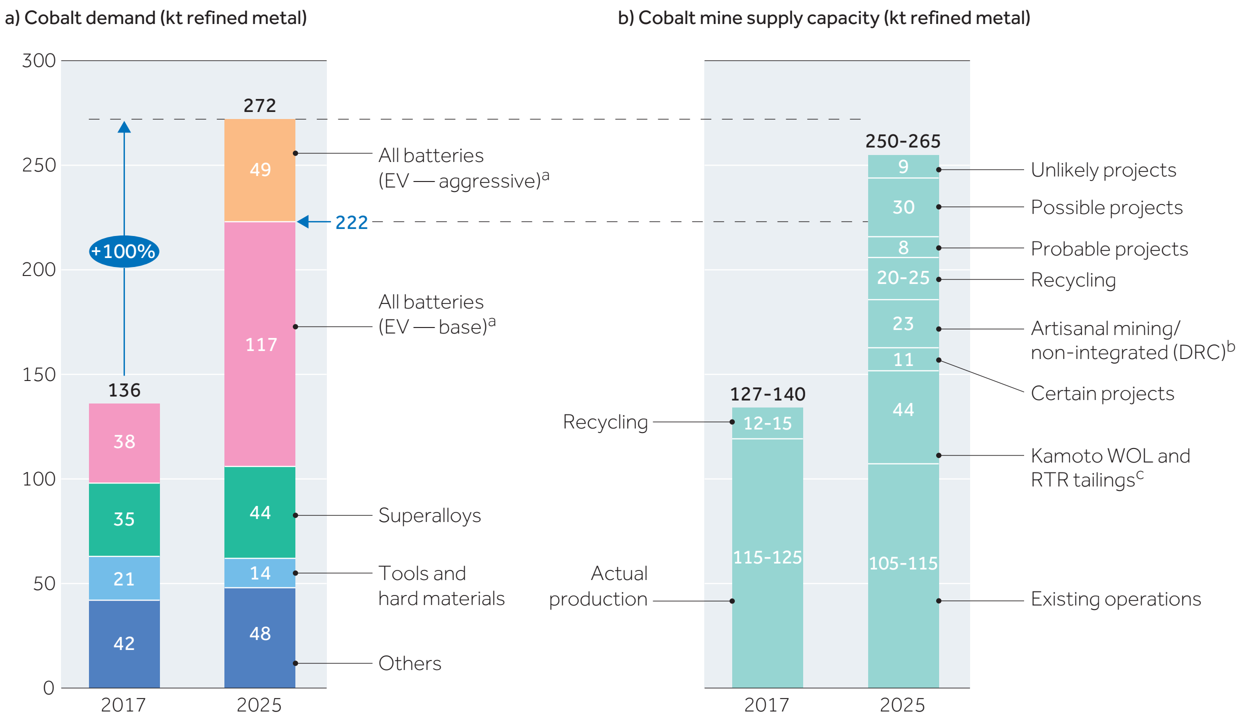
  The feasibility of meeting the increased lithium demand by 2040 is therefore uncertain. There may be sufficient lithium, however the rate of lithium production could be the limiting factor. Furthermore, so few countries control the majority of lithium that supply issues could occur.

Cobalt

- More than half of global production is concentrated in Kinshasa in the Democratic Republic of Congo (DRC), with Russia, Cuba, Australia and Zambia accounting for the other half of global supply, according to Ricardo. By 2025, nearly 100% of the global cobalt supply will come from the Congo, according to Wood Mackenzie.
- The cobalt mine supply is currently fragmented in terms of producers, and the top three players account for 40% of global mine supply — Glencore (22%); DRC state miner Gecamines (9%); and China Molybdenum (7%).
- According to McKinsey & Company (see Figure 7 on page 31), the industry could add capacity expansions of between 110–120 kt by 2025, bringing the total potential mine supply to 225–235 kt. Additionally, recycling could provide an additional 25 kt of supply by 2025, bringing the total refined cobalt supply to around 255 kt by 2025.
  - 45 kt of cobalt mine capacity additions by 2025 are expected to come from two expansion projects, both in the DRC (DRC will then represent 75% of global cobalt mine supply).
- There are concerns about whether the supply of cobalt will be able to meet the growth in demand, given:
  - the uncertainty about announced projects;
  - the lack of transparency in the value chain;
  - DRC country risk; and
  - concern for child labour.
- These concerns are increasing the focus on low-cobalt NMC batteries. According to Ricardo, in the long term, alternatives to cobalt-containing batteries will be available, although some of these may not achieve the same level of performance.

