Task 40 CRM4EV:

Critical Raw Materials for Electric Vehicles

Final report 2018-2022

***Participants**: IEA HEV member countries (11): Austria, China, France, Germany, Netherlands, Norway, Republic of Korea, Spain, Sweden, USA, UK; **external participants**: Government of Western Australia, AVERE, Copper Alliance, Botree (China), Valuad (Belgium). In addition, 6 industrial participants of the battery materials supply chain joined the task from 2018-2021 (Anglo American, Cobalt Institute, IGO, Nickel Institute, Umicore, Vale) as well as JOGMEC from Japan.*

1 Summary conclusions and recommendations for policy makers

Electric vehicles and Li-ion batteries

Battery Electric Vehicle (BEV) penetration and Li-ion battery deployment grow (much) quicker than forecasted. BEV penetration rates have been underestimated in virtually all expert and stakeholder forecasts over the last 10 years. This results in unprepared supply chains and may worsen short term supply issues of minerals and intermediates.

Key technologies (also) continue to develop much faster than forecasted. For example, a few years ago there was a general view that high-nickel batteries would dominate the battery market, especially for cars, until 2030 or beyond. This is already no longer the reality, and zero nickel & cobalt chemistries are expected to become dominant within a few years. See annex 1 for some of the most recent (2023) developments.

Li-ion battery recycling processes to recover most of key minerals exist and will continue to improve. Large scale plants are operational in China and many smaller scale projects are implemented or announced elsewhere. Legislation to drive actual recycling will be an important factor to scale up rapidly.

Life cycle impact analyses have demonstrated that BEVs have lower (carbon) footprints than conventional vehicles and that the footprints of the BEV as well as the in-use phase will be further reduced continuously. The continued rapid development of key EV technologies will reduce the full life cycle impacts of BEVs significantly in this decade.

Key minerals for BEVs

Nickel: availability for EV batteries by 2030 could be (as a max) 1.2 million ton per year (analyst view). The supply of nickel will be dominated increasingly by Indonesia (mining) and China (refining). Alternative battery technologies without nickel will be able to fill any nickel supply gap in medium to long term. The likely limitation of available nickel (for EV batteries) on short/medium will limit the application of nickel containing EV batteries but will not impact mass EV deployment as alternative chemistries will be deployed for EV batteries.

Cobalt: does not seem to an issue, large potential from (new nickel) Indonesian sources and scale-up potential DRC. Also, alternatives without cobalt can fill the gap.

Lithium: very large resources available which will be further extended, no structural shortage expected but possible short term supply shortages (USGS: lithium reserves 2019 of 14 million ton, resources 62 million ton; 2021: 21 million ton reserves and resources of 86 million ton). Lithium is the mineral for which there is not (yet) a viable alternative at the scale required.

Copper: application in EV batteries will remain a small part of the copper supply, the assumption is that there will be no shortage for EV (batteries).

Graphite: large potential for additional mining, also graphite is made through chemical processes so no structural shortage expected, with the development of silicon-graphite, the graphite content will be reduced. Also, solid-state batteries do not use graphite as anode material.

Rare earths are currently commonly used for e-traction motors. Supply of the specific rare earths used (neodymium, praesidium, dysprosium) is already stretched and concentrated in China. It is unlikely that enough rare earths can be supplied, in a sustainable way or not, for the future medium to long term growth. Alternative solutions not using rare earths are available and further developed. Tesla has announced to eliminate rare earth for its future generations of e-traction motors.

Platinum Group Metals: BEVs do not need PGMs as they do not have catalytic convertors. Currently, 80% of palladium and rhodium and 25% of platinum supply is being used for catalytic convertors. This combined, with the very high recycling rate of PGMs, will reduce the net demand for PGMs very rapidly with increasing BEV sales. Especially palladium and rhodium net demand could reduce very significantly.

Geological availability of minerals is not an issue, bringing new supply to stream within such short timescales may be an issue. Conversion capacity as well as environmental & social local conditions are other important considerations. Secondary supplies will grow in importance but remain limited.

Recommendations for policy makers

In forecasts and policy development (scenarios), consider a “faster than expected” (mass) deployment of BEV and EV batteries.

Consider that technology changes and improvements towards higher performance, lower impact technologies and the reduction or elimination of potentially critical minerals go faster than expected. See annex 1 for some of the most recent (2023) developments.

Technology development policies and stimulation should support the development of new technologies aimed at reducing or eliminating critical mineral content, environmental and social impacts. Avoid being locked in (subsidized) critical mineral dependent technologies. For batteries this is valid for all applications in transport and stationary energy storage.

Reducing geographical/geopolitical dependency is more important than ever, especially for resource-poor countries / regions like the EU. This should include mining but also intermediate steps like refining for minerals.

Recycling as means to reduce impacts and to reduce the need for virgin minerals will become increasingly important. Development and deployment of high-quality recycling processes recovering intermediates and a wide range of minerals is key.

Rare earth minerals are not needed for e-drive motors and phasing-out of the current rare earth based permanent magnet motors should be promoted.

The transition to BEVs reduces the use of PGMs drastically (up to -80% for the current palladium and rhodium demand). This impact should be considered in the overall impact analysis of the transition.

2 Introduction

In 2017, 82 million cars were sold of which only 850 thousand BEVs and about half as many PHEVs. Although the EV sales have grown rapidly in the preceding years, with only 62 thousand BEV sold in 2012, EVs were not considered by most stakeholders from industry, public authorities, expert consultancies, or advocacy groups to become mainstream in the coming decade if at all. However, concerns on the potential criticality of some raw materials like rare earths and cobalt for the transition to renewable energy and transport were already being voiced by researchers and headline news occasionally.

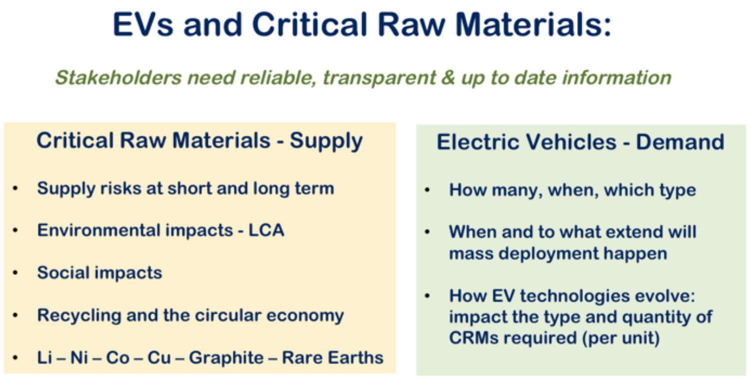
For the mass deployment of EVs several topics concerning raw materials needed to be clarified. Raw Materials under consideration included in the scope of Task 40 CRM4EV are those materials which are economically and strategically important for the mass deployment of Electric Vehicles and have a high-risk associated with their supply. It is important to note that these materials can be classified as 'critical' for various reasons (figure 1).

In 2022, more than 10 million EVs have been sold of which almost 8 million BEVs. This ten-fold growth compared to 2017 has completely changed the view on and role of BEVs as part of the transition to zero-emission (tailpipe) transport. The EU has the intention to allow only the sale of zero-emission vars as of 2035. The outlook of a rapid transition has only increased the urgency to consider the sustainable supply of materials required for EVs.

For the additional information on the Task objectives, organization, approach, and intermediate results, please consult the Task 40 contributions in the HEV 2022 and the HEV 2021 annual reports.

3 Task objectives, approach and participants

The overall objective of Task 40 was to generate and continuously update the relevant information by and for Task 40 CRM4EV participants related to critical raw materials for EVs. Data collection and (scenario) analyses included validation through various discussions within the workshops.



EVs and Critical Raw Materials:

Stakeholders need reliable, transparent & up to date information

Critical Raw Materials - Supply

- Supply risks at short and long term
- Environmental impacts - LCA
- Social impacts
- Recycling and the circular economy
- Li – Ni – Co – Cu – Graphite – Rare Earths

Electric Vehicles - Demand

- How many, when, which type
- When and to what extend will mass deployment happen
- How EV technologies evolve: impact the type and quantity of CRMs required (per unit)

Figure 1 Key supply & demand issues for raw materials important for electric vehicles – geopolitical risks were not formally included in the scope of the Task as defined in 2018.

