Critical Raw Materials for Electric Vehicles

Bert Witkamp – Operating Agent Task 40

Task 40 CRM4EV 2017 – 2022

15th December 2022 – Task 40 Joanneum Research Webinar

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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?
- 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 are EV technologies evolving which impact the type and quantity of CRMs required (per unit)?

Geo-political risks were not specifically part of the scope

CRM4V participating countries and organisations 2018 - 2022

IEA HEV Members

Agencies

British Geological Survey

ivl Svenska Miljöinstitutet

Geological Survey of Norway - NGU -

mriwa Minerals Research Institute of Western Australia

Office for Low Emission Vehicles

Rijkswaterstaat Ministry of Infrastructure and Water Management

Research

Argonne National Laboratory

Birmingham Centre for Strategic Elements and Critical Materials

Institute of Process Engineering, Chinese Academy of Sciences

DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center Institute of Vehicle Concepts

ifp Energies nouvelles

IREC

JOANNEUM RESEARCH LIFE

The Faraday Institution

ReLiB Reuse & Recycling of Lithium Ion Batteries

울산대학교 University of Ulsan

Other participants

AVERE The European Association for Electromobility

BOTREE 博萃循环

Copper Alliance

VALUAD Sustainable Future

Industry participants 4/2018 – 4/2021

AngloAmerican

Cobalt Institute

Nickel Institute knowledge for a brighter future

igo

umicore materials for a better life

VALE

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Task 40 participation external parties

- Invaluable insights and support, without the participation Task 40 could never have gained the insights it has in the last 4 years.
  - In the area of mining expertise and mineral supply, the participation of Western Australia government, geological services, mining companies and representative industry organisations.
  - In the area of battery materials China Academy of Sciences and Umicore.
  - Other parties like JOGMEC (Japan) and AVERE.
- Relevant site visits and discussions with mineral / battery supply (Australia, China) – *COVID has unfortunbately ended this*
- Many bilateral contacts between participants of Task 40
- Additional budget for Task 40 work
- ***On the minus side: commercial companies have their specific interests and limitations can make it hard to make specific statements.***

Task 40 CRM4EV: examples of outputs

- Electric vehicle deployment, battery demand and raw material requirements scenarios (update every year)

- Battery technologies paper (peer-reviewed by external experts)

- Meta study of (50+) EV and raw material forecasts

- 3 Task 40 CRM4EV Workshops and site visits, virtual events as of 2020

- About 100 internal presentations by Task 40 pariticpants and external experts and 15 presentations at external events

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CRM4EV outputs

Electric Vehicle transition scenarios

EV penetration 2030 likely to be (much) higher than forecasted

- Battery chemistry development (into commercial applications) has proven to be much faster than forecasted:
  - High nickel NMC into 622, 811 chemistries (or even 955)
  - LFP storage density at cell and pack level (+ cell-to-pack design)

2019 of 14 million ton, resources 62 million ton; 2021: 21 million ton reserves and resources of 86 million ton)

- Graphite: large potential for additional mining, also graphite is made through chemical

- Assume a strong domination of high nickel battery chemistries (2030 horizon); this concluded from the scenario details provided and CRM4EV analysis.

Facts & Assumptions on batteries technology dev

If in 2021 equippe would batteries

Assumptions on key mineral availabilities and potential supply issues

Will th lithium there b chemist lithium (w per

External scenarios fo (B)EV growth and sale

(IEA, GBA-WEI EV30@30, BNEF most consultancies

Assumptions on BEVs deployment

BEVs are lower in purchase cost than conventional cars around 2025, combined with lower fuel and maintenance cost this should accelerate growth

- In many cases BEVs are already lower in TCO at present, lower taxes can be a deciding element

CRM4EV scenarios

cover external scenarios, ...litical ...ferent ...tries, ...state ...on-Li

Bert Witkamp - Task 40 CRM4EV

November 2021

Battery market (GWh): Global scenarios, forecasts & targets 2030 for ... CE

Scenario:	30% growth CRM4EV	40% growth CRM4EV	50% growth CRM4EV	GBA base	GBA target	EV30@30 midpoint	IEA STEPS	Road transport 100% electric

Battery market (GWh): Global scenarios, forecasts & targets 2030 for EV, ESS

...rio:	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"

RM4EV scenarios "High NiCo Li-ion battery demand" 2030 for EV

	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"