Figure 7: Cobalt supply versus demand, 2017 vs 2025

Source: McKinsey & Company (2018)



[a] 'Batteries' include automotive (HEV, PHEV, BEV), trucks and buses (light, medium, heavy), 2- and 3-wheelers, machinery (forklifts and others), grid storage, consumer electronics.

[b] Includes non-integrated capacity which is reliant on purchased ore and/or preconcentrate from smaller and/or artisanal operations. This capacity is not tracked on a mine-by-mine basis, but tracked on a processing plant level, assumed to be fed by mines not tracked individually in the other buckets.

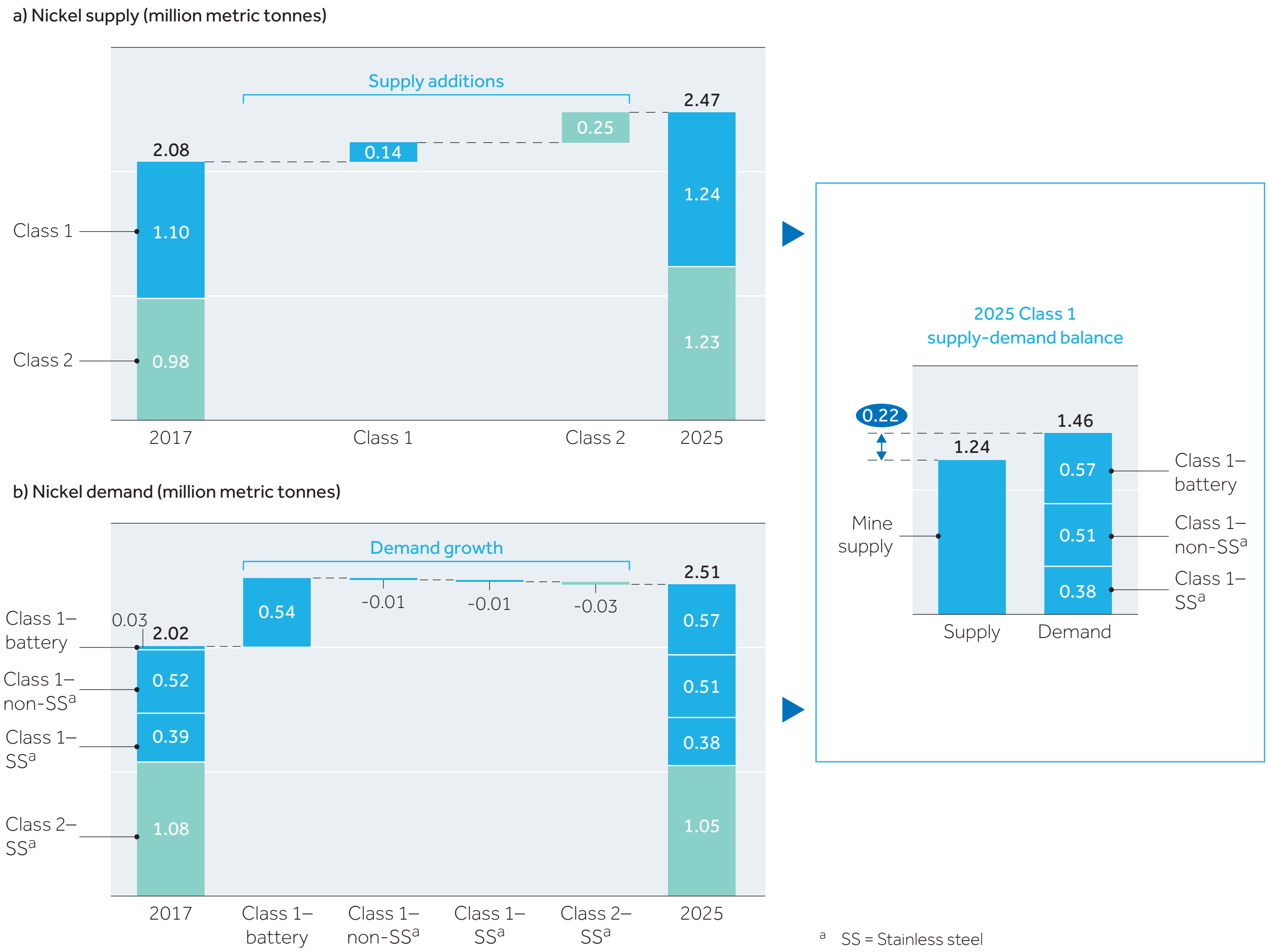
[c] Large increase explained largely by ramp-up of WOL (whole ore leach) operations by Glencore (commissioned in 2017) and ERG's Metalkol Roan Tailings Recovery (RTR) project (commissioned in 2018). Together, these projects account for ~41 kt.