To achieve this, the Task has built a global representative network on the topic "Critical Materials for EVs" with stakeholders from administrations, industry, policymakers, researchers, and other relevant stakeholders representing the different value chains of the identified "in-scope" critical materials. External experts are involved as well. At the HEV ExCo meeting in November 2020 it was decided to extend Task 40 with 1.5 years. For this extension period the number of stakeholders was reduced to avoid potential conflict-of-interest.

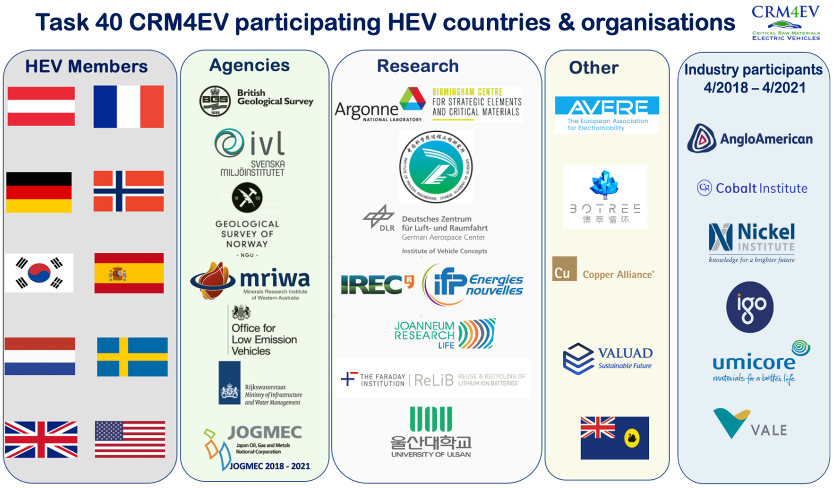


Figure 2 Task 40 CRM4EV participants and representative organizations delegated by IEA HEV participants (original project April 2018-April 2021 and the 1 year extension phase till April 2022).

In the area of mining expertise and mineral supply, the participation in Task 40 of the Western Australia government, JOGMEC from Japan, geological services, mining companies and representative industry organizations has proven to be very valuable. In addition, relevant mining conferences were attended where Task 40 work was presented and discussed. The HEV participant representative organizations and external participants provided world class knowledge regarding battery (chemistry) development and recycling and life cycle impact analyses.

Workshops and site visits were organized several times a year until 2020 when only virtual workshops and presentations were possible (COVID restrictions). Attendance of the face-to-face workshops has been 30 to 40 people (each) from Task 40 CRM4EV participants and external experts and companies. The webinars were open to public with an attendance of 80 to 190 people.

4 Results

4.1 Task 40 CRM4EV scenarios and analyses

For electric vehicle deployment, battery demand and raw material requirements the following scenarios were made:

- Passenger cars (Global, Fast-moving countries, Rapid shift to zero/low-Cobalt battery chemistries).
- Scenarios for all road vehicles and other battery applications.
- Impact of recycling and the contained minerals stock (for battery materials).
- Passenger cars use of rare earth elements for electric drive and the recycle potential.
- Avoided PGM mineral consumption scenario (BEVs do not require PGM catalysts).

In addition, a battery technologies paper (peer-reviewed by external experts) was made to model the development of the different chemistries and their market shares 2020 – 2035. A meta study of (50+) external EV and raw material forecasts was executed.

4.2 Battery and key mineral demands 2030

In the HEV 2022 and 2021 annual reports, the CRM4EV scenario studies and results have been presented. For the external (GBA, IEA, EV30@30) scenarios analyzed, the EV sales forecasts translate in a 2,500 - 3,500 GWh Li-ion battery demand for transport with mineral requirements of 1.5 million tons of nickel, 260-290 kton cobalt and 380 kton lithium (metal).

Nickel demand will outstrip supply according to our analysis in most external scenarios. Based on expert input, we estimate a maximum of 1.2 million ton nickel extra available for batteries by 2030 from “conventional” nickel sources. Any additional nickel volumes will have to come from surface mining of NPI (nickel pig iron) in Indonesia as is happening at this moment or deep-sea mining in the long term. Both may have large negative impacts on ecosystems.

CRM4EV developed in 2019 global scenarios for the deployment of BEV cars: 20, 30, 40, 50% growth year on year with 30% as the mid range “target” scenario. In 2019 most external forecasts were in the low 20’s % growth, 30% was perceived as “too optimistic, not realistic”. In 2020 forecasts trended towards 30%

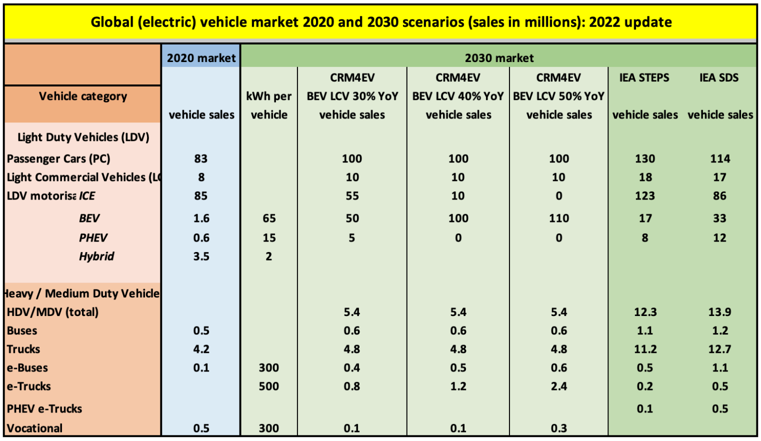
growth per year. An analysis was made of the publicly available global scenarios from key organizations and consultancies.

Task 40 CRM4EV produced in 2019 a battery technology (chemistry) paper for BEV cars. The paper was peer-reviewed by global experts for the USA, Europe, and China. At that time an increasing dominance of nickel-based chemistries and a trend towards higher nickel, low cobalt chemistries were forecasted. Also, at that time no alternatives for lithium-based chemistries to be commercialized before 2030-2035 and solid-state batteries with lithium metal anode entering larger scale commercial applications between 2025 and 2030. As developments have shown, this is changing rapidly. In 2021 the battery scenarios were extended to include significant growth in zero-nickel/cobalt battery applications.

EV market 2030: external forecasts and CRM4EV scenarios

In 2021 an updated review has been made of the 2030 forecasts from organizations like IEA, Global Battery Alliance (GAB), and major consultancies. The current - sort of - consensus view which appears from the analysis of these 2030 forecasts a 30% penetration (of BEV cars), or 30 million BEV cars sold, high nickel batteries remaining (by far) the dominating technology for EVs.

According to our experience and work, the BEV deployment as forecasted for 2030 is likely to be underestimated (2022). To attain a 30% BEV (cars) penetration rate in 2030 requires only a 23% year-on-year growth whereas actual growth rate is much higher, over 50% per year over the last 10 years and more than 100% in 2021. For other (heavy duty) vehicles, a very low penetration rate (less than 10% of sales) is forecasted for 2030. Here we also expect a much higher penetration as full electric trucks are already cost-competitive in many cases, a trend which will further increase, and which will also increase the overall demand for batteries for electric vehicles. In figure 3, the CRM4EV scenarios for EV penetration are compared with the two major IEA scenarios for 2030. Underestimation of EV sales and the potential of EV as zero emission transport solution has been structural over the last decade. This has resulted for example in Europe to a lag in investments in battery manufacturing and to an underestimation of the mineral requirements for EVs.