Nickel demand (kton): CRM4EV scenarios "High LFP and High Mn Li-ion battery demand 2030" for EV

...ario:	Weighted Average Ni content in application kgNi/kWh	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"
les	...7	387	754	1198	267	386	338	211	429	150	1198
	...7	42	21	0	45	65	48	31	51	32	0
	...3						14	0	0	6	10

50% growth CRM4EV	GBA base	GBA target	EV30@30 midpoint	IEA STEPS	IEA SDS	BNEF	Road transport 100% electric "COP 21"
8905	2332	3389	2651	1490	2980	1322	10230
9195	2622	3679	2941	1687	3305	1612	10520
97	*89*	*92*	*90*	*88*	*90*	*82*	*97*
4400	1003	1398	1365	767	1463	706	4924
	1061	1584		657	1584		
2920							3444
1401							1487
719	191	274	220	129	251	111	805
	214	290		109	263		
820							918
411							427
1039	243	330	332	177	346	182	1189
	164	378		164	378		

- **CRM4EV scenarios developed to date:**
  - Cover the external scenarios, both in BEV growth rate as well as battery chemistry mixes: CRM4EV "High NiCo Li-ion demand" scenario at 30% YoY growth
  - Cover (much) higher BEV growth rates, in line with current trends and OEM/country ambitions (40% and 50%)
  - Cover 3000 – 9000 GWh battery demand by 2030
  - **Cover the current trends in battery chemistries for commercial applications (LFP, high-Mn) as well as announced developments (High-Mn and LFP scenarios)**
  - Cover a higher penetration of electrification for heavy duty vehicles

- **CRM4EV scenarios to be developed:**
  - Non-lithium based battery chemistries for commercial EV applications
  - Faster than "expected" growth of Solid State Batteries
  - Trends to reduce significantly (average) battery sizes of EVs

Battery and mineral demand scenarios

...cenarios and external global scenarios

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Topics adressed in this presentation

- Rare earth elements for EV e-motors
- PGM savings from BEV deployment
- EV, Battery deployments and key mineral requirements
- A vision for 2030 & policy recommendation for Europe

Rare earth elements for EVs

E-motors using Permanent Magnets

Rare earths not necessary and better avoided for EVs

- Rare earth market is not very transparent
- Shortages of Nd magnets are already predicted: 60 kton by 2030, 206 kton by 2035 or 1/3 of the total market
- Rare earths shortage for magnets by 2030 equal tot total Chinese production 2021, PM rare earth market (Nd/Pr/Dy) to triple by 2035
- **BUT the – always higher than expected – EV growth will only increase supply risks**
- **REE-PMs are very important for off-shore windturbines !!**
- **Recycling PM/RE from cars is VERY COMPLEX, from windturbines very EASY**

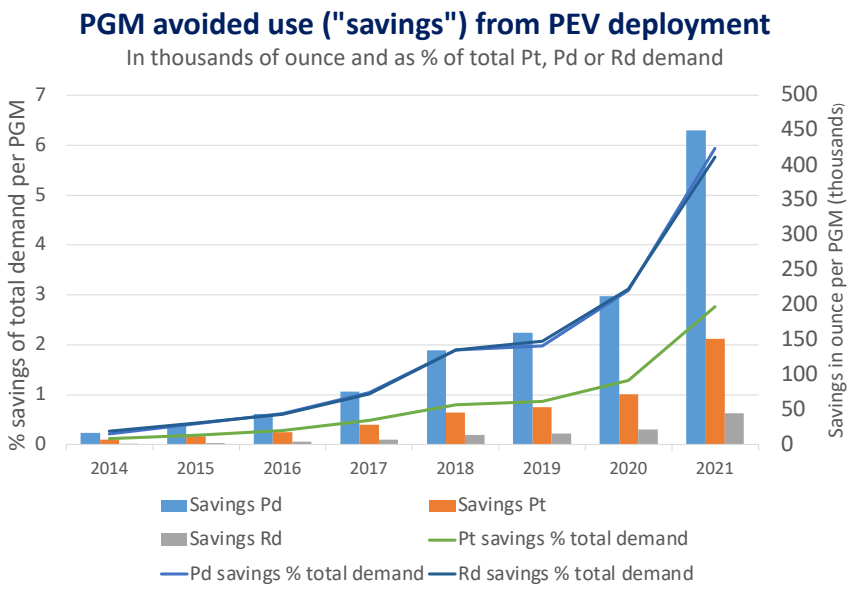
Market forecast: Adamas Intelligence (April 2022)

