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THE FARADAY INSTITUTION

Lithium, Cobalt and Nickel: The Gold Rush of the 21st Century

Ending UK sales of new vehicles running on diesel and petrol by 2035 will massively increase the demand for lithium, cobalt and nickel used to manufacture electric vehicle batteries. Many countries around the world are embarking on a similar path to electrification. Even so, global markets for raw materials should be able to deliver the demand in the UK and elsewhere. But action is needed now to iron out likely bottlenecks in supply chains.

Introduction

The UK Government has recently announced a consultation on bringing forward the end to the sale of new petrol, diesel and hybrid cars and vans from 2040 to 2035.[1] Europe and many other countries around the globe are adopting similar policies to help meet climate change targets. Such a global transition in the automobile industry will require substantial amounts of raw materials to manufacture the large quantities of lithium-ion batteries required for electric vehicles (EVs).

Raw materials are needed for all parts of the battery including the cathode powder, graphite for the anode, separators and other key chemicals that are used in the manufacturing process. This Faraday Insight quantifies the demand for key raw minerals from EVs over the 2020 to 2050 period and particularly whether global resources and reserves of lithium and cobalt are adequate.

Different EV Battery Chemistries

The main driver of demand for raw materials is the chemistry of the battery and the manufacture of the cathode in particular that requires the largest amount of raw materials. Lithium-ion is currently the most common battery chemistry used for EVs, but lithium-ion batteries (on the market today and in the future) have many different anode and cathode compositions, requiring different amounts of raw materials.[2] Most of the differences between the different types of lithium-ion batteries reside in the chemistry of the cathode, with combinations of cobalt, manganese, phosphate and iron being the main materials used. Key cathode chemistries used in the EV market today are lithium iron phosphate (LFP), lithium nickel cobalt aluminium (NCA) and lithium nickel manganese cobalt (NMC). The strengths and weaknesses of each are shown in the table below.

Table 1: Strengths and weaknesses of key EV lithium-ion battery cathode chemistries

Cathode material	Strengths	Weaknesses
Lithium nickel cobalt aluminium oxide (NCA)	• High specific energy, good specific power • Long life cycle	• Safety issues • Cost
Lithium nickel manganese cobalt oxide (NMC)	• Ni has high specific energy; Mn adds low internal resistance • Can be tailored to offer high specific energy or power	• Nickel has low stability • Manganese offers low specific energy
Lithium iron phosphate (LFP)	• Inherently safe; tolerant to abuse, acceptable thermal stability • High current rating, long cycle life	• Lower energy density due to low operating voltage and capacity

Source: Automotive Batteries 101, WMG University of Warwick (2018).

[1] Consultation by the Office for Low Emission Vehicles (February 2020). Consulting on ending the sale of new petrol, diesel and hybrid cars and vans.
[2] There are also a wide range of other potential battery chemistries that are not currently being used commercially for the EV market but may be in the future (e.g. lithium-sulfur, sodium-ion and solid-state batteries).

Lithium cobalt oxide (LCO) is another prominent lithium chemistry but is typically used for personal mobile devices rather than EVs. Whilst the cells manufactured have the advantage of high energy density, the relative cost is a major drawback for use in EVs as the cathode contains a particularly large proportion of cobalt. Cobalt is much more expensive than other materials and a lot of cathode material is required for an EV compared to a mobile phone.

Lithium manganese oxide (LMO) is often used as a blend with other chemistries to improve performance such as with NMC in the early Nissan Leaf models.[3] Whilst the cost of the materials are low, the battery has a shorter lifecycle as the cells are not as stable (e.g. battery malfunctions caused Nissan to move away from this technology).[4]

Other potential battery chemistries for EV application in the future include lithium-sulfur and sodium-ion. Lithium-sulfur stores more energy than a typical lithium-ion battery of the same weight and can operate in a wider operating temperature range. This chemistry may also offer safety and cost improvements. The major drawback is cycle life, as current Li-S batteries have a lifetime of less than 1000 cycles, making them unsuitable for EV application.

