RSC
Sustainability

PAPER

View Article Online
View Journal | View Issue

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Check for updates

Cite this: *RSC Sustainability*, 2024, **2**, 2275

Future material demand and greenhouse gas emissions implications for electrification of the UK light-duty vehicle fleet†

Ben Davies, [*a] Jorge A. Llamas-Orozco,[a] Fanran Meng, [*b] I. Daniel Posen, [c] Heather L. MacLean,[c] Amir F. N. Abdul-Manan [d] and Jon McKechnie [a]

The UK zero-emissions vehicle (ZEV) mandate aims for battery electric vehicles (BEVs) to account for 100% of new sales by 2035. This study presents a fleet-scale life cycle assessment model of UK light duty vehicles through 2050, integrating a dynamic material flow analysis to evaluate the implications on critical battery materials. Rapid uptake of BEVs is projected to grow demand for primary materials within 15 years, particularly for lithium, nickel, and cobalt, exceeding current UK consumption by at least five-fold. In the longer-term, the successful creation of a closed-loop battery recycling ecosystem has the potential to mitigate further increases in demand for primary critical materials. With the adoption of efficient closed-loop, domestic recycling practice, the EU's regulations for battery recycled content requirements could be met for nickel and lithium, though cobalt remains a challenge as the recycled content targets could only be met two to three years later. The ZEV mandate is projected to be effective in reducing overall life cycle GHG emissions by 57% in 2050, relative to 2021. Even with an ambitious target like the UK's 2035 ZEV mandate, internal combustion engine vehicles will continue to operate on the road for years to come given that the fleet average is a 15 years vehicle lifetime. Thus, it is prudent to also consider low-carbon fuels as a complementary strategy to deliver the UK's net-zero target.

Received 5th March 2024
Accepted 11th June 2024

DOI: 10.1039/d4su00112e

rsc.li/rscsus

Sustainability spotlight

The UK government is pursuing an aggressive zero-emissions vehicle (ZEV) mandate, aiming for 100% of new passenger vehicle sales to be battery electric from 2035. Whilst the mandate could result in more than 50% reduction in overall life cycle GHG emissions, supplying the necessary critical battery materials is a potential challenge, with demand for nickel, cobalt, and lithium estimated to exceed current UK consumption by at least five-fold. In the context of the UN Sustainable Development Goals (SDG) for clean energy (SDG 7), responsible consumption and production (SDG 12), and climate action (SDG 13), we draw insights on the implications of several different electrification trajectories for the UK's light-duty vehicle sector, including the creation of a more circular battery ecosystem, a switch to a less material-intensive battery technology, a delay in the delivery of the ZEV mandate, and a more conservative uptake of renewables in the power sector.

1. Introduction

The transport sector in the UK is set to follow a zero-emissions vehicle (ZEV) mandate, requiring 100% of new light duty vehicle (LDV) sales to emit zero tailpipe emissions from 2035.[1] At 106 Mt CO_2 eq., the transport sector contributed 26% to the UK's national greenhouse gas (GHG) emissions in 2021, with the operation of LDVs in turn responsible for 57 Mt CO_2 eq.[2] Battery electric vehicles (BEVs) have emerged as a key technological solution[3] that have the potential to contribute significantly toward the UK's national carbon budgets and overall Net Zero 2050 emissions target.[4] BEVs are expected to gain widespread adoption under the ZEV mandate. A BEV has zero tailpipe emission and, when paired with low-carbon electricity generation, could offer large overall GHG reductions compared to conventional combustion-based vehicles.

From a life cycle assessment (LCA) perspective, use-phase emissions are not the only consideration in a vehicle's life cycle; materials production, manufacturing, and end-of-life management are important contributors to the overall impact of vehicle technologies.[5] Therefore, an LCA study can be useful for informing discussion on the overall life cycle impacts of an

---

[a] *Low Carbon Energy and Resource Technologies, University of Nottingham, Nottingham, UK. E-mail: Ben.Davies@nottingham.ac.uk; Tel: +44(0) 115 951 4002*

[b] *Department of Chemical & Biological Engineering, University of Sheffield, Sheffield, UK. E-mail: F.Meng@sheffield.ac.uk; Tel: +44(0) 114 222 7510*

[c] *Department of Civil & Mineral Engineering, University of Toronto, Toronto, Ontario, Canada*

[d] *Strategic Transport Analysis Team, Transport Technologies R&D, Research & Development Center (R&D), Saudi Aramco, Dhahran, Saudi Arabia*

† Electronic supplementary information (ESI) available. See DOI: **https://doi.org/10.1039/d4su00112e**

© 2024 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

ZEV mandate; not just on the GHG reduction potentials, but also the resulting material implications of an aggressive electrification plan. Specifically, the widespread adoption of BEVs will raise the demand for traction batteries and the constituent critical metals used in the production of battery cathodes.

In 2022, there were 2.3 million combined hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and fully electric BEV light duty vehicles in the UK fleet, with 685 000 new electric vehicles registered that year.[6] This represents a 21% year-on-year growth in sales, with electrified powertrains accounting for 42% of the 2022 new vehicle sales market; comprising 20% HEV, 6% PHEV, and 16% BEV. With the ambitious policy targeting 100% zero-tailpipe emission LDV sales from 2035, annual new traction battery demand in the UK is projected to increase from 100 kt in 2020 to 900 kt in 2035.[7] The policy targets and projected growth in the UK BEV market are indicative of similar commitments by policymakers around the world. More than 20 countries have announced electrification targets – from nations across Europe, East Asia, and Canada – projecting global electric vehicle sales to increase from 3 million in 2020 to 37 million vehicles in 2030, with the equivalent order of magnitude growth in battery demand.[8] The challenge of delivering a rapid growth in electric vehicle sales simultaneously across multiple geographical regions comes with the need to better understand the demand on critical material supply and associated GHG impacts. This is particularly relevant for a country like the UK where there is currently limited domestic battery production capacity, which may hinder access to key materials and technology to achieve low-carbon targets.[9]

Lithium-ion batteries (LIBs) are currently the technology of choice for electric vehicle powertrains. LIBs can be further categorised based on the chemistry of the constituent cathode; leading technologies in automotive applications include lithium nickel cobalt aluminium oxide (NCA), lithium nickel manganese cobalt oxide (NMC), and lithium iron phosphate (LFP).[10] The different chemistries offer varying performance characteristics that may be selected for cost, energy density, safety and reliability, or materials composition. The British Geological Society (BGS) and UK Critical Minerals Intelligence Centre (CMIC) have advised on a number of minerals with high criticality of supply, in which those relevant to battery manufacturing include lithium (Li), nickel (Ni), cobalt (Co), manganese (Mn), and graphite (Gr).[9] These minerals are highlighted given projected future growth in demand, anticipated limitations in geographic availability and accessibility, and concerns over reliability of supply.

There is a growing body of work that explores the availability and flows of these critical battery materials for regions including the EU,[11] China,[12] and, in our previous work, the US.[13] There is significant uncertainty in the future global requirement for critical minerals for batteries; overall, studies show that global annual material demands for Li, Co, and Ni are expected to far exceed production capacities, though worldwide reserves may be sufficient to meet overall requirements through 2050.[14] To address this challenge, global policymakers are proposing interventions to build resilience, mitigate risks, and promote efficient use. In parallel to the UK critical minerals strategy,[9] the EU has adopted regulation to set mandatory minimum levels of recycled content in new battery manufacture.[15] For the prospective UK battery manufacturing industry to access the European market it will need to align with the EU's recycled content regulation.[16] The targets that are initially to be met by 2031 are for 6% lithium, 6% nickel, and 16% cobalt to be derived from secondary sources, which will be raised, by 2036, to 12% lithium, 15% nickel, and 26% cobalt.

Life cycle assessment provides a methodology to study the impacts of a given product, process, or service; single LDVs are assessed for the environmental and resource implications that go into raw material processing, manufacture, logistics, fuel use in operation, and final disassembly and end-of-life treatments.[17] LCA studies of single vehicles or products are traditionally static with respect to time, with constant parameters, and assuming the "life" (production, use, end-of-life) occurs at one point in time.[18] This approach benchmarks vehicle design and comparable competing technologies, however, the simplifying assumptions mean the results may only be valid for a short window of time and do not evaluate the outcomes of policy across the national LDV fleet.[19,20] Extending this method to incorporate temporal dynamics allows for a more representative analysis that includes emerging technologies and the evolution of life cycle processes.[21] This is particularly relevant in the use-phase, where fleet operations are expected to decarbonise in the future.[22–24] Vehicle battery technologies are undergoing similarly rigorous life cycle assessment.[25,26] Studies have reported the GHG impacts of new battery production[27,28] including our previous study, Llamas-Orozco *et al.*,[29] which completes a state-of-the-art assessment of emissions factors in the global supply chains for LIB materials.

Extending the LCA method to assess many vehicles, their concurrent lifetimes, and the future development of technologies, produces a fleet-scale LCA model uniquely suited to analyse the transport sector.[30] This approach evaluates the impacts of many individual vehicles, and accommodates the evolution of technologies over time, interactions with the energy sector, and the potential outcomes of planned transport sector policies. Recent studies have assessed LDV electrification in fleet-scale LCA methods for North America,[5,31,32] Europe,[33–35] and Asia.[36,37] Previous fleet-level LCA and materials flow analysis (MFA) studies for the UK market[7,38] consider a limited set of vehicle technologies (ICEV and BEV, excluding PHEV which constitute a significant share of the UK transport strategy[39]), do not consider the increasing use of LFP batteries as intended by key manufacturers,[40] and have not accounted for the current UK ZEV mandate[41] and EU battery recycling regulation.[15]

Thus, there is scope to update a UK-specific fleet LCA investigation, including more representative vehicle and battery technology combinations, and in the context of current policy. This analysis will align with the UN sustainable development goals (SDG)[42] for the use of renewable energy (SDG 7), responsible consumption of mineral resources (SDG 12), and transport policies that integrate climate action (SDG 13).