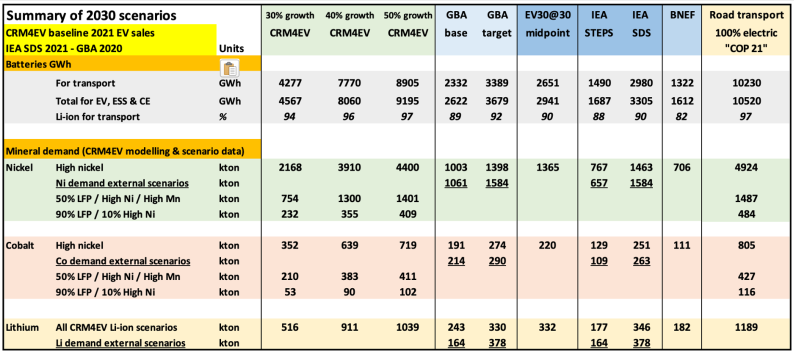
Global (electric) vehicle market 2020 and 2030 scenarios (sales in millions): 2022 update

	2020 market	2030 market					
			CRM4EV	CRM4EV	CRM4EV	IEA STEPS	IEA SDS
Vehicle category		kWh per	BEV LCV 30% YoY	BEV LCV 40% YoY	BEV LCV 50% YoY		
	vehicle sales	vehicle	vehicle sales	vehicle sales	vehicle sales	vehicle sales	vehicle sales
Light Duty Vehicles (LDV)							
Passenger Cars (PC)	83		100	100	100	130	114
Light Commercial Vehicles (L	8		10	10	10	18	17
LDV motoris *ICE*	85		55	10	0	123	86
BEV	1.6	65	50	100	110	17	33
PHEV	0.6	15	5	0	0	8	12
Hybrid	3.5	2					
eavy / Medium Duty Vehicle							
HDV/MDV (total)			5.4	5.4	5.4	12.3	13.9
Buses	0.5		0.6	0.6	0.6	1.1	1.2
Trucks	4.2		4.8	4.8	4.8	11.2	12.7
e-Buses	0.1	300	0.4	0.5	0.6	0.5	1.1
e-Trucks		500	0.8	1.2	2.4	0.2	0.5
PHEV e-Trucks						0.1	0.5
Vocational	0.5	300	0.1	0.1	0.3		

Figure 3 Road vehicle and electric road vehicles 2020 market and 2030 scenarios. 2020: sources OICA, (US light trucks are in PC); EV data source Valuad); 2030 estimates CRM4EV (sources BNEF, own estimates) and IEA scenarios; CRM4EV scenarios YoY BEV growth rates 2020 - 2030: 30%, 40%, 50%. The IEA scenarios include minibuses and some light truck categories in the category MDV/HDV, commonly these are included in the LDV category.

In figure 4, the results for the various external and CRM4EV scenarios for battery demand and key mineral demand are provided. To meet demand of certain critical minerals, significant impacts and risks will occur (supply, environmental, social, cost, geopolitical). Any "faster than anticipated" BEV growth will exponentially aggravate the impacts of the supply chain.

Nickel demand will outstrip supply according to our analysis in most external scenarios. Based on expert input, we estimate a maximum of 1.2 million ton nickel extra available for batteries by 2030 from "conventional" nickel sources. Any additional nickel volumes will have to come from surface mining in Indonesia as is happening at this moment or deep-sea mining in the long term. Both may have large negative impacts on ecosystems.



Summary of 2030 scenarios CRM4EV baseline 2021 EV sales IEA SDS 2021 - GBA 2020		Units	30% growth CRM4EV	40% growth CRM4EV	50% growth CRM4EV	GBA base	GBA target	EV30@30 midpoint	IEA STEPS	IEA SDS	BNEF	Road transport 100% electric "COP 21"
Batteries GWh												
	For transport	GWh	4277	7770	8905	2332	3389	2651	1490	2980	1322	10230
	Total for EV, ESS & CE	GWh	4567	8060	9195	2622	3679	2941	1687	3305	1612	10520
	Li-ion for transport	*%*	*94*	*96*	*97*	*89*	*92*	*90*	*88*	*90*	*82*	*97*
Mineral demand (CRM4EV modelling & scenario data)												
Nickel	High nickel	kton	2168	3910	4400	1003	1398	1365	767	1463	706	4924
	Ni demand external scenarios	kton				1061	1584		657	1584		
	50% LFP / High Ni / High Mn	kton	754	1300	1401							1487
	90% LFP / 10% High Ni	kton	232	355	409							484
Cobalt	High nickel	kton	352	639	719	191	274	220	129	251	111	805
	Co demand external scenarios	kton				214	290		109	263		
	50% LFP / High Ni / High Mn	kton	210	383	411							427
	90% LFP / 10% High Ni	kton	53	90	102							116
Lithium	All CRM4EV Li-ion scenarios	kton	516	911	1039	243	330	332	177	346	182	1189
	Li demand external scenarios	kton				164	378		164	378		

Figure 4 Current public global scenarios for battery and key mineral demands 2030 compared to CRM4EV scenarios and the COP21 (100% zero emission transport by 2050). The mineral requirements are based CRM4EV modelling or taken from the different scenarios (underlined data.)

Technologies to reduce or replace potentially critical materials for Li-ion batteries

Focus has been to develop nickel-cobalt based chemistries like NCA (by Panasonic/Tesla) and NMC (by all other OEMs) as these present the fastest option for low cost – high performance batteries for cars. These technologies are still further developed and optimized with a trend to increase the nickel content to reduce cobalt and to increase the storage capacity further. This roadmap is currently the most adapted and used in scenarios. In this development, the storage capacity per kg material will continue to increase by increasing the operating voltage and other optimization, so effectively reducing the metal content per kWh storage capacity. This is also the Task 40 CRM4EV "base case" scenario.

We expect LFP and other low nickel (high manganese) chemistries to play a much more important role than generally expected, it is already the dominant technology in China. According to MIT, LFP had a global market share of 10% in 2018 and 40% in 2022, in China the 2022 market share of LFP was 61%. LFP batteries have a lower cost, longer lifetime, safer, and a lower environmental footprint. This will likely provide an attractive alternative more since with the improving storage density of LFP. The rapidly increasing fast charging networks as well as the faster charging will reduce the need for large battery capacities. In our scenario where 50% of the batteries for transport are based on zero nickel & cobalt and a significant part of the remainder on high manganese chemistry, the expected demand of nickel can be met. Manganese is not considered in CRM4EV as a critical mineral. Manganese is the 12th most abundant element in Earth's crust, reserves are 630 million ton, and 1.7 billion ton of resources are identified, global production of manganese was 20 million ton in 2022 (USGS).

Solid state batteries likely to become relevant faster and more significantly than projected currently. In our view, reaching a 20 to 40% market share by 2030 is possible. Advantages are lower weight, higher storage density, less materials, safer and a (much) higher fast charging capability.

The potential of sodium (Na) to replace lithium partially / substantially / mainly will become clear in this decade and commercial application will start in 2023/2024. Although lithium is geologically widely available, the current mining capacity is limited and will require a large effort to keep pace. Even a partial replacement of lithium with sodium will have a large impact. The “holy grail” for batteries for transport using none of the potentially critically materials like lithium, nickel, cobalt but also graphite or manganese may to be in reach.

We can expect battery optimization and alternative technologies to reduce nickel and cobalt demand very significantly. Lithium will remain to be the anode material of choice for the coming years, but alternatives will continue to be developed and improved. A long-term scenario without lithium (dominance) should be considered.

Some other alternative chemistries are:

LMO “Lithium-rich”, LiMnOxide, LFMP: no nickel, no cobalt. This technology is also improving quickly, already used in e-bike and low speed cars (comparable with L6/L7 vehicle categories for Europe) in China. We can expect this technology to be commercialized in China within the next few years. It is the low material cost technology.

Argonne National Laboratory and other are working on chemistries whereby part of the nickel in NMC is replaced by manganese (or aluminum) as well as part or all the cobalt. These types of improvements are developed by some OEMs and will reduce nickel and cobalt. First commercial applications around 2025?

We can expect battery optimization and alternative technologies to reduce nickel and cobalt demand very significantly. Lithium will remain to be the anode material of choice for the coming years, but alternatives will continue to be developed and improved. A long-term scenario without lithium (dominance) should be considered.

4.3 Recycling in task 40 CRM4EV

Li-ion batteries: recycling can be done, processes to do so are already operational and many more are in development including automated processes to dismantle the batteries. Recovery of components which then can be re-used as such is also done (for example to recover modules, to repair modules). Metals like nickel and cobalt can be recovered (yield above 90%) in all processes. To recover other materials needs more elaborate processes but it can be done. The significance of recycling as secondary raw material will increase coming 10 to 15 years. In 2021 in China, 7% of nickel and cobalt, 4% of lithium and 5% of manganese used in battery production came from spent power batteries or battery production scraps (source Botree). This is related to the long-life time of the batteries (vehicle lifetime or more) and the possible second-use life of EV batteries. The main financial benefits of recycling used to come from the recovery of nickel and cobalt. However, with the high price of lithium (2022) the recycling of lithium is currently in China the most profitable part. Collection and recycling will not be always a guaranteed profit-making operation by itself and everywhere. Legislation is required and already implemented partially to assure an at least partial recycling.