Sodium is a low cost and abundant mineral. Advantages of sodium-ion batteries include high energy and power density and improved thermal stability relative to lithium-ion. Their relatively low cost makes them particularly attractive for next generation static energy storage applications and low-cost EVs such as e-bikes or e-rickshaws.[5] In 2019, the Faraday Institution launched a programme of research on next generation sodium-ion batteries (NEXGENNA) to exploit these benefits.[6]

Solid-state batteries are another distinct class of batteries that may be used in EVs in the future. They are distinguishable by their lack of liquid electrolyte. Faraday Insight 5[7] outlines their main advantages, which include improved safety, higher energy density, faster charging times and longer lifetime.

Modelling the Demand and Supply of Raw Materials

The Faraday Institution has developed a model that estimates the raw materials required in battery production based on projections of:

(1) EV sales and the battery manufacturing supply required (i.e. GWh per annum);

(2) the mix of different types of battery chemistry (e.g. NMC 811); and

(3) the critical material intensity of each battery chemistries (i.e. kg/kWh).

(1) Global and UK Battery Manufacturing Demand

The Faraday Institution has forecast[8] that the UK and global EV battery demand in 2040 would reach 137 GWh per annum and 5.2 TWh per annum respectively (see Table 2). The global forecasts are likely to be exceeded if more and more countries bring forward the end to the sale of petrol, diesel and hybrid cars in a similar fashion to the UK and Europe.

Table 2: Global and UK battery demand 2020 - 2050

Year	GWh per annum	
	UK	Global
2020	3	60
2025	18	320
2030	50	1120
2035	92	2770
2040	137	5210
2045	144	5470
2050	151	5760

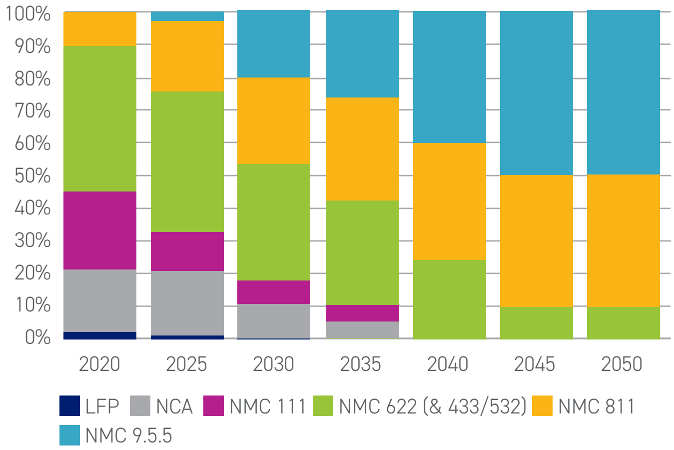
(2) Changes in Battery Chemistry to 2050

The nickel manganese cobalt (NMC) cathode chemistry is currently the primary choice for EVs and is estimated to account for around 80% of the global market. Penetration of NMC batteries is expected to rise even further and probably reach 90% by 2030, as LFP and NCA cathode chemistries decline in importance.

Figure 1 summarises our modelling assumption on how the different types of cathode chemistries evolve to 2050. These assumptions should be seen as a plausible illustrative scenario but not necessarily a forecast.[9] It is difficult to forecast the exact path of future battery chemistries as it will change as technologies are created and new products and applications are developed. The price of raw materials and the extent to which new mineral reserves are discovered and exploited will also have an impact on the optimal battery chemistry going forward.

[3] GreenBiz (13 August 2019). Who will win the battery wars?
[4] Arthur D Little (May 2018). Future of batteries - winner takes all?
[5] The UK company Faradion already manufactures sodium-ion cells for e-bikes and e-rickshaws commercially.
[6] Faraday Institution NEXGENNA project.
[7] Faraday Insight 5: Solid-State Batteries: The Technology of the 2030s but the Research Challenge of the 2020s.
[8] The Faraday Institution (2020). UK Electric Vehicle and Battery Production Potential to 2040.
[9] Batteries with solid-state electrolytes are projected to take 30% share in the late 2030s and 2040s with innovations in the material of the electrolyte. These innovations are not taken into account in this modelling scenario as it is difficult to make predictions about the specific chemistries that will be successful.