PGM savings from BEV deployment

Palladium – Platinum – Rhodium

Transition to BEV will transform PGM industry

PGM mining has significant environmental and social impacts as well as geopolitical risks

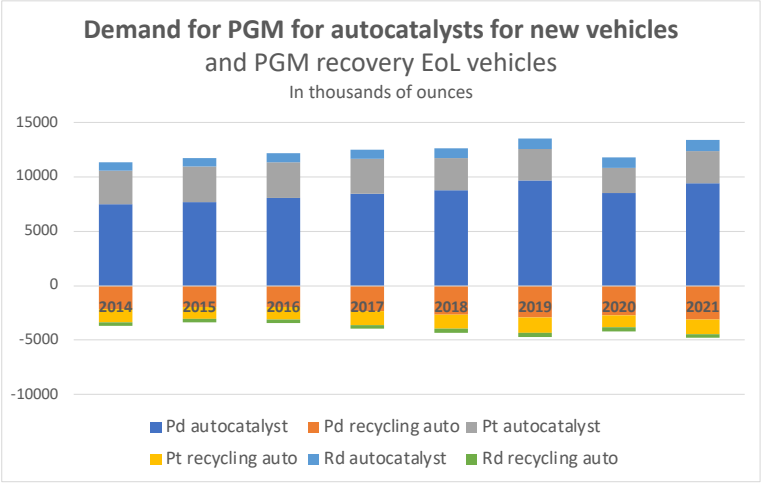


- BEV in 2021 have reduced the total net demand for PGM with 6%, for Pt this is 3%
- Pd and Rh are used primarily for gasoline cars and Pt for diesel cars and trucks, the shift from diesel to gasoline cars (Europe) will increase the demand for Pd/Rh autocatalysts.

Autocatalyst demand determines the PGM market

BEV growth will reduce PGM demand while PGM from recycling will increase the coming decade

PGM demand could drop 75% or more by 2030



- **Over 80% of net Palladium and Rhodium demand is for autocatalyst**
- Around 50% of net Platinum demand is for autocatalyst
- **Recycling of autocatalysts yields around 35-40% of required PGM for catalyst**
- Fuel cells require significant amount of PGM per vehicle

EV & Battery deployments and key mineral requirements

CRM4EV and external scenarios

2021 – 2022 YTD growth rates will lead to near 100% penetration by 2030

2022 Analyses

Global (electric) vehicle market 2020 and 2030 scenarios (sales in millions): 2022 update							
	2020 market	2030 market					
Vehicle category	vehicle sales	kWh per vehicle	CRM4EV BEV LCV 30% YoY vehicle sales	CRM4EV BEV LCV 40% YoY vehicle sales	CRM4EV BEV LCV 50% YoY vehicle sales	IEA STEPS vehicle sales	IEA SDS vehicle sales
Light Duty Vehicles (LDV)							
Passenger Cars (PC)	83		100	100	100	130	114
Light Commercial Vehicles (LC	8		10	10	10	18	17
LDV motorisa *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					
Heavy / 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		

- 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 2022 - 2030: 30%, 40%, 50%. IEA figures HDV/MDV includes “mini-buses” as used in Africa and Asia.

Battery and mineral demand scenarios

CRM4EV scenarios & external global scenarios

Forecasts & scenarios for (B)EV

(IEA, GBA-WEF, EV30@30, BNEF; most consultancies)

The 2021 / 2022 "consensus" view for 2030

- **30% penetration (BEV cars), or 30 million BEV cars sold**
- **High nickel batteries the dominating technology for EVs**
  - **But increased importance of LFP indicated**
- 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!)
- **High risk of shortages of (perceived) critical minerals**
  - For batteries: nickel, cobalt, lithium,….
  - For e-motors: rare earth elements (for permanent magnets)
  - Supply, price and environmental risks

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EV/battery/mineral scenarios

- Cover the external scenarios, both in growth rate as well as battery chemistry mixes: CRM4EV “High NiCo Li-ion demand” scenario at 30% YoY growth
- Cover higher EV growth rates, in line with current trends and OEM/country ambitions (40% and 50%)
- **Cover the current trends in battery chemistries for commercial applications (LFP, high-Mn) as well as probable/logical developments: <u>90% (in 2030) LFP scenarios</u>**
- Cover a higher penetration of electrification for heavy duty vehicles