The figure below gives an indication of the type and quantities of materials used for a typical 60 kWh EV battery pack as function of the battery chemistry used. For a NMC811 battery of this size, the mineral use is 6 kg of lithium, 40 kg of nickel, 5 kg of cobalt and 5 kg of manganese. A LFP battery will require 6 kg of lithium and about 24 kg of phosphorus.

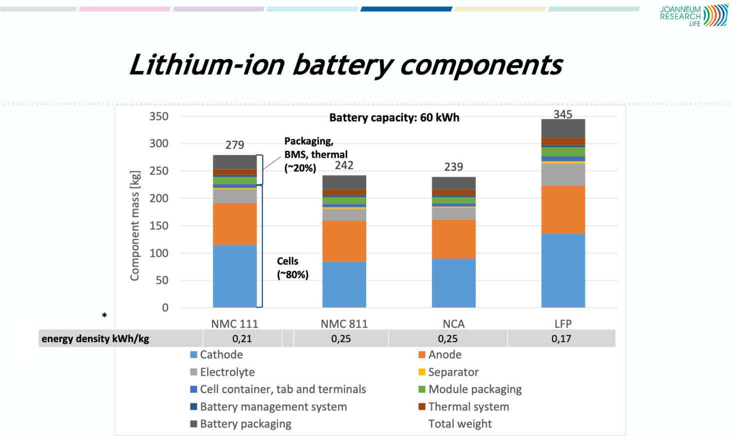


Figure 5 Composition of typical EV battery technologies (kg materials for a 60 kWh battery pack). Source: JOANNEUM RESEARCH, with data inventory based on Greet2 2021 (ANL, US), energy density for battery pack with high share of Aluminum in module and pack casing.

Recycling Processes and the Circular Economy

What is the best thing to do with recovered materials? In an ideal circular economy, we would extract materials from the earth, use them to make a product, and reuse the product repeatedly, with whatever refurbishment or repair Is necessary, without extracting additional materials. The options for used products form a hierarchy, with those requiring minimal new resources at the top. For Li-ion batteries, reuse in less-demanding applications such as low-speed vehicles or stationary storage is gaining some acceptance. However, eventually batteries can no longer hold sufficient charge for even those uses and have reached their end of life. But, in keeping with circular economy thinking, we recognize that spent batteries are still a valuable resource that can be recycled. Lithium-ion batteries are already recycled commercially by well-known processes, but these do not extract the maximum value from their feedstock.

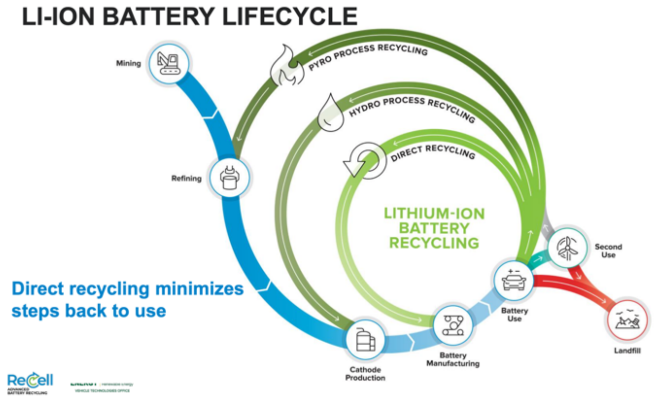


Figure 6 Different recycle processes for EV batteries. Pyrometallurgy: metal recovery as alloy (Ni, Co, Cu), requires hydrometallurgical refining for metal recovery. Li, Mn, Al into slag (recovery is challenging), energy intensive process. Hydrometallurgy: pre-treatment / sorting of different battery chemistries for constant process input, long process time, wastewater treatment. Direct recycling/ sorting of different chemistries, very sensitive to changes in input material.

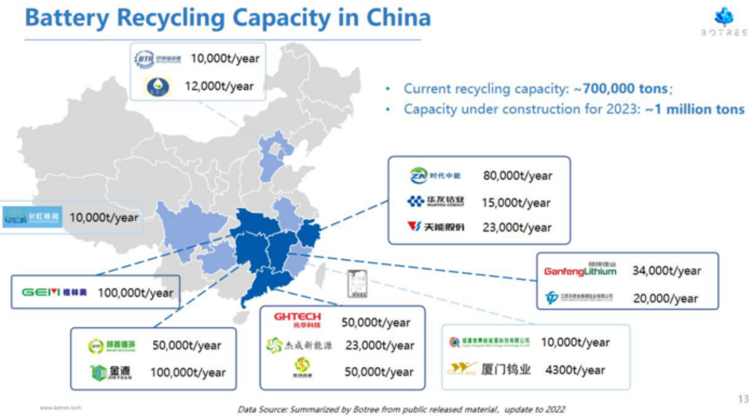
Pyrometallurgy, or smelting, treats the input as if it were an ore, exposing it to high temperature (over 1100°C) to volatilize, combust, or melt and reduce all of the components of the cell. The product is a mixed alloy of cobalt, nickel, and manganese, which must then be treated hydrometallurgically to separate the component metallic elements. All of the organic (carbon-containing) materials– the carbon anode, plastic separator, and electrolyte solvents– are oxidized and lost. The lithium and aluminum are entrained as oxides in the process slag, and it is generally not economical to recover them.

Hydrometallurgy, or leaching, is used in several large new plants in China and Korea. Cells are shredded, the product sieved to remove pieces of the copper and aluminum foil current collectors (which are then sent to a copper recycler), and the remaining material dissolved in strong acid to break up the crystal structure of the cathode material. The carbon anode does not dissolve and could be recovered if it were economical. A series of solvent extraction and precipitation processes separates the different metal ions, which can then be used to produce cathode precursors like cobalt sulfate.

Direct recycling: keep the cathode crystal structure intact. We define direct recycling as the recovery, regeneration, and reuse of battery components directly without breaking down the chemical structure. It has also been called direct cathode recycling and cathode-to-cathode recycling. By recovering cathode material, several energy-intensive and costly processing steps can be avoided. Direct recycling could be used now for manufacturing scrap at low volumes. Advantages include low temperature and low energy consumption, and avoidance of most impacts from virgin material production Lifecycle analysis of a lithium-ion battery (Fig.6) shows the contributions to various impact factors from the production of the various battery components. NMC powder makes large contribution so its recovery in usable form minimizes impacts. The challenges will be discussed in the context of more detailed process discussion below.

Figure 7 Direct recycling process unit operations

Production scrap (from battery (materials) production) is another important source of material for recycling. Scrap rates for lithium-ion battery production are estimated to be about 5% for the best producers, 10% for typical producers, and as high as 30% or more during start-up phases. Whatever the actual rates are, this is a lot of material compared to that coming back at end of life because it is based on the current production rate, which is much higher than the rate when the EOL material was produced, because of rapid growth. ReCell scientists have already demonstrated that recovered cathode from manufacturing scrap can be used in new cells directly, without any steps to upgrade it. Scrap is an important feedstock for North American recyclers like Li-Cycle and American Manganese. Redwood Materials gets scrap from Panasonic, which “alone provides about one gigawatt of material annually and (also) a dozen other partners contribute a similar amount, for a total equivalent of about 20,000 tons of material per year.” In China, Hunan Brunp mainly produces ternary precursors for power batteries, using battery scraps from CATL as its main feedstock.


Battery Recycling Capacity in China

- Current recycling capacity: ~**700,000 tons**;
- Capacity under construction for 2023: ~**1 million tons**

Data Source: Summarized by Botree from public released material, update to 2022

Figure 8 Li-ion battery recycles plants in China 2022.