Nickel

- Major production sites include Indonesia, Canada (meteoric origin), New Caledonia, Russia and Madagascar.
- The nickel market has been driven by stainless steel production using both high-purity class 1 and lower-purity class 2 nickel.
- High-purity class 1 nickel is required for battery manufacture.
- The industry faces a major challenge in the lack of an easy and sustainable way to increase the supply of class 1 nickel. According to McKinsey & Company, class 1 supply will lag demand by 2025, with only 1.2 Mt of supply available to meet a demand of 1.5 Mt.
- A shortfall in class 1 nickel seems likely.

Figure 8: Nickel supply versus demand, 2017 vs 2025

Source: McKinsey & Company (2017)



[a] SS = Stainless steel

Prices

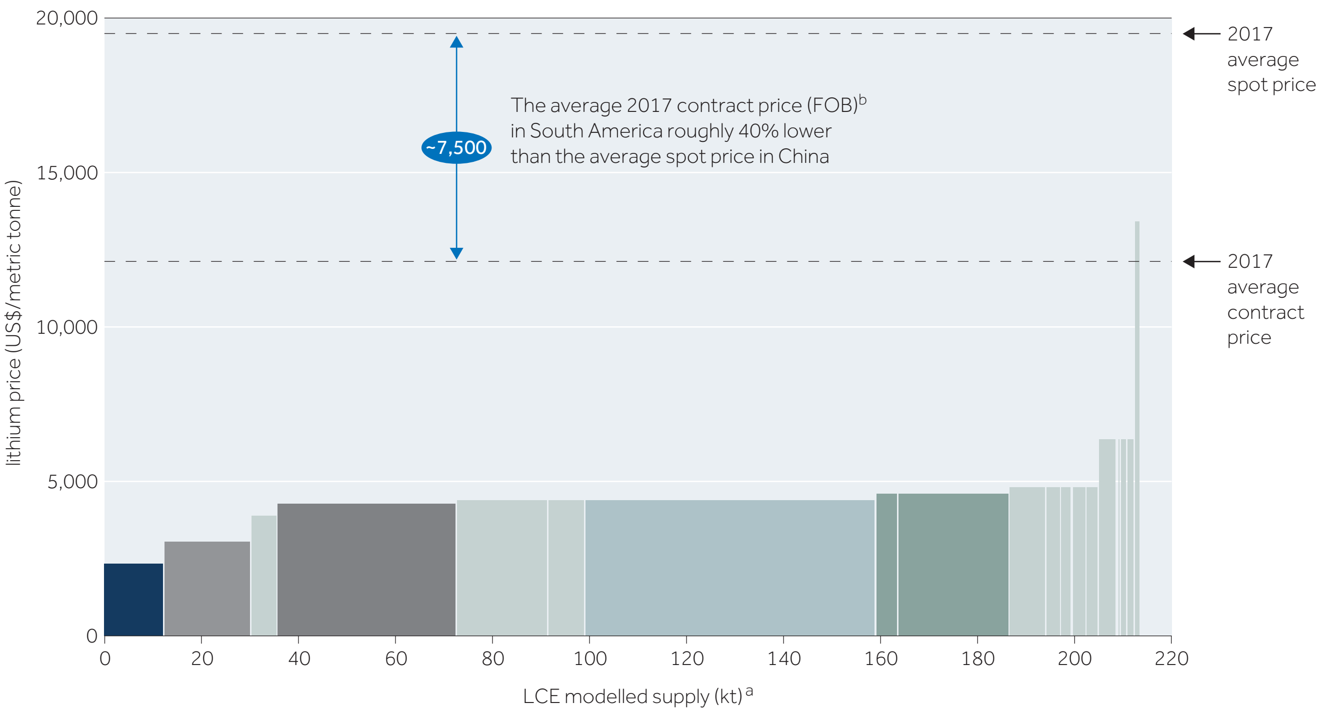
The EV revolution is reflected in the dramatic increase in the price of lithium and cobalt that has taken place over the past two years.

