The road to sustainable e-mobility batteries

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Key Messages

- Battery Electric Vehicles can reduce air pollution and carbon emissions in cities, but current lithium batteries rely on environmentally and socially harmful extraction practices.
- Batteries based on iron and phosphates, sodium, or organic compounds are innovating the e-mobility industry and have the potential to mitigate its negative impacts.
- Light vehicles as well as public transport will become increasingly instrumental in exploring and maximizing the potential of battery innovations.
- Investments in improving rapid-charging infrastructure for e-mobility and research for improving the energy density of sodium-ion and organic batteries are necessary.
- Enforcing due diligence laws and promoting transparency in cobalt and lithium supply chains is critical to reduce the human and environmental burden of metal mining for batteries.

Introduction

After reaching a record high of **electric vehicle (EV)** sales in 2020,[1] the demand for EV batteries is projected to increase from $7 billion to $58 billion between 2020 and 2024.[2] A growing awareness of the climate impacts of **internal combustion engine (ICE) vehicles** and government incentives, like financial assistance for EV purchasing and planned ICE bans, are key drivers of this boom.[3,4] EVs are deemed more sustainable alternatives to ICEs as they do not produce tailpipe emissions of greenhouse gases (GHGs) and toxic fumes,[5] which are of particular concern in densely populated cities. This is especially important in light of the COVID-19 pandemic, as long-term exposure to air pollution can be correlated to the COVID-mortality rates.[6] (see Annex 1 for glossary)

The current production of EV batteries relies heavily on environmentally and socially harmful practices to extract finite metals such as lithium, cobalt, nickel, and manganese.[7–10] With the rapid uptake of EVs, the International Energy Agency projects that lithium demand will amount to 42 times the current level by 2040.[11] Demand for cobalt and nickel is also predicted to grow; exceeding supply by 2030 and 2037, respectively.[7] Continuing to rely on heavy metals for EV batteries will likely lead to widespread resource shortages and increased battery pack prices,[7,12] both of which would hinder the global transition to e-mobility. Slowing the rollout of electrified transport perpetuates reliance on ICE vehicles and their detrimental effects on the global climate and human health. To address EVs' dependence on scarce metals, this report explores the potential performance, applications, and shifting burdens of EV battery innovations that use more abundantly available natural resources.

A Comparative Approach to EV Battery Innovations

Issues related to metal scarcity and the ethics of metal procurement have spurred many innovations in EV battery production. **Lithium-ion batteries** (**LIB**) are the standard EV battery, of which the most common is based on **nickel, manganese, and cobalt (NMC)**. Recently, companies have started reducing the ratio of cobalt and nickel in their NMCs and are increasingly using **LIBs based on iron and phosphates (LFPs)** in their vehicles. **Sodium-ion batteries (SIB)** are a further innovation which uses the abundantly available metal sodium instead of lithium. Finally, metal-free **organic batteries** are promising for environmental sustainability, but are unlikely to be available for e-mobility in the short- and medium-term.

The development of the different batteries follows a timeline which illustrates how they will contribute to shaping the e-mobility landscape for the coming decades (see Table 1). The subsequent analysis focuses on the environmental and social **burden-shifting** in the transition from ICE vehicles to current and emerging batteries for EVs. A comparative approach based on existing literature and expert perspectives allows for an evaluation of performance, technological readiness, and the social-environmental impact of each battery (see Annex 8). Finally, the brief introduces recommendations on policy measures that contribute to minimizing harm from large-scale adoption of e-mobility in cities. This report does not aim to promote or justify any geopolitical dynamics and recognizes that reducing metal dependency and diversifying the extraction of raw materials is in the best interest of every country in the world.[2] Building resilient and ethical supply chains will be instrumental in mitigating global climate change and avoiding future resource scarcity.

Table 1. Burdens and impacts shift in the transition toward electric mobility

	Technology			BURDENS & IMPACTS: *Environmental*	BURDENS & IMPACTS: *Human*
Now	**ICE** Internal Combustion Engine			Air pollution, toxic fumes, GHG emissions[5], magnified by congestion[13].	Noise pollution, respiratory issues, magnified by congestion[14].
	ELECTRIC MOBILITY	**NMC** Nickel Manga-nese Cobalt		High water depletion (lithium)[8,15–17]; high toxicity[18,19] & GHG emissions (cobalt + nickel)[17,18]; deep-sea destruction (cobalt + manganese)[9,20].	Child labor, exploitation (cobalt)[21]; income source for small-scale, artisanal mining (cobalt)[9]; depletion marine food sources[10]; destruction & flooding of agricultural land (lithium)[15,17] & displacement of people (lithium)[15,17].
				Reduced toxic fumes, air pollution, CO2 emissions.	Political conflicts & division within communities[15] (lithium); reduced noise pollution.
		BATTERY INNOVATIONS			
		LFP Lithium Iron Phos-phate		High water depletion (lithium)[8,15–17], medium toxicity[19] & GHG emissions (iron; phosphates; copper; graphite)[18]; no deep-sea mining.	Reduced mining, potentially reduced exploitation & child labor; reduced income for artisanal miners[9].
					Need more charging (points + time); less congestion (smaller vehicles).
10 Years		**SIB** Sodium Ion Battery		Minor water depletion & GHG emissions[19,22]; no toxicity[19].	Potential for reduced political conflict & displacement.
					Need more charging (points + time); less congestion (smaller vehicles); more affordable mobility.
>20 Years		**Org** Organic Battery		No water depletion; carbon capture; potential GHG emissions[23–25].	No demand for mining; potential increased land use for agriculture; risk of deforestation[23,25].
				Biodegradable disposal[24].	More speed charging points; less total charging points[26]; less charging time; more affordable mobility.