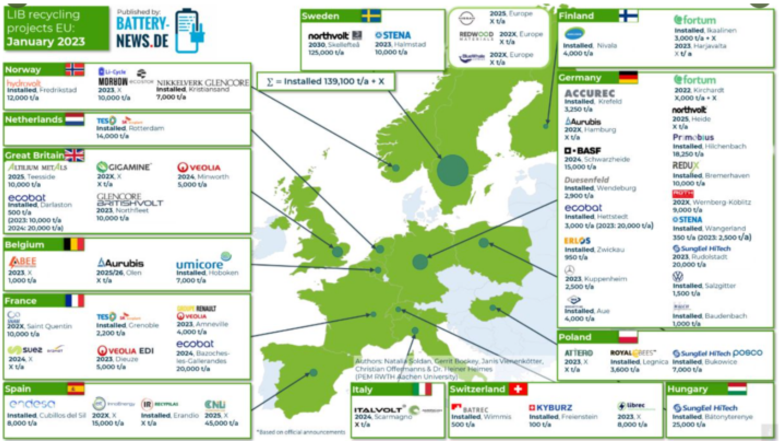


Figure 9 Li-ion battery recycle plants and pilots in Europe 2022.

Outlook for improvements of battery recycling processes: The EV battery cathode metal elements, like nickel, cobalt, manganese, and lithium can be efficiently recycled, and even upgrading into better performance battery-grade materials. On the contrary, other components, like anode, separator, and electrolyte in the EV battery can hardly be reused. Most of time, they are experiencing down-cycling, or even incineration and landfill.

The EV battery recycling technology is still evolving, nickel, cobalt, lithium, especially lithium, their recovery rate still has room for improvement. Yet, no mature technologies are available to generate high value use of graphite and electrolyte. The core is to improve the separation efficiency and accuracy of dismantling process, optimize separation and purification processes, and develop new types of separation agents and systems.

In our view, the roadmap for recycling technology development can be illustrated as below.

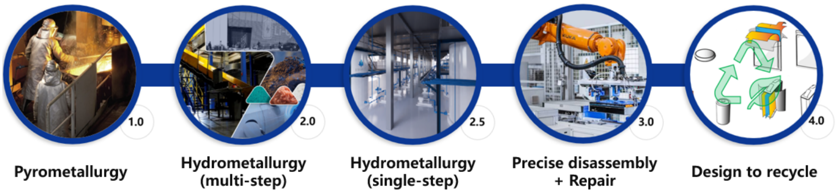


Figure 10 Improvement steps of the Li-ion battery recycling

Currently, the state-of-art technology is using hydrometallurgical process with short route extraction steps, which can reduce the chemical/energy consumption and wastewater volume compared to traditional hydro one. However, the process still requires working at atomic level to dissolve everything, then regenerate into materials. Future technologies shall directly focus on material level recovery and take recycle into consideration even at the initial design stage. To achieve that, it relies on high-throughput and high-security disassembly production line; meticulous disassembly technology (adaptable to different models, structures, assembly methods of batteries, and automation); efficient social battery collection and classification system; safe battery transportation system; stable and easy-to-industrialize repair technology.

EV battery critical minerals can, from a technical perspective, almost completely be recovered, as minerals or intermediates. In the EU and China legislation is in place and is being further developed, this will have implications across the whole supply chain. Battery recycling will be part of the vehicle life cycle from an OEM, consumer, and legislator point of view. Currently, already a high number of recycling (pilot) initiatives are in place from actors across the supply chain.

For the section on recycling, text contributions gave been provided by Argonne NL ("Direct Recycling R&D at the ReCell Center - MDPI") and Botree (China).

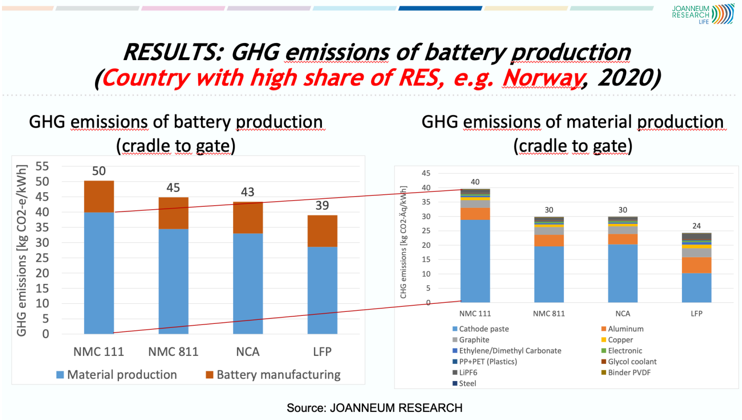
4.4 Life Cycle impacts of EV batteries

When looking at EV impacts, we must look at the full lifecycle. In Task 40, the focus has been on the impacts of the battery materials and manufacturing, the impacts of BEVs in use and the impacts of recycling of the batteries.

Within this analysis, GHG and energy demand have been studied in detail. Existing LCA studies and expertise of Task participants has been used. An important attention point for future work is the harmonization of methodologies in existing CRM-LCA studies to better compare results. As EV batteries and EVs as well are evolve and improve very rapidly it is important to take these future developments into account through LCA scenario studies. For example, a doubling in battery lifetime will (about) half the impacts of its manufacturing.

GHG emissions from battery materials and manufacturing

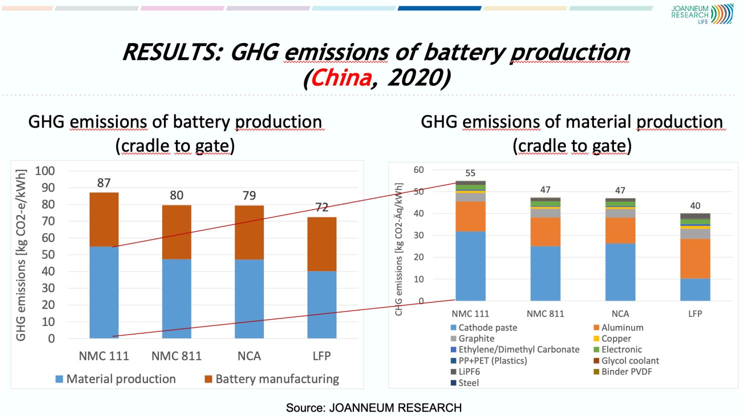
For Li-ion batteries, most of the GHG emissions come from the materials used. In figures 11 and 12 the GHG emissions for battery material production and the battery manufacturing are detailed for the "low emission" Norway and the "high emission" China situation. Battery manufacturing accounts for about 20% of the GHG emissions. For mined materials, global values are used. Nickel for example in the NMC811 battery pack has an emission of about 5.4 kg CO2 per kWh. A shift in nickel sourcing to Indonesian NPI (Nickel Pig Iron) would increase this nickel related emission 3 to 10-fold. Cathode paste and aluminum (for casing) represent the highest impact materials for batteries. LFP has the lowest GHG emission per kWh.



RESULTS: GHG emissions of battery production
(Country with high share of RES, e.g. Norway, 2020)

Source: JOANNEUM RESEARCH

Figure 11 GHG emissions for Li-ion battery manufacturing using 2020 Norway electricity grid (21 g CO2/kWh) for intermediate production and battery manufacturing.



RESULTS: GHG emissions of battery production
(China, 2020)

Source: JOANNEUM RESEARCH

Figure 12 GHG emissions for Li-ion battery manufacturing 2020 China electricity grid (756 g CO2/kWh) for intermediate production and battery manufacturing.

GHG impact reduction of Li-ion batteries through recycling

Recycling can help reduce the overall life cycle carbon footprint of EV batteries by generating valuable secondary materials, though the product format really depends on the recycling techniques employed. Hereafter, battery recycling using a physical pretreatment followed by hydrometallurgical process has been evaluated. Assuming a 100% end-of-life collection rate, with overall 90% nickel, 90% cobalt, 90% manganese, 80% lithium, 90% copper and 90% aluminum recovery rate, the carbon footprint of EV battery can be reduced by 22%~27.7%, depending on the battery chemistry.