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Summary of scenarios for battery (GWh) and key minerals demands (kton) for EVs

Summary of 2030 scenarios			30% growth	40% growth	50% growth	GBA	GBA	EV30@30	IEA	IEA	BNEF	Road transport
CRM4EV baseline 2021 EV sales			CRM4EV	CRM4EV	CRM4EV	base	target	midpoint	STEPS	SDS		100% electric
IEA SDS 2021 - GBA 2020		Units										"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		

- Current public global scenarios compared to CRM4EV scenarios and the COP21 (100% zero emission transport by 2050)
- Mineral requirements are based CRM4EV modelling or taken from the different scenarios (underligned data)

External forecasts & scenarios for (B)EV 2030

Nickel already outstripping potential supply?!
(excluding deep sea & excessive Indonesia supply)

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2030 view: history repeating itself?

- **Underestimating BEV growth (again!)?**
  - 30% BEV (cars) penetration in 2030 = 23% year-on-year growth (2021 and beyond) **or 3 to 4 times lower than actual growth rate**
  - Very low penetration forecasted for other (heavy duty) vehicles
- **Focus on "old NiCo chemistries" : demand for 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**

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Critical Raw Materials Electric Vehicles

Global experience & insights in EV and battery development and market dynamics

EV future: critical mineral use per EV has to be reduced FAST

CRM4EV 2030 view

BEV (car) penetration, 50 – 70 million / year

Battery demand 5,000 GWh or much higher

- **LFP likely to become the chemistry of choice within a few years**
  - Lower cost, longer lifetime, lower footprint, zero Ni & Co
  - > 75% LFP needed to avoid major supply issues
- **(semi) Solid state batteries likely to become relevant faster** and more significantly than projected currently, 20 – 40% by 2030?
  - Lower weight, higher storage density, less materials, more stable
- **The potential of sodium (Na) to replace lithium partially / substantially / mainly will become clear in this decade and commercial application will start in a few years**
- **Geopolitical risks have become very real and very high: mineral independence is KEY, especially for Europe, Japan, Korea, India,…**

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Critical Raw Materials Electric Vehicles

Assumptions on key mineral availabilities and potential supply issues

Will there be enough lithium available OR will there be an alternative chemistry not requiring lithium soon enough?

- **Nickel**: availability for EV batteries by 2030 could be (as a max) 1.2 million ton per year (analyst view), very large shift to ZERO nickel chemistries required
  - **Only a massive expansion of Indonesian nickel could increase supply but at high environmental cost**
  - **"Zero nickel" LFP is already the dominant battery chemistry (2022)**
- **Cobalt**: does not seem to an issue, large potential from (new nickel) Indonesian sources and scale-up potential DRC, shift to ZERO Ni/Co chemistries
- **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).
  - **R&D has demonstrated effective and low-cost lithium recovery from sea water 200 billion ton!)**
- **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 and solid state batteries do not use graphite as anode material.
- *The geological availability 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.*

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Critical Raw Materials for Electric Vehicles

Outlook @2030 & recommendations (personal view)

The battery revolution has just started! @ 2030 :

- **Very limited or no critical minerals required**
- **High performance**: very long lifetimes, lower cost, higher density, more stable
- **Lower impacts & risks** : environmental and social impacts, geoplitical risks

LFP batteries: energy storage density high enough for most BEV and improving

LFP & Tesla: 60 kWh pack @ 125 kWh/kg density at pack level; 75 kWh @ 160 kWh/kg (announced)
BYD Blade: 150 kWh/kg pack level
Gotion: 180 kWh/kg (estimated) pack level 2021, further improvements announced