Figure 1: Distribution of different types of EV battery cathode chemistries 2020 - 2050



Source: Faraday Institution estimates; McKinsey, Avicenne Energy, BNEF, Bernstein and BMO Bank of Montreal.

The illustrative scenario shows EV battery cathode chemistries gradually moving further to NMC. There is still, however, considerable innovation in the types of NMC batteries used as cell manufactures utilise different NMC compositions to reduce cost and drive up performance.

One such innovation is the move to high nickel batteries such as NMC 811 (in which metals in the cathode are comprised of 80% nickel, 10% manganese and 10% cobalt) instead of NMC 622 (60% nickel, 20% manganese and 20% cobalt). The low cost and high capacity of nickel relative to cobalt makes it an attractive prospect for mass-market applications. The major trade-off is between capacity and stability. Higher nickel content offers more energy, but reduced cycle times, and also higher manufacturing costs as dry rooms are required.

Other innovations that may take a significant share of the market in the late 2030s and 2040s are solid-state chemistries, such as lithium-lithium metal oxide (Li-LMO), lithium-sulfur (Li-S), and lithium-air (Li-air), which typically use more lithium than other chemistries.

(3) Material Intensity of Key Battery Chemistries

Table 3 sets out estimates of the quantities of raw materials used per kWh by each EV cathode chemistry and illustrates the extent to which the newer NMC 811 chemistry uses a much lower amount of cobalt than the older NMC 111 technologies.

Table 3: Material intensity of key cathode chemistries (kg/kWh)

	Lithium	Nickel	Cobalt	Manganese
NCA	0.10	0.67	0.13	0.00
NMC 111	0.15	0.40	0.40	0.37
NMC 622	0.13	0.61	0.19	0.20
NMC 811	0.11	0.75	0.09	0.09
LFP	0.10			

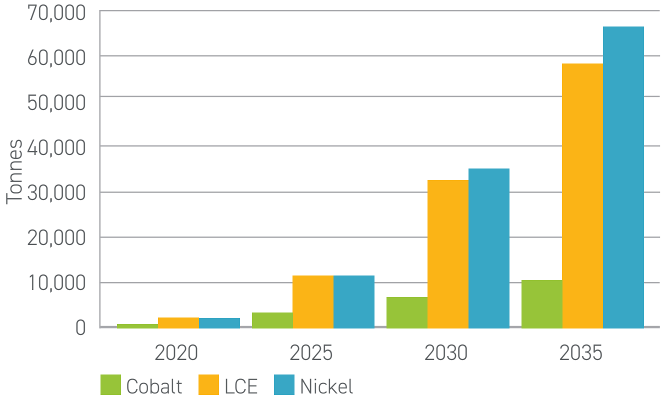
Source: Global EV Outlook 2018 (Table 6,1); Argonne Battery Cost Model

UK and Global Demand & Supply for Raw Materials

Taking into account EV sales, battery demand, chemistry mix and material intensity, we can estimate the overall amount of raw materials required. We estimate:

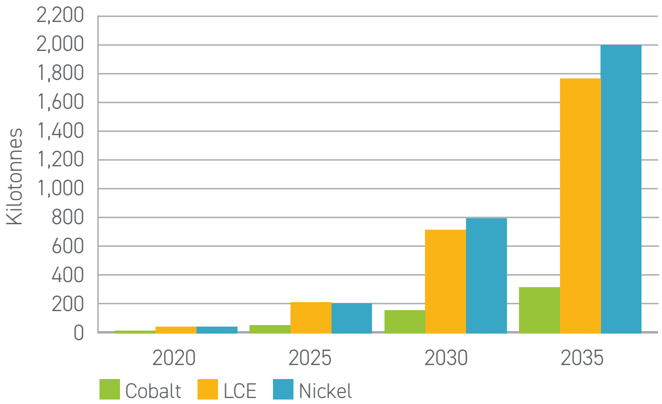
- UK 2035 demand of 10,600 metric tonnes cobalt, 59,000t lithium carbonate equivalent (LCE)[10] and 67,000t nickel under a projection of 92 GWh of UK EV battery production; and
- Global 2035 demand of around 320kt cobalt, 1,760kt LCE and 2,000kt nickel under a projection of 2.8 TWh of global EV battery production.