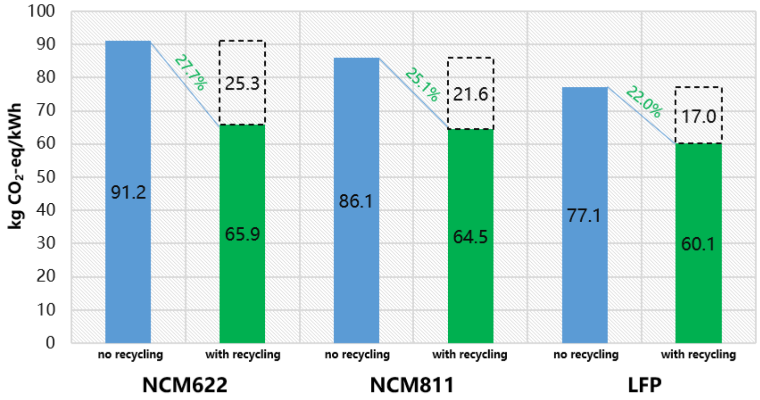
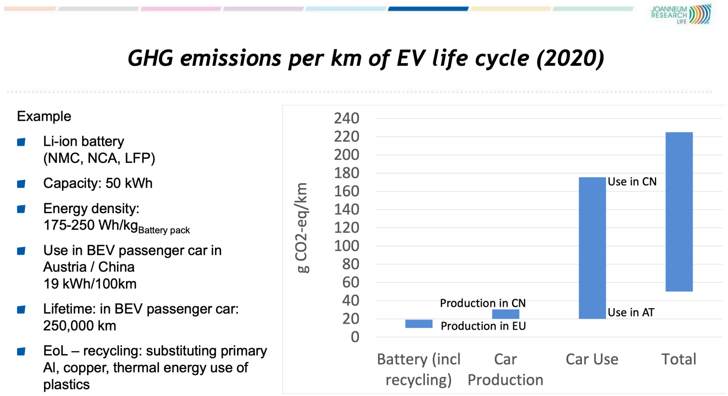


Figure 13 Impact of recycling on the GHG emissions of Li-ion batteries. (note: source Botree for the situation in China, data somewhat different than those represented in figures 12 but same trend).

GHG emissions from BEVs over the full life cycle for two scenarios is presented in figure 14. The lifetime GHG emissions for a BEV made in the EU and used in Austria is compared with the GHG emissions of a BEV used in China with a battery made in China. The large impact of the use-phase is evident and depends on the emissions related to the production of electricity.



GHG emissions per km of EV life cycle (2020)

Example

- Li-ion battery (NMC, NCA, LFP)
- Capacity: 50 kWh
- Energy density: 175-250 Wh/kg$_{\text{Battery pack}}$
- Use in BEV passenger car in Austria / China 19 kWh/100km
- Lifetime: in BEV passenger car: 250,000 km
- EoL – recycling: substituting primary Al, copper, thermal energy use of plastics

Figure 14 GHG emissions from BEVs over the full life cycle for two scenarios

Continuous improvements of EVs and Li-ion batteries

Li-ion battery and EV technologies develop very rapidly and in general with a trend which reduces the lifecycle impacts. Less materials used, replacing scarce materials with more abundant materials, simpler manufacturing processes and larger scale manufacturing, more efficient electronics and drive motors are examples of these developments. Also, the increased use of renewable energy in manufacturing processes and in the use of the EV and better recycling contribute to the reduction of impacts. The impacts of these developments reinforce each other in many cases. Some examples of (partly already achieved) developments are given below.

Battery energy densities are increasing rapidly, for example for the Tesla Model Y from China using LFP chemistry 125 Wh (watt hour) per kg batteries from CATL are being used (as of 2021), for 2023 an increase to 160 Wh per kg is announced. CATL announced a LMFP variant increasing a further 15 to 20% on this. Production of the Qilin NMC batteries with a density of 255 Wh per kg has started in 2023. Best in class energy densities at pack level were 100 Wh per kg in 2015 and 200 Wh per kg in 2020.

Battery lifetimes x 10: EV batteries are in general guaranteed to maintain as a minimum 70% of charge for 8 years or 100.000 km of service. The actual performance is better. However, “1 million mile” batteries are developed (even 2 or 4 million miles) meaning a significant increase well beyond the vehicle lifetime will happen.

Energy use -50%: The Mercedes-Benz VISION EQXX is how we imagine the future of electric cars. Just one-and-a-half years ago, we started this project leading to the most efficient Mercedes-Benz ever built – with an outstanding energy consumption of less than 10 kWh per 100 kilometers. It has a range of more than 1,000 kilometers on a single charge using a battery that would fit even into a compact vehicle (Chairman of the Board, Daimler, 2022). This is about half of what comparable BEVs in 2022 realize.

Next to these performance improvements, gains are made by more efficient manufacturing processes for batteries and vehicles, use of renewable energy in manufacturing processes and for the use of EVs.

4.5 Rare earth elements for EVs

Electromotors for propulsion are currently almost exclusively based on permanent magnets (PM)motors (a publication of 2021 mentioned 93%) containing rare earths. The most notable non-PM motor being used is the induction motor in the earlier Tesla model S and X. PM based motors offer a slightly higher efficiency. As the supply dependence and uncertainty of rare earths is high, much research goes into the rare earth free motors. CRM4EV scenarios indicate clearly that a continuation of the current REE based drive motors for EVs is not sustainable. Tesla has announced (2023) to eliminate all rare earths from its next generation PM motors. For this next generation drive units, Tesla states: “Lower Cost & Higher Efficiency Drive Units Using Zero Rare Earths” (Tesla investor day 2023).

The rare earths used are Neodymium (Nd) and Praseodymium (Pr) for the magnetic performance and Dysprosium in small quantities for the temperature stability. Per PEV 2.5 kg PM is required on average for the e-drive motor is assumed (quantity depending on motor power); currently containing 27% Nd/Pr and 3% Dy for a total of 0.75 kg.

For EVs, it can be stated that the PM based motor is the preferred option in 2022 but that if needed alternatives exist. A lack of rare earths (for PMs) will not hinder substantially the transition to electric drive. In addition, future drive units without rare earths may be lower in cost and higher in efficiency. Tesla announced as much for its future generation drive motor at the Tesla Investor Day 2023.

Rare earth demand and supply for electric drive motors

Demand rare earths for PMs is increasing rapidly with several drivers. The two most important drivers are the use of PMs in electric drive motors for EVs and wind turbines.

Task 40 has made a scenario with the 30% growth scenario for EVs, the demand will grow to about 100 kton Nd/Pr per year in 2030, based on 100% market share for PM based motors. This is more than twice the current production of these rare earths. This also considers an expected reduction of the Neodymium/Praseodymium content in PMs in the mid-20's.

Rare earths are mined as a mix, which differs from deposit, but which does not enable selective mining of specific rare earths. The stronger growth in PMs production and use – more than in most other REE applications – has resulted in an imbalance in the supply and demand at the level of REE. This imbalance is expected grow as the demand of the "non-PM" rare earths is expected to grow slower or even decline. Rare earths are not "rare" as such and reserves / resources are abundant. The main issues are the mining and refining costs and environmental impact this has. A significant part of the Chinese production comes from "illegal" mining which is supported at local level.

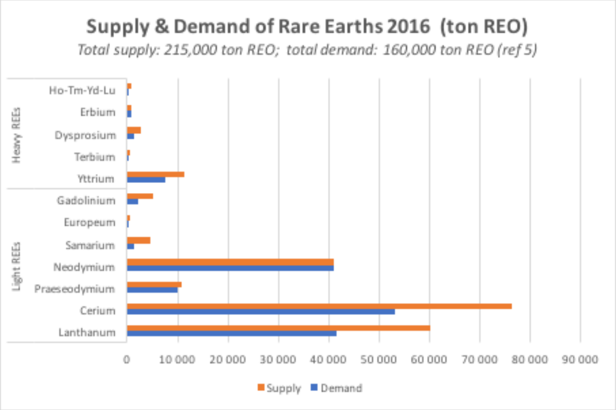


Figure 15 Supply and demand for individual REOs in ton, 2016. It demonstrates that the REOs Nd and Pr used for PMs are in balance while for other REO like Ce and La an oversupply is generated. For 2017 this oversupply is estimated at 55,000 ton.

For the supply-demand imbalance for Nd/Pr is forecasted to be increased the coming years (Adams Intelligence). For every ton of Nd/Pr produced, 3 tons of other rare earths for which there is no real demand is produced as well as rare earths as mined and refined as a mix of different elements. They presume a continued use of rare earths for EV traction motors for the coming decades and forecast a ten-fold market increases (by 2035) and long-term supply shortages. This analysis is more likely just confirming the fact that for EVs alternative solutions will be implemented.

