Research on Environmental Sustainability and Energy Efficiency of Electric Vehicles

Final Report

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EXECUTIVE SUMMARY

This is the Final Report summarising the findings of research on environmental sustainability and energy efficiency of electric vehicles (xEVs), prepared by Ricardo for FIA. The aim of the study is to perform research and analysis into a range of aspects relating to the sustainability of EVs and how this is communicated to consumers, to improve understanding of the factors and the variation in impacts, and to inform the development of suitable policy recommendations. The work has involved conducting a range of research in five key areas relating to EVs, namely the following:

1. Lifecycle emissions
2. Sustainability of manufacturing processes
3. Real world operational energy efficiency
4. Battery life and second-life applications
5. Transparency and consumer information

The study has culminated in this summary report on the findings, including the development of potential policy recommendations.

The scope of the work is focused on passenger cars sold and operated within the EU/Europe.

LIFECYCLE EMISSIONS

Lifecycle Assessment (LCA) is a methodology for assessing the environmental impacts of a product or process, across all its life cycle stages. Understanding the lifecycle emissions of electric vehicles (EVs) is critical for evaluating their environmental benefits compared to conventional internal combustion engine vehicles (ICEVs). An in-depth assessment of the lifecycle emissions of EVs compared to conventional internal combustion engine vehicles (ICEVs)[1] was undertaken, with a focus on greenhouse gas (GHG) emissions across all lifecycle stages, i.e. from production, use and end-of-life.

The research findings revealed that xEV **production** generally results in higher GHG emissions than ICEVs due to the additional mass and energy-intensive manufacturing of batteries. For instance, production emissions for BEVs are typically double or more those of ICEVs (but not as high for xEV powertrains with smaller batteries). However, advancements in battery technology and decarbonisation of manufacturing processes are expected to mitigate these emissions in the future.

However, during the **use phase**, BEVs demonstrate significantly lower GHG emissions compared to ICEVs, mainly due to their use of electricity rather than fossil fuels (with other types of xEV also showing lower GHG savings potentials). Studies have shown that, even without considering future grid decarbonisation in calculations, current BEVs can reduce GHG emissions by approximately 43% in Europe, 29% in North America, and 23% in Asia and Australia compared to gasoline ICEVs over a 15-year service life. Studies that do account for future changes in the electricity supply mix show even greater savings.

Considering the **entire lifecycle**, BEVs emerge as the least carbon-intensive option. In Europe, current BEV models could reduce lifecycle GHG emissions by up to 63% compared to gasoline ICEVs when future grid decarbonisation is factored in, based on Ricardo's analyses. Projections for 2050 indicate that BEVs will achieve nearly 80% reductions in lifecycle GHG emissions in Europe, assuming continued technological advancements and significant grid decarbonization. In contrast, even with optimistic scenarios for biofuels and e-fuels, ICEVs are expected to achieve a maximum of 50% reduction in lifecycle GHG emissions.

The adoption of BEVs offers substantial net environmental benefits over ICEVs, primarily through significant reductions in use-phase and overall lifecycle GHG emissions. Continued policy support, technological innovation, and infrastructure development are crucial to maximizing these benefits and facilitating a transition