Text in green indicates applicability to all batteries — effects within the city — effects outside of the city

Analysis of Burden-Shifting

Each EV battery burdens humans and the natural environment in their own way. Table 1 visualizes how these imposed burdens can shift depending on the selected raw materials for EV batteries.

Moving from fossil-fuel cars to EVs with cobalt-rich NMC batteries comes with undeniable benefits for climate stability and human health through the reduction of GHG emissions, as well as air and noise pollution in cities, which are of particular concern in the face of global climate and COVID-19 crises. However, the environmental and social costs of urban mobility with NMC-based EVs fall on communities and ecosystems around metal mines and manufacturing plants. While reducing emissions from use, the production of NMC batteries still emits great amounts of GHGs during the extraction and refinement of rare metals.[17] Additionally, NMC-based EVs must travel over 21,725 kilometers and be charged with emission-free energy to achieve nominal GHG emissions reduction.[27]

Since minerals used in iron-based LFPs are more abundant and have well-established recycling industries,[28] it is likely that the impact associated with commuting to work by an LFP-based EV is smaller than in an NMC-based EV. LFPs could potentially eliminate child labor associated with cobalt mining,[21] but moves income away from **artisanal** miners, and increases the mining of iron, phosphates, graphite, and copper.[9,29] LFPs are currently most suitable for short-range EVs and electric buses (BEBs). An increase in LFP EVs will presumably require more charging infrastructure,[30] but also has the potential to reduce congestion as these vehicles take up less road space.[31]

Sodium is up to 10,000 times more abundant in brine than lithium.[22] As such, SIBs could significantly reduce the water intensive extraction of lithium from brine mining while avoiding the displacement of indigenous populations and degradation of unique salt flat ecosystems.[15,16,32] Shifting to SIBs could also replace rock mining with seaside salt extraction, which is more efficient in terms of GHG emissions and does not flood or degrade agricultural land.[17]

Organic batteries rely fully on biomass derivatives from crops, crop waste, or fossil fuels.[25,33,34] This could eliminate burdens associated with mining but may also impose the burden of resource extraction on agriculture or forestry instead.[25,35] While resource extraction experts agree mining cannot be done without harming the natural environment,[9,15,17,25] agriculture and forestry could contribute to fostering biodiversity and capturing carbon from the atmosphere. However, large-scale agriculture of specific high-value crops could threaten food security and lead to environmental destruction similar to biofuels.[35] The low price of organic batteries could make urban mobility more accessible to low-income communities, but their low range and potentially high charging rate would affect charging behavior and require the installation of more ultra-rapid charging points in the city, while reducing the total number of charging ports required.[26]

Comparing Performance and Impact of Battery Innovations

Table 2. Overview of battery performance characteristics and impacts, see Annex 2, 7, 8

		Lithium		Non-lithium	
	ICE	NMC	LFP	SIB	Org
Climate	---	+	+	+	++
Environmental	---	---	--	-	+/-
Human impact	---	---	--	+/-	+/-
TRL / timeframe	Current	Current	Current	10 years	>20-30 years
Cost price	-	---	--	-	n/a
Vehicle type (currently)	bus, heavy car, light car, 2 wheelers	bus, heavy car, light car, 2 wheelers	bus, light car, 2 wheelers	2 wheelers	n/a
Range	+++	++	+	+/-	+/-
Charging speed	+++	+	+	+	+++
Cycle life	n/a	+	++	++	+/-
Fire safety	++	++	++	+++	+++

+++ indicates best performance
bus — light car / short-range
heavy car / long-range — 2 wheelers & mini cars

Cost

Affordability is key to the large-scale adoption of EVs.[36,37] While purchase costs of EVs are high (relative to ICE vehicles), costs per kilometer are much lower. To compete with heavily subsidized fossil fuel-based ICEs, EV prices need to drop below \$80/kWh (from \$137 in 2020).[38] NMCs are unlikely to achieve this due to the scarcity, toxicity,[39] and price volatility of the metals (cobalt, lithium) in this battery.[40]

The LFP battery, on the other hand, is lower in cost than the NMC chemistry, due to the lack of expensive cobalt in its composition. SIBs have the potential to be significantly cheaper than NMCs and LFPs due to being free from lithium and containing sodium instead, which is widely available.[41] However, SIBs will initially be more costly due to market entry costs and lower energy density.[42] Organic batteries based on renewable and widely available waste products have the potential to be the cheapest battery.[23,25] However, major investments are needed in R&D to apply organic batteries to e-mobility.[25,43]

Energy Density and Vehicle Type

The second major impediment to large-scale uptake of EVs by individuals is range anxiety, which is the common fear of running out of power between charging points.[36,44,45] Range anxiety can be remediated by purchasing long-range vehicles, or by improving charging speed through rapid-charging or battery exchange stations, to the point where it compares to filling up an ICE with gas.[26,46] NMC LIBs currently offer the highest **energy density** in the market, meaning they carry a large amount of energy in a small space, and therefore can have a large range. Since NMCs can also deliver a lot of **power**, they are most suitable for heavy vehicles, which have greater negative impacts on urban quality of life.[47–49]

LFPs cannot propel heavy cars over long distances in the way NMCs can, due to their lower energy density. However, LFPs' long life expectancy and high power are ideal for any type of short-distance vehicle and can be more easily applied to city buses than long-range cars. For city transportation, LFPs may well become the new standard.[29] Currently, SIBs can only be applied to e-bikes and slow vehicles because of their low power and energy density.[50] However, they will likely develop similar performance to LFPs in the near future.[22] Fully organic batteries offer even lower energy density. For this reason, they seem to be currently unsuitable for mobility. Nevertheless, one company, NexusPower, claims to commercialize organic batteries for two- and three-wheelers in the coming two years.[34] Since LIBs were able to quadruple their energy density over the course of 20 years through extensive investments in R&D,[51] it is also feasible to tackle this challenge for alternative batteries.