Rare earths from PMs: recycling processes are under development but very complex and costly. The EU Horizon project REE4EU has developed processes to recycle rare earths from PMs. They are however technically compex and only tested at small pilot plant scale, other processes are mentioned in literature. An even bigger challenge is to collect PMs from EoL e-motors which is a logistically and technically difficult and costly operation.

4.6 Platinum Group Metals demand and supply

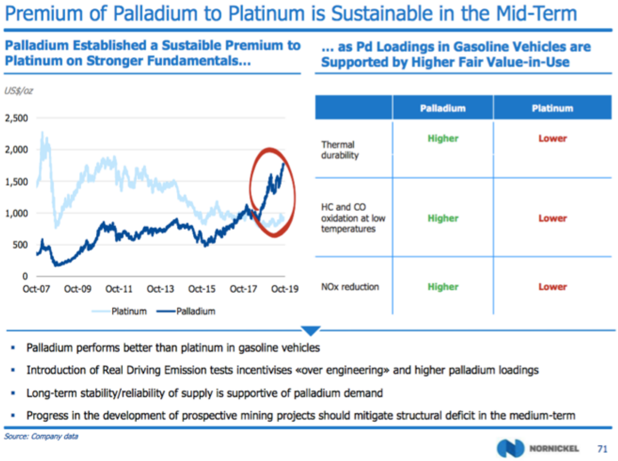
"A complete transition to BEV will reduce 60% of the net Platinum Group Metals demand"

The use of PGMs in cars.

The platinum group metals (PGM) Palladium (Pd) and Platinum (Pt) and Rhodium (Rh) are used in conventional combustion engine cars, hybrid cars, PHEVs and in the fuel cells of FCEVs. The use in these cars is in the catalytic convertor used to reduce NOx emissions. With the increase in air quality and emission regulation, the use of catalytic convertors is on the increase globally.

Platinum's main use is in diesel vehicles, whereas palladium tends to be used in petrol engines. But rhodium is the most effective catalyst for nitrous oxide (N2O) emissions in petrol engines, as much as seven times more effective than palladium. Platinum can substitute for palladium in petrol engines, but this substitution only tends to kick in when the palladium price is double that of platinum.

Typical uses of PGM per car (sources Fraunhofer, Nornickel) are 2 to 6 grammes in combustion engine cars. The quantity depends on the engine size and the emission reduction required, trend for both is to go up. The type of PGM used on fuel type and PGM price. For FCEVs, 40 grams of platinum (expected to be reduced to 20 grams by 2030) for a 95kW fuel cell (Fraunhofer). For commercial vehicles (diesel) the catalytic convertors require 6-30 grams PGM per vehicle.



Premium of Palladium to Platinum is Sustainable in the Mid-Term

Palladium Established a Sustaible Premium to Platinum on Stronger Fundamentals...

... as Pd Loadings in Gasoline Vehicles are Supported by Higher Fair Value-in-Use

	Palladium	Platinum
Thermal durability	Higher	Lower
HC and CO oxidation at low temperatures	Higher	Lower
NOx reduction	Higher	Lower

- Palladium performs better than platinum in gasoline vehicles
- Introduction of Real Driving Emission tests incentivises «over engineering» and higher palladium loadings
- Long-term stability/reliability of supply is supportive of palladium demand
- Progress in the development of prospective mining projects should mitigate structural deficit in the medium-term

Source: Company data

NORNICKEL 71

Figure 16 Palladium is the preferred auto catalyst PGM for gasoline cars and will continue to be used even with higher palladium prices.

The overall use of PGMs in new vehicles with a combustion engine was on average 3.8 grams per vehicle in 2018 globally, all vehicle categories and all vehicles.

Of the net global demand (gross demand-recycling) of palladium and rhodium 80% is used for autocatalysis, for platinum this is 30% and for the PGM 60% (figure 17). More than 80% of the recycled PGMs come from autocatalysts and recycling represents about one third of the total supply.

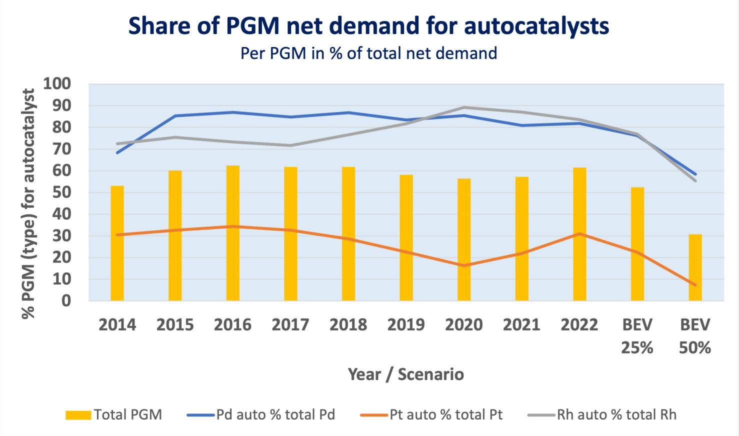


Figure 17 Percentage of the PGMs used for autocatalysis as % of the total net demand for each PGM.

Impact of BEV deployment on the net PGM demand

In figure 18, the calculated savings from actual BEV deployment is provided in ounces as well as percentage for the different PGM. It presumes that one BEV avoids one ICE car with an average PGM content of 3.8 gram per car. With 80% of palladium and rhodium used for autocatalysts, the impact is already significant.

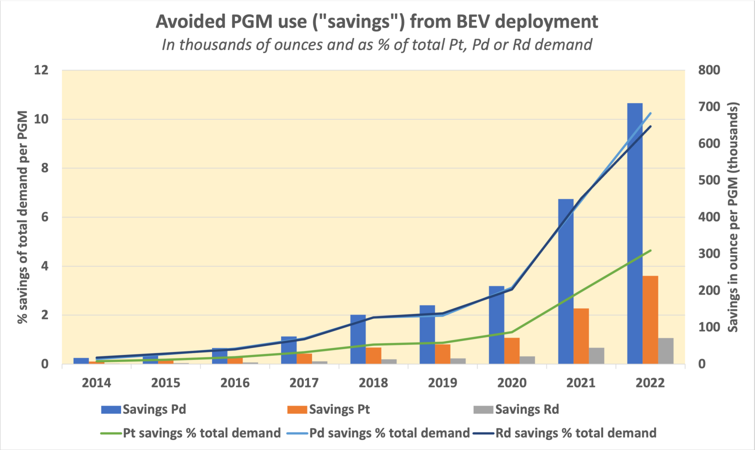


Figure 18 Impact of global BEV sales on the demand for PGMs for autocatalysis. Scenario in which one new BEV avoids one average car containing 3.8 gram of PGM.

In figure 19, 3 scenarios are presented with 25, 50 and 100% BEV market share for new vehicles (4 wheels or more). If this transition happens within 15 to 20 years, the recycling of autocatalysts will still be at or near today's levels assuming a catalyst lifetime of about 15 years. In the extreme case of a rapid 100% transition, the vehicle sector could become a net PGM supply. For palladium and rhodium no mining would be required for several years and then level of about 10% of the 2022 volume of 7 million ounce, assuming no changes in other uses. As palladium is mainly used for (gasoline) cars, a rapid decline scenario is realistic. In the same 100% scenario (around 2035-2040), platinum net demand could be reduced 60 to 70%, to rebound back to around 70% of the 2022 net demand of 5 million ounce.

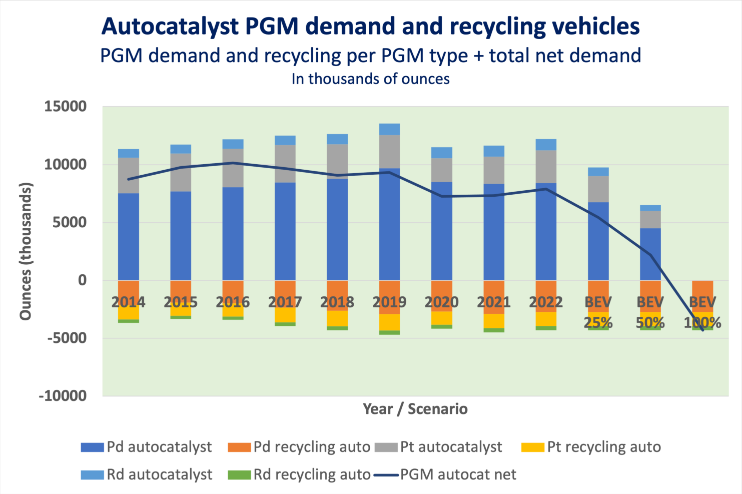


Figure 19 PGM demand for new vehicles and the recovery of PGM through recycling of end-of-life autocatalysis. Years 2014 – 2022 + BEV deployment scenarios 25% / 50% / 100%.