- According to company CEO Li Zhen, Volkswagen's Chinese battery partner Gotion High-Tech has achieved industrialisation of the battery cell with LFP chemistry presented at the beginning of 2021, which offers an energy density of 210 Wh/kg. The company is also working on a semi-solid-state battery that is expected to reach 360 Wh/kg.
- Li confirmed this during his appearance at the China EV100 Forum 2022. In addition, Gotion plans to bring LFP cells with an energy density of 230 Wh/kg to series production by the end of this year.
- The energy densities mentioned, with 210 Wh/kg, are the energy density at cell level, not the gravimetric energy density in the ready-to-install battery pack. There is no confirmed statement from Gotion on this value. The portal *InsideEVs* estimated at the time that it could rise "to about 180 Wh/kg".
- By comparison, CATL's LFP cells, which are installed in the Tesla Model 3 and Model Y in Shanghai, reportedly come to 125 Wh/kg at pack level. CATL itself also presented the third generation of its cell-to-pack technology at the China EV100 Forum, which is said to enable 160 Wh/kg at pack level. Based on Tesla's 60 kWh pack, this 28 per cent improvement could enable a 76 kWh pack in a mid-size sedan – with LFP cells.
- In addition to LFP cells, Gotion High-Tech is also working on semi-solid-state batteries, such a cell should reach 360 Wh/kg. Volkswagen has been the largest shareholder in Gotion since June 2020.
- Compared to NMC cells, these cells have a lower energy density; but this is no longer the only criterion for a good battery. Chinese manufacturers such as BYD with the 800-volt platform 3.0 and the large-volume, so-called "blade" cells (English: sword) are showing the way. BYD's Blade battery. These are known to be LFP cells, which initially had 140 Wh/kg, but in the current long-range version of the BYD Yuan Plus already reach 150 Wh/kg.

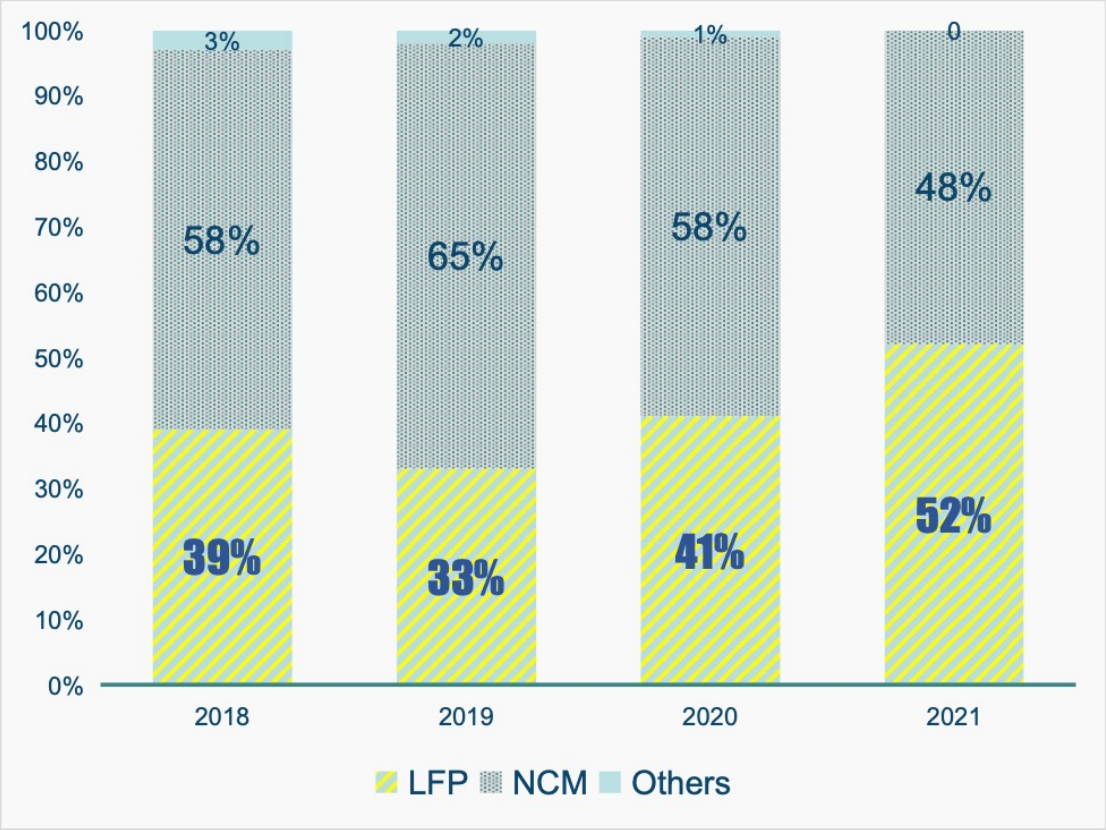
Installed capacity of LFP EV batteries in China

中国科学院 CHINESE ACADEMY OF SCIENCES

From the perspective of China, the EV battery market was inverted by LFP in 2021.