Figure 2: UK demand for raw minerals to 2035



Source: Faraday Institution estimates

Figure 3: Global demand for raw minerals to 2035



Source: Faraday Institution estimates

In terms of the long-term demand and supply of raw materials, the following questions need to be considered:

1. Will the annual production for lithium, cobalt and nickel be sufficient in the short- to medium-term to enable battery companies to manufacture the required quantities of batteries to meet EV demand, and will the corresponding UK and global mineral and chemical supply chains work efficiently?

2. Does the world have enough long-term resources and reserves[11] available in the ground to meet the long-term demand to make the vast majority of vehicles used to be battery-electric by 2050?

[10] In the battery market, lithium content is usually measured in terms of lithium carbonate equivalent (LCE). Lithium carbonate (Li_2CO_3) contains 18.8% lithium so 1t of lithium is equivalent to 5.3t of LCE.
[11] Reserves are defined as the quantities of raw materials that are already discovered, recoverable and commercial. Resources are much larger and include reserves and refer to the amount of raw minerals that are likely to be physically contained in the earth.

Annual Production of Critical Raw Minerals

A quadrupling in global lithium and a doubling in global cobalt production will be needed between 2018 and 2035 (Table 4). This is the 'gold rush of the 21st century'. Nickel used for EV batteries accounts for a much smaller proportion of the total nickel market than lithium and cobalt. In the medium to long-term, the demand for raw materials could be partly served by increased battery recycling.[12]

Such growth in global production will not be easy and there could be shortages and bottlenecks, particularly as lead times for capital investment in the minerals industry are typically quite long.[13] Inevitably, there will be a volatile market with fluctuations and spikes in prices when demand diverges from the supply in any given year. For example, the price of lithium is currently nearly one-third the peak of November 2017 when a major supplier took time to respond to a market deficit.[14]

Table 4: UK & global demand and supply of key minerals

	Mineral	Cobalt Kilotonnes	Lithium Kilotonnes	Nickel Kilotonnes
Global demand & supply	Global annual 2018 production	140	85	2,300
	Global annual 2035 demand	320	330	2,000
	Ratio 2035/2018	2.3	3.9	0.9
Long-term resources	Global reserves	7,000	17,000	89,000
	Global resources	25,000	80,000	130,000

Source: : Mineral Commodity Annual (2020) Summaries, USGS (US Geological Survey)

The UK will face a similar scale-up challenge but more focused on the chemical industry, imports and the supply chain rather than mineral extraction. The UK is exploring some domestic supplies of raw material including deposits in Cornwall and Wales, but it does not have abundant reserves available. The UK also has some important commercial strengths such as the second biggest nickel factory in the EU, Cornish Lithium (which is currently re-evaluating Cornwall's mineral potential) and Johnson Matthey (a global leader in battery material production).

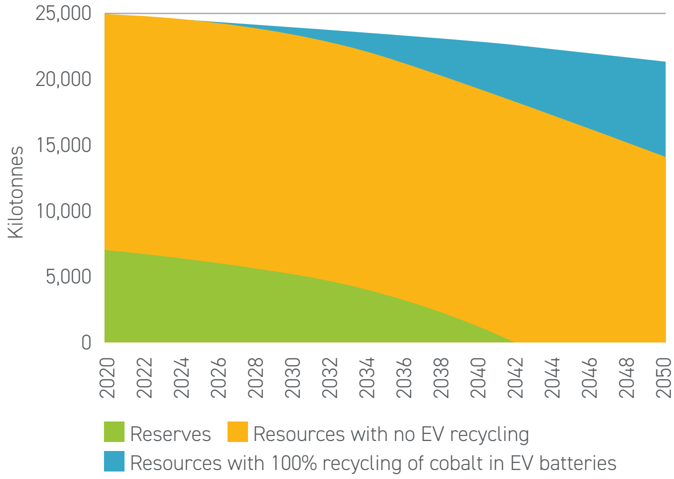
In the UK chemicals industry, the Advanced Propulsion Centre has identified a £4.8 billion opportunity[15] for UK chemical and material companies, building on strengths such as Phillips P66, the largest synthetic needle coke producer globally. It recommends that industry and government work together to help fill supply chain gaps and identify signal future demand to give companies the confidence to scale-up.