This study contributes a fleet-scale life cycle assessment model to specifically examine the outcomes of the UK's

© 2024 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

aggressive electrification target. Using the ZEV mandate as input, we model the evolution of annual and cumulative GHG emissions for the UK's LDV fleet and the dynamics of critical material flows, which can then be interrogated against the intended targets under the UK's net-zero policy and EU's recycled battery content regulation.

2. Methods

The UK Fleet Life Cycle Assessment and Material Flow Estimation (UK-FLAME) model – a fleet-scale LCA model of UK light-duty vehicles – is developed to quantify the impacts of the ZEV mandate on life cycle GHG emissions and critical battery material demands. The simulation period is defined from 2020 to 2050, encapsulating the delivery of the ZEV mandate on the path towards Net Zero 2050. Annual and cumulative life cycle GHG emissions reveal the contributions both from transport sector operations, and the supporting manufacturing and energy industries. Critical material flows are quantified to estimate future demand and to identify the potential contribution of secondary supply (from end-of-life vehicles), determining whether proposed battery material recycled content targets in 2031 and 2036 could be met with closed-loop recycling in the UK transport sector.

2.1 UK-FLAME model

The UK-FLAME model is an adaptation of the original FLAME model, which was created to assess the impacts of vehicle chassis lightweighting strategies within the US LDV fleet.[43] The UK-FLAME model has adapted the methodology for UK-specific fleet dynamics and policy scenarios, as well as expanded the scope of the materials and manufacturing demands for lithium-ion battery technologies. The modular structure of the UK-FLAME model, shown in Fig. 1, allows for scenario-based modelling to investigate possible outcomes of the UK ZEV mandate. Milovanoff *et al.*[43] gives detail to the US-FLAME modelling approach; the following introduces the adaptations for the UK-specific model.

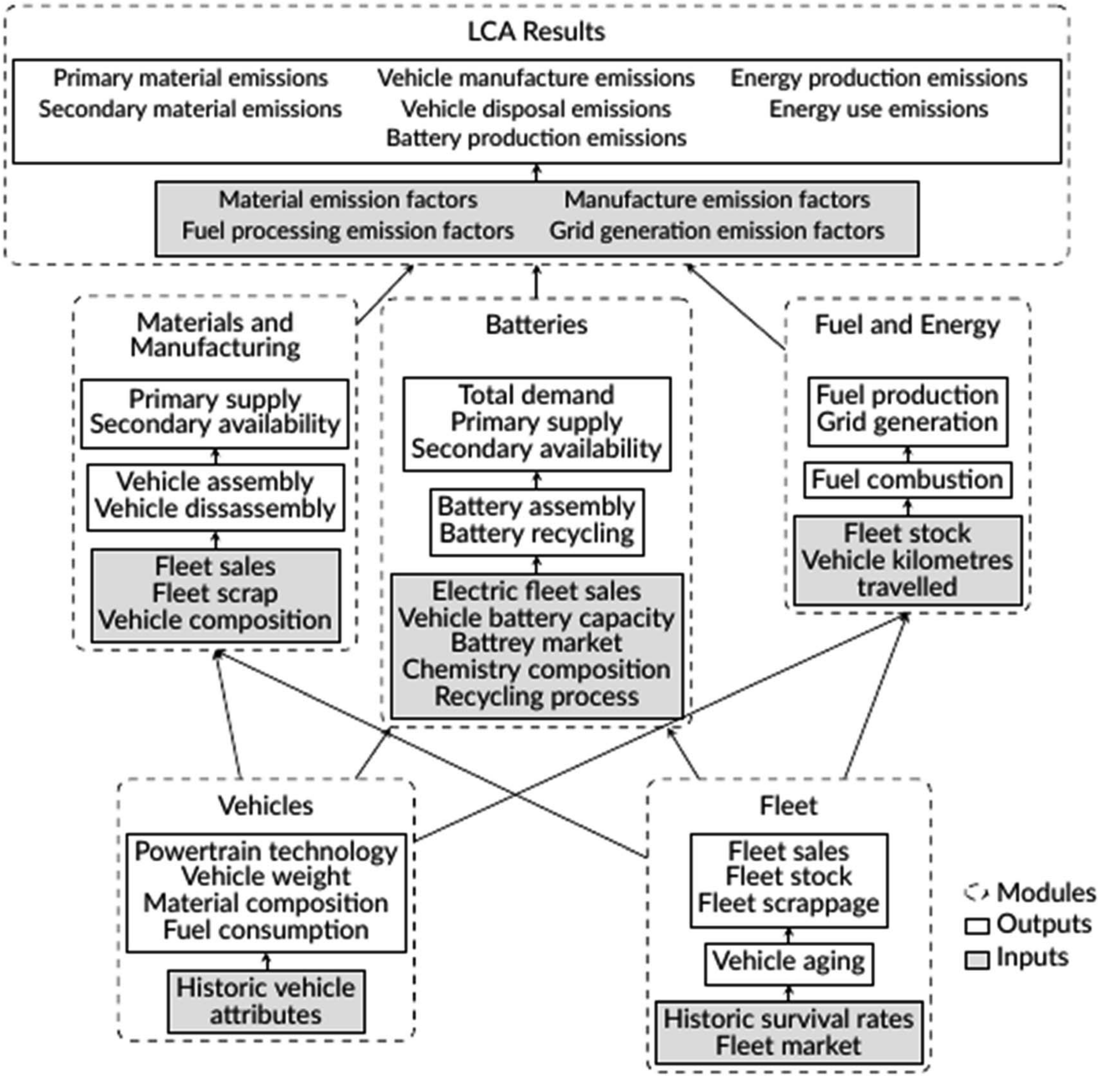

Fig. 1 Structure of the UK-FLAME model. The model comprises six modules (vehicle, fleet, materials and manufacturing, batteries, fuel and energy, and LCA results) and simulates the UK LDV-fleet from 2020 to 2050.

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

2.1.1 Vehicles module. Five vehicle categories are defined with respect to their powertrain technologies: petrol-ICEV (P-ICEV), diesel-ICEV (D-ICEV), hybrid electric (HEV), plug-in hybrid electric (PHEV), and battery electric (BEV). The UK fleet is characterised by a high proportion of diesel-fuelled vehicles, like that of continental Europe and in contrast to North American and Asian markets which are dominated by petrol vehicles. Vehicles are defined for fleet-category average kerb weight (kg),[44] material compositions (% share),[45] and fuel economy (l or kW h per 100 km).[46] Vehicle characteristics can be found in the ESI,† Tables S1–S4. The kerb weight and materials profile exclude the traction battery in electrified powertrains; this mass is addressed in the specific battery module.

2.1.2 Fleet module. The historic composition of the UK national LDV fleet is recorded by Driver and Vehicle Licensing Agency (DVLA) vehicle statistics to the end of 2022 at the time of writing.[6] From this data, the authors have extracted UK-specific statistical distributions for the survival rates of vehicles on the road as a function of age, summarised in the ESI,† Fig. S1. The fleet simulation retires an appropriate proportion of vehicles in each year of simulation, allowing a turn-over to new "sales" to satisfy transport demand.

2.1.3 Materials and manufacturing module. The start-of- and end-of-life activities – manufacturing and end-of-life treatment, respectively – are assigned relative to the lifetime of the vehicle. A single manufacturing process is assigned per vehicle at the year of sale, and a separate disassembly process in the year of scrappage. Vehicle materials – steel, aluminium, copper, plastics, and rubber, but excluding battery materials – have well-established supply chains, including the use of secondary materials in modern production processes. As such, open-loop recycling is assumed, and end-of-life materials are processed to scrap and returned to the supply chain.[47] The detail of battery materials and manufacturing processes is presented in Section 2.1.4.

2.1.4 Batteries module. The materials flow model for the traction battery module is depicted in Fig. 2. This process follows closed-loop end-of-life recycling and thus estimates the supply of secondary battery materials. In manufacturing, materials are first sourced from this recycled availability. Where demand exceeds that secondary supply, the deficit is complemented with primary raw materials. The expected progression is for batteries to be produced with a majority of primary materials in the near future, until sufficient time has passed for a considerable number of electric vehicles to be retired from the fleet that secondary materials become available later in the simulation period.

A global and dynamic perspective on the production of battery materials is employed, as published previously.[29] Emission factors are quantified based on existing battery supply chains, with location-specific primary materials production and projections for future process decarbonisation. The present study focuses on the material flow analysis for five critical battery materials: nickel, cobalt, lithium, manganese, and graphite. Battery materials are summarised in the ESI,† Table S5. Recycling process recovery rates and emissions factors are discussed further in section 2.2.2.

2.1.5 Fuels and energy module. The fuel and energy module calculates the total demand from vehicle-technology fuel or electricity consumption and fleet-average annual usage, expressed in vehicle kilometres travelled (VKT). All vehicles operating within the LDV fleet are assumed to be operated similarly at 14 000 km per year, based on Department for Transport Road Traffic Statistics.[48] Outputs from this calculation are the volume of fuel (l) or amount of electric energy (kW h) required to enable fleet transport operations each year of simulation.

Fuel and energy production is assigned in the year of demand. Conventional petrol and diesel fuels production are mature processes with GHG emission factors that are assumed to be static throughout the simulation. This is a simplifying assumption due to lack to information on how these processes may evolve. Grid electricity is defined as a national mix of technologies, including generation from fossil fuel, nuclear, and renewable wind, solar, and hydro sources.[49] This provides the dynamic analysis for BEVs and PHEVs benefiting from renewable and low-carbon electricity generation which is deployed in parallel to the delivery of the ZEV mandate.