Technological Readiness

NMCs and LFPs are major contenders in the EV industry and are projected to further grow their global market share, albeit, applied in different vehicle types and markets.[52] In late 2021, Tesla made the decision to expand its use of LFPs in vehicles outside of the Chinese market.[53] When it comes to SIBs, their commercialization for small vehicles is "imminent",[54] reflecting technological readiness. However, organic batteries are in their early stage of research and will likely need at least 20 years of development before they are suitable for mobility.

Towards Sustainable Urban E-Mobility

The EV batteries highlighted in this brief represent crucial contributions for future electric mobility in cities. SIBs and organic batteries entail relatively low environmental and human burdens as compared to the higher environmental and human costs of LFPs and NMCs. However, neither of these batteries can yet compete in terms of range, technological readiness, or affordability.

Switching to EVs plays an important role in rapidly decarbonizing the transport sector. However, a switch to heavy EV fleets cannot be sustainable in terms of resource depletion, energy use, and space efficiency. A shift to public transport and lighter EVs, such as mini cars, scooters and e-bikes are preferable and would also make urban transport more inclusive. In this case, China's large LFP-based light EV fleet can be seen as an example of such EV rollout.[55] In Europe and North America, large private vehicles are unfortunately preferred due to perceived social status, safety, and long-range.[26,44] Thus, manufacturer and consumer cultural changes need to occur. This can be driven both by local and national governments through incentives and strict regulations.

Cities, where distances are short and traffic is dense, are the perfect place for such incentives, which is why local governments can play a key role in making cities adapted to light e-mobility through fundamental changes in urban planning.[15,17,44,46] Improved and faster charging infrastructures,[26] e-scooter battery exchange stations, reserved lanes and financial incentives are some of the many tools local policymakers can use to tackle barriers for e-mobility (i.e. range anxiety, road unsafety).[56–58] Specifically, city planners should integrate considerations of battery chemistry and vehicle type of EVs into their charging station implementation plan.[26]

However, choosing more efficient vehicle types and batteries alone does not guarantee a reduced overall impact. Considering the critical environmental and social burdens associated with the production of EV batteries, it is essential that stricter norms and regulations be upheld regarding the sourcing of raw materials. Lack of supply chain transparency is a major challenge for the EV industry regardless of the source material used for battery production, leaving entrepreneurs incapable of following due diligence practices.[15,46] It is therefore necessary for transnational governments to implement cohesive due diligence laws,[59] and design binding Environmental Impact Assessment standards and regulatory tools.[9,17,59] Local governments should assist adherence to such laws by providing trainings, standardized questionnaires, and financial assistance to EV businesses.[60] Ultimately, to achieve greener and more sustainable urban mobility, extraction must be reduced as much as possible, while making sure that the extraction that does take place is done with minimal negative impacts on the human health and the environment.

Key Recommendations

- Promote competitive pricing of EVs by cutting fossil fuel subsidies and providing financial incentives for producers, vendors, and end-users of cobalt-free EV batteries.
- Encourage the adoption of light and short-range EVs through financial incentives and improving road safety.
- Address range anxiety and shorten charging time by expanding rapid-charging and battery-swap infrastructure for EVs in cities, e.g. at petrol stations to emulate the experience of filling up an ICE.
- Fund investments in R&D for the improvement of energy density and optimization of other performance indicators of SIBs and organic batteries.
- Assist EV businesses at the municipal level in adhering to international supply chain due diligence laws to ensure ethical and sustainable sourcing of raw materials.
- Call upon governments to require publicly available and independently verified Environmental Impact Assessments from the battery production industry in anticipation of shifting burdens.

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Annex

ANNEX 1. Glossary of Key Terms

Artisanal mining: Mining done by hand, which implies direct exposure for miners. Cobalt mining is predominantly done in the Democratic Republic of the Congo, in artisanal and industrial mines, both of which have a range of social and environmental harms (see Annex 8 for more details). About 10-30% of cobalt is produced in the artisanal mining sector and serves as an income source to 150,000-200,000 artisanal miners.[61]

Battery: A storage device "that converts chemical energy into electrical energy and vice versa".[62] It is composed of a negative electrode (or anode), a positive electrode (or cathode), a charge material, and finally electrolytes and a separator that allow the charge material to flow from the anode to the cathode once it has lost one of its electrons.

Burden-shifting: The shifting of environmental and social impacts to new areas that accompanies the shift to using new technology.

EV - Electric Vehicle: A vehicle that uses an electric motor instead of an internal combustion engine.

Energy density: The battery's energy storage capacity relative to its size, typically measured in watthour per liter (Wh/L). High energy density indicates high energy storage capacity in a smaller space, which is preferred in EVs as it allows for a longer range.

Fully Organic Batteries: Batteries that use no metal for the anode, the cathode and the charge material. Instead, they use carbon- and hydrogen-based organic compounds (which can be sourced from either biomass or fossil fuels).

ICE – Internal Combustion Engine: An engine that functions through the combustion of fuel. Non-electric vehicles all have this type of engine, and the combustion of fuels that happens with ICEs contribute significantly to urban air pollution and smog, effectively damaging the environment as well as human health.

LIB – Lithium-Ion Batteries: A type of rechargeable (or *secondary*) battery, where the charge material is lithium. The discovery of LIBs has played a major role in the development of electronics and EVs, because of their enormous advantages: They are dense in energy and power, have a long cycle life, no 'memory effect', useability in a large temperature range, etc. (see Annex 8 for more details).

LFP – Lithium Iron Phosphate: A type of positive electrode (cathode) for batteries; It does not include cobalt (because of its ethical and environmental impacts as well as high costs) and is instead based on phosphate and iron, which is considered an abundant metal (see Annex 8 for more details).

NMC – Nickel Manganese Cobalt: A common type of cathode that is based on nickel, manganese and cobalt. NMCs show a great combination of longevity and performance, which make them applicable for all vehicle types. They however rely on a range of scarce metals which come with mining-related harms like environmental degradation and human exploitation (see Annex 8 for more details).

Power: "Power is the amount of energy that a device can deliver in a unit of time",[63] measured in Watt. One Watt (W) equals to a Joule (J) per second (s) $1W=1J*s^{-1}$).

Power density: Similarly to energy density, power density is the battery's power capacity relative to its size (typically measured in watt per litter (W/L)). In the case of EVs, a higher power density means a higher acceleration capacity.

SIB – Sodium Ion Batteries: A type of battery that uses sodium instead of lithium as the charge material. Sodium has similar chemistry properties as lithium, but is significantly more abundant. Drawbacks from using sodium includes lower energy density. SIBs use different anodes from LIBs, because of the larger size of the sodium atom. Many of the different cathodes designed for LIBs however apply to SIBs, such as (but not limited to) NMCs and NFPs (equivalent to LFPs). See Annex 7 for more details.

ANNEX 2. Table 2 explained

Table 2 presents a simplification of the research findings, in order to give a clearer overview for the readers. The table does not follow scientific methodology and should not be thought of as such. For further details, please consult Annex 7 & 8.

1. *Climate: climate impact based on GHG emissions in the resource extraction, manufacturing and use phases.*

ICEs are fully dependent on fossil fuels and emit GHGs during all stages of life.

NMC; LFP; SIB emit GHGs during resource extraction and manufacturing. Assuming that batteries are charged with GHG-neutral electricity, emissions during use are none.

Organic batteries emit GHGs during resource extraction and manufacturing. Assuming raw materials are derived from crops or crop waste, there is also a potential for carbon capture during extraction.

2. *Environmental: based on: toxicity, pollution risk, land and water use, resource depletion.*

ICEs environmental impacts are mainly due to the sourcing and processing of fossil fuels as well as from tailpipe emissions.

NMCs extraction and manufacturing of nickel, manganese and cobalt are associated with imminent resource depletion, high toxicity & pollution risk, as well as high land, water, and energy use due to the limited availability of the materials, which leads to extensive environmental degradation. To meet future demand, deep-sea mining will also need to be employed, which threatens pristine ecosystems.

The impacts of lithium are mostly related to water and land use during brine extraction: through depletion of groundwater in arid regions, salt-flat ecosystems and desert vegetation are destroyed.

LFPs while the use of lithium remains the same as with NMCs, extraction and manufacturing of iron, phosphates, and additional copper and graphite are associated with low or medium toxicity & pollution risk, as well as reduced land, water, and energy use due to abundance of the materials, which leads to reduced ecosystem degradation.

SIBs extraction of sodium reduces the effects of lithium by a factor 1000. Effects of large-scale sodium manufacturing are hard to predict and partially depend on the choice of cathode material. SIB manufacturing processes currently do have a high water consumption and rely on metal catalysts.

Organic batteries that are derived from biomass (wood, crops, or crop waste) have limited negative impacts during resource extraction and manufacturing. However, agriculture and forestry have a great potential for deforestation if industrialized.

3. *Human impact: Based on: Labor conditions, displacement, and livelihood impacts due to environmental degradation.*

NMC: Cobalt mining relies heavily on exploitation of workers, including child labor, is linked to regional destabilization in the DRC and threatens the livelihood of residents of small island states in the Pacific.

NMC + LFP: Lithium mining is responsible for displacement of local people across the world: In Serbia, lithium extraction leads to destruction of agricultural land, as well as flooding risks. Water depletion around Andean salt flats is highly detrimental to the livelihood and community cohesion of indigenous populations, while their right to free, informed, and prior consent is disregarded.

SIB: Extraction of lithium can be done virtually anywhere, so human impact is largely dependent on local worker conditions and regulations.

Organic: Extraction of organic compounds can be done virtually anywhere, so human impact is largely dependent on local worker conditions and regulations.

4. *Time frame: Time frame until large-scale commercialization.*

SIB is already used for niche applications. Its adaptation to EVs on a large scale is not fully certain yet, but many factors indicate it could be done within the decade.

Organic batteries are still in early development for niche applications. A lot more research is needed before these can be applied to EVs, particularly concerning energy density and operating temperature.

5. *Cost price: Total vehicle price for users, including fuel/electricity price*

ICEs are a fully developed technology and use few rare building materials, which keeps costs down.

NMC vehicles are significantly more expensive than their ICE counterparts, due to the battery price.

LFP, **SIB** and **organic batteries** use cheaper materials and have a longer cycle life than NMCs, which might bring the costs down.

6. *Vehicle type: Types of vehicles currently commercialized with this type of battery*

NMCs can be used like ICE, with a slight range limitation.

LFPs have seen progress on the range & power limitation, which makes them applicable for every type of vehicle except for long-range cars.

SIBs can be used for light mobility and heavier mobility with predictable journeys, such as city buses.

1. *Range: Range a vehicle can travel on one charge/fuel tank, which depends on energy density*

ICE uses oil, which is very energy dense and can be recharged very quickly.

NMC uses a mix of high-capacity metals, which is very energy dense and can have a high range.

LFP uses metals with lower capacity, but structural improvements allow for a reasonable driving range.

SIB & organic batteries use low-density materials with a short driving range, but structural and chemical improvements are likely to tackle this challenges as research progresses.

2. *Charging speed: Charging speed depends on the charge rate (or C-rate)*

ICEs can fill up a tank of fuel in a matter of minutes.

NMC; LFP; SIB vehicles use batteries with a C-rate of 0.5-2, so batteries take multiple hours to charge.

Organic batteries have a C-rate up to 400 times as fast as current EV batteries, which allows for recharging in the course of minutes, comparable to filling up an ICE.

3. *Cycle life: Number of charging-discharging cycles a battery can hold before losing 20% of its capacity, which is important for sustainability and user's return on investment.*

NMC batteries use cobalt to stabilize lithium, which gives them a life expectancy of ~1000 cycles.

LFP; **SIBs** have a notably longer cycle life than **NMCs,** up to 5000 cycles.

Organic batteries still have stability issues, making it unclear how long their cycle life will be.

4. *Fire safety: Likeliness of the fire, dangerousness*

NMC; LFPs have a very low risk of fire, but lithium fires very difficult to extinguish if ignited.

SIBs; Organic batteries have a higher overheating point and are more resistant to shocks. If ignited, their fires are easy to extinguish.

ANNEX 3. Experts consulted in interviews

Expert	Institution	Position	Date	Country	Topic
Shailesh Upreti	iM3NY, C4V (companies)	Founder & chairman	11 Nov	USA	Cobalt- & nickel-free batteries for e-mobility
Miroslav Mijatović	PAKT (Podrinje anti-corruption team); Coalition of Organizations against Environmental Corruption	President & board member	17 Nov	Serbia	Environmental & social impacts of lithium extraction in Serbia
Nikita Baliarsingh	Nexus Power (company)	Co-founder	17 Nov	India	Organic & biodegradable batteries for e-mobility
Samuel IJsselmuiden	Swugo (company)	Co-founder	18 Nov	Taiwan	Light mobility & e-mobility
Mikhail Vagin	Linköping University	Researcher	19 Nov	Sweden	Batteries, chemistry, electricity
Thea Riofrancos	Providence College	Researcher, assistant professor, author, journalist	19 Nov	USA	Environmental, social & political impacts of lithium extraction in Latin America
Stéven Renault	University of Nantes	Associate professor	24 Nov	France	Organic batteries
Shan Zhang	Uppsala University	PhD researcher	25 Nov	Sweden	Environmental impacts of organic batteries
Michael Reckordt	PowerShift (NGO)	Raw materials policy officer	26 Nov	Germany	Environmental & social impacts of raw materials extraction, policy & strategy
Pelenatita Kara	Civil Society Forum Tonga	National Deep Sea Mining Coordinator	Aug 5	Tonga	Social-environmental implications of deep-sea mining
Franky Bedoya	Ecole Polytechnique Fédérale de Lausanne	PhD Researcher	30 Nov	Switzerland, Colombia	Cobalt-free olivine-structure cathodes, especially manganese phosphate
Carmen Aalbers	Wageningen University & Research	Senior researcher & advisor	1 Dec	Netherlands	Sustainable urban development, urban mobility
Sjoerd Moorman	EVconsult	Consultant Electric Mobility & Charging Infrastructure	12 Dec	Netherlands	Sustainable urban development, e-mobility & charging infrastructure

ANNEX 4. Key messages from expert interviews

Expert	Key messages from the interview
Shailesh Upreti USA-based founder & chairman of iM3NY, a company developing cobalt- and nickel-free batteries for e-mobility.	• Prices of cobalt and nickel increasing; using these metals is not a sustainable way of making batteries; • LIBs are here to stay for the short- and medium-term future, but the chemistries within these batteries can be improved and made greener.
Miroslav Mijatovic Serbia-based president of PAKT; Coalition of Organizations against Environmental Corruption.	• Serbian context: lithium mining is displacing people through risk of flooding (due to drilling), water scarcity (water-intensive extractive activity), corruption of the quality of the soil; • Extractive company and national government work together, with profit as the main interest.
Nikita Baliarsingh India-based co-founder and COO of Nexus Power, a company developing biodegradable organic batteries for e-mobility.	• Nexus batteries are biodegradable EV batteries with an inner chemistry made from agricultural waste (combination of proteins and carbon); • Obstacle in implementing e-mobility: infrastructure & need for incentives from the government; • The big problem with e-mobility is that the energy source relies on fossil fuels.
Samuel IJsselmuiden Taiwan-based co-founder of start-up “Swugo”, specializes in lightweighting of vehicles & light e-mobility.	• EV batteries are not likely to change in the next 10 years, because of how complex the chemical process are; • Biggest challenge in transition to e-mobility (& sustainable mobility): lack of infrastructure to make EVs in cost-effective way & making cars unattractive should be focal point for sustainable mobility; • Due diligence on raw material level is very difficult because there is no strict tracing & laws change depending on the country context; • Current recycling practices not efficient; for cobalt- & nickel-free batteries, less incentive to recycle because those metals are what is more precious.
Dr Mikhail Vagin Sweden-based researcher at Linköping University.	• Aggressive chemistry translates to safety concerns; when chemical safety is needed, it makes the battery more expensive; • Concept of balancing the electricity grid depending on energy consumption, which is not constant.
Thea Riofrancos USA-based journalist & researcher focused on the extractive node of the supply chain in lithium extraction in Chile, the EU, and the USA.	• Social impacts of lithium extraction: local communities’ livelihoods & agricultural practices at risk; multinational corporations are taking power in the absence of governmental oversight, providing employment & growing the economy, but there is a lack of regulatory tools; • *“I think what we're starting to see is a new wave of extraction around the world that is linked to the energy transition, not just to electromobility, but to the production of solar panels, transmission lines, wind turbines, etc. And that is going to put communities in the crosshairs of these very harmful sectors”;* • State and extraction companies working together (corruption).
Dr. Stéven Renault France-based associate professor at University of Nantes, specialized in organic batteries.	• Organic batteries are currently more suitable for stationary use rather than mobility & cell phones; they are not likely to be commercialised in next 5 years at least; • Common challenges for organic batteries: low energy density, organic compounds dissolving / decomposing, poor electronic conductivity, self-discharge;

- Source material: either from biomass (but needs extensive processing which is very expensive and energy intensive), or from oil (fossil fuel);
- *"The LCA could be much better than inorganic, or much worse. The only clear thing is that for recycling of organic batteries is by far, much better than regular batteries."*

Shan Zhang
Sweden-based conducting her PhD on the environmental impacts of organic batteries.

- Organic batteries are still at a very early stage of development (TRL 4);
- First LCA shows that impact of ORB is lower than LIB, with low energy and water use during manufacturing, even when derived from fossil fuels;
- Use of solvents is responsible for main environmental impacts;
- Organic raw material could be lignin from trees, which might have impacts on land use and biodiversity;
- Investments need to be made for developing efficient supply & production chains and in further research.

Michael Reckordt
Germany-based geographer working at PowerShift on raw material extraction and strategies in the EU, specifically connected to batteries.

- Social impact of mining: bribery & corruption (involves billions of euros of investment);
- Reducing metal use isn't the solution because communities on the ground dependent on it; need for due diligence for mining practices;
- Most important for sustainable mobility: designing light, small cars with a focus on circularity, & developing national regulations surrounding mining;
- Environmental impact assessments should be accessed publicly and there needs to be a binding international standard.

Pelenatita Kara
Tonga-based National Deep-Sea Mining Coordinator for the Civil Society Forum Tonga.

- The majority of the population in Tonga (& Pacific islands) is highly reliant on the ocean for their subsistence and livelihood, she is against deep-sea mining for fear of harming local and global marine ecosystems as well as Pacific-island communities.

Franky Bedoya
Switzerland & Colombia-based post-doctoral researcher on LMP cathode electrochemistry.

- Main criteria for battery success: high specific capacity, structure stability (which affects lifetime), price;
- Lithium-Manganese-Phosphate (LMP) are not ready because of serious stability issues;
- More research needs to be done in cobalt-free batteries.

Dr. Carmen Aalbers
Netherlands-based senior researcher & advisor governing sustainable urban development.

- It's very difficult to reorganize transport because cars have systemic dominance, and are associated with high social status, which reinforces care dependency;
- Electric cars are not an inclusive way of transport due to their high price and they continue car dominancy, consume a lot of space, and form a barrier for wildlife and the environment;
- Transport innovation should focus on taking away tarmac and pavement (for example by elevated transport like sky trains) in order to have more green space and climate adaptation;
- Policy and planning for mobility should be much more integral/holistic and consider social, environmental and economic factors and intersections between gender, age, social status.

Sjoerd Moorman
Netherlands-based e-mobility & charging infrastructure consultant for the city of Amsterdam at EVconsult.

- Planning for future charging infrastructure in Amsterdam: taking into consideration a trend towards faster charging batteries & charging points, need to charge less often, increase of light EVs & car-sharing services;
- The use of the EV is more determining of its charging need than the type of EV;
- Currently battery type & chemistry are not considered when planning charging infrastructure;
- Importance of switching to fast charging batteries & charging spots: more attractive to consumers, more (space-)efficient charging infrastructure in cities, more interesting business-wise.

ANNEX 5. Overview of performance indicators definitions

Copied and adapted from MIT Electric Vehicle Team, December 2008[62]:

A battery is a device that converts chemical energy into electrical energy and vice versa.

Battery Basics

- **Cell, modules, and packs**: hybrid and electric vehicles have a high voltage battery pack that consists of individual modules and cells organized in series and parallel. A cell is the smallest, packaged form a battery can take and is generally on the order of one to six volts. A module consists of several cells generally connected in either series or parallel. A battery pack is then assembled by connecting modules together, again either in series or parallel.

- **Battery Classifications**: not all batteries are created equal, even batteries of the same chemistry. The main trade-off in battery development is between power and energy: batteries can be either high-power or high-energy, but not both. Often manufacturers will classify batteries using these categories. Other common classifications are High Durability, meaning that the chemistry has been modified to provide higher battery life at the expense of power and energy.

- **C- and E- rates:** in describing batteries, discharge current is often expressed as a C-rate in order to normalize against battery capacity, which is often very different between batteries. A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. For a battery with a capacity of 100 Amp-hrs, this equates to a discharge current of 100 Amps. A 5C rate for this battery would be 500 Amps, and a C/2 rate would be 50 Amps. Similarly, an E-rate describes the discharge power. A 1E rate is the discharge power to discharge the entire battery in 1 hour.

- **Secondary and Primary Cells:** although it may not sound like it, batteries for hybrid, plug-in, and electric vehicles are all secondary batteries. A primary battery is one that cannot be recharged. A secondary battery is one that is rechargeable.

Battery technical specifications

- **Capacity or Nominal Capacity (Ah for a specific C-rate)**: the coulometric capacity, the total Amp-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage. Capacity is calculated by multiplying the discharge current (in Amps) by the discharge time (in hours) and decreases with increasing C-rate.

- **Energy or Nominal Energy (Wh for a specific C-rate)**: the "energy capacity" of the battery, the total Watt-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage. Energy is calculated by multiplying the discharge power (in Watts) by the discharge time (in hours). Like capacity, energy decreases with increasing C-rate.

- **Cycle Life (number for a specific DOD)**: the number of discharge-charge cycles the battery can experience before it fails to meet specific performance criteria. Cycle life is estimated for specific charge and discharge conditions. The actual operating life of the battery is affected by the rate and depth of cycles and by other conditions such as temperature and humidity. The higher the DOD, the lower the cycle life.

- **Specific Energy (Wh/kg)**: the nominal battery energy per unit mass, sometimes referred to as the gravimetric energy density. Specific energy is a characteristic of the battery chemistry and packaging. Along with the energy consumption of the vehicle, it determines the battery weight required to achieve a given electric range.
- **Specific Power (W/kg):** the maximum available power per unit mass. Specific power is a characteristic of the battery chemistry and packaging. It determines the battery weight required to achieve a given performance target.
- **Energy Density (Wh/L)**: the nominal battery energy per unit volume, sometimes referred to as the volumetric energy density. Specific energy is a characteristic of the battery chemistry and packaging. Along with the energy consumption of the vehicle, it determines the battery size required to achieve a given electric range.
- **Power Density (W/L):** the maximum available power per unit volume. Specific power is a characteristic of the battery chemistry and packaging. It determines the battery size required to achieve a given performance target.

ANNEX 6. Methodology & aim of the research

Methodology

In this brief, a comparative analysis was applied in combination with components from a life-cycle analysis. The steps of a life-cycle analysis (goal & scope definition, inventory analysis: data collection, impact assessment and interpretation) were condensed and simplified. First the scope was defined by identifying the key battery innovations we wanted to focus on (LIBs, LFPs, SIBs, and organic) as well as the life-cycle stages to focus on (primarily extraction and production). According to this scope, data was collected in the form of an extensive review of recent literature. In addition, experts in the battery and energy field, as well as civil society and academics working on or related to this technology were consulted. The life-cycle analysis influenced the selection of countries researched (i.e. due to a majority of cobalt being extracted in the DRC, this country was included, among other countries). From the literature review and expert interviews, the conditions under which the materials for these batteries are extracted and what the impact of extraction is (i.e. GHG emissions, human rights abuses) were analyzed and compared. Also, performance characteristics (energy density, cost, etc.) of the different batteries were compared. Finally, the data was evaluated to understand how and when burdens from production would shift when switching from one battery to another and the implications of this for the city context. This evaluation was based to a greater extent on the literature review than the interviews.

Aim of the research

The aim of our research was to assess the practical and economic feasibility of emerging EV batteries as a more sustainable alternative to current e-mobility battery standards, to explore the potential shifting of environmental and social burdens associated with alternative EV battery production, and to formulate policy recommendations that could stimulate the adoption of sustainable e-mobility options in cities.

Research question

Our main research question was: To what extent can cobalt-free innovations in EV batteries shift the burdens and mitigate impacts on human rights and the environment associated with their production, and facilitate EV adoption in cities?

ANNEX 7. Materials and performance characteristics comparison

Category		**Current lithium-ion**		**Non-Lithium, non-organic**	**Fully Organic Radical Battery**	
Name		NMC (Nickel Manganese Cobalt)	LFP (Lithium Iron Phosphate)	Sodium-ion	Polypeptide	Redox-Polymer-Based Proton
Current/expected use		Electronics, all EVs	Electronics, light EVs, shared EVs	Stationary storage, light EV	Small devices, smart apparel[25]	Small devices, smart apparel[25]
MATERIALS	**Charge**	Lithium-ion	#	**Sodium**-ion	biTEMPO polypeptide[24]	pEP(QH2)E[64,65]
	Cathode (+)	$LiNiMnCoO_2$ (Proportion of Ni, Mn and Co varies)	$LiFePO_4$	Most LIB cathodes can be used (with Na replacing Li)	biTEMPO polypeptide[24]	pEP(QH2)E[64,65]
	Cobalt?	10-33% of cathode[2]	No	Depends	No	No
	Anode (-)	Graphite	#	Aluminium / Hard Carbon	viologen polypeptide[24]	pEP(NQ)E[64,65]
	Electrolyte	Typically lithium salt (e.g. LiPF6) in organic solvents[66]	#	Typically sodium salt in organic solvents	0.5 M $TBACF_3SO_3$ in propylene carbonate[24]	0.5m H_2SO_4 (aq)[64,65]
	Separator	Typically 2 to 3 layers of poly(ethylene)/ poly(propylene)[67]	#	#	Filter paper soaked in electrolyte[24]	Sulfuric acid[64,65]
Energy density/ Specific energy (Wh/kg)		Industry: 150-220[22,68–70]	Lab: 530[69,71]	Industry: 106-160[54,72–74] Lab: 520[71]	Lab: 57.2[75]	-
Energy density (Wh/L)		Industry: 272[76] Lab: 530[22]	Industry: 200-350[22,73]	Lab: 180-400[54,71,73]	-	Low[25]
Rate capability (C-rate)		0.7-2[68]	4[77]	-	10-400[75]	-
Cycle life		1000-2000[68]	5000+[54,73,77]	1200-5000[54,71,73]	250+[24]	500+[65]
Price, 2020 avg ($/kWh)		$137[38]	$78-100[78–80]	2018: $248[81] Lab: 45-100[73]	-	-