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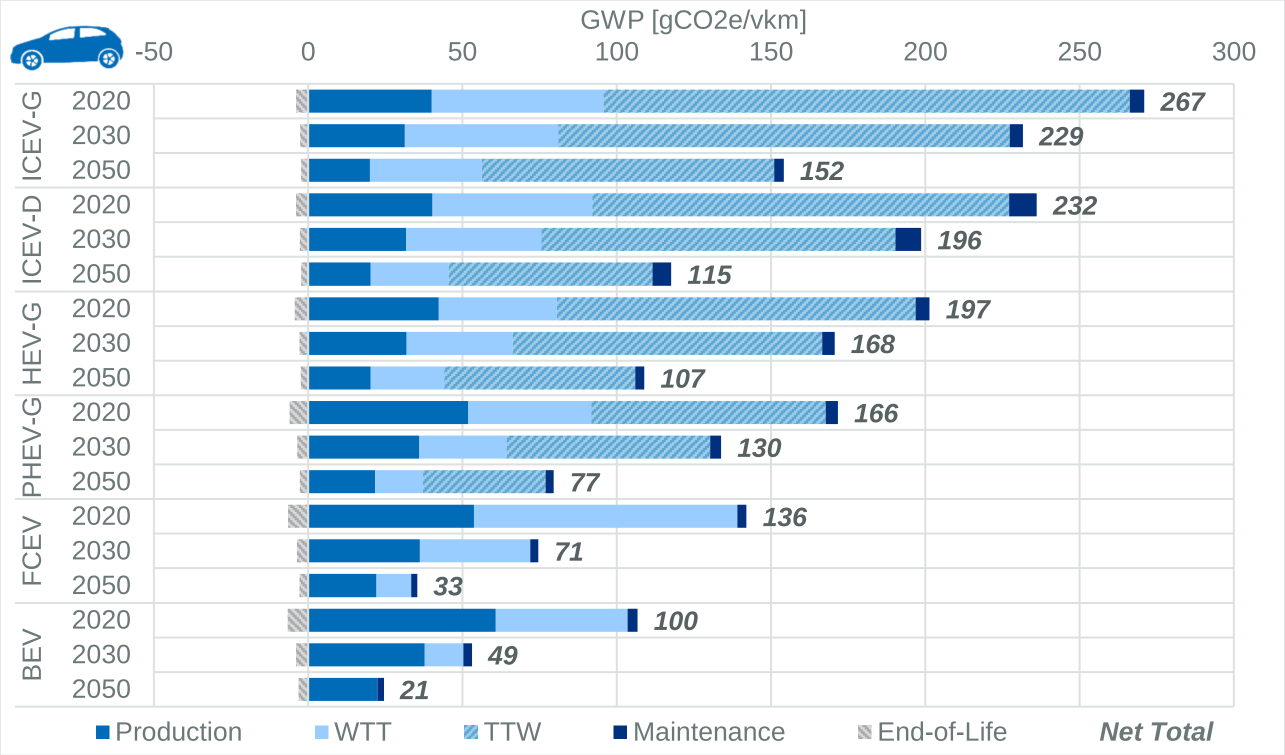
[1] Covering internal combustion vehicles (ICEVs) and hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs).

towards a low-carbon transportation sector. The figure below presents the breakdown of the future outlook for life cycle GHG impacts for a Lower Medium Car, 2020 / 2030 / 2050, EU27.



Notes: Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. GWP = Global Warming Potential.

SUSTAINABILITY OF MANUFACTURING PROCESSES

The sustainability of manufacturing processes with a focus on reducing lifecycle greenhouse gas (GHG) emissions in vehicle production was evaluated. Key strategies to improve sustainability include enhancing energy efficiency, developing alternative battery chemistries, and improving recycling efficacy.

The largest contributor to GHG emissions in the manufacturing of current electric vehicles (EV) is the vehicle's glider, primarily composed of steel and aluminium (and which is similar also for conventional vehicles), accounting for a significant share of overall emissions. For instance, increasing the use of recycled aluminium can substantially reduce emissions. In battery production, emissions are heavily influenced by the materials used and the energy intensity of manufacturing processes. For fuel cell electric vehicles (FCEVs), the use of carbon fibre in high-pressure hydrogen storage vessels is a major contributor to the footprint. Transitioning to renewable energy (RE) sources in raw materials processing and battery production can significantly mitigate these emissions.

Advancements in battery technologies are crucial for reducing emissions. Improvements in battery energy density and the development of new chemistries, such as cobalt-free lithium-ion batteries and sodium-ion batteries, are expected to lower the environmental impact of battery manufacturing. Additionally, the shift towards green hydrogen for steel production and the use of inert anodes in aluminium smelting can further decrease emissions from these key structural materials used in all vehicle types. While reducing the environmental impact of energy inputs required to manufacture batteries will be relatively straightforward, in comparison, the impacts of materials and their associated supply chains will remain challenging.

The use of recycled materials and implementing "Design for Circularity" strategies are vital for reducing manufacturing emissions, and also maximising potential lifecycle impact reductions through improved end-of-life material recycling. For example, using recycled steel and aluminium, which emit significantly less GHG compared to their primary production, can lead to substantial GHG savings. Furthermore, increasing the efficiency of the manufacturing process and utilising RE can further enhance sustainability.