2.1.6 LCA results module. The final module in the UK-FLAME model estimates the overall life cycle greenhouse gas emission results, expressed in kg CO_2 eq. This calculation collates the materials, energy, and process demands provided

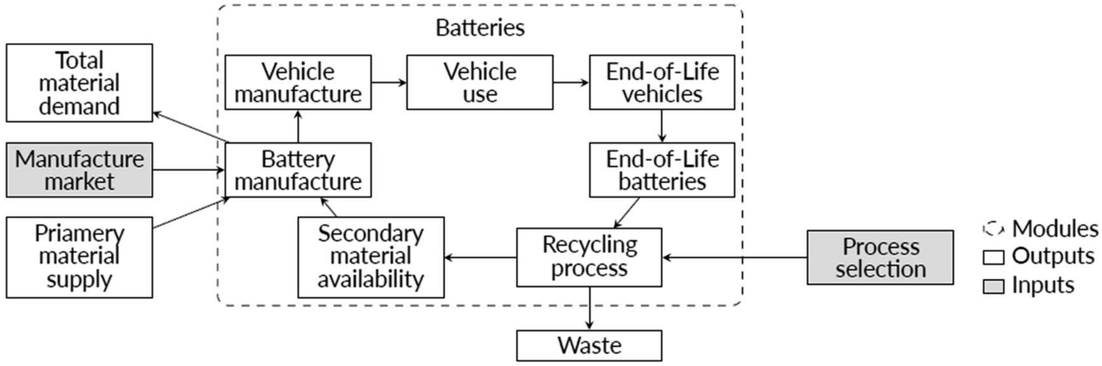

Fig. 2 Detail of the Batteries module in the UK-FLAME model, featuring closed-loop, end-of-life recycling, and simulation inputs for battery markets and recycling processes.

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

by each module based on the projected LDV fleet operations in every year of the simulation. Emission factors follow the 100 years Global Warning Potentials of the IPCC 2013 fifth assessment report,[50] with materials and process emission factors drawn from the ecoInvent database,[51] electricity grid mix from National Grid,[49] and battery production emission factors defined in previous study.[29]

The GHG results calculated in the LCA module study have implications across national and international industries: in metallurgy, manufacturing, energy generation, and, of course, transportation. GHG emission results are contextualised against the ambitions of the UK's national carbon budgets. The carbon budgets have been legislated with increasing ambition, towards a pledge of net zero by 2050. The 6th Carbon Budget is defined for the period 2033 to 2037, with the fleet electrification policies featuring prominently.[52] There is no definitive allocation for different sectoral emissions, however, historically, the totality of the transport sector contributes approximately a quarter to the national profile. Of transport operations, LDV fleet use phase emissions in turn contribute 50–60%, equalling the 57 Mt CO_2 eq. p.a. reported in 2021. These tailpipe emissions are required to abate to approximately 0.9 Mt CO_2 eq. in 2050 to deliver the net zero pledge.[39] This residual value accounts for combustion-based vehicles that have not yet been retired from the fleet, with the expectation that other sectors of the economy will enable carbon-offsetting to reach economy-wide net zero. Fig. 3 shows the legislated national carbon budgets and recorded GHG emissions, projected forward to the 9th and Final Carbon Budget, 0 kg CO_2 eq. for 2048 to 2050, and beyond.

2.2 Scenario definitions

Each of the modules described present several opportunities for variable inputs which describe different policy or industrial scenarios. The following introduces these inputs and the combinations which may be applied to the UK LDV fleet. Where a module is not discussed the inputs are not varied beyond the reference case definitions; vehicle parameters, and materials and manufacturing emission factors are fixed throughout the simulation period, such that analysis focuses on the relative impacts of fleet electrification and the demand for vehicle traction batteries.

2.2.1 Fleet module scenarios.

The ZEV mandate prescribes targets for the annual sales of new zero-emission vehicles.[41] This policy is given in Table 1, under the ZEV-2035 scenario. Historical values in Table 1 are based on the reported data from the DVLA vehicle statistics up to the end of 2022 at the time of writing.[6] These statistics may slightly overestimate the ZEV sales in recent years,[53] however the DVLA data is retained for consistency. A slower than modelled initial BEV uptake would result in a slightly faster growth in critical material demand approaching the legislated sales targets but will not materially influence qualitative results if the ZEV mandate is met.

The UK government has however demonstrated an appetite to change the policy delivery,[54] moving the sales ban on new ICEVs from 2030 to 2035; thus, the ZEV-2040 scenario examines the potential for five years of further delay to the ZEV mandate. This delayed scenario is defined as a more linear transition

Table 1 Annual targets for ZEV sales shares in the UK LDV fleet from 2020 to 2050, adopted from ref. 41. ZEV-2035 represents the existing legislation, ZEV-2040 is adapted for a delayed scenario

Year	ZEV-2035	ZEV-2040	Year	ZEV-2035	ZEV-2040
2020	6.5%	6.5%	2036	100%	84%
2021	11%	11%	2037	100%	88%
2022	16%	16%	2038	100%	92%
2023	20%	20%	2039	100%	96%
2024	22%	22%	2040	100%	100%
2025	28%	28%	2041	100%	100%
2026	33%	33%	2042	100%	100%
2027	38%	38%	2043	100%	100%
2028	52%	43%	2044	100%	100%
2029	66%	49%	2045	100%	100%
2030	80%	54%	2046	100%	100%
2031	84%	59%	2047	100%	100%
2032	88%	64%	2048	100%	100%
2033	92%	70%	2049	100%	100%
2034	96%	75%	2050	100%	100%
2035	100%	80%			

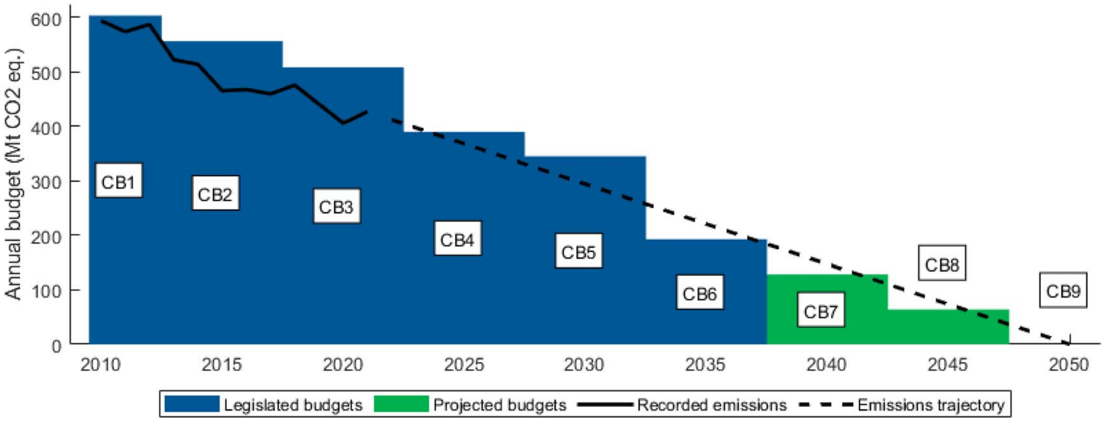

Fig. 3 Progression of the UK carbon budgets and national GHG emissions. Carbon budgets (CB) have been legislated until 2037, with the future budgets estimated through to the commitment of net zero in 2050.

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

from 2024 to 2040. BEVs are considered the ZEV solution for the UK light-duty vehicle market.[39] Other technologies, such as hydrogen fuel cells, are at an earlier stage of development and deployment, and their future success in the fleet is uncertain.[55]

Alongside the deployment of BEVs in the market, PHEVs are seen as an important lower-emission technology in the transition to a 100% ZEV fleet.[55] The historic sales share for PHEVs has been growing alongside BEVs, reaching 6% of the market in 2022.[6] The UK Committee on Climate Change suggest sales of PHEVs could peak at 25% in the 2030s, before declining with all other non-ZEV technologies.[39] The sales for ICEVs and HEVs are decreased proportionally from the current share to complete the market.

2.2.2 Battery module scenarios. Two markets of battery manufacture have been adopted from work by Xu *et al.*[10] The NCX market focuses on lithium-ion batteries containing nickel and cobalt in the cathode chemistries; nickel cobalt aluminium (NCA) and nickel manganese cobalt (NMC). These battery chemistries exhibit high energy density and are the presumed technology of choice for UK electric vehicles. There is an ongoing trend in battery manufacturers to use cobalt more efficiently, primarily for cost concerns.[56] This is reflected in the planned progression from chemistries with higher cobalt content (NMC111, 1 : 1 : 1 ratio of nickel, manganese, cobalt) to reduced content (NMC955, 9 : 0.5 : 0.5 ratio of nickel, manganese, cobalt). The alternate battery market is for LFP batteries, with the sector favouring lithium iron phosphate chemistry. LFP has the principal drawback of exhibiting lower energy density than nickel cobalt chemistries, leading to larger and heavier battery packs for the same performance. However, LFP chemistries are popular in some regional markets and are the battery of choice for BEV manufacturer Tesla.[40] Detail of the battery markets can be found in the ESI,† Fig. S3.

For the selection of the closed-loop recycling process, two existing and commercialised technologies have been identified: the pyrometallurgical process[57] and the hydrometallurgical process.[58] Pyrometallurgy is emissions intensive and only able to recover nickel and cobalt from the end-of-life battery, whilst hydrometallurgy is more complete, also recovering lithium, manganese, and graphite.[29,59,60,61]

Table 2 summarises the emissions factors associated with the primary and secondary processing of the critical materials to the metal salts that are used in battery manufacture. Mass allocation is followed to estimate the emission intensity as, in the context of this closed-loop recycling process, all economic value remains in the transportation system, displacing the need for primary material production.

2.2.3 Fuel and energy module scenarios. Two scenarios are adopted to investigate future decarbonisation progression. UK National Grid presents pathways to achieve ambitious energy sector decarbonisation with the outlook falling from 230 g CO_2 eq. per kW h in 2020 to less than 10 g CO_2 eq. per kW h by 2050.[49] This is planned to be achieved through a majority of capacity being provided by wind and solar renewable generation, supported by nuclear power, with the decommissioning of extant natural gas generation. Representing the UK's planned development, this defines the base case for the fuel and energy module.

The second electricity scenario represents more conservative grid decarbonisation, in line with the rate projected as a European average by the IEA Global Energy Outlook.[3] In comparison, this projection would expect a higher share of natural gas generation maintained into the future. By 2050, the conservative case predicts generation at 120 g CO_2 eq. per kW h. This scenario will test the outcomes of the ZEV mandate for sensitivity to a higher-carbon intensity electricity source. Detail of the grid decarbonisation projections can be found in the ESI,† Fig. S4.

2.2.4 Scenario combinations. Table 3 summarises the module combinations that give model scenarios for application across the 2020 to 2050 simulation period. The core scenario is the reference case, following the electrification policy as stated, with nickel–cobalt batteries continuing to be the battery of choice for manufacturers, pyrometallurgical recycling selected as the most economic process, and the National Grid projected decarbonisation being achieved. The alternate scenarios consider delaying the electrification policy's completion; hydrometallurgical recycling used in preference for the ability

Table 2 Emissions factors and recycling recovery rates for key critical battery materials, adapted from ref. 60

Material	Primary production emissions factor, kg CO_2 eq./kg	Recycling process	Recycling process allocated[a] emissions factor, kg CO_2 eq./kg	Recovery rate
Nickel sulphate	18.53	Pyro	9.78	98%
		Hydro	2.28	98%
Cobalt sulphate	7.33	Pyro	9.78	98%
		Hydro	2.28	98%
Lithium carbonate	13.08	Pyro	—	0%
		Hydro	2.28	90%
Lithium hydroxide	24.80	Pyro	—	0%
		Hydro	2.28	90%
Manganese sulphate	1.43	Pyro	—	0%
		Hydro	2.28	90%
Graphite	4.44	Pyro	—	0%
		Hydro	2.28	90%

[a] Allocation by mass recovered.

© 2024 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Table 3 Summary of the simulation model scenarios evaluated in this study

Scenario	Fleet market	Battery chemistry	Battery recycling	Grid mix
Core scenario	ZEV-2035	NCX	Pyro	Base
Delayed policies	ZEV-2040	NCX	Pyro	Base
Improved recycling	ZEV-2035	NCX	Hydro	Base
Reduced cobalt batteries	ZEV-2035	LFP	Hydro	Base
Delayed policies with reduced cobalt batteries	ZEV-2040	LFP	Hydro	Base
Conservative grid decarbonisation	ZEV-2035	NCX	Pyro	Conservative

to recover lithium; battery manufacturing preferring the LFP cathode chemistry – greatly reducing the demand for cobalt – and a sensitivity study on the influence of conservative progress in grid decarbonisation. With the LFP battery scenarios only hydrometallurgical recycling is considered; the high proportion of lithium in the battery construction will make pyrometallurgical recycling less economical and presuppose a more complete material recovery technique.[62]

3. Results

3.1 Effects of ZEV mandate on fleet electrification

The successful implementation of the ZEV mandate could drive significant uptake of BEVs in the UK LDV fleet by 2050. This is shown in Fig. 4 respectively for: (A) the ZEV-2035 scenario following the stated policy, and (B) the ZEV-2040 scenario with delayed electrification. In both scenarios, BEVs are projected to account for the majority of vehicles on the road by 2040. However, even if new sales of vehicles are completely replaced by BEVs in line with the ZEV mandate, there will still be over 15 million combustion-based vehicles – including ICEVs, HEVs, and PHEVs – on the road in 2035, which will continue to be driven for years before they are retired from the fleet. This reflects the historical rate of vehicle turnover in the UK fleet, with an average lifetime of 15 years. Combustion-based vehicles are still expected to comprise 1.9% and 5.3% of the total fleet in 2050 under the ZEV-2035 and ZEV-2040 scenarios, respectively. This corresponds to between 660 000 and 1.9 million combustion-based vehicles on the road in 2050. Therefore, decarbonising the ongoing use of existing ICEVs may also require a complementary strategy based on introducing lower-carbon liquid fuels into the UK transport system, or other mechanisms to offset or avoid the residual emissions.

3.2 Annual flows of primary and secondary critical battery materials

Fig. 5 depicts the annual net demand for primary critical battery materials – (a) nickel, (b) cobalt, (c) lithium, (d) manganese, and (e) graphite. Five materials scenarios are presented together and contrasted against the 2020 material consumption by UK industries, as reported by the British Geological Society[63] – note that at 52 kt, historic manganese consumption is beyond the scale of the graph.

For all five materials, primary demand is projected to increase significantly through 2035, corresponding to the expected growth in the sales of PHEVs and BEVs. Scenarios following the ZEV-2035 sales market, Table 1, show accelerated deployment after 2027. Peak demand is reached as the ZEV mandate is implemented fully – 2035 for the core, or 2040 for the delayed scenarios – and then most scenarios see decreasing demand through 2050 as secondary material becomes available when electric vehicles reach their end-of-life. However, for lithium, manganese, and graphite in the core scenario and delayed policies scenario demand reaches a plateau, as there is no secondary material available through closed-loop pyrometallurgical processing, and therefore modelled demand can only be met with primary materials.

The greatest demand for nickel, cobalt, and manganese is observed in the NCX battery markets; respectively peaking at 92, 20, and 15 kt in 2035 in the core scenario. For nickel and cobalt,

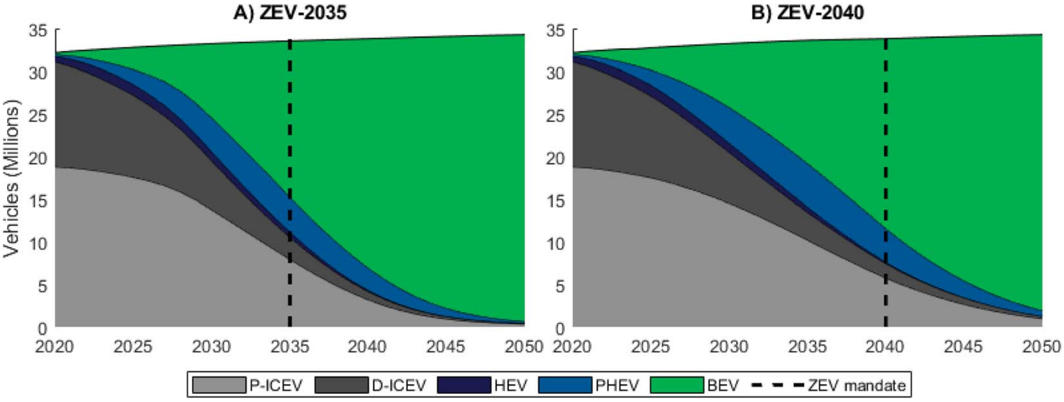

Fig. 4 Projection of the total UK LDV fleet, by vehicle powertrain technology, following the two scenarios of ZEV mandate implementation – (A) ZEV-2035, (B) ZEV-2040. The dashed lines indicate the date of the ZEV mandate being implemented.

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

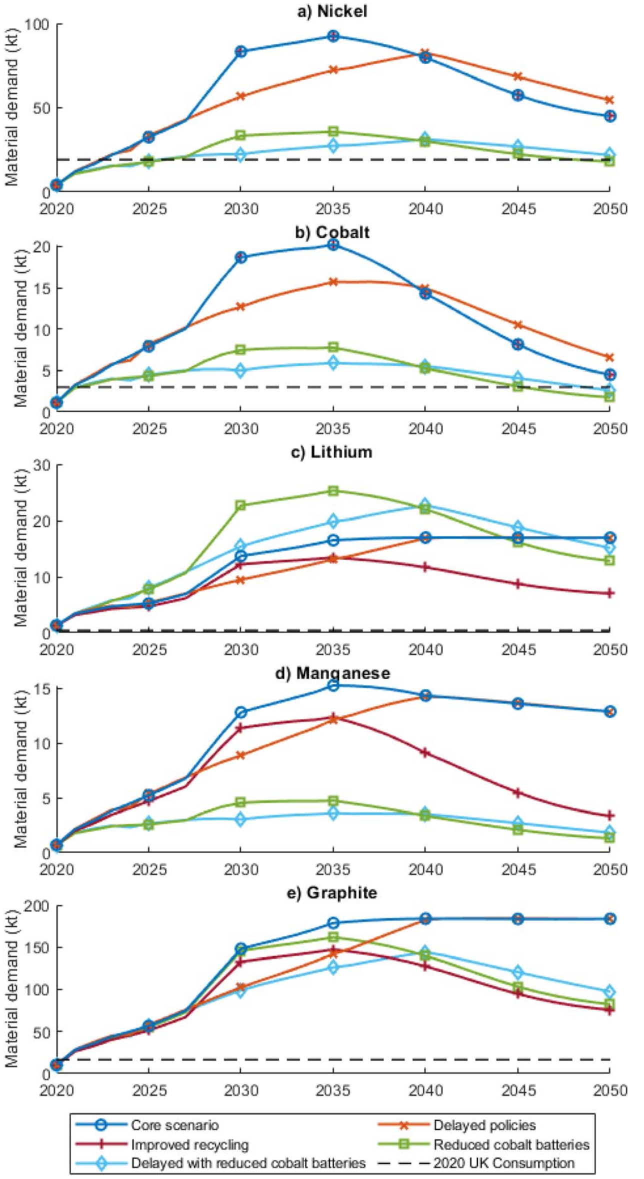

Fig. 5 Projections for annual primary critical battery materials in the UK, alongside 2020 UK consumption as reported by:[63] nickel 19 kt, cobalt 3 kt, lithium 400 t, manganese 52 kt (out of scale), graphite 17 kt.

these are significantly above the current consumption by UK industries; 4.8 times greater for nickel and 6.7 times for cobalt. However, switching to the LFP-dominant battery market can be effective in reducing the demand for primary nickel, cobalt, and manganese; peak demand is respectively 35, 7.7, and 4.7 kt in 2035 under the reduced cobalt batteries scenario.

Although an LFP-dominant battery chemistry could reduce demand for nickel, cobalt, and manganese, it raises the demand for lithium. The lower energy density of the LFP battery technology results in greater material demands to meet the same energy storage capacity for electrified vehicle powertrains. The reduced cobalt batteries scenario sees peak demand for primary lithium at 25 kt; this is a 61-times greater than the UK's current usage, with little domestic battery production. Graphite is an essential material for all battery chemistries. All scenarios see a peak demand between 140–180 kt, approximately 10 times greater than the 2020 UK demand.

Fig. 6 presents the proportion of secondary materials that are available for new LIB manufacture from the purely closed-loop vehicle recycling modelling. Fig. 6 also displays the target secondary material content shares for nickel, cobalt, and lithium, as laid out in the EU regulation.[15] Secondary content requirements for manganese and graphite are not currently mandated within the EU legislation.

All scenarios surpass the content targets for nickel; the closed-loop recycling process is predicted to be sufficient whether pyro- or hydrometallurgy is employed in the automotive sector. The targets are partially met for secondary cobalt

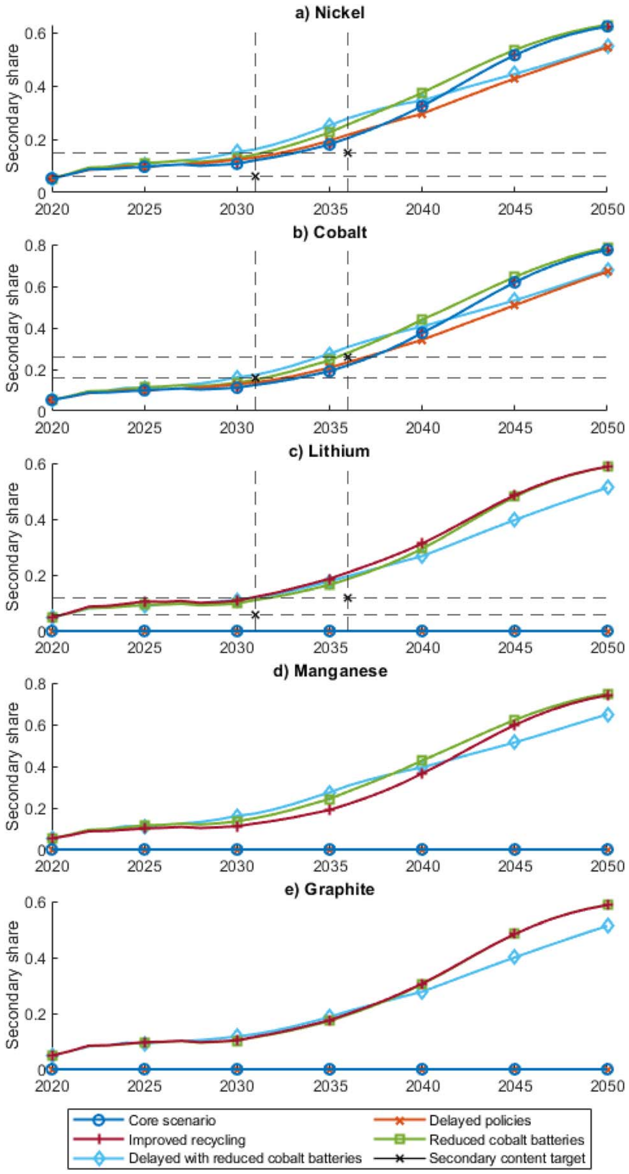

Fig. 6 Projection for the share of secondary critical battery materials that are used in new LIB manufacture, for five scenarios effecting materials demand. Nickel, cobalt, and lithium are presented with the 2031 and 2036 targets for recycled content from EU battery regulation.[15]

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

content. Under the NCX battery market – the core scenario, delayed policies scenario, and improved recycling scenario – the 16% target would be met in 2034, three years late, and the 26% target would be met in 2038, two years late. At most, 4% of cobalt demand would need to be obtained from non-BEV secondary sources to meet the targets. The lower overall demand in the reduced cobalt batteries scenario means that the only missed target is in 2031. The combination of delayed with reduced cobalt batteries is projected to meet all of the recycled content targets.

Closed-loop lithium recycling can also be effective for meeting the secondary content targets, assuming hydrometallurgy is followed. The inability to recycle lithium with pyrometallurgical recycling (as used in the core scenario and delayed policies scenario) means that no secondary lithium is available from end-of-life LDVs, and all recycled material would need to be sourced externally to the UK LDV fleet to satisfy the EU targets. Though no targets are in place for manganese and graphite content the wastage in pyrometallurgy is also seen, meaning all manufacturing would need to be satisfied through primary supply chains.

The availability of secondary materials for battery manufacture grows steadily through the simulation period. In the initial growth period of the BEV market, the majority of manufacturing demand will be met with primary materials, as noted in Fig. 5. In the closed-loop recycling process there is a necessary delay for BEV vehicles to age and retire from the fleet before their constituent materials may be recovered. It is noteworthy that, outside of the noted wastages in pyrometallurgy, all materials in all other scenarios could see new LIB manufacture achieved with greater than 50% of recycled content by 2050.

3.3 Annual and cumulative fleet-scale life cycle GHG emissions for UK LDV electrification

Deployment of 100% ZEV by 2035 achieves a total life cycle GHG emissions reduction of 57% by 2050 relative to the post-pandemic 2021 reference under the Core scenario, Fig. 7. The use-phase emissions – the portion directly targeted by the government ZEV mandate – are reduced by 98.5% relative to 2021, as almost all ICEVs have been removed from the LDV fleet by 2050. With decarbonised electricity generation supplying the electrified fleet, this leads to a reduction in fuel and electricity production emissions from 14 Mt CO_2 eq. in 2020 to 0.8 Mt CO_2 eq. in 2050.

The vehicle cycle, including raw materials production, manufacturing, and assembly for both the vehicle and traction battery, remains an important source of life cycle GHG emissions, which are projected to increase alongside the growing adoption of BEVs in the UK LDV fleet. By 2050, the vehicle cycle will contribute over 95% of the total fleet life cycle GHG emissions. Typically, battery-related activities can account for up to 50% of the total vehicle-cycle GHG emissions. Primary production of critical materials can contribute significantly to the overall battery manufacturing emissions, though the gradual decarbonisation of the supply chain and the growing use of secondary materials are expected to reduce the battery life cycle GHG emissions by 20% from its peak in 2035. However, consistent with the material flow analysis presented in the preceding section, there is an expected delay in realizing the GHG reduction from the use of secondary materials due to the time it takes for the BEVs to retire from the fleet.

The vehicle-specific materials and manufacturing contributions, excluding the battery, contribute a steady 22 Mt CO_2 eq. per year throughout the post-pandemic simulation period. BEVs are still LDVs with much of the same underlying construction before the powertrain is included, and the ongoing demand for transportation will necessitate new manufacturing as older vehicles are retired from the fleet. This study has focussed on the evolution of material supply and GHG emissions contributions of battery-specific materials; the impact factors for vehicle materials remain fixed. This is a simplification which allows for the impacts of the ZEV mandate to be better understood. In reality, there might be greater decarbonisation associated with many of the supporting industries involved in the UK LDV fleet ecosystem – steel and aluminium production, component manufacture, *etc.* – and the emissions from these industries are also likely to decrease through 2050.

Fig. 8 shows the cumulative GHG results across the simulation period. From 2020 to 2050, cumulative life cycle LDV fleet emissions in the Core scenario total 1.97 Gt CO_2 eq., of which 1.00 Gt CO_2 eq. is attributable to all vehicle-cycle contributions, 237 Mt CO_2 eq. to fuel production and electricity generation, and

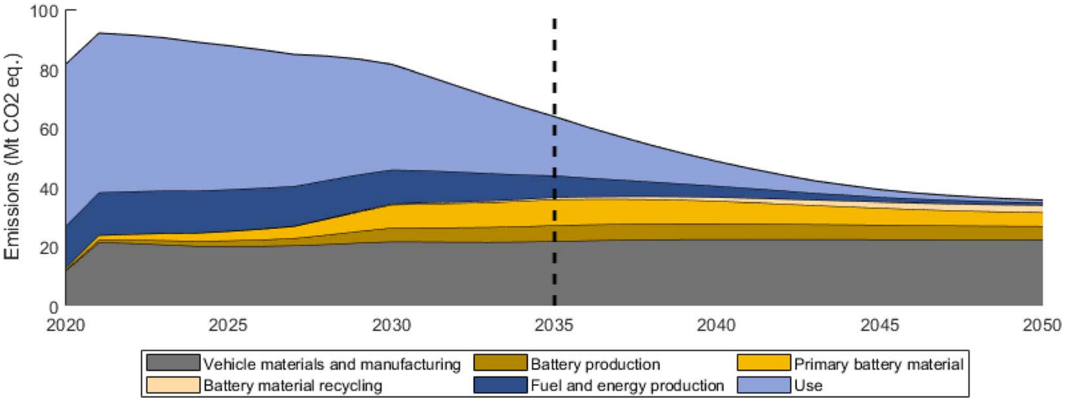

Fig. 7 Projection of annual UK LDV fleet GHG emissions from 2020 to 2050 under the core scenario, by simulation module contribution.

© 2024 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

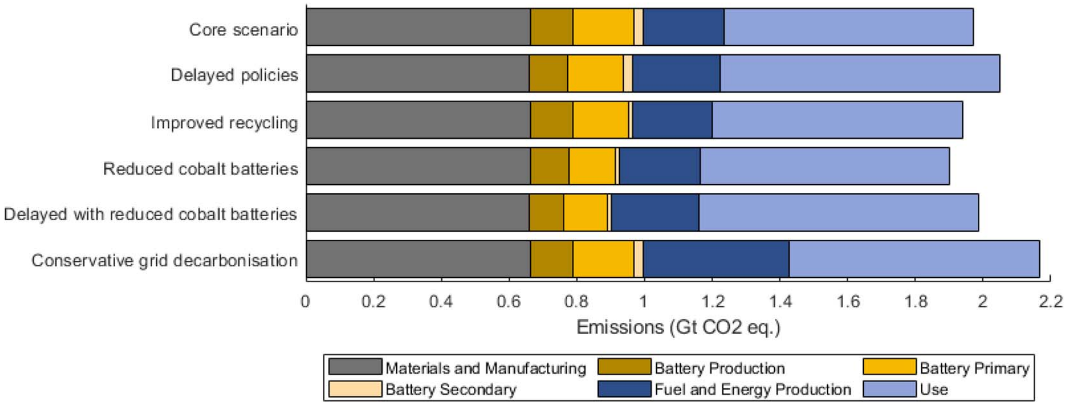

Fig. 8 Projection of cumulative UK LDV fleet GHG emissions from 2020 to 2050 for each scenario, by simulation module contribution.

738 Mt CO_2 eq. to the direct use-phase emissions. The cumulative emissions allowance for LDV use – estimated from the planned and future carbon budgeting, Fig. 3 – is 0.8–1 Gt CO_2 eq. for the same time period; the modelled result is in line with net zero 2050 targets. Importantly, this suggests that the challenges of LDV fleet electrification in the UK need to be addressed in a timely manner for the ZEV mandate to facilitate a proportionate decarbonisation in the transport sector, in-line with the UK's LDV carbon-budget to 2050. These results highlight the relative contribution of materials and manufacturing to the overall life cycle of electric vehicles, and though not investigated here, similar decarbonisation of the supporting industries would be necessary to achieve economy-wide net zero targets.

However, a delay in the implementation of the 100% ZEV mandate by 5 years to 2040 has a relatively modest 4% increase in cumulative GHG emissions in the simulation period – the cumulative use phase emissions are still within the UK's carbon-budget for the LDV sector. The higher overall lifecycle emission is due to the greater fuel production and combustion emissions – respectively, 9 and 12% greater than the reference core scenario – due to a greater proportion of ICEVs operating in the fleet. Whilst the current policy focus is to electrify LDVs, further emission reductions from the fleet could be achieved with the use of lower-carbon fuels to enable the remaining combustion-based vehicles on the road to contribute to the UK's ambitious climate mitigation target.[64]

Switching to the hydrometallurgical recycling process decreases fleet-scale emissions by 1.6%, with all the reduction coming from the critical materials processing. Though hydrometallurgical recycling has a much lower carbon intensity than the pyrometallurgical process, Table 2, the majority of the demand for new LIB manufacturing is met with higher-intensity primary minerals, so only a modest benefit is observed during the fleet transition. Hydrometallurgy is less industrially mature in Europe than pyrometallurgy, though considering the recent EU recycling content regulation there may be further developments in this area.

When electric LDVs are manufactured with batteries of the reduced cobalt LFP chemistry, this has the greatest potential emissions reduction of 3.6% to 1.90 Gt CO_2 eq. cumulatively. Again, this decrease is achieved in the battery life cycle, combining the reduced usage of nickel and cobalt, and the effective recycling of lithium. Analysis by Tarabay *et al.* does indicate that the heavier LFP batteries come with a penalty in vehicle energy consumption and the associated use phase emissions,[13] though this is of less impact with the lower carbon intensity for UK electricity, compared to the study's US emissions factor. Several authors do also point to the low economic value in recycling LFP batteries,[65,66] indicating this scenario could be reliant on other external factors including the provision of regulatory incentives.

Importantly, the conservative grid decarbonisation scenario highlights the importance of continuing the UK's grid decarbonization trajectory. Cumulative fleet-scale GHGs are 9.9% higher in the conservative grid decarbonisation scenario (2.17 Gt CO_2 eq.) than the reference core scenario, where the additional emission is attributable only to electricity generation. The degree of emissions reduction achieved by the UK's ZEV mandate is directly proportional to the speed and consistency at which the electricity powering the future BEV fleet will be decarbonised. Currently, the UK already enjoys a lower-carbon electricity generation compared to many other countries, thus offering an immediate advantage to fleet electrification.[67] Nonetheless, the conservative grid decarbonisation scenario demonstrates that there are cross-cutting GHG emission savings achievable if the ambitious renewable energy generation targets are equally upheld.

4. Discussion

There is a strong desire to decarbonise transport, and LDV fleet electrification has emerged as a promising technological solution favoured by policymakers around the world. The UK has recently introduced a ZEV mandate with the target of achieving 100% new LDV sales by 2035, similar to many other upper-middle and high-income regions like the EU, China, and Japan, as well as the state of California. The UK ZEV mandate is projected to result in a fleet that is comprised of 98.1% BEVs by 2050 and reduce the overall life cycle GHG emissions by 57% relative to 2021. Delaying the ZEV mandate from 2035 to 2040

© 2024 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

increases the cumulative 2020–2050 GHG emissions by 4% from 1.97 Gt to 2.04 Gt.

An aggressive shift to BEVs could raise serious challenges for the UK – and other countries pursuing similarly aggressive BEV deployment strategies – in meeting the rapid growth in demand for traction batteries and the constituent materials. Nickel, cobalt, lithium, manganese, and graphite are all critical battery materials with existing production highly concentrated in several countries and therefore potentially posing significant risk that may expose vulnerability in the global supply chains. Our analyses reveal that the ZEV mandate in the UK could raise demand for these critical materials by several times within the decade. Of particular concern are nickel, cobalt, and lithium, which could see demand exceeding current total UK-wide consumption by 4.8, 6.7, and 40 times, respectively, in 2035 in the reference core scenario.

These are important considerations given that the UK has a very limited domestic battery production capacity to meet its demand for BEVs. The UK will need to quickly develop a resilient and diverse network of global supply in primary materials for LIBs to ensure adequate and timely access to support its ambitions for the transport sector. This dependence could remain for many years before a recycling ecosystem can be effectively put in place to recover materials. Importantly, the UK represents a relatively small LDV fleet compared to other countries that are also implementing their own ZEV mandates. In perspective, the projected 2035 demand for nickel, cobalt, and lithium in the UK under the core scenario accounts for 3.3, 15, and 14% of the total 2021 global productions, respectively.[68] Therefore, the UK will have to compete for access with other regions like the EU, the US, and China, and with other industries, including the electronics sector, to ensure adequate access to these key materials to achieve its ZEV mandate.

Adopting reduced cobalt battery chemistries could be one strategy to manage the demand for critical battery materials. The LFP technology is growing in popularity among vehicle manufacturers, and could reduce the peak demand for nickel, cobalt, and manganese by over 60% in 2035, though at the compromise of greater dependence on lithium. Graphite will continue to be a key material in all LIB technologies.

To reduce the reliance on primary materials, the UK will need to quickly establish a circular battery ecosystem domestically. Recycling end-of-life batteries has great potential to manage the demand for primary materials into the future; effective application of closed-loop recycling processes could reduce peak demand by 20% for all minerals and provide approximately 60% of battery material demand in 2050. This creates increasing sustainability for the supply of critical battery materials, as the stock remains within the UK transport sector. However, the amount of secondary material available is subject to the rate of electric vehicles retiring from the fleet, which is expected to see a 10–15 years delay for the secondary market volumes to grow.

Importantly, the UK should follow the EU regulation on secondary material content in LIB manufacture to ensure future export opportunity. A closed-loop vehicle recycling strategy as modelled would allow the UK to meet the secondary nickel content requirement of the EU regulation. Similarly, lithium recycling targets could be met, though only under the application of the more complex hydrometallurgical recycling process. The targets for recycled cobalt content are projected to be missed by several years at both regulatory milestones, meaning that secondary material would need to be obtained from sources external to the LDV fleet, to meet the regulation. For example, whilst only end-of-life recovery has been explored in this study, UK-specific insights have suggested that successfully recovering scrap material from start-of-life battery manufacturing could contribute a further 4–11% of secondary material availability, helping to complete the EU recycled content targets.[69]

Success in meeting the EU regulation is achieved under the assumption that battery recycling processes are readily available and keep pace with the rate of vehicles retiring from the UK fleet. Pyrometallurgy is the more mature technology and is primarily deployed in Europe and North America.[61] This method typically involves wasting much of the battery in combustion, and losing the important lithium to slag, making it incompatible with the proposed highly circular future manufacture. Hydrometallurgical processing has the opportunity for more complete recycling, including lithium recovery. Hydrometallurgy is however less economical in Europe, with China leading in commercialisation. New UK industry would need to be established to utilise this recycling process.

Like any prospective simulation, this study has potential limitations that may influence the findings reported. The fleet-scale LCA results are subject to many diverse interdependencies that may not be fully realised in the modelling scope and assumptions. Of particular note are the fixed parameters for the vehicle cycle materials and manufacturing. There is much uncertainty in these future technological developments, for example the decarbonisation of steel production, or vehicle design for lightweighting. By fixing the vehicle cycle, this study has focussed on the potential impact of electrification and critical material demand. Thus, these results may somewhat overestimate the combined fleet GHG emissions through 2050. For completeness, future study should combine the results of LCA studies in these areas.

Following the UK's ZEV mandate, the share of BEVs in new LDV sales is projected to grow significantly. Even when sales of all new vehicles in 2035 are BEVs, there will still be over 15 million combustion-based vehicles on the road, and over 600 000 in 2050. The average vehicle lifetime in the UK is about 15 years, which means that combustion vehicles will continue to be driven on the road for many more years before they retire from the fleet. To achieve its net zero pledge, the UK may need to consider complementary strategies to decarbonise the combustion-based vehicles on the road. Lower-carbon fuels, including advanced biofuels and renewable fuels of non-biological origin, could accelerate the decarbonization of the UK fleet by specifically targeting on-road conventional vehicles.

5. Conclusion

This work presents a fleet-scale life cycle assessment of the UK LDV fleet under the planned ZEV mandate, and concomitant material flow implications associated with the projected

© 2024 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

demand for critical battery materials. By 2050, the planned ZEV mandate could enable 57% reduction in annual life cycle GHG emissions relative to the year 2021. With BEV sales projected to grow rapidly, accounting for 100% of new vehicle sales within 15 years, the demand for nickel, cobalt, and lithium will increase significantly, far exceeding the current consumption in UK industries today. Although closed-loop recycling of end-of-life batteries has the potential to reduce primary material demand, this is not likely to have a large impact in the near-term as it takes time for newly introduced BEVs to retire from the fleet. It is important for the UK, and other countries globally, to integrate materials demand in any mobility transition strategy. This should consider the global competition and access to critical raw materials and the time it takes to build-up new capacities to serve the rapid growth in demand for clean energy technologies. Failure to account for supply chain realities may pose a bottleneck that could undermine policy effectiveness.

Abbreviations

BEV	Battery electric vehicle
DVLA	Driver and Vehicle Licensing Agency
GHG	Ggreenhouse gas
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicle
LCA	Life cycle assessment
LDV	Light duty vehicle
LIB	Lithium-ion battery
PHEV	Plug-in hybrid electric vehicle
SDG	Sustainable development goal
ZEV	Zero-emission vehicle

Author contributions

Ben Davies: conceptualisation, methodology, investigation, data curation, visualisation, formal analysis, writing – original draft, writing – review & editing. Jorge Llamas-Orozco: formal analysis, writing – review & editing. Fanran Meng: conceptualisation, investigation, formal analysis, supervision, writing – original draft, writing – review & editing. I. Daniel Posen: conceptualisation, investigation, funding acquisition, writing – review & editing. Heather L. MacLean: conceptualisation, investigation, funding acquisition, writing – review & editing. Amir F. N. Abdul-Manan: conceptualisation, investigation, funding acquisition, writing – review & editing. Jon McKechnie: conceptualisation, methodology, investigation, data curation, visualisation, formal analysis, funding acquisition, supervision, writing – original draft, writing – review & editing.

Conflicts of interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Author A. F. N. Abdul-Manan is employed by Saudi Aramco. The research was funded in part by Saudi Aramco Technologies Company. The academic authors retained scientific independence in pursuing this work and no editorial control was exercised by the sponsor.

Acknowledgements

This project was funded in part by Saudi Aramco Technologies Company.

References

1 Department for Transport, Decarbonising Transport: A Better, Greener Britain, 2021, Available: https://www.gov.uk/dft.

2 C. Waite, 2021 UK Greenhouse Gas Emissions, Final Figures, 2023, Accessed: Apr. 26, 2023, Available: https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2021.

3 International Energy Agency, International Energy Agency (IEA) World Energy Outlook 2022, 2022, p. 524, https://Www.Iea.Org/Reports/World-Energy-Outlook-2022/Executive-Summary, Available: https://www.iea.org/reports/world-energy-outlook-2022.

4 BEIS, *Net Zero Strategy: Build Back Greener*, no. October. 2021, Available: https://www.gov.uk/government/publications/net-zero-strategy.

5 A. Milovanoff, I. D. Posen and H. L. MacLean, Electrification of light-duty vehicle fleet alone will not meet mitigation targets, *Nat. Clim. Change*, 2020, **10**(12), 1102–1107, DOI: 10.1038/s41558-020-00921-7.

6 Department for Transport and Driver and Vehicle Licensing Agency, *Vehicle licensing statistics: 2022*, National statistics, Available: https://www.gov.uk/government/statistics/vehicle-licensing-statistics-2022.

7 M. Raugei, M. Kamran and A. Hutchinson, Environmental implications of the ongoing electrification of the UK light duty vehicle fleet, *Resour., Conserv. Recycl.*, 2021, **174**, 105818, DOI: 10.1016/j.resconrec.2021.105818.

8 IEA, Global EV Outlook 2021, in *Global EV Outlook*, OECD, 2021, DOI: 10.1787/3a394362-en.

9 BEIS, *Resilience for the Future: the United Kingdom's Critical Minerals Strategy*, London, 2022.

10 C. Xu, Q. Dai, L. Gaines, M. Hu, A. Tukker and B. Steubing, Future material demand for automotive lithium-based batteries, *Commun. Mater.*, 2020, **1**(1), 99, DOI: 10.1038/s43246-020-00095-x.

11 S. Bobba, F. Mathieux and G. A. Blengini, How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries, *Resour., Conserv. Recycl.*, 2019, **145**, 279–291, DOI: 10.1016/j.resconrec.2019.02.022.

12 A. Elshkaki, Long-term analysis of critical materials in future vehicles electrification in China and their national and global implications, *Energy*, 2020, **202**, 117697, DOI: 10.1016/j.energy.2020.117697.

13 B. Tarabay, A. Milovanoff, A. F. N. Abdul-Manan, J. McKechnie, H. L. MacLean and I. D. Posen, New cathodes now, recycling later: Dynamic scenarios to reduce

© 2024 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

battery material use and greenhouse gas emissions from U.S. light-duty electric vehicle fleet, *Resour., Conserv. Recycl.*, 2023, **196**, 107028, DOI: 10.1016/j.resconrec.2023.107028.

14 C. Zhang, J. Yan and F. You, Critical metal requirement for clean energy transition: A quantitative review on the case of transportation electrification, *Adv. Appl. Energy*, 2023, **9**, 100116, DOI: 10.1016/j.adapen.2022.100116.

15 European Commission, *Regulation (EU) 2023/1542 of the European Parliament and of the Council concerning batteries and waste batteries*, The European Parliament and The Council of the European Union, 2023, Accessed: Sep. 13, 2023, Available: http://data.europa.eu/eli/reg/2023/1542/oj.

16 A. Walton *et al.*, *Securing Technology-Critical Metals for Britain: Ensuring the United Kingdom's Supply of Strategic Elements & Critical Materials for a Clean Future*. 2021.

17 Polestar, Life cycle assessment: Carbon footprint of Polestar 2, 2020, Available: https://www.polestar.com/global/news/polestar-2-lca-report/.

18 R. Garcia and F. Freire, A review of fleet-based life-cycle approaches focusing on energy and environmental impacts of vehicles, *Renewable Sustainable Energy Rev.*, 2017, **79**(April), 935–945, DOI: 10.1016/j.rser.2017.05.145.

19 P. Ahmadi, Environmental impacts and behavioral drivers of deep decarbonization for transportation through electric vehicles, *J. Cleaner Prod.*, 2019, **225**, 1209–1219, DOI: 10.1016/j.jclepro.2019.03.334.

20 Ö. Andersson and P. Börjesson, The greenhouse gas emissions of an electrified vehicle combined with renewable fuels: Life cycle assessment and policy implications, *Appl. Energy*, 2021, **289**, 116621, DOI: 10.1016/j.apenergy.2021.116621.

21 K. J. Dillman, Á. Árnadóttir, J. Heinonen, M. Czepkiewicz and B. Davídsdóttir, Review and Meta-Analysis of EVs: Embodied Emissions and Environmental Breakeven, *Sustainability*, 2020, **12**(22), 9390, DOI: 10.3390/su12229390.

22 H. Ambrose, A. Kendall, M. Lozano, S. Wachche and L. Fulton, Trends in life cycle greenhouse gas emissions of future light duty electric vehicles, *Transportation Research Part D: Transport and Environment*, 2020, **81**, 102287, DOI: 10.1016/j.trd.2020.102287.

23 K. Glensor and B. María Rosa Muñoz, Life-cycle assessment of Brazilian transport biofuel and electrification pathways, *Sustainability*, 2019, **11**(22), 6332, DOI: 10.3390/su11226332.

24 F. Del Pero, M. Delogu and M. Pierini, Life Cycle Assessment in the automotive sector: a comparative case study of Internal Combustion Engine (ICE) and electric car, *Procedia Struct. Integr.*, 2018, **12**, 521–537, DOI: 10.1016/j.prostr.2018.11.066.

25 J. Porzio and C. D. Scown, Life-Cycle Assessment Considerations for Batteries and Battery Materials, *Adv. Energy Mater.*, 2021, **11**(33), 2100771, DOI: 10.1002/aenm.202100771.

26 X. Lai, *et al.*, Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: A lifespan perspective, *eTransportation*, 2022, **12**, 100169, DOI: 10.1016/j.etran.2022.100169.

27 H. Ambrose and A. Kendall, Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility, *Transportation Research Part D: Transport and Environment*, 2016, **47**, 182–194, DOI: 10.1016/j.trd.2016.05.009.

28 M. Raugei and P. Winfield, Prospective LCA of the production and EoL recycling of a novel type of Li-ion battery for electric vehicles, *J. Cleaner Prod.*, 2019, **213**, 926–932, DOI: 10.1016/J.JCLEPRO.2018.12.237.

29 J. A. Llamas-Orozco, *et al.*, Estimating the Environmental Impacts of Global Lithium-Ion Battery Supply Chain: A Temporal, Geographical, and Technological Perspective, *PNAS Nexus*, 2023, **2**(11), pgad361, DOI: 10.1093/pnasnexus/pgad361.

30 F. Field, R. Kirchain and J. Clark, Life-Cycle Assessment and Temporal Distributions of Emissions: Developing a Fleet-Based Analysis, *J. Ind. Ecol.*, 2000, **4**(2), 71–91, DOI: 10.1162/108819800569816.

31 J. Palazzo and R. Geyer, Consequential life cycle assessment of automotive material substitution: Replacing steel with aluminum in production of north American vehicles, *Environ. Impact Assess. Rev.*, 2019, **75**, 47–58, DOI: 10.1016/j.eiar.2018.12.001.

32 J. H. Gawron, G. A. Keoleian, R. D. De Kleine, T. J. Wallington and H. C. Kim, Deep decarbonization from electrified autonomous taxi fleets: Life cycle assessment and case study in Austin, TX, *Transportation Research Part D: Transport and Environment*, 2019, **73**, 130–141, DOI: 10.1016/j.trd.2019.06.007.

33 R. Garcia, J. Gregory and F. Freire, Dynamic fleet-based life-cycle greenhouse gas assessment of the introduction of electric vehicles in the Portuguese light-duty fleet, *Int. J. Life Cycle Assess.*, 2015, **20**(9), 1287–1299, DOI: 10.1007/s11367-015-0921-8.

34 B. Blat Belmonte, A. Esser, S. Weyand, G. Franke, L. Schebek and S. Rinderknecht, Identification of the Optimal Passenger Car Vehicle Fleet Transition for Mitigating the Cumulative Life-Cycle Greenhouse Gas Emissions until 2050, *Vehicles*, 2020, **2**(1), 5, DOI: 10.3390/vehicles2010005.

35 A. Dirnaichner, *et al.*, Life-cycle impacts from different decarbonization pathways for the European car fleet, *Environ. Res. Lett.*, 2022, **17**(4), 044009, DOI: 10.1088/1748-9326/ac4fdb.

36 V. K. K. Upadhyayula, A. G. Parvatker, A. Baroth and K. Shanmugam, Lightweighting and electrification strategies for improving environmental performance of passenger cars in India by 2030: A critical perspective based on life cycle assessment, *J. Cleaner Prod.*, 2019, **209**, 1604–1613, DOI: 10.1016/j.jclepro.2018.11.153.

37 D. Ma, *et al.*, The Characteristics of Light-Duty Passenger Vehicle Mileage and Impact Analysis in China from a Big Data Perspective, *Atmosphere*, 2022, **13**(12), 1984, DOI: 10.3390/atmos13121984.

38 M. Kamran, M. Raugei and A. Hutchinson, A dynamic material flow analysis of lithium-ion battery metals for electric vehicles and grid storage in the UK: Assessing the impact of shared mobility and end-of-life strategies,

Open Access Article. Published on 13 Mezheven 2024. Downloaded on 2026-05-06 22:35:27.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Resour., Conserv. Recycl., 2021, **167**, 105412, DOI: 10.1016/j.resconrec.2021.105412.

39 Committee on Climate Change, *The Sixth Carbon Budget: Surface Transport*, 2020.

40 H. Walvekar, H. Beltran, S. Sripad and M. Pecht, Implications of the Electric Vehicle Manufacturers' Decision to Mass Adopt Lithium-Iron Phosphate Batteries, *IEEE Access*, 2022, **10**, 63834–63843, DOI: 10.1109/ACCESS.2022.3182726.

41 Department for Transport, *Zero Emission Vehicle (ZEV) Mandate Consultation: Summary of Responses and Joint Government Response*, 2023.

42 United Nations, *Transforming Our World: the 2030 Agenda for Sustainable Development*, 2015.

43 A. Milovanoff, H. C. Kim, R. De Kleine, T. J. Wallington, I. D. Posen and H. L. MacLean, A Dynamic Fleet Model of U.S Light-Duty Vehicle Lightweighting and Associated Greenhouse Gas Emissions from 2016 to 2050, *Environ. Sci. Technol.*, 2019, **53**(4), 2199–2208, DOI: 10.1021/acs.est.8b04249.

44 European Environment Agency, *Decarbonising Road Transport – the Role of Vehicles, Fuels and Transport Demand*, Luxembourg, 2022, DOI: 10.2800/68902.

45 GREET, GREET Life Cycle Model User Guide, Argonne National Laboratory, pp. 169–232, 2020, Available: http://www.impact-test.co.uk/.

46 Vehicle Certification Agency, *Fuel Consumption & CO2 Databases*, Accessed: Jun. 05, 2023, Available: https://www.vehicle-certification-agency.gov.uk/fuel-consumption-co2/.

47 G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz and B. Weidema, The ecoinvent database version 3 (part I): overview and methodology, *Int. J. Life Cycle Assess.*, 2016, **21**(9), 1218–1230, DOI: 10.1007/s11367-016-1087-8.

48 Department for Transport, *Road Traffic Estimates, Great Britain 2021*, 2022.

49 National Grid, *Future Energy Scenarios*, 2021, Available: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021.

50 T. F. Stocker *et al.*, *IPCC, 2013: Climate Change 2013: the Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, 2013.

51 ecoInvent, ecoinvent database V3.7, Accessed: May 25, 2022, Available: https://ecoinvent.org/.

52 Committee on Climate Change, *The Sixth Carbon Budget: the UK's Path to Net Zero*, 2020.

53 Society of Motor Manufacturers and Traders, SMMT Vehicle Data: Car Registrations, Available: https://www.smmt.co.uk/vehicle-data/car-registrations/.

54 S. Francis, Rishi Sunak delays petrol car ban in major shift on green policies, BBC News, Sep. 21, 2023, Available: www.bbc.co.uk/news/uk-politics-66871457.

55 Department for Transport, *The Road to Zero*, 2018.

56 M. Azevedo, N. Campagnol, T. Hagenbruch, K. Hoffman, A. Lala, and O. Ramsbottom, Lithium and cobalt-a tale of two commodities, McKinsey&Company Metals and Mining, pp. 1-25, 2018, Available: https://www.mckinsey.com/~/media/mckinsey/industries/metals and mining/our insights/lithium and cobalt a tale of two commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx.

57 B. Makuza, Q. Tian, X. Guo, K. Chattopadhyay and D. Yu, Pyrometallurgical options for recycling spent lithium-ion batteries: A comprehensive review, *J. Power Sources*, 2021, **491**, 229622, DOI: 10.1016/j.jpowsour.2021.229622.

58 D. Thompson, C. Hyde, J. M. Hartley, A. P. Abbott, P. A. Anderson and G. D. J. Harper, To shred or not to shred: A comparative techno-economic assessment of lithium ion battery hydrometallurgical recycling retaining value and improving circularity in LIB supply chains, *Resour., Conserv. Recycl.*, 2021, **175**, 105741, DOI: 10.1016/j.resconrec.2021.105741.

59 Z. Dobó, T. Dinh and T. Kulcsár, A review on recycling of spent lithium-ion batteries, *Energy Rep.*, 2023, **9**, 6362–6395, DOI: 10.1016/j.egyr.2023.05.264.

60 Q. Dai, J. Spangenberger, S. Ahmed, L. Gaines, J. C. Kelly, and M. Wang, *EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model Energy Systems Division*, 2019, Accessed: Jul. 25, 2022, Available: http://www.anl.gov/.

61 M. Chen, *et al.*, Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries, *Joule*, 2019, **3**(11), 2622–2646, DOI: 10.1016/j.joule.2019.09.014.

62 S. Yasa, O. Aydin, M. Al-Bujasim, B. Birol and M. Gencten, Recycling valuable materials from the cathodes of spent lithium-ion batteries: A comprehensive review, *J. Energy Storage*, 2023, **73**(PC), 109073, DOI: 10.1016/j.est.2023.109073.

63 T. Bide, E. Evans, N. E. Idoine, and J. Mankelow, *United Kingdom Minerals Yearbook 2022*, 2023, DOI: 10.1016/s0301-4207(97)90036-2.

64 S. S. Ravi, C. Brace, C. Larkin, M. Aziz, F. Leach and J. W. Turner, On the pursuit of emissions-free clean mobility – Electric vehicles *versus* e-fuels, *Sci. Total Environ.*, 2023, **875**, 162688, DOI: 10.1016/j.scitotenv.2023.162688.

65 M. Chen, *et al.*, Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries, *Joule*, 2019, **3**(11), 2622–2646, DOI: 10.1016/j.joule.2019.09.014.

66 L. Lander, *et al.*, Financial viability of electric vehicle lithium-ion battery recycling, *iScience*, 2021, **24**(7), 102787, DOI: 10.1016/j.isci.2021.102787.

67 F. Del Pero, M. Delogu and M. Pierini, Life Cycle Assessment in the automotive sector: a comparative case study of Internal Combustion Engine (ICE) and electric car, *Procedia Struct. Integr.*, 2018, **12**, 521–537, DOI: 10.1016/j.prostr.2018.11.066.

68 N. E. Idoine *et al.*, *World Mineral Production: 2017-2021*, 2023, Available: https://nora.nerc.ac.uk/id/eprint/534316/1/WMP_2017_2021_FINAL.pdf.

69 APC, UK's biggest opportunity from battery waste is to feed its cathode manufacturing industry, 2022, Available: https://www.apcuk.co.uk/uk-battery-waste-recycling/.

© 2024 The Author(s). Published by the Royal Society of Chemistry