In terms of the pricing mechanism, lithium and cobalt have been seen in the past as 'minor metals', and, unlike copper, aluminium and steel, there is little transparency or liquidity in relation to pricing.

Lithium contract prices can be 60% below the spot price inside China (see Figure 9). The spot price is used predominantly in China for speculation rather than for large-scale negotiations. Furthermore, lithium prices could depend heavily on the policies of the Chilean government, which is currently planning large mining policy changes.

Figure 9: 2017 lithium cost curve and 2017 average price (USD/t LCE, kt LCE of modelled supply)

Source: McKinsey & Company (2018)

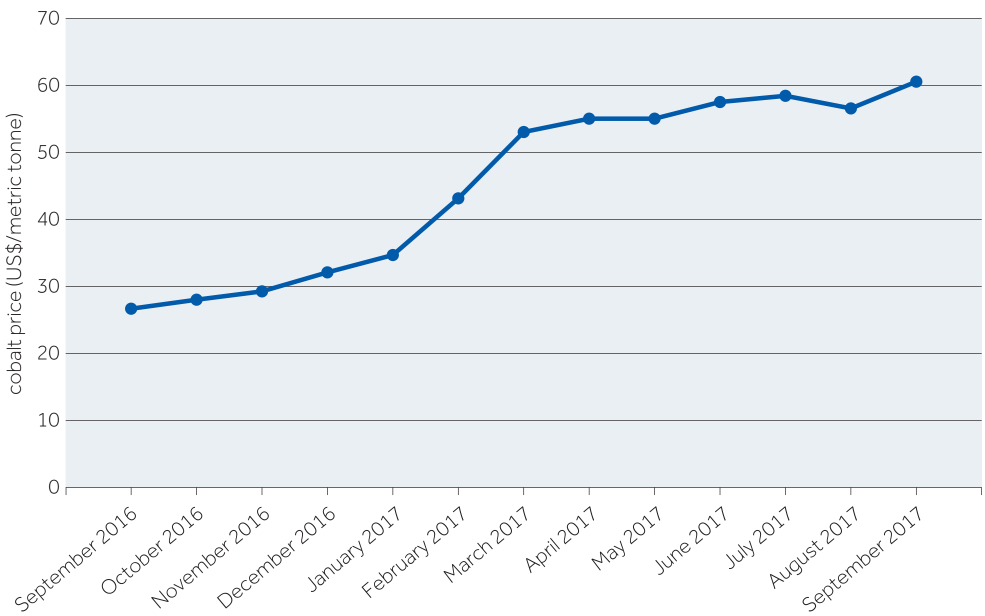


[a] kt of LCE modelled supply; Chinese capacity utilisation is modelled at 30% and rest of world at 90%.

[b] FOB = free on board.

Trading in cobalt is much less transparent, with deals structured well below the spot price and not publicly announced. This instability in Congo (Kinshasa) is a factor in the 128% increase in the price of cobalt in 12 months (see Figure 10). Over time, liquidity and transparency are expected to increase as the markets increase in size.