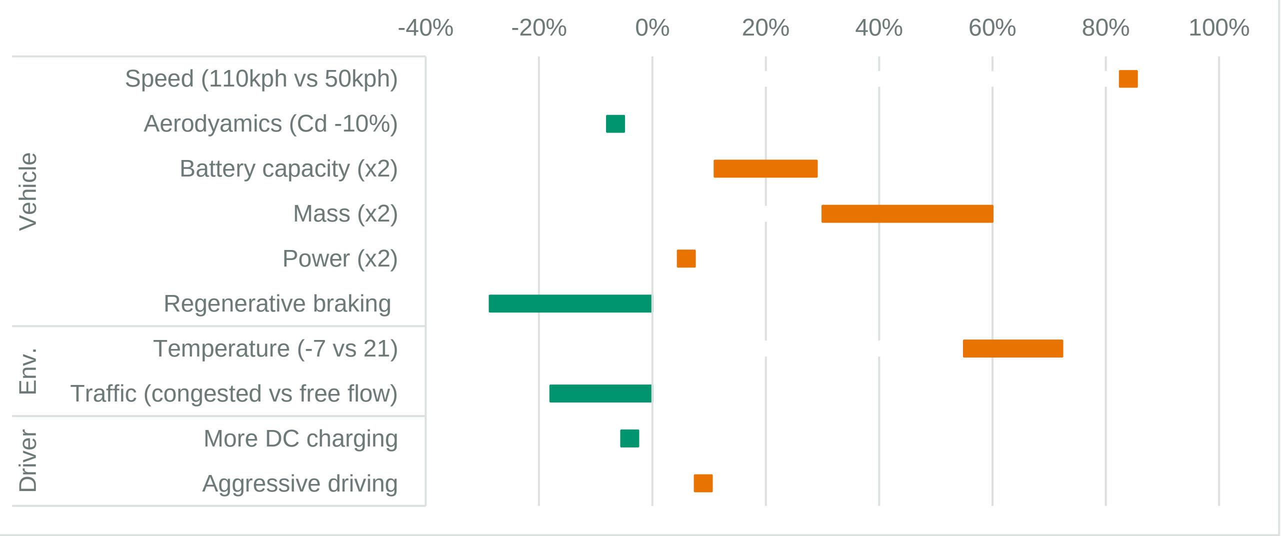
To achieve these goals, mass reduction in vehicle design has an important role to play, as this reduces energy storage capacity requirements for a given range, lowering both energy and materials demand and leading to cuts in GHG emissions. Policies and technological innovations aimed at improving the recyclability of materials, closing the loop on pre-consumer waste where it is more feasible to preserve the purity of materials needed for vehicle manufacturing, and ensuring the use of RE in manufacturing processes are critical for achieving long-term sustainability in vehicle production. Locating battery manufacturing in regions with higher shares of RE in the grid mix will also have a key positive impact.

Overall, the research highlights the importance of adopting comprehensive strategies to reduce the environmental impact of manufacturing processes, emphasising the need for continued policy support, technological advancements, and collaboration across the automotive industry to achieve significant reductions in lifecycle GHG emissions.

REAL-WORLD OPERATIONAL ENERGY EFFICIENCY

A review and analysis of the operational energy consumption of electric vehicles and how this varies in real-world conditions was undertaken[2], with a focus particularly on BEVs (typically measured in kWh/100km or similar units). This is an important metric for consumers to understand how much range they can get from a fully charged battery and is a significant determinant of a BEV's use-phase emissions. However, the efficiency consumers feel in the 'real-world' often differs to the figures that manufacturers report, which can lead to disparities between expectations and realised outcomes. For plug-in hybrid electric vehicles (PHEVs), the impacts on the efficiency of real-world operation in electric mode is similar to BEVs. However, the overall energy consumption of PHEVs is also very strongly influenced by both the electric range of the vehicle and user behaviour. Historically, regulatory testing of PHEVs has significantly over-estimated the share of operation on electricity for PHEVs, however amendments to the EU's regulatory testing using WLTP to be applied from 2025 are expected to improve this.

A literature review was conducted on the key factors affecting the real-world energy consumption of BEVs, a summary of which is provided in the figure below. Determinants are grouped into vehicle-, environmental- and driver-related factors. Significant increases in energy consumption are observed under high speeds (+85%), cold temperatures (+55-72%), and heavy loads (+30-60%). Moderate increases occur with larger batteries (+11-29%), during aggressive driving (+9%), and with more powerful engines (+7%). Regenerative braking (particularly in urban traffic) and aerodynamic improvements can significantly reduce energy consumption (by up to -18% and -7% respectively), while greater use of rapid charging can slightly reduce charging losses (by up to 5%).



The factors above all contribute to differences between real-world and manufacturer reported (Certificate of Conformity - CoC) energy efficiency. Data from Green NCAP testing shows that while CoC energy

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[2] Consideration of the full lifecycle energy efficiency was out of scope for the analysis, however a limited amount of information is provided in the main report under the lifecycle emissions chapter.