Global Resources and Reserves of Raw Minerals

Many commentators argue that there are insufficient amounts of raw minerals available in the ground for the transition to EVs, but we believe these are often based on flawed assumptions. The British Geological Survey also cautions against making reserves projections: "This complex, dynamic and uncertain situation is not conducive to robust long-term planning and decision making."[16] Clearly, long-term forecasts to 2050 are subject to a wide range of uncertainty, but there is some value in setting out a plausible scenario of how the quantities of global resources and reserves might evolve in order to illustrate the scale of the underlying challenge.

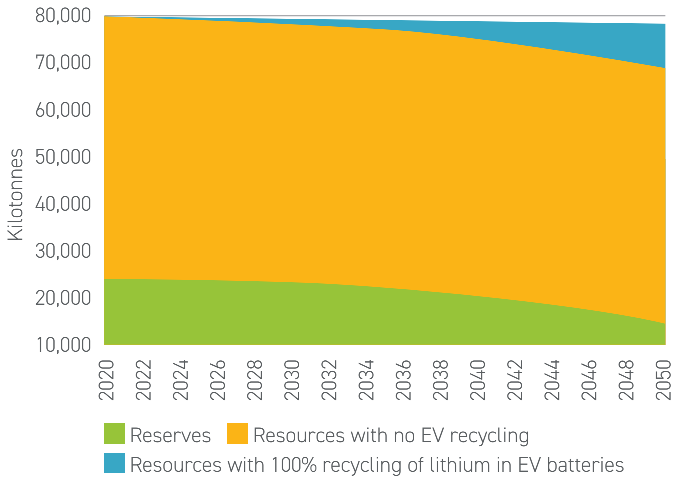
Figures 4 & 5 summarise the results of the modelling in the form of a projection of lithium and cobalt resources and reserves required for both EV and non-EV applications to 2050. Supply pressures are more acute for cobalt.

Figure 4: Global cobalt resources and reserves to 2050



Source: Faraday Institution estimates

Figure 5: Global lithium resources and reserves to 2050



Source: Faraday Institution estimates

[12] The 8- to 10-year expected life of an average EV battery means that new batteries manufactured today will only reach the recycling market in about 2030. Over the 2020s, therefore, the manufacture of new EV batteries will largely be based on substantial mineral resource extraction.
[13] Wood Mackenzie (July 2019). Can Metals Supply Keep Up with Electric Vehicle Demand?
[14] Benchmark Mineral Intelligence (January 2020). Lithium Price Assessment.
[15] Advanced Propulsion Centre UK and Innovate UK (2019). Automotive Batteries.
[16] British Geological Survey (2020). Briefing Note on Raw Materials for Batteries in Electric Vehicles.

Global cobalt resources were about 25,000 kilotonnes in 2018[17] but our modelling indicates that resources will decline by nearly one half to around 14,000 kilotonnes by 2050. Moreover, global cobalt reserves will be entirely used up by the early 2040s, so the cobalt market will only continue to function after then if some resources are turned into reserves.

Cobalt has properties that make it ideal for EV battery applications: thermal stability (which is important for battery safety) and high energy density (which allows energy to be stored and transferred at a scale suitable for vehicle applications). However, it is expensive and more resource-constrained, with social issues around mining. All these factors are resulting in a concerted effort by the Faraday Institution and other organisations to develop battery chemistries containing less cobalt.

Much more lithium will be required than cobalt for EVs, but the issues for this element appear to be about the scale-up of annual global production levels rather than resources available. The increasing challenge for lithium is also to convert it to a battery-grade product. The purity level, as well as the impurity requirements, are becoming more and more stringent for the battery industry and for many battery manufacturers this is where much of the challenge lies. In many cases, the available lithium supply does not meet the quality requirements of the battery industry and therefore is only suitable for industrial applications.

As reserves and resources decline, increasing amounts of raw minerals will reside in existing batteries themselves, creating a massive opportunity and necessity for recycling (illustrated in blue in Figures 4 and 5). The Faraday Institution's ReLiB project[18] is developing the technological, economic and legal infrastructure to allow close to 100% of the materials in lithium-ion batteries to be recycled. More generally, the Faraday Battery Challenge is playing a leading role in promoting the recycling and reuse of battery components. The recycling opportunity not only covers the manufacture of new EV batteries using recycled materials but also their use in second-life applications such as domestic and industrial energy storage.

Geographic, Political and Social Issues

As well as demand and supply issues, there are also important economic and social considerations from mineral extraction. In particular, the geopolitical risks related to the concentration of mineral resources and reserves in a small number of countries and the social issues related to cobalt artisanal and small-scale mining (ASM). Uneven spatial distribution in the supply of raw materials is likely to exacerbate the impact of any supply chain disruption.[19]

Lithium, cobalt and nickel are predominately found in a small number of countries. The Democratic Republic of Congo (DRC) for example is the biggest producer of cobalt, supplying more than 60% of the world's cobalt while key quantities of lithium are found in Chile, Australia and Argentina.

This concentration of resources creates significant risks around the supply chain and the security of supply. The UK's historical strength in the global mining industry could be leveraged to counter the security threat and transform the country into a major player that supplies the global automotive and energy sectors with raw and partial processed critical metals. As well as supply chain and security issues, cobalt mining in DRC has the added concerns around social and human rights issues due to ASM, which is low-tech and labour intensive.

Social issues around ASM of cobalt, security of supply and managing the supply chain for raw minerals will be covered in a future Faraday Insight.

Conclusions and Implications

The shift from the internal combustion engine to EVs will substantially increase the demand for the raw materials required to manufacture their batteries in the UK and globally. The key issue with delivering this change appears to be about scaling up annual global production levels and supply change issues rather than whether the world has enough resources. The current production of raw minerals is far from adequate to meet future demand and the global industry will need to scale-up significantly over the coming years. However, there are more than enough resources to supply the manufacture of EV batteries to 2050, giving time for an EV battery recycling industry to become widely established and able to deliver significant volumes of key battery raw materials for future production requirements.

The exact supply challenge for the UK will be determined by the nature of the EV transition (i.e. whether we import or manufacture EV batteries).[8] Increased demand for raw materials combined with the long investment cycle and lead-times required to exploit existing mineral reserves could put the global raw minerals supply chain under pressure in the coming decade. Supply bottlenecks, mineral price spikes and a slower transition could happen unless action is taken now to mitigate and manage supply chain risks. As well as scale-up and supply chain issues, large quantities of the raw materials contained in batteries will need to be recycled.

Tackling resource pressure and social issues with cobalt will require innovations in battery cell technology and the successful development of alternatives such as solid-state batteries.

[17] US Geological Survey (2020). Mineral Commodity Annual Summaries.
[18] ReLiB website
[19] The EV revolution: The road ahead for critical raw materials demand by Ben Jones, Robert J. R. Elliott and Viet Nguyen-Tien (2020, unpublished).

About the Faraday Institution and Faraday Insights

The Faraday Institution is the UK's independent research institute for electrochemical energy storage research and skills development. We bring together academics and industry partners in a way that is fundamentally changing how basic research is carried out at scale to address industry-defined goals.

Our 'Faraday Insights' provide an evidence-based assessment of the market, economics, technology and capabilities for energy storage technologies and the transition to a fully electric UK. The insights are concise briefings that aim to help bridge knowledge gaps across industry, academia and government. If you would like to discuss any issues raised in this 'Faraday Insight', or our wider battery research programme, please contact Stephen Gifford.

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