Figure 10: Trend in global cobalt prices in the 12 months to September 2017



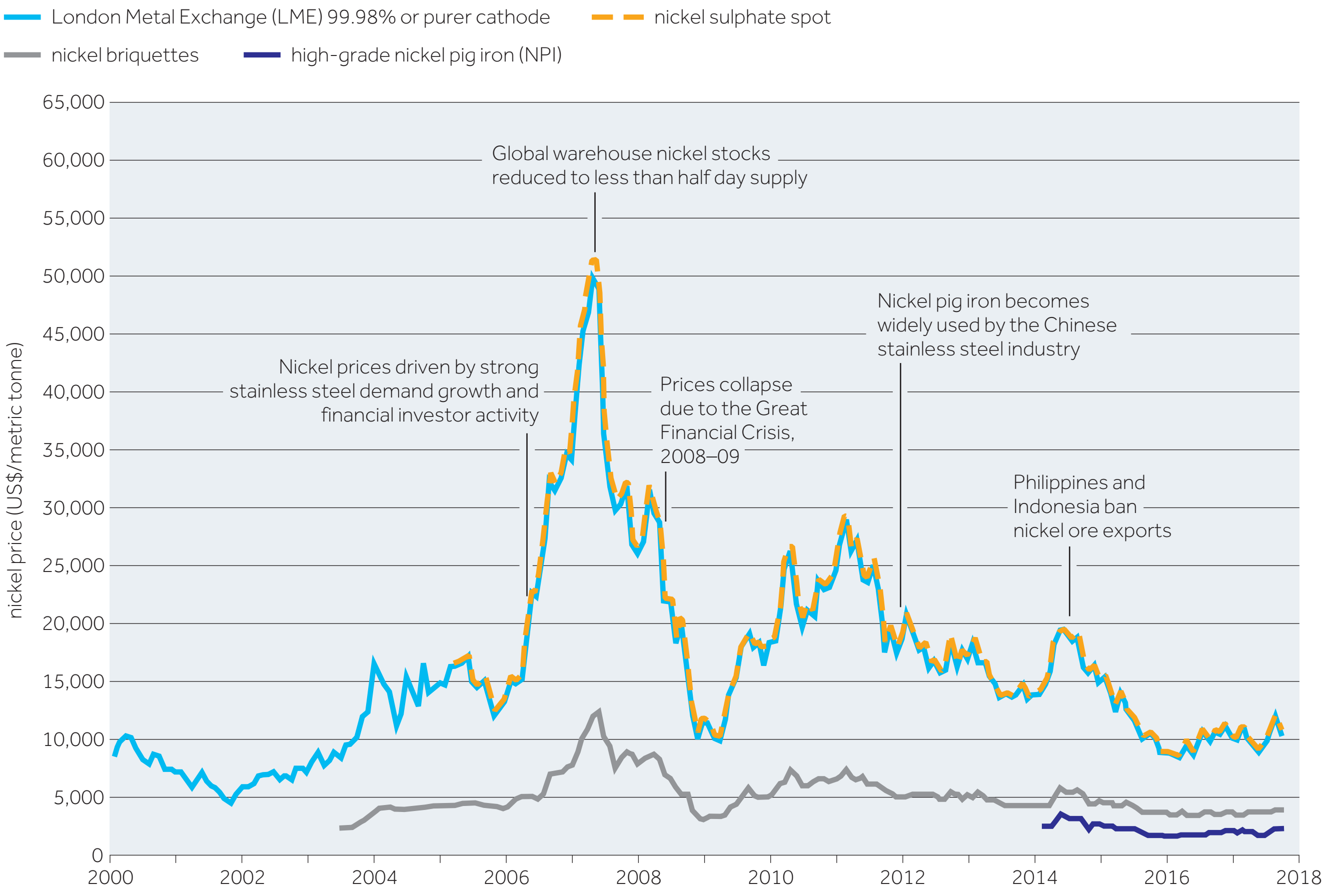
The price of nickel has fallen over the past decade due to the expansion of low-cost class 2 nickel capacity (see Figure 11).

Currently, nickel is priced in relation to the London Metal Exchange (LME) reference grade (98.8% or higher). The need for additional class 1 capacity driven by the demand for EV batteries would influence both future nickel prices and the pricing mechanism.

With regard to the impact on EV battery costs, McKinsey & Company estimates that raw materials represent 10% of the cost of a battery pack in 2018 (around 22$ of the total 200$/kWh), increasing from 3% in 2010.

Figure 11: Evolution of nickel prices by product

Source: McKinsey & Company (2017)



Notes:

- Pure nickel is traded on the LME with premiums/penalties for different nickel products.
- Briquettes are traded at a premium; nickel pig iron is traded at a penalty to reflect its lower quality.
- Nickel sulphate is based on the London Metal Exchange price adjusted for nickel content in the salt.

Although lithium prices influence the EV battery cost, battery economics are more sensitive to cobalt prices, as shown in Figure 12.