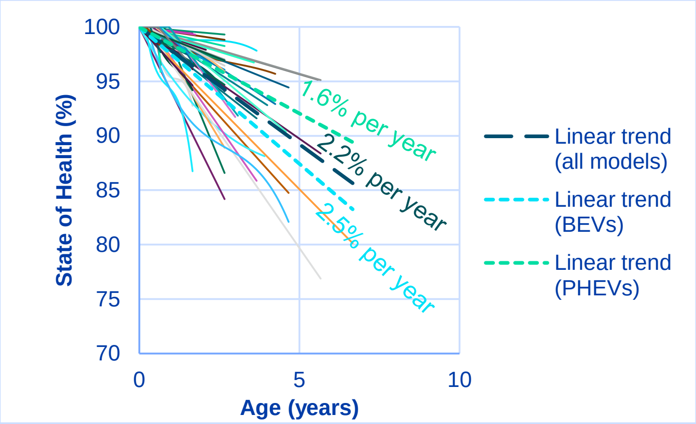
consumption values range from 13.9 kWh/100km to 20 kWh/100km, real world values measured through PEMS tests ranges from 14.2 kWh/100km (Dacia Spring) to 26.4 kWh/100km (Ford Mustang Mach-E). The VW ID7 is estimated to be the most efficient per kilogram of mass within the sample, while the Fiat 500 is the least.

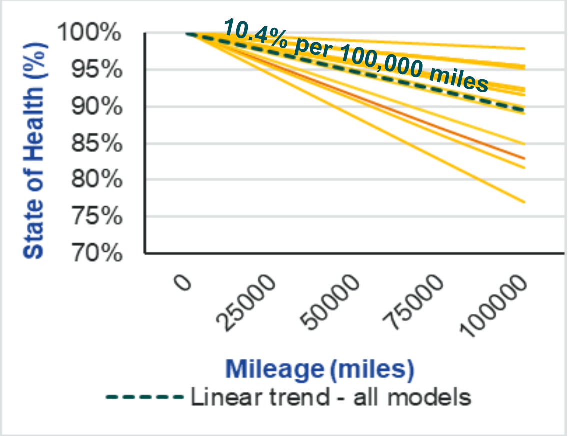
There is some evidence to suggest that, per unit mass, improvements in vehicle energy efficiency are being made over time. Nevertheless, analysis of open-access datasets from the Netherlands suggests that fleet average real-world energy consumption is increasing overall as vehicles become heavier. However, this trend is masked by a slight decrease in manufacturer-reported energy consumption, with the gap between real-world and reported consumption widening from 15% in 2020 to 25% in 2023.

BATTERY LIFE AND SECOND LIFE APPLICATIONS

Battery life/durability and second-life applications for those used in passenger cars was examined, focusing on battery degradation rates, repurposing feasibility, and strategies to reduce environmental impacts.

Battery durability is a key uncertainty for consumers and therefore available degradation data was reviewed to better understand what range of degradation may be expected in practice, the factors that cause degradation and strategies to extend xEV battery life. Available data shows that an average degradation rate of 2.2% per year and 10.4% per 100,000 miles, with results presented in the figures below. Newer xEV models demonstrate slower degradation due to advances in battery technology and thermal management systems. Regulation such as the new Euro 7 standard is also expected to address consumer concerns as it will set requirements for minimum levels of battery durability and inclusion of user viewable battery state of health (SOH) monitors in new vehicles.





Repurposing of used xEV batteries for stationary applications such as the energy storage applications is technically feasible. While there are several ongoing pilots and demonstrations across EU, the real-world applications as of 2024 are limited, technical challenges persist and regulations for xEV batteries for repurposing are limited. Technical challenges such as battery safety concerns, lack of standardisation in battery design and uncertain life expectancy need to be addressed. For battery owners, the decision to repurpose rather than recycle hinges on the relative revenue generated by either option. Several publications consider repurposing of end-of-life xEV batteries as an attractive economic opportunity due to cheaper purchase price of repurposed xEV batteries (usually) compared to new xEV batteries, additional revenue stream for OMEs and reduced xEV cost for buyers. However, several of the literature sources reviewed consider recycling as the near-term favourable route as the economics of repurposed xEV batteries is highly affected by the cost of acquisition, labour and transport, which is currently high. Policies promoting data sharing, standardisation, and local repurposing infrastructure, along with improved testing and certification protocols, can enhance the feasibility and adoption of repurposed xEV batteries for energy storage.

Environmental improvement opportunities for reducing the environmental impact of xEV batteries focus on production, usage, and disposal stages. During production, emissions can be minimized by using RE, improving manufacturing efficiency, and adopting low-emission battery chemistries like lithium iron phosphate (LFP) batteries. Locating production facilities near low-carbon energy sources and implementing carbon tariffs can further incentivise greener practices. In the usage phase, sourcing renewable electricity for charging and extending battery lifespan through better management can reduce environmental impact. For disposