Electrifying Transport:

The Good, the Bad, and the Ugly

LOCOMOTION

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List of Abbreviations

EGD – European Green Deal

CO_2 - Carbon Dioxide

EU - European Union

EV - Electric Vehicle

ICEV - Internal Combustion Engine Vehicle

GHG - Greenhouse Gas

IAM - Integrated Assessment Model

WILIAM - Within Limits Integrated Assessment Model

LMO - Lithium Manganese Oxide

NMC - Nickel Manganese Cobalt

NCA - Nickel Cobalt Aluminum

LFP - Lithium Iron Phosphate

ESOI - Energy Stored Over Energy Invested

VAT - Value Added Tax

R&D - Research and Development

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Introduction

In 2020, the European Union launched the European Green Deal (EGD) as its flagship policy package to reach a carbon-neutral economy by 2050. The decarbonisation of the transportation sector, which today contributes to around one-third of global emissions,[1] is a priority for the EGD. But, by pledging to reduce sectoral CO_2 emissions by 55% by 2030, the EU is faced with the challenge of re-imagining the mobility system: a system which currently relies on CO_2-intensive and individual transportation practices.

So far, in line with the global trend, the decarbonisation strategy of governments across the EU has been centered around the electrification of the transportation sector. While abandoning a fossil fuel-based transportation system can yield many advantages, the idea of carrying out a full electrification of the mobility system with no change in mobility patterns raises some eyebrows in the scientific community. Skepticism arises from the huge lifecycle energy requirements of large-scale electrification, as well as the amount of raw materials (some critical) and the supporting infrastructure needed for EV battery production.

Using a strong evidence-based approach, this policy brief sheds light on the energy and material implications of transport electrification based on the scientific paper "Material and Energy requirements of Transport Electrification"[2], a peer-reviewed investigation into decarbonising the transportation sector as part of the LOCOMOTION project.

LOCOMOTION is an EU Horizon 2020 project, with the ambition to develop an Integrated Assessment Model (IAM) to compare and understand the effects of different policy options. The model, called MEDEAS-W, simulates four different policy scenarios and their projected consequences on the economy, society, and the environment. Each scenario is based on different political assumptions on how to reach carbon-neutrality by 2050, and accordingly, each scenario includes a set of specific decarbonisation policies.

This policy brief starts from the four different policy scenarios to build a case for the most energy- and material-sustainable policy pathways to stay within the Paris Agreement's climate targets. The following section delves deeper into the characteristics of each scenario.

The three sections of this paper are structured as follows.

Section 1: "The energy requirements of the transition" starts with broader energy considerations on the electrification of transport, then continues by showing WILIAM's results on each scenario's energy implications of electrification of transport. Similarly,

Section 2: "The material requirements of the transition" first delves into the broader material challenges that electrification will face; secondly, results from the WILIAM model are shown, projecting material scarcities across time and for each scenario. Finally, the policy brief concludes with policy recommendations (Section 3).

[1] Transport - Energy System, IEA. Available at: https://www.iea.org/energy-system/transport

[2] Energy Environ. Sci.,2022, 15, 4872. https://pubs.rsc.org/en/content/articlelanding/2022/ee/d2ee00802e

The 4 decarbonisation scenarios

The four policy scenarios are developed starting from different sustainability strategies and assumptions (e.g., green growth, degrowth, etc.). The different policy approaches that they entail result in different outcomes in terms of energy and material requirements for the economy to function and reach carbon-neutrality by 2050.

The four scenarios are:

Scenario 1
Expected EV trends

In this scenario the evolution of transport electrification is projected based on past and current trends in the sector and in EV demand.

Scenario 2
High EV

This scenario promotes extreme electrification in land transport. It assumes a 1-to-1 replacement of the current fleet of ICEVs (Internal Combustion Engine Vehicles) with an EV one: all personal vehicles, buses, motorcycles, and light-duty will run on battery; for heavy-duty vehicles (e.g., trucks for freight transportation) it envisions that 80% will be hybrid. This scenario demonstrates a model of extreme electrification without altering cultural transportation patterns.

Scenario 3
E-bike

This scenario envisions changes in mobility patterns. It is expected that 60% of private vehicles will be replaced with 2-wheeled EVs, and another 20% by electric bicycles. Heavy duty vehicles still run on liquid fuels (due to limitations tied to battery requirements for heavy vehicles); however, a 30% shift from truck transportation to electric rail is assumed, increasing the share of freight transportation covered by electric rail from the current 30% to 60% by 2050.

Scenario 4
Degrowth

This scenario assumes a future where serious efforts are made to shift from a growth-oriented economy to one that fulfils human needs without constant growth. It enables policies that allow for overall reduction of transportation demand (especially from the most affluent individuals) and a modal shift from private vehicles to public transport. This scenario envisions an average reduction of inland and water transport of 60% and a reduction in aviation transport of 85% (vis-á-vis 2020 trends).

[2] *Energy Environ. Sci.,2022, 15, 4872*

The energy requirements of the transition

Opportunities and challenges

The European Union's transportation sector has facilitated the application of a growth-centric capitalist model. From an industry perspective, the development of widespread and convenient forms of freight transport allowed producers to expand their market reach across national borders, feeding production needs with an ever-increasing pool of demand. From a behavioural point of view, easy accessibility to private forms of transport (from private vehicles to air travel) facilitated a shift to societal behaviours that incentivize unconscious mobility. As a result, in the last 20 years, the transportation sector has experienced an astonishing growth (18%, 86%[3], and 22% growth, for car, air and freight transport, respectively)[4].

The benefits of this growth (e.g., increased commerce, improved connectivity etc.) have come at a dreary cost for the environment. Today the transportation sector accounts for 25% of the EU's overall yearly GHG emissions and it represents the only economic sector in which emissions have consistently increased since 1990[5] (at an annual average rate of 1.7%)[6]. As the EU has pledged to reach carbon neutrality by 2050 it has identified in the transportation sector the paramount challenge to tackle.

Efforts to decarbonize and mitigate transport emissions have mostly focused on efficiency. Today, the average ICE vehicle has an efficiency between 15% - 40%[7], meaning that less than half of the fuel energy used is turned into actual energy for movement. The rest is lost through attrition or heat. Technological progresses that increase vehicle efficiency allow less energy to be exploited to perform the same mileage: this is in turn associated with reductions in GHG emissions. As such, the quest for gains in efficiency has been highly incentivized and recognized as an important decarbonization avenue. Since 1992, with the first Euro 1 Emission Standards Directive, the EU has tried to regulate vehicles' GHG emissions by incentivizing gains in efficiency. Since then, the EU has enforced six new standards' Directives (the last one, Euro 6, was applied in 2014) and, despite improvements in efficiency, GHG emissions from the transportation sector have increased consistently: between 2010 and 2015 only, emissions from the sector have increased by 2.5% annually[8].

[3] *Part of this astonishing growth for the aviation sector is given by the increasingly cheap fares that airlines are able to provide, as they do not pay taxes on fuel*

[4] *European Environment Agency (EEA), Transport and Mobility. Available at: https://www.eea.europa.eu/en/topics/in-depth/transport-and-mobility*

[5] *Energy Environ. Sci.,2022, 15, 4872. https://pubs.rsc.org/en/content/articlelanding/2022/ee/d2ee00802e*

[6] *Transport - Energy System, IEA. Available at: https://www.iea.org/energy-system/transport (Accessed: 04 October 2023).*

[7] *Albatayneh, A., Assaf, M., Alterman, D. & Jaradat, M. (3920). Comparison of the Overall Energy Efficiency for Internal Combustion Engine Vehicles and Electric Vehicles. Environmental and Climate Technologies,24(1) 669-680. https://doi.org/10.2478/rtuect-2020-0041*

[8] *Energy Environ. Sci.,2022, 15, 4872. https://pubs.rsc.org/en/content/articlelanding/2022/ee/d2ee00802e*

The graph below showcases this increase: except for the year 2020, when global mobility was impacted by COVID-19, CO2 emissions associated with cars and vans have steadily increased.

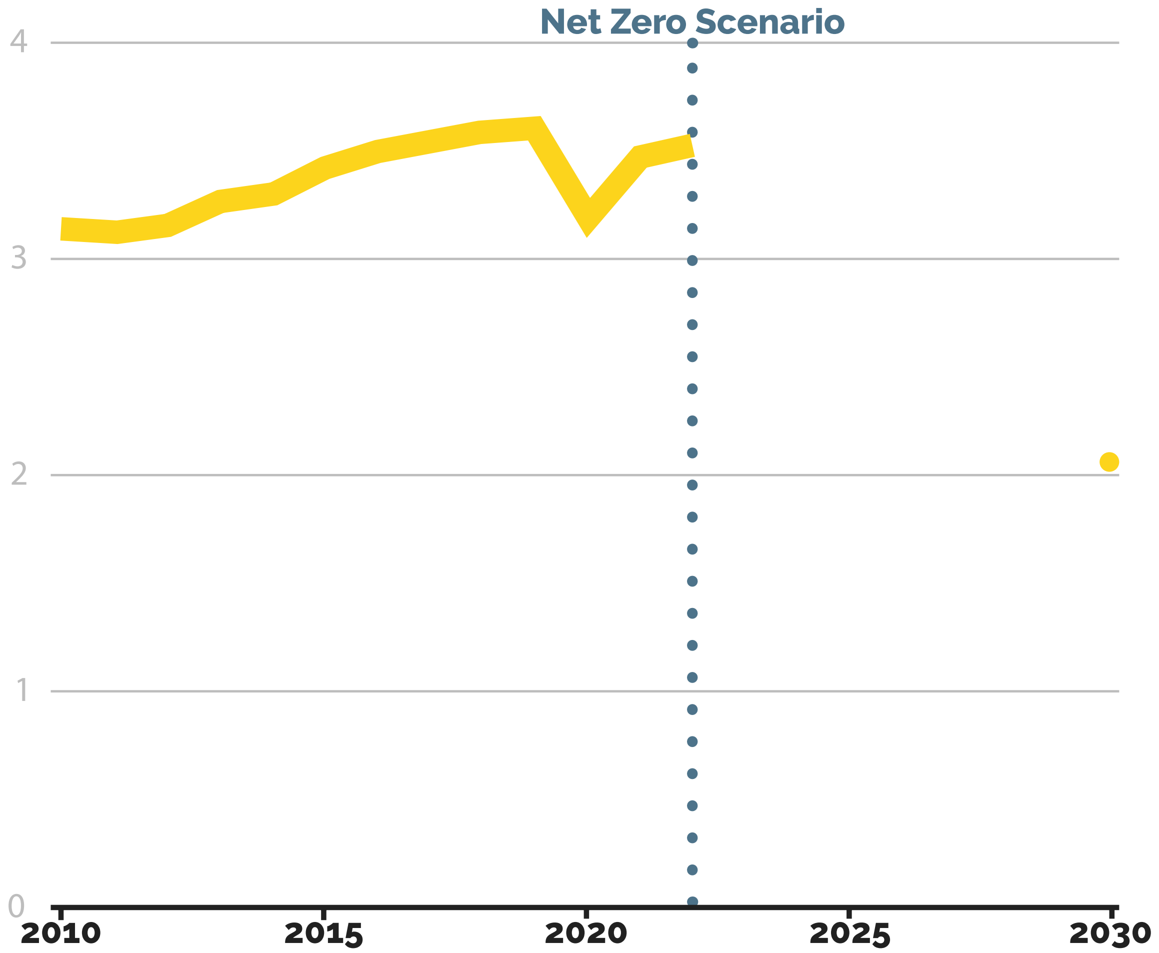

Fig. 1: CO_2 emissions from cars and vans in the Net Zero Scenario, 2000-2030

Source: IEA, CO_2 emissions from cars and vans in the Net Zero Scenario, 2000-2030, IEA, Paris https://www.iea.org/data-and-statistics/charts/co2-emissions-from-cars-and-vans-in-the-net-zero-scenario-2000-2030-2, IEA. Licence: CC BY 4.0

As of today, and as showcased by global EV trends, the global economy is betting on EVs to replace the use of fossil fuels and curb further increases in CO_2 emissions. Exchanging the current ICEVs fleet with an EVs one will require new investments in road infrastructure, power grids and charging systems, as well as a strong institutional signal to steer private investments in the electric vehicles' market, incentivizing major carmakers to shift production as well as consumers to buy electrically powered vehicles. At the EU level, this signal arrived in the form of the final agreement on the 'Fit for 55' package (presented by the European Commission on 14 July 2021 under the European Green Deal), under which the European Commission has vowed to ensure that all new cars registered in Europe will be zero-emission by 2035[9].

Many other governments embarked on similar paths to decarbonise the transport sector. The USA is a clear example of an even more ambitious strategy to accelerate a full conversion to an electric fleet of vehicles. Through the Inflation Reduction Act, the Biden-Harris Administration is seeking to tackle the global energy crisis while at the same time curbing climate change. Through a series of investments and production tax credits, the Act is meant to provide signalling to energy organisations, investors, and consumers to accelerate the transition to a clean energy economy.

As a result of these political signals, global market trends point to noticeable increases in EVs'sales. Despite the Covid-19 supply chain challenges and a depressed car market, EV sales keep reaching yearly record highs and in 2021 accounted for 9% of the global car market (17 million EVs)[10]; a figure that might seem small but is impressive when considering that it represents four time the 2019 EVs' market share.

China is currently leader in EV vehicle deployment. The country's fleet is the world's largest (counting more than 8 million in 2022[11]) and is forecasted to follow impressive growth rates as the government's new five-year plan sets renewed and ambitious medium-term targets for itself (e.g., reaching 20% EV market share in 2025) and as investments from previous years increase production and yield market results.

Not far from China's EV take up is the EU's market: it registers the greatest growth rates in EVs worldwide (60% annual growth rate over the 2016-2021 period)[12] and across the EU EVs account for 17% of total market share. As in the case with China, EV vehicle deployment is only at its initial phases and upcoming increases in growth rates are expected as the European Union tightens CO_2 emission standards.

The energy gains brought by EVs compared to ICEVs (EVs' efficiency is typically assessed to be 2–3x better than ICEVs[13]), together with the benefits in terms of GHG emissions reduction provide a fertile ground for policymakers to keep on sustaining the

[9] *European Parliament. (2023, February 14). Fit for 55: zero CO_2 emissions for new cars and vans in 2035 [Press release]. https://www.europarl.europa.eu/news/en/press-room/20230210IPR74715/fit-for-55-zero-co2-emissions-for-new-cars-and-vans-in-2035*

[10] *IEA (2022), Global EV Outlook 2022, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2022, License: CC BY 4.0*

[11] *Ibid.*

[12] *Ibid.*

[13] *Energy Environ. Sci.,2022, 15, 4872. https://pubs.rsc.org/en/content/articlelanding/2022/ee/d2ee00802e*

above-mentioned growth in sales. However, both these assumptions have been challenged.

Firstly, on emissions, the idea that EVs are comparably less pollutant is still controversial. Throughout the use phase, EVs do emit less than their combustion engine counterparts; however, EV's carbon emissions are considerably higher in the manufacturing phase, compared to ICEVs. This is due to the high material-intensity in the production of batteries and other EV components. Specifically, while ICEs and EVs have similar embedded emissions from producing the body of the vehicle (between 5 and 10 tons of CO_2), the extra production of EVs' battery produces more than ˜7 tons of CO_2 alone (75-kWh battery pack). In fact, the main battery components (nickel, lithium, cobalt, etc.) emit substantial levels of GHG when mined, transported, and refined[14] [15].

Secondly, still very few studies extend energy calculations beyond vehicles and batteries, to include the vast energy infrastructures and processes needed to fully operate EVs (e.g., charging stations, power grids, energy requirements from assembly factories). Fully accounting for these would showcase even further how the production of EVs is still a very energy-intensive process. The next section of this policy brief will explore exactly this issue: results from the MEDEAS-W model, by considering the whole of the energy system feeding into EVs, will give more comprehensive answers to questions surrounding the overall energy requirements of aiming at full transport electrification.

To conclude, the current push for decarbonization is happening under the implicit assumption that new 'green' technologies like EVs will grow continuously and become widespread at a scale able to effectively curb climate change. However, legitimate hesitation stems from the limited perspective adopted by a narrative that pushes for replacing the whole of the current ICEV fleet with an EV one. This perspective fails to understand the broader environmental and social dimension that is at stake and that should be addressed when thinking about our modes of transport: energy demand from production, resource depletion from mining extraction, damage to water and air from battery manufacturing. In a growth economy, systemically centred around increasing demand and production, the electrification of the transport system overlaps with the need to preserve our growth model, while hoping to keep global warming within the recommendations of the scientific community. Decarbonization of transport is pursued exclusively to reduce GHG emissions as a consequence of further mobility demand growth, without decreasing transportation footprint in absolute terms. Furthermore, a decarbonisation strategy of this sort, does not consider concerns of social justice and accessibility to the EVs market in the green transition: the hefty price tag that EVs carry make it virtually inaccessible to lower income households, who are the ones already suffering the most from poor air quality from tailpipe emissions[16].

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[14] *Linder, M., & Nauclér, T. (February 2023). The race to decarbonize electric-vehicle batteries. McKinsey & Company. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-race-to-decarbonize-electric-vehicle-batteries#/*

[15] *Indonesia is a paradigmatic case. Indonesia is the world's largest nickel producer and its reserves, estimated at a quarter of the world's total, will turn the country into an EV powerhouse. Indonesia's nickel production rose by 60% in 2022, accounting for half of global production. But this "green" ambition comes with a climate toll, given that the nickel industry is hugely energy intensive. And in Indonesia, the electricity grid is dominated by coal. In 2022, Indonesia burned 33% more coal than the previous year making it the world's sixth largest emitter of fossil CO_2, behind Japan.*

[16] *Christina H. Fuller, Doug Brugge, Chapter 20 - Environmental justice: Disproportionate impacts of transportation on vulnerable communities, Traffic-Related Air Pollution, 2020, Pages 495-510, ISBN 9780128181225, https://doi.org/10.1016/B978-0-12-818122-5.00020-X.*

Energy requirements: results from the model.

In the first part of the paper that forms the basis to this policy brief, the authors question the above-mentioned assumption of energy savings embedded in the production and use of EVs. Through a selection of relevant technologies, they calculate the lifecycle energy requirements from batteries and from the overarching system (i.e., charging stations, development of connection to the existing electric grids) needed to sustain a fully electrified fleet of vehicles.

Energy net calculations are computed from the difference between the amount of energy that EV batteries are able to store compared to the energy 'used/invested' to manufacture the battery and make it work during its lifetime. This energy relationship is measured by the ESOI ratio (Energy Stored Over Energy Invested): a higher ESOI ratio reflects higher technological performance of the battery, as it implies that it is able to store more of the energy that it is "fed". Hence, an ESOI ratio above 1 means that the battery stores more energy than it receives. An ESOI ratio less than (or equal to) 1 means that the energy used

The ESOI ratios considered in this work are:

1. **The ESOI standard ($ESOI_{st}$)**
   It calculates the energy stored in the battery compared to the energy used in manufacturing the battery.

2. **The ESOI final ($ESOI_{final}$)**
   It is a more comprehensive indicator of energy requirements: the energy stored by the battery is compared to the overall energy used by the whole overarching infrastructure, needed to produce and operate the EV fleet. Namely, it includes the energy used by the chargers, as well as connections to existing grids.

The following section presents the $ESOI_{st}$ and $ESOI_{final}$ of five different Li-ion batteries (LiBs)[17]: LMO, NMC-622, NMC-811, NCA, and LFP. LiBs are considered the most suitable for electric mobility[18]: around 75% of electric vehicles[19] today use Li-ion batteries, including main EV manufacturers (e.g., Tesla uses LFP batteries in its Model Y EV). The reason lies behind LiBs' superior ability to store energy: one of the highest of any battery technology today (i.e.,100-265 Wh/kg or 250-670 Wh/L). Simply, this means they have a longer battery life in relation to their weight and compared to other battery technologies.

Table 1 below showcases the different levels of $ESOI_{st}$ and $ESOI_{final}$ for each type of EV battery.

	Mileage (km)	LMO	NMC 622	NMC 811	NCA	LFP
ESOIst	200 000	1.1 - 1.5	1.1 - 1.5	1.4 - 2.2	1.4 - 2.3	1.4 - 2.1
ESOIfinal	200 000	0.4 - 0.7	0.4 - 0.7	0.4 - 0.9	0.4 - 0.9	0.4 - 0.9
ESOIst	100 000	0.5 - 0.7	0.5 - 0.7	0.7 - 1.1	0.7 - 1.1	0.7 - 1
ESOIfinal	100 000	0.2 - 0.4	0.2 - 0.4	0.2 - 0.5	0.2 - 0.5	0.2 - 0.5

Table 1: $ESOI_{st}$ and $ESOI_{final}$ over the lifetime for two different mileages (200 000 and 100 00 km) for each type of EV battery for a 4-wheeler household private vehicle.

Source: *Energy Environ. Sci., 2022,15, 4872-4910*

[17] *The ESOI results obtained are computed (over the lifetime) for the EV battery of a 4-wheeler, household private vehicle. Moreover, given the sensitivity of the results to mileage, the results are calculated for 100 000 km and 200 000 km, which represent respectively the average vehicle usage per capita, in Europe and the USA respectively.*

[18] *Energy Environ. Sci.,2022, 15, 4872. https://pubs.rsc.org/en/content/articlelanding/2022/ee/d2ee00802e*

[19] *For a "shared" car, authors find that $ESOI_{final}$ would increase respectively to 0.5–1 : 1 and 0.6-1.7 : 1 (considering 300 000km and 400 000 km respectively). Similarly, electric urban buses showcase an ESOIfinal of 0.7–1.8 : 1 and 0.8–2.5 : 1, respectively for a 300 000 km and 400 000 km mileage.*

Two important remarks stand out from the table. First, difference in mileage has a considerable impact on energy returns (ESOI): going from an initial 200 000 km down to 100 000 km decreases energy returns by almost half.

Similarly, only accounting for the energy needed to manufacture EV batteries, compared to the amount these batteries can store ($ESOI_{st}$), results are modest: ratios are above one (meaning that batteries store more energy than what they are "fed"). However, when considering the energy needed by the whole of the system (i.e., charging points, electric grids) to manufacture and use EV batteries, so our $ESOI_{final}$, results become more disappointing and the ratios showcased in the table are below 1 (i.e., batteries store less energy than the amount used by the whole system). The LMO battery sub-technology stands out as the worst performing one.

It can be concluded that, across all types of batteries, the amount of energy required (for manufacturing and operating the vehicle throughout its lifetime) is higher than the energy delivered by the vehicle in its full lifetime. Extending energy calculations to the manufacturing and operating energy requirements of EVs, allows to paint a more comprehensive picture of the intensive use of energy that EVs will still require.

In search of a more optimistic note, the authors explore the question of whether a behavioural shift towards more sustainable modes of transportation could have different results. This is a shift that implies a less intensive use of private forms of transportation and a shift in preferences towards car sharing options and public transportation. Interestingly, results from the model show that through a shift in transportation preference, electric vehicles, whether as part of a 'car sharing' fleet or as part of a public transportation system, have much higher energy returns (i.e., higher $ESOI_{final}$)[20]. These results point to an important finding, namely that a modal shift in our mobility patterns can represent a significant improvement in the overall energy we will require for the transition: societal efficiency is higher with widespread sharing modes than pursuing the efficiency of individual vehicles.

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[20] *For a "shared" car, authors find that ESOIfinal would increase respectively to 0.5–1 : 1 and 0.6-1.7 : 1 (considering 300 000km and 400 000 km respectively). Similarly, electric urban buses showcase an ESOIfinal of 0.7–1.8 : 1 and 0.8–2.5 : 1, respectively for a 300 000 km and 400 000 km mileage.*

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The material requirements of the transition

Overview of the challenges

This section of the paper delves into the material requirements of transport electrification and the expected challenges.

As mentioned, transitioning to a fully electrified transport system will require the mainstreaming and increased production of several ‘transition technologies’ (i.e., EVs and EV batteries, charging stations, new grids, etc.), which are made up of materials different from the ones today used in ICEV technology and/or that require more quantities of the same material. Examples of this increased material necessity/intensity span from EV production (e.g., the extra copper necessary for the wiring of EVs compared to ICEVs[21]) up to battery production (e.g., lithium, graphite and cobalt – traditionally not used in ICEVs) and the whole system’s infrastructure (i.e., extra materials needed for different types of charging stations and for the whole length of the grid). It is clear then, how the transition to a fully electrified transport system is highly mineral-intensive - meaning that it is heavily dependent on the availability of finite material resources.

EV batteries in particular are the greatest claimant of material resources. Of the five Li-ion batteries already seen in the previous section (i.e., LMO, NMC-6[22], NMC-811, NCA, and LFP), each require a different set of materials in order to be produced. So, for example, while all types of batteries require Aluminium and Lithium, not all of them rely on Manganese or Nickel. This is relevant as each battery’s material needs (and challenges), combined with their level of performance, will determine their future market relevance.

[21] *IEA, Minerals used in electric cars compared to conventional cars, IEA, Paris https://www.iea.org/data-and-statistics/charts/minerals-used-in-electric-cars-compared-to-conventional-cars, IEA. Licence: CC BY 4.0*

[22] *The estimates come from Table 4 of the LOCO paper and are obtained by the authors through literature review collating data from real batteries. For easy comparison across batteries, the analysis is standardized, establishing that each battery is used for same number of hours, has a capacity of 60kW h and 100kW of power.*

The Table below shows:
1) on which critical raw materials each battery technology relies on and
2) the material intensity of each material.

For each battery, the sum of the materials' masses is calculated in the **total material weight**[22]. Calculated at the bottom row, this parameter affects technical performance: the heavier the weight of the battery the least performant.

kg MW^{-1}	LMO	NMC 622	NMC 811	NCA	LFP
Aluminium	139.65	75.6	75.6	75.91	93.9
Copper	80.72	46.8	46.8	46.3	54.3
Iron	0	0	0	0	48.6
Lithium	9.6	7.8	6.6	4.8	6.1
Manganese	142.2	12	6	0	0
Nickel	0	36.7	45.1	40.2	0
Cobalt	0	12	6	6.3	0
Phosphorus	0	0	0	0	27
Graphite flake	86.58	44.2	44.2	38.5	52.4
Rest (plastics, electronics)	193.35	91.58	98.95	116.88	156.02
Oxygen	82.903	33.323	30.758	27.416	55.696
TOTAL	735KG	360KG	360.1KG	356.31KG	494.01KG

Table 2: Material intensities (kg MW^{-1}) of the selected EV batteries; based on a 60 kW h battery with a power of 100 kW

Source: *Energy Environ. Sci., 2022,15, 4872-4910*

[23] *The estimates come from Table 4 of the LOCO paper and are obtained by the authors through literature review collating data from real batteries. For easy comparison across batteries, the analysis is standardized, establishing that each battery is used for same number of hours, has a capacity of 60kW h and 100kW of power.*

As showcased by **Table 2**, each battery presents a different chemical mix and resulting total weights, delineating a well-known trade off in the production of EVs, between dependence on the most critical materials (e.g., cobalt and manganese) and the overall weight (=performance) of the battery.

As a clear example of this trade-off: LMO and LFP batteries stand out for their independence from both Nickel and Cobalt. These materials' availability is hampered by strong demand from the rest of the economy (in the case for Nickel) or by scarcity and geopolitical challenges (as for the case of Cobalt: today 70% of the world's Cobalt is mined in the Democratic Republic of Congo[23], and the country accounts for nearly half of the world's reserves[24]). Hence, battery sub-technologies that do not require these critical materials would be ideal to drive the transition to full electric mobility. However, LMO and LFP also show the highest total material weights and as such have relative worst technical performances compared to the other batteries (although with an important discrepancy between the two – LFP performing better than LMO).

The Table provides a thorough breakdown and useful overview of the crucial materials that will be in demand in the coming years: Aluminium, Copper, Lithium, Manganese, Cobalt, and Nickel, will be indispensable to facilitate the electrification of our transportation system and decarbonize the transportation sector. Acknowledging this requires practical considerations on the extent to which these materials will be available at the pace required by transition objectives and the potentially hazardous (environmental and social) consequences of an uncontrolled race to satisfy a soaring EV demand.

At this point, drawing a distinction between resources and reserves is helpful to understand the upcoming global efforts of mineral extraction to satisfy growing demand. Resources are natural concentrations of minerals; however, their presence in the earth's crust is not sufficient to ensure that mineral extraction will take place, because of legal, economic, infrastructural, or environmental concerns. On the other hand, reserves are a subset of resources and represent that portion of resources which, after detailed evaluation programmes, are considered economically mineable[25].

Current reserves will not be able to satisfy the transition demand of EV trends, and massive investments to expand mining frontiers have already begun and are expected to increase in the coming years. In fact, although mining currently already influences 37% of the Earth's terrestrial land[26], the race for critical minerals has accelerated: most industrialized countries are competing to secure deals with nations rich in critical materials. A very recent example is Ursula Von Der Leyen's trip to South America to establish and solidify partnerships with local governments, securing supply of critical raw materials to EU countries. Other strategies include massive investing to promote and intensify domestic explorations and supply chains: the Biden-Harris Administration, through its Inflation Reduction Act, is preparing to fund the exploration of critical mining projects in the US, to support the development of domestic processing and manufacturing of battery components.[27] Similarly, the Australian government, through its "Exploring the Future Program" (2020) and "Critical Minerals Mapping Initiative" (2018) is planning to identify potential minerals' corridors and "improve the knowledge of critical material concentrations"[28].

[23] *Nick, S. (January 2022). The first step in combatting cobalt shortages? Stop throwing it out. Frontier Group. https://frontiergroup.org/articles/first-step-combatting-cobalt-shortages-stop-throwing-it-out/*

[24] *Statista. Reserves of cobalt worldwide in 2022, by country. https://www.statista.com/statistics/264930/global-cobalt-reserves/*

[25] *British Geological Survey, Centre for Sustainable Mineral Development. (2023). What is the difference between resources and reserves for aggregates? https://www2.bgs.ac.uk/mineralsuk/mineralsYou/resourcesReserves.html*

[26] *Sonter, L.J., Dade, M.C., Watson, J.E.M. et al. Renewable energy production will exacerbate mining threats to biodiversity. Nat Commun 11, 4174 (2020). https://doi.org/10.1038/s41467-020-17928-5*

[27] *U.S. Department of Energy. (October 2022). Biden-Harris Administration Awards $2.8 Billion to Supercharge U.S. Manufacturing of batteries for Electric Vehicles and Electric Grid. https://www.energy.gov/articles/biden-harris-administration-awards-28-billion-supercharge-us-manufacturing-batteries*

[28] *International Energy Agency (IEA). Policies Database. Critical Minerals Mapping Initiative. https://www.iea.org/policies/16093-critical-minerals-mapping-initiative*

However, as demand projections of these critical transition minerals increase, it must inevitably face supply-side considerations: supply bottlenecks, geopolitical arm-wrestles, and communities' rightful opposition to mining projects that harm their land and disregard their rights to consultation. The EU represents only 6% of the global population but consumes almost 30% of the globally produced metals[29], raising questions about equity in current and future resource consumption. As projected demand increases and new mining explorations and projects will inevitably arise, we must question the impact on local communities: new research shows that around 54% of minerals' resources necessary for energy transition are located on or near the lands of Indigenous or peasant people, two groups whose rights to consultation and consent are protected by the United Nations declarations[30].

Furthermore, the growth of primary extraction carries several climate and environmental risks:

1) spillages are not infrequent and permanently damage water sources and local biodiversity (this is especially relevant if we consider that most mineral reserves are located in high biodiversity areas[31])

2) deforestation of vast portions of land and the scraping off of topsoil

3) release of significant CO_2 emissions and other gases toxic for the environment and human health

4) disposal of waste into ecosystems[32]

Table 2 provides a more thorough breakdown of the social and environmental effects of mining.

n conclusion, although some level of resource exploration and new mining will be necessary to undertake the task of reaching a zero-emission economy, the volume of extraction and the size of the EV market that must be fed is still not a given. They can and must be shaped by policies attentive to environmental, climate, social and human rights' needs. Moreover, potential confutations, arguing that a transition from fossil fuel mining to other minerals will ultimately provide a net benefit of the extent of mining, should be disregarded. In fact, while fossil fuel deposits in the earth's crust are found in already high concentrations, in the case of minerals we find ourselves in exactly the opposite situation (between <20% and <1% concentration). This very low concentration means that, extraction processes, as well as subsequent refining processes, are more intensive and damaging than ones for fossil fuel extraction. Furthermore, the environmental impacts of a conventional crude oil wells are very different from those associated with open pit coal mining, which also differ substantially from those associated with metallic mining, so the social and environmental impact are not proportional to the mass of materials removed[36].

Environmental and social impacts are only one side of the coin: the inevitable scarcity of raw materials that we will have to face poses other sets of challenges to the complete electrification of transport. The following section aims at shedding some light on the matter by projecting material scarcity of key materials, depending on potential decarbonisation strategies pursued by policymakers.

LOCOMOTION

[29] *négaWatt Association. (June 2023). Climate neutrality, Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables. Clever Network.* https://clever-energy-scenario.eu/wp-content/uploads/2023/06/clever_final_report-exec_summary.pdf

[30] *Owen, J.R., Kemp, D., Lechner, A.M. et al. Energy transition minerals and their intersection with land-connected peoples. Nat Sustain 6, 203–211 (2023).* https://doi.org/10.1038/s41893-022-00994-6

[32] *Fletcher, L., Pryde, S., Shields, K., Sheng, J. (Aprile 2023). Greenlight or Gaslight? The transition Minerals Dilemma for Australia. Jubilee Australia Research Centre.* https://www.jubileeaustralia.org/storage/app/uploads/public/645/2cc/90a/6452cc90a05b2016702864.pdf

[36] *Capellán-Pérez. (February 2023). Requerimientos minerales de la transición energética. Ecologistas en acción.* https://www.ecologistasenaccion.org/284674/informe-requerimientos-minerales-de-la-transicion-energetica/

Table 2

	Projections[33]	Environmental Impact	Cases of impact on communities
Lithium	Today EVs claim less than 50% of the total Lithium demand (~125 kt). By 2050, the mineral's demand will increase by more than 30%.[34]	**Lithium extraction/ processing:** • is highly water intensive and worsens hydrological conditions in already water-scarce regions. • arries high chances of spilling chemicals into freshwater sources, killing local fauna (e.g., Ganzizhou Rongda mine disaster)	In Chile's Salar de Atacama, mining has caused the loss of 65 percent of the region's fresh water, putting local communities' access to water in danger. In 2023 the Jujuy province in Argentina unconstitutionally granted new extracting permits on Indigenous land. Manifestations are currently being repressed with police brutality.
Nickel	Today Nickel's demand for EVs is around 10% of total demand. By 2050, EVs will represent more than 50% of the material's total demand. As demand from other sectors of the economy remain stable, the amount of extracted Nickel will have to grow considerably.[35]	**During extraction and processing, Nickel:** • emits huge quantities of CO_2 and sulfur dioxide (a contributor to acid rains) and requires large scale deforestation. • Is treated with highly toxic acids (e.g., sulfuric acid) at risk of leakage into waterways and air. • Faces waste management issues. Waste is often stored in ecosystems.	Open cut mines prevalent in the Asia-Pacific exhume atmospheric dust which have proved to cause respiratory illnesses and cancer (e.g., Rio Tuba mine in Palawan) The Kanaky community has long protested against Nickel mining in New Caledonia, which in the past 30 years has increased 100-fold, subtracting land and resources.
Manganese	By 2050, this mineral's demand will increase by more than 40%. Driven by the adoption of EVs alone.	**During mining and processing, Manganese:** • Is known to release heavy metals and pollutants into nearby water sources.	In the Kalahari Manganese Field (South Africa), mining activity has proved to be detrimental to the health of local communities, increasing the chance of developing respiratory illnesses and asbestosis.
Cobalt	Demand of Cobalt by EVs will increase the total demand for Cobalt by more than 10%.	In Congo, toxic dumping during cobalt extraction, pollutes water and contaminates crops. A study that collected fish from Tshangalale lake, which is adjacent to mining towns, found that the fish were contaminated with prominent levels of cobalt. This contamination is easily spread to humans through the consumption of fish.	Congo's Cobalt is mined through artisanal mining: a highly dangerous and labour-exploitative practice, where people are working in subhuman degrading conditions. Studies have shown that the risk of birth defects, such as limb abnormalities and spina bifida, greatly increased when a parent worked in a cobalt mine, linked to high levels of toxic pollution caused by the extraction of cobalt.

[33] *Projections only include demand from EVs. However, the electrification of the whole system will claim further increases in demand. Projections follow IEA's "Net Zero Emission by 2050" Scenario.*

[34] *IEA (2023), Critical Minerals Data Explorer, IEA, Paris https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer*

[35] *ibid*

Material scarcity: results from the model

In the scientific paper that provides the basis to this policy brief, the authors try to answer the pivotal question of which and how many materials will be needed for decarbonizing the transportation sector. As per the energy considerations, for each decarbonisation strategy, the paper analyses demand for each material (accounting for some rate of recycling), material-intensity and resulting scarcities[37].

It is important to notice that the demand for materials in each of the decarbonisation paths incorporates demand coming from (1) the degree of electrification of transport envisioned by the scenario's transition, and (2) the rest of the economy[38]. This allows for broader and more realistic projections of future material scarcities. Unsurprisingly, as for the energy requirements in the previous chapter, each scenario leads to different material demand and intensity of use, highest in the EV high scenario and lowest in the Degrowth one.

Figure 4 represents the projection of material scarcity into the future for each of the considered decarbonisation strategy. Each raw material is projected through time, until 2050, and for each the level of reserve and resource depletion is observed. Depletion is measured through a "material scarcity" indicator, which is represented on the y-axis of each graph. A value of 100% on the y-axis indicates that global resources are fully depleted; a value between 0 and 100% suggests that reserves are depleted, but resources still available. Finally, the indicator is steady on 0% when current existing reserves are not depleted over the analysed time period and resources are kept untouched.

While the availability of some materials, like Aluminium, do not pose a pressing threat to demand in none of the scenarios, other's depletion rates pose more questions. Manganese and Nickel both deplete their reserves by 2030 (2025 for Nickel, with a demand highly driven by other sectors of the economy as well) and their resources by 2050. This is the case for all relevant scenarios, although the rate of depletion varies: Degrowth is overall the least material-intensive scenario and only reaches depletion for Nickel in 2045 and never reaches full depletion for Manganese.

[37] *The amount of currently estimated reserves and resources is generally taken from the USGS.*

[38] *While electrification of transport creates a new avenue of demand for materials, the rest of the sectors of the economy will still be demanding the same materials for their production needs. For example, Nickel will be a necessary component to produce batteries; however, this material is also extensively employed in the production of stainless steel (used, among others, in the housing sector). Nickel's demand will be split between electrification needs and needs from the rest of the economy, with the result of an overall increased demand.*

Other materials, such as Cobalt and Copper, do not reach full depletion of resources (by 2050), but both their reserves exhaust before 2035. The lower rates of material scarcity depend on the lower dependence of other sectors of the economy on Cobalt and Copper, as well as the greater abundance of the materials on the earth's surface.

Finally, Lithium represents an interesting case in which all reserves and resources are depleted exclusively in the Green Growth (i.e., EV high) scenario, respectively in 2035 and 2050, while all other (less material intensive) scenarios do not exhaust their reserves before 2050.

Policy scenarios similar to EV high or EV trends count on the extractivist assumption that a growing demand can be satisfied by the expansion of extractive frontiers (i.e., investing in turning (proven) mineral resources into reserves or exploring the earth's crust for new resources). However, new and ambitious mining projects take time and technological advancements to take place, creating supply bottlenecks, and bringing a range of important socio-ecological impacts. Furthermore, and paradoxically, the material intensity of these ever-growth scenarios will ultimately still result in complete depletion of materials over the next couple of decades. According to the below graphs, the growth-intensive scenarios are the most at risk of complete depletion: this represents a major contradiction of 'green growth' policy scenarios.

As mentioned, faster depletion of some materials over others will be one of the factors influencing which battery technology will dominate the market. Another important factor, as seen from the previous chapter, are net energy returns ($ESOI_{final}$). By crossing results on material availability and energy returns, **Figure 5** projects the market evolution over time of the five battery technologies (LMO, NMC-622, NMC-811, NCA, and LFP)

Regardless of the decarbonisation scenario simulated (EV trends, EV high, E-bike, Degrowth), the dynamic across the different technologies is the same. In the first years, the battery market is dominated by NCA and NMC battery technologies – both Cobalt-intensive technologies. However, as cobalt begins to become scarcer these technologies are abandoned in favour of LFP batteries, which experiences a marked increase from 2025 onwards. LFP battery technology represents the biggest share of the market in all scenarios, reaching shares of over 40% and maintaining its dominance until 2050. LFP's projected market control can be explained by its better net energy returns ($ESOI_{final}$), relative to other batteries, and by its independence from the most critical materials (Nickel, Cobalt, and Manganese). On the other hand, LMO is the worst performing battery technology. The main driver of its discouraging performance is the low net energy returns ($ESOI_{final}$) and the scarcity of manganese **from 2030 onwards.**

SCENARIO

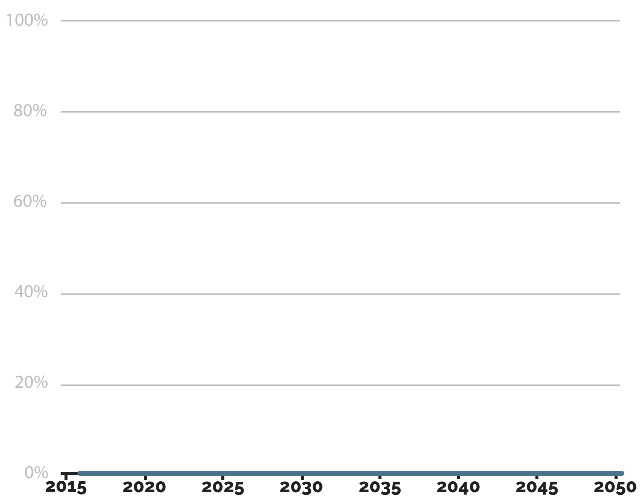
- EV trends
- EV High
- Degrowth
- E-bike

Fig 4: Material scarcity indicator for each simulation for the relevant materials in EV batteries.

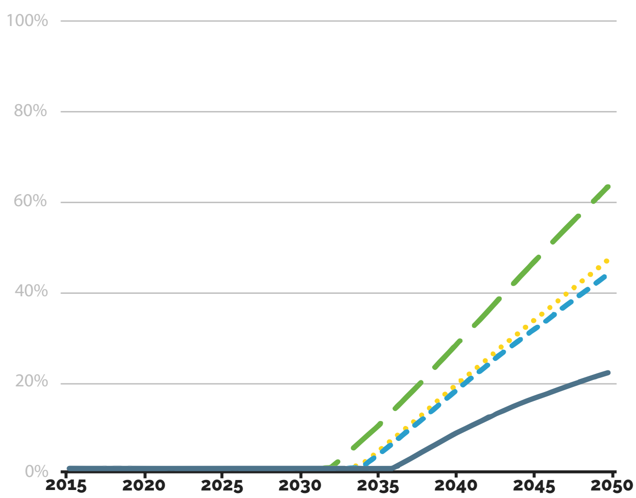
Materials availability include the demand from low carbon technologies and the rest of the economy.

Source: Energy Environ. Sci., 2022,15, 4872-4910

a
material scarcity
Aluminium



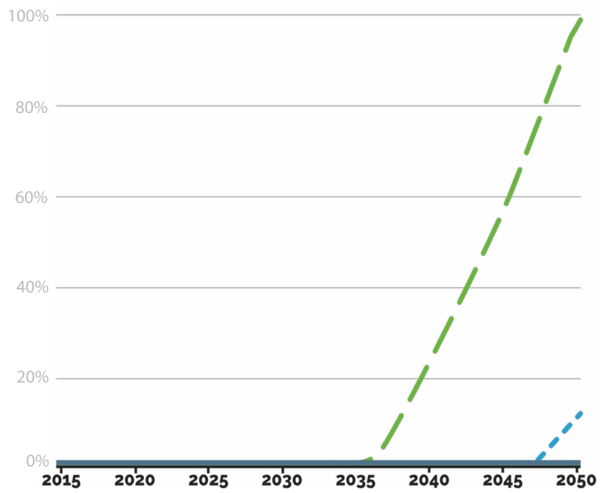
b
material scarcity
Copper



c

material scarcity

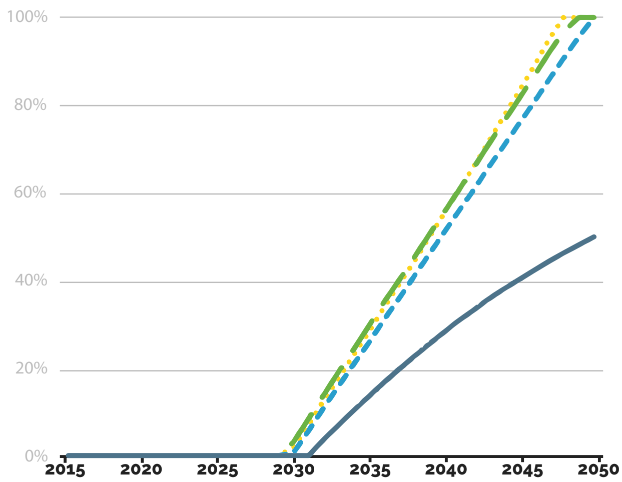
Lithium



d

material scarcity

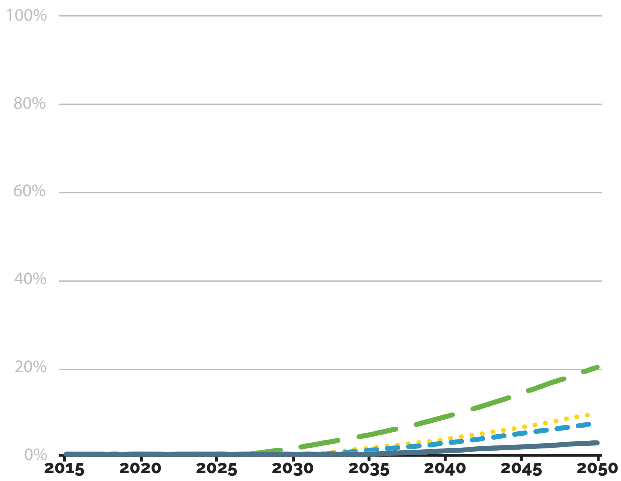
Manganese



e

material scarcity

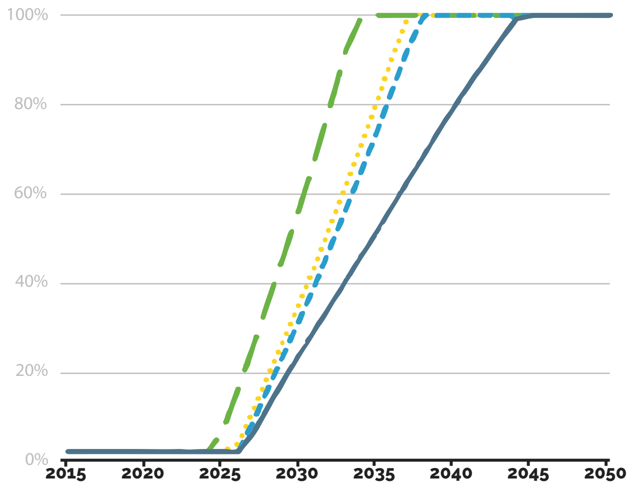
Cobalt



f

material scarcity

Nickel



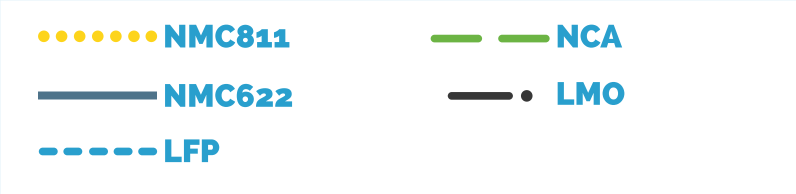
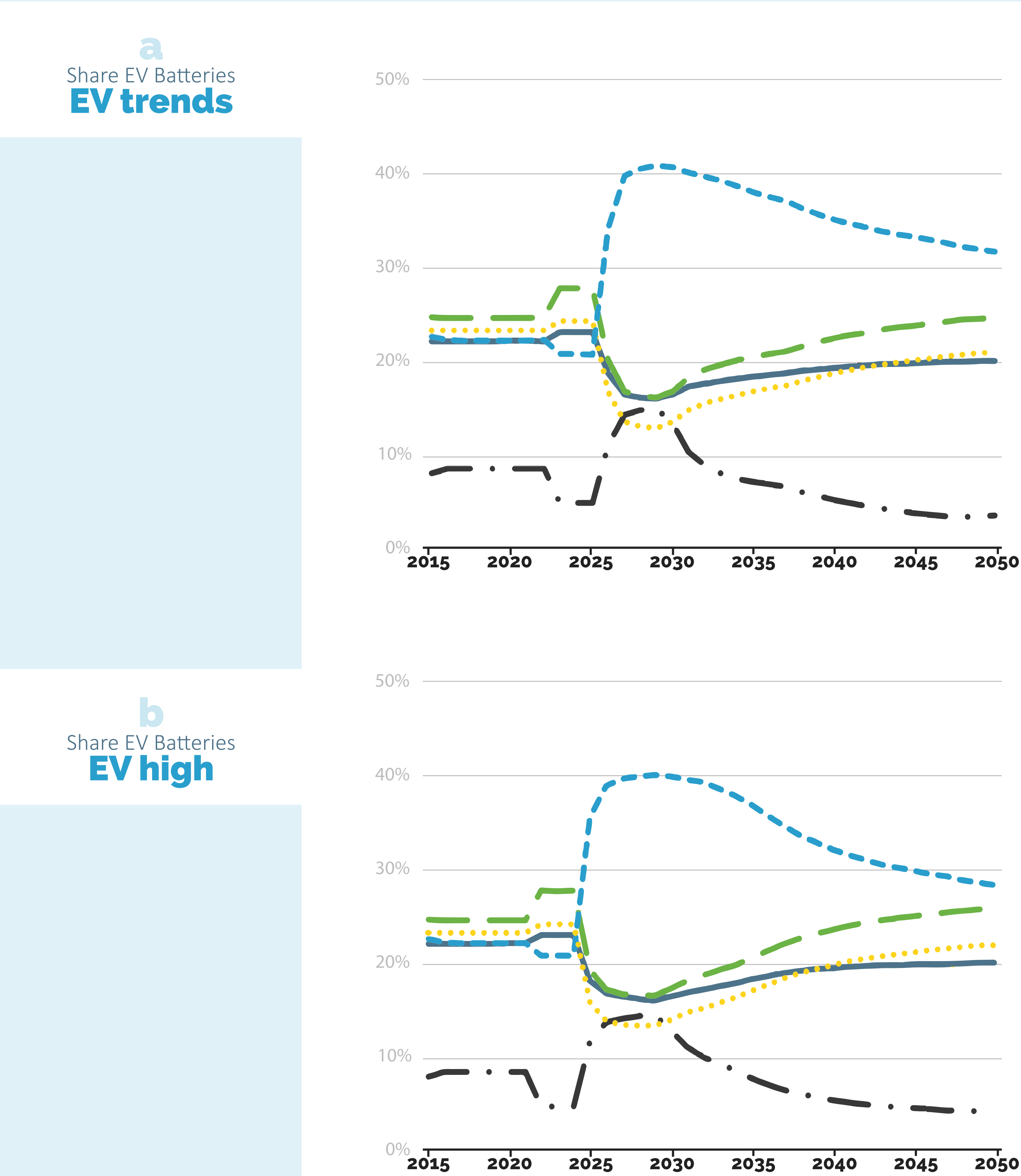
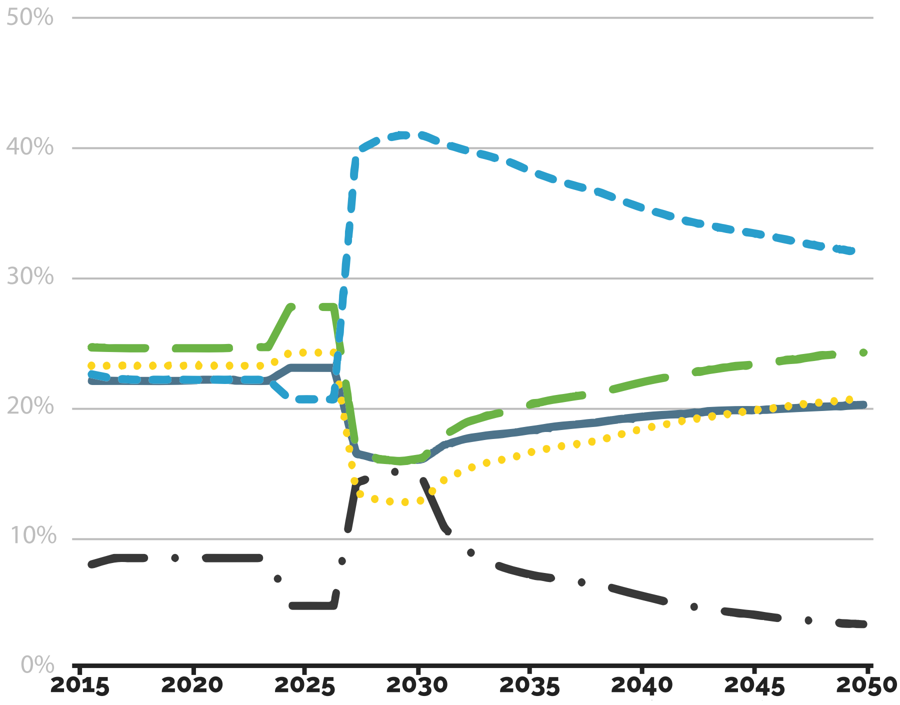


Fig 5: Market share of EV batteries over time by scenario

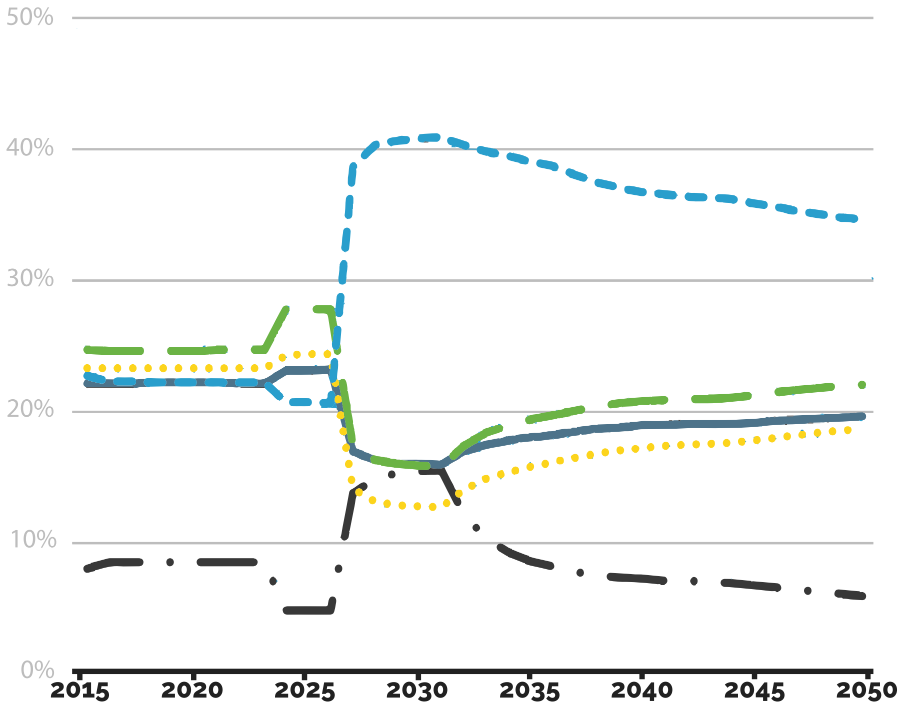
Source: *Energy Environ. Sci., 2022,15, 4872-4910*



c
Share EV Batteries
E-bike



d
Share EV Batteries
Degrowth



Policy Recommendations

The coming years will be crucial for steering governments at national and supranational level onto truly sustainable policy pathways. As clearly shown by the research presented in this policy brief, pursuing a full electrification of our current transportation system would bring insurmountable challenges and limitations. Only by changing our cultural approach to mobility will we bring a low-carbon future into reach. As a starting point, we propose the following policy recommendations.

Truly sustainable mobility

The energy section of this policy brief has already pointed out the energy limits of trying to electrify the whole fleet of ICEVs currently circulating on our roads. It is clear that efforts to electrify the whole sector with no change in mobility patterns is not a feasible option and will not allow the EU to sustainably decarbonise by 2050. The following interventions will be needed:

1. Promote policies that make it more attractive and easier for citizens to shift from private modes of transport to cheaper and cleaner mobility alternatives that are less energy and travel intensive. This requires actively supporting the development of transport networks (i.e., EU-wide connections as well as local ones). Travelling by private vehicles must be discouraged by promoting widespread and accessible, fair, safe and affordable public alternatives. As seen, from their higher ESOI levels, these alternatives are proven to be less energy- and material-intensive and a more feasible decarbonisation pathway.

2. Apply a sufficiency perspective on mobility and avoid the need for a 1-for-1 swap with electric cars by reconsidering urban spaces, revolving around incentivising active mobility (e.g., walking and cycling) and short-distance travels through intelligent spatial planning that promotes strategic proximity to key services. This could be achieved, for example, through the generation of proximity cities where all services and needs are available and accessible within a radius of a 15-minute walk, keeping in mind the needs of people with reduced mobility.

3. Implement strong regulation over unsustainable modes of transport. Some examples would be introducing taxes for frequent flyers, increasing VAT for flights,[39] banning short-haul flights and heavy vehicles (i.e., SUV) and expanding or strengthening zero emission zones.

4. Promote the electrification of fleets first and foremost: shared cars and taxi for instance have a much higher utilisation ratio than the average private cars hence can deliver a much higher amount of climate and environmental benefit per Kg of material used.

[39] *négaWatt Association. (June 2023). Climate neutrality, Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables. Clever Network.* https://clever-energy-scenario.eu/wp-content/uploads/2023/06/clever_final_report-exec_summary.pdf

Environmentally aware transition

As shown by our research, current EV trends face some limits in terms of material availability, but more importantly their material need represents a danger to the environment. As EVs are today being held as the flagship for a decarbonisation strategy, policymakers currently fail to recognize the wider and more comprehensive environmental impact that EVs might have, if left to develop at their current rate. The following policies should be enacted to decarbonise the transportation sector in a sustainable manner:

1. **Promoting a technological shift to smaller and less mineral-intensive batteries.** This should be incentivised through Research & Development funding in battery technology and the introduction of regulatory incentives (e.g., tax credits, subsidies) for manufacturers (consumers) that produce (purchase) EVs equipped with more sustainable batteries.

2. **Only 'indispensable extraction' should be pursued,** by setting thresholds for sustainable extraction, that align with the principles of environmental preservation. Environmental Impact Assessments should be mandatory before granting mining permits and must consider factors like biodiversity loss, water resources, GHG emissions etc. This must be parallel to policies that aim to reduce the need for new mining in all economic sectors altogether.

3. **Guarantee that the rights and interests of local communities and indigenous people are preserved.** The "Right to Say No" principle must be safeguarded and mechanisms that ensure that local communities are involved in the decision-making process of new extractive projects must be put in place.[40] Local and environmental needs must be prioritised over those of

4. **Foster international cooperation and agreements on responsible sourcing and extraction of critical raw materials.** Specifically, a global governance mechanism should be put in place during the green transition to regulate the extraction, processing, and waste management of raw materials. This would allow for a common global framework for sustainable mining to be established and ensure accountability for socio-ecological crimes.

[40] *Voskoboynik, Daniel Macmillen; Farrugia, JD. (2022). The nickel nexus: mapping the frontiers of carbon neutrality. JHU-UPF Public Policy Center (UPF-BSM) Serial Reports 1/2022. https://repositori.upf.edu/handle/10230/54138*