\# same as classic li-ion **-** information could not be found

For the sake of readability, only the batteries that appeared in the final brief have been kept in this table.

ANNEX 8. Environmental & social impact comparison of EV batteries

Four key impact areas were defined as follows: (i) total energy use & emissions, (ii) toxicity, (iii) habitat destruction, and (iv) social impact.[19]

	Aspect	Cobalt Li-ion (NMC)	Iron Li-ion (LFP)	Sodium-ion (Na-ion)	Org-ORB*
	Major materials	- Lithium - Cobalt - Nickel - Manganese - Graphite	- Lithium - Iron - Phosphates - Copper - Graphite	- Sodium (CA) - Carbon (AN)	- Organic proteins (CA) - Carbon (AN)
	Source	Ore, brine, rock & deep-sea mining	Ore, brine & rock mining	Sea + brine & rock mining	Biomass[4,5]
Stage					
Resource-to-gate	**GHG's (CO_2 eq/kWh)**	- 140-196 kg[18]	- 160 kg[18]	-140 kg[18,82]	?
Resource extraction	**Water use (L/kWh)**	- Li: 208.24 (CA) [8,83] - 65% of available water in Atacama desert[8]	- Li: 177.46 (CA)[8,83] - 65% of available water in Atacama desert[8]	- Na: 107.17 (CA)[84] (Negligible % of seawater)	?
	Energy use	- High(CA)[19]	- 50% less (CA)[19]	- Low: 0.01-1% of Li-ion (CA)[19]	- Depends on source[33] - >90% less (CA)[23,85]
	Pollution & toxicity	- Pollution surface waters[86] - Degradation of agricultural land[17]	- Pollution surface waters[86] - Degradation of agricultural land[17]	- Nontoxic[82]	- Nontoxic[23,87]
	Habitat destruction (Terrestrial & Riverine)	- Reduction groundwater level in Atacama desert(CA)[15] - Salt flat food-chains (CA)[15] - Flooding of river sheds (CA)[17]	- Reduction groundwater level in Atacama desert(CA)[15] - Salt flat food-chains (CA)[15] - Flooding of river sheds (CA)[17]	- 0.01-1% of Li-ion salt flat destruction (CA)[19] - Low land use (SP)[19] - 1m²/kWh[19]	- Land use for sugar cane, beet or corn cultivation (CA & AN)[88] - Low land use (SP)[19]

		- High land use (SP)[19] - 9.5m^2/kWh[19]	- High land use (SP)[19] - 10.5m^2/kWh[19]		
	Habitat destruction (Marine)	- Deep sea ecosystems[20]			
	Human & labor rights	- Child Labour[19,21] - Hazardous working conditions[21] -Disrupted access to drinking water[19] - Violation of Indigenous peoples' right to prior consent[15,32,86,89]	- Hazardous working conditions[21] -Disrupted access to drinking water[1977] - Violation of Indigenous peoples' right to prior consent[15,32,86,89]		- Loss of income[9,15]
	Human health	- Severe respiratory & organ damage[19] - Increased risk of birth defects[19]			
	Displacement	- Indigenous peoples Argentina[32], Chile[15], & USA[89] - Rural population Serbia[17]	- Indigenous peoples Argentina[32], Chile[15], & USA[89] - Rural population Serbia[17]		
Manu-facturing	**Energy**	~950-1110 BTU/Wh[19]	~1000-1225 BTU/Wh[19]	~625 BTU/Wh[19]	- Low[23,25]
	Transport emissions	High (CA)[19]	Low(CA)[19]		
	Water use (L/kWh)	- High[25]	- High[25]	- High[84]	- Low
	Pollution & toxicity	- High toxicity score: 5.5[19] - SO2 emissions: High acidification potential (AP)(CA)[19]	- Medium toxicity: 4[19] - Low AP (20% of NMC) (CA)[19]	- Low to no toxicity: 1.2[19] - Low AP (20% of NMC) (CA)[19]	- Low toxic catalysts used in controlled environment[85] - Reduced pollution risk[85]
	Human rights	n/a	n/a	n/a	n/a

FU (Functional Unit) = 1 kW h of storage capacity & 1 kW h of lifetime energy storage capacity[2]

<u>Legend</u>

- (AN): associated with anode production
- (CA): associated with cathode production
- (SP): associated with separator production
- (EL): associated with Electrolyte production
- (So): associated with solvents
- (Ct): associated with catalysts

*: Analysis only includes biomass-based organic batteries, even though many current experimental organic batteries still rely on fossil fuel derivatives[3]