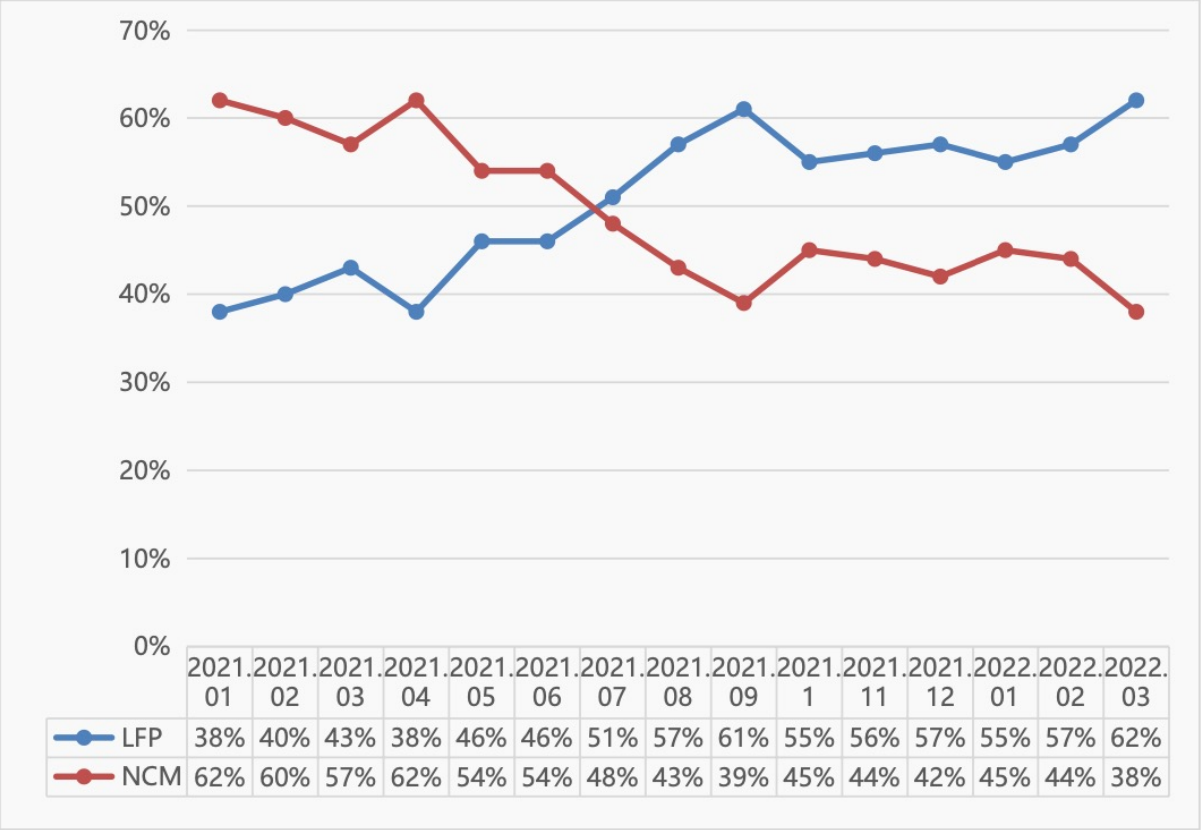
LFP battery officially surpassed NCM battery with 52% installed capacity.

Figure: Proportion of installed capacity of various batteries in China's EV battery market from 2018 to 2021



Source: TrendForce, April 2022

Figure: Proportion of installed capacity of various batteries in China's EV battery market from 2021.01 to 2022.03



	2021.01	2021.02	2021.03	2021.04	2021.05	2021.06	2021.07	2021.08	2021.09	2021.1	2021.11	2021.12	2022.01	2022.02	2022.03
LFP	38%	40%	43%	38%	46%	46%	51%	57%	61%	55%	56%	57%	55%	57%	62%
NCM	62%	60%	57%	62%	54%	54%	48%	43%	39%	45%	44%	42%	45%	44%	38%

Source: CABIA, 2022

Sodium based batteries

Elimination of last potentially critical mineral?
+ other alternatives for lithium around the corner?!