PGM demand for FCEV

For FCEV especially platinum is being used, currently (2021) 40 grams for a 95 kW FCEV. Technology improvements are expected to reduce this to 20 grams by 2030.

The additional PGM demand for 1 million FCEV sales by 2030 would be about 0.6 million ounces (demand FCEV-demand regular ICE cars) or about 10% of the current total platinum demand (all applications). A mass deployment of FCEV with the current PGM based fuel cells will not be possible without multiplying platinum mining capacity.

Reduction or replacement of potentially critical materials for PGMs for auto-catalysts or hydrogen fuel cell vehicles

Technology developments are expected to reduce the need for PGM for hydrogen fuel cells (for vehicles). Fraunhofer states a 50% reduction by 2030, whether this is realistic or can be overachieved is not investigated. The amount of research going into hydrogen fuel cells will also depend on the success of (mass deployment of) FCEVs, something which is not foreseen now to happen any time before 2040 – 2050 if at all. The outlook for large scale deployment of FCEVs is becoming less likely as BEVs improve rapidly and the production and distribution of renewable based hydrogen is not advancing significantly.

The optimization of autocatalysis is not investigated, it is out of scope of this EV materials driven review, the trend is the opposite with the average PGM demand per ICE vehicle going up.

Full electric BEVs do not require PGMs for emission control or for the EV drive system and are the most effective technology to reduce PGMs in cars.

Recycling of PGMs from autocatalysis is done with profit as PGMs are very high value materials. PGMs from PEMs (hydrogen fuel cells): Platinum and ruthenium, as well as other valuable and rare metals, are recovered in pyrometallurgical metal recycling processes. However, the pyrometallurgical recycling of fuel cells produces highly toxic fluorine compounds from the fluorinated nafion membrane, which means that a large-format conversion requires very complex waste gas purification. Up to now, there are no recycling processes that can be used efficiently on an industrial scale to sufficiently separate the polymer membranes prior to melt preparation. New recycling processes avoiding this waste stream are under development.

Annex 1 A few examples of current (2023) technology developments and announcements.

April 12, 2023, The New York Times “Why China Could Dominate the Next Big Advance in Batteries”. China is far ahead of the rest of the world in the development of batteries that use sodium, which are starting to compete with ubiquitous lithium power cells.

April 11, 2023, Batteries News: CALB unveils new battery tech, boasting significant performance gains over traditional cylindrical cells. CALB officially unveiled its new battery with a “U” type structure at the recent China EV 100 Forum event, an innovation based on its One-Stop minimalist design concept, according to an article by the CATL rival. The battery is based on structural and chemical innovations developed by CALB in-house, the industry’s first “U” type structure, according to the article, which features a presentation by an executive.

This design allows the battery to reduce the resistance of structural components by 50 percent, achieve an energy density of 300 Wh/kg, and support fast charging of more than 6C, achieving a significant increase in performance compared to traditional cylindrical batteries, according to CALB. As background, C refers to the battery’s charge multiplier, and 6C means that the battery could theoretically be fully charged in one-sixth of an hour — 10 minutes. Xie Qiu, CALB vice president said in a presentation at the China EV 100 Forum, said: We have made a disruptive innovation to the structure of the cylindrical battery by introducing the ‘U’ type structure.

April 6, 2023, Oilprice.com: “Tokyo Scientists Unveil Solid-State Battery Breakthrough”. Tokyo University of Science researchers have improved the response speed of solid-state batteries by two orders of magnitude. Researchers used a novel technique to investigate and modulate electric double layer dynamics. These findings can lead to the commercialization of all-solid-state batteries with diverse applications, particularly electric vehicles.

March 30, 2023, Autoevolution: “Oxygen-Ion Batteries Are Safe, Cheap To Produce, and Last Forever”. Li-ion batteries power almost everything these days, but their star is waning as more promising chemistries are developed. Scientists at the Technische Universität Wien (TU Wien) in Austria have invented a new battery type that uses abundant materials. The Oxygen-ion battery is cheap to produce and can last forever. Their Oxygen-ion cell is a new type of battery that is perfect for energy storage and probably for other domains too. Its main characteristic is that its capacity does not degrade in time, which makes it worthy of the title of “forever battery.” The oxygen it uses for energy storage might be lost in secondary reactions but adding more from the air is simple and ensures that oxygen-ion batteries will last basically forever.

Oxygen-ion batteries don’t need expensive or rare materials and use mostly ceramic materials. They can take in and let go of doubly negatively charged oxygen ions. When the oxygen-ion battery charges, oxygen ions move from one ceramic electrode to another. They can also be made to migrate back again, thus generating electricity. The principle is very similar to the lithium-ion battery, but with marked advantages.

24 March 2023, Reuters : China's CATL to start mass output of M3P batteries this year. Chinese battery giant CATL (300750.SZ) plans to start this year the mass production and delivery of batteries based on a new materials technology, M3P, which will perform better and cost less than nickel and cobalt-based ones, its chairman said.

M3P batteries will have greater energy density and perform better than lithium-ion phosphate batteries, a market CATL dominates. They will also be cheaper than nickel and cobalt-based batteries, Zeng Yuqun told an online investor briefing on Friday. CATL disclosed in August last year that it was working on M3P technology, which can enable an electric vehicle to run 700 km (430 miles) per charge when combined with CATL's next generation of battery-pack technology.

21 March 2023, Electrek: CATL begins mass production of its Qilin batteries with 13% more power than other 4680 cells. According to recent reports out of China, the world’s leading battery manufacturer CATL has successfully achieved mass production of its energy dense Qilin batteries capable of delivering 1,000 km (621 miles) of range. CATL’s new cells utilize the 4680 pack structure and will debut on the upcoming ZEEKR 009 multi-purpose vehicle (MPV).

In June of 2022, CATL announced its third generation cell-to-pack (CTP) “Qilin” battery cells, which utilize the 4680 pack structure popularized by automakers like Tesla. At the time, the battery developer began promising the Qilin cells would deliver record-breaking volume utilization efficiency of 72% and an energy density of up to 255 Wh/kg, equating to a five-minute hot start and ten minutes of fast charging to get from 10-80% state of charge.

February 22, 2023, ARGONNE NATIONAL LABORATORY
“New design for lithium-air battery could offer much longer driving range compared with the lithium-ion battery”. New batteries could one day power cars, airplanes, trucks. New safer battery, tested for a thousand cycles in a test cell, can store far more energy than today’s common lithium-ion batteries. Many owners of electric cars have wished for a battery pack that could power their vehicle for more than a thousand miles on a single charge. Researchers at the Illinois Institute of Technology (IIT) and U.S. Department of Energy’s (DOE) Argonne National Laboratory have developed a lithium-air battery that could make that dream a reality. The team’s new battery design could also one day power domestic airplanes and long-haul trucks. “The lithium-air battery has the highest projected energy density of any battery technology being considered for the next generation of batteries beyond lithium ion.” — Larry Curtiss, Argonne Distinguished Fellow.

More importantly, the team’s battery chemistry with the solid electrolyte can potentially boost the energy density by as much as four times above lithium-ion batteries, which translates into longer driving range.

The main new component in this lithium-air battery is a solid electrolyte instead of the usual liquid variety. Batteries with solid electrolytes are not subject to the safety issue with the liquid electrolytes used in lithium-ion and other battery types, which can overheat and catch fire.

Contact Details of the Operating Agent

For further information, please contact:

Operating Agent Task 40 CRM4EV
Mr. Bert Witkamp
Valuad Ltd
Visé, Belgium
bert.witkamp2@gmail.com

co-Operating Agent Task 40 CRM4EV
Mr. Stephan Schmid
German Aerospace Center (DLR)
Institute of Vehicle Concepts
Germany
stephan.schmid@dlr.de