Figure 12: Battery costs for NMC in different lithium and cobalt price scenarios (US$/kWh)

Source: McKinsey & Company (2018)

2018 NMC 622 cathode, **Cobalt price** (US$/lb)

Li_2CO_3* price (US$/t)	15	25	40
5,000	-6% / 196	-2% / 205	+2% / 213
10,000	-3% / 201	~ / 208	+5% / 218
14,600	-1% / 206	+2% / 213	+7% / 223

2018 NMC 811 cathode, **Cobalt price** (US$/lb)

Li_2CO_3* price (US$/t)	15	25	40
5,000	-4% / 121	-2% / 123	0% / 126
10,000	-2% / 124	~ / 126	+2% / 129
14,600	+1% / 127	+2% / 129	+5% / 132

NMC 622 is more sensitive to changes in cobalt price compared to NMC 811

Δ, percent to base / Δ, US$ to base

* Li_2CO_3 = lithium carbonate

Recycling

Currently, the industry is focusing on recycling as a way to extract valuable battery raw materials at a low cost. Until now, the industry has been more concerned with the disposal of potentially hazardous used consumer electronic products than with the potential for extracting materials for reuse.

Lithium recycling is still in its infancy. In 2017, no lithium was recovered, and no well-defined routes are currently available for the recycling of Li-ion batteries; however, numerous techniques exist at the prototype stage, which utilise pyrometallurgical and hydrometallurgical processes to attempt to extract the valuable metals. According to Ricardo, battery recycling to recover lithium could become a large industry by 2050. However, lithium recovery may not be economically feasible for all battery types (for example, LFP batteries have little recyclable material of value). Furthermore, lithium recovered from recycled batteries will have a limited impact on the total virgin lithium required by 2050.

Cobalt has, historically, been recycled because of its high value application in alloys. In 2017, 12–15 kt of cobalt was recovered through recycling.

In 2017, approximately 90 kt of nickel was recovered from purchased scrap in the US. This represented about 39% of consumption for the year. Processes now exist for recycling nickel from spent rechargeable batteries.

Environmental impacts of material production

Environmental impacts from material extraction are being reduced in some regions. However, there is a risk that large-scale exploitation of lithium, cobalt and nickel resources could lead to significant environmental impacts, according to Ricardo.

Impacts of lithium production

- Lithium for battery production is typically extracted from brines in South American salars with an evaporative beneficiation process carried out in a series of pools. Lithium ore is extracted using open-cut mining.
- The water requirement for the lithium extraction is significant and puts pressure on local water supplies, which in some cases is heavily relied upon for local agriculture.
- Tourism in the salar areas is a major source of employment, and could be affected by increased lithium production.

Impacts of cobalt production

- Cobalt is extracted using open-cut or underground mining.
- Exposure to cobalt can impact human health. In addition, mining for cobalt (where cobalt is the intended product rather than a by-product of nickel or copper mining) often targets arsenide ores, which can have further environmental and human health impacts.
- Additional environmental impacts can occur that are similar to those associated with nickel production. In the Congo (Kinshasa) cobalt region it is suggested that there is little control of pollutants from cobalt mining.

Impacts of nickel production

- Nickel extraction typically uses open-cut mining.
- Historically, nickel mining has caused significant emissions of SO_2, as well as soil contamination and water acidification, although process improvements are reducing all of these effects.

Summary

As a summary, some of the challenges and uncertainties related to EV battery raw materials reviewed in this article are listed below:

Challenges

- Capacity of supply
- Sensitive regions (e.g. the Congo)[4]
- Risk of disruption to supply
- Lack of transparency in prices
- Metals recycling
- Environmental impacts of material production.

Uncertainties

- Extent and speed of EV adoption
- The preferred standard for battery technology in the future
- Many players: mining companies, battery producers, automotive OEMs, financial players and consumers.

[4] In contrast with oil production, where the largest share of oil reserves or production in any country is 18% of the global supply, the shares of lithium in Chile or cobalt in Congo (Kinshasa) amount to ~50%. The oil supply is therefore less dominated by any one country, which may be beneficial considering the uncertainties associated with some countries that have large oil reserves or production capacities. However, as Ricardo claims, there is a key difference between oil and battery materials:

- Oil is required to *operate* an ICE vehicle: the price effects the *running costs*.
- Battery materials are required to *manufacture* an EV: the price effects the *capital costs*.

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A summary of the report is also available here: https://www.concawe.eu/wp-content/uploads/RD18-001912-3-Q015713-Summary-Report-Mass-EV-and-Low-Carbon-Fuels-Scenarios-1-1.pdf
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