ELECTRIC SINGULARITY

SODIUM-ION BATTERIES

Sodium-ion batteries are an emerging rechargeable battery technology

Inexpensive

- Secure supply and a predictable price
- No copper current collector
- No cobalt
- BoM 70% of LFP / NMC

Sustainable

- Sodium is abundant and ubiquitous
- No Lithium
- No copper current collector
- No cobalt related ethical or environmental issues
- No toxic lead

Safe

- Can be transported or stored in their low energy state at 0V
- Excellent safety testing results

Scalable

- Same operation principle and format as lithium-ion batteries
- Diverse chemistries are possible
- Are manufactured using existing plants

2

- Lower and less fluctuating cost
- Geopolitical supply risks (very) low
- Much more R&D needed: policy priority!
- Other Li-free alternatives exist!
- Sodium-ion batteries
- Scientists in Japan are working on new types of batteries that don't need lithium like your smartphone battery. These new batteries will use sodium and they'll be up to seven times more efficient than conventional batteries.

(semi) Solid state batteries:
- longer range
- lower cost
- higher energy density
- ultra fast charging

- Nissan: The new all-solid-state battery will seek to replace the lithium-ion battery by 2028. It will also be about half the size of current battery models and achieve a **full charge in a mere 15 minutes,** cost of $75 per kWh in 2028 and $65 per kWh thereafter.
- Solid-state batteries are the next barrier to break. Volkswagen and Mercedes, now Honda and first Toyota, have been hailing it as the holy grail. VW first pilot plants in 2025 or 2026.
- Volkswagen trusts in QuantumScape; Prologium just unveiled an actual battery powering Gogoro's LEVs, while Toyota is now thinking to team up with Panasonic to share the burden of investment.
- Gotion High-Tech's ternary lithium semi-solid-state batteries with an energy density of 360Wh/kg will be in mass production **this year**, the Volkswagen-backed Chinese power battery giant said today.

Very long life times of batteries:

1.5 million?
3.5 million ?
5 million ?
kilometers

- With “special additives”, the batteries (***announced by Tesla in 2020 as 1 million miles***) should be able to withstand 10,000 cycles. Assuming a relatively conservative 350 kilometer range per cycle (i.e., a full charge from 0 to 100 percent), this would be 3.5 million kilometers. Whether 3.2 or **3.5 million kilometers**: the one million miles or 1.6 million kilometers announced in September 2019 seem to be clearly surpassed.
- If the cells were treated more carefully, i.e. if the complete charge stroke from 0 to 100 percent were not used, the cells **should even last 15,000 cycles**, according to Dahn.
- **Batteries with high number of cycles:**
  - Vehicle-to-Grid: EV as part of grid when not in use, including for grid energy storage
  - No recycling of batteries required (for dozens of years), second use in new EVs or other applications
  - (Very) high cycle applications (ferries, aircraft,…)

BEV efficiency 2x as high

- Mercedes-Benz aims to produce electric cars consuming as little as 10 kilowatt hours of energy per 100 km (62 miles)
- Mercedes unveiled its Vision EQXX prototype, boasting a 1,000 km-range with a battery half the volume of its flagship EQS model, in January 2022. The car spent 8.7 kilowatt hours of energy per 100 km on its 11-and-a-half hour drive to France, Mercedes-Benz said, about twice as efficient as Mercedes models on the market and Tesla's longest-range car on offer, the Model S 60.
- On EV battery size: "There'll be a further increase for some time before a fall, which will happen once charging infrastructure is as available as petrol stations".

A different future of batteries and EVs @2030 –2035:

A typical BEV car will have a 30 kWh battery pack which last several decades

- Batteries: no use of critical minerals, low cost, low environmental and social impacts, no geopolitical risks, “eternal” lifetime, many applications.
- Electric motors: not using any rare earth elements
- EVs: (virtually) all new vehicles are electric, when not in use part of the electricity grid, battery sizes used are half or less than those used today with much more efficient vehicles, faster charging, denser charging network and higher confidence of EV drivers.

A fantasy ☺ ! ??

In 2015 Electric Vehicles were also a fantasy and not a serious proposal….

New battery developments will provide a solid basis for a sustainable and rapid transition to electrified transport

Political, policy and R&D support need to focus on this

Politicians & policymakers choice:

1 - Stay in the – current – mineral constrained EV growth with high geopolitical dependancies and supply risks (this future is currently forecasted by organisations like GBA, IEA, many industry parties – *doubling, tripling nickel production – rare earths*

OR

2 - Align EV policies (including R&D) ambitions and strategy to how EVs and batteries performance will likely become in @2030 – sharply reducing use of critical minerals and geopolitical dependencies

- **Focus policies and R&D on the FUTURE battery and EV technologies *not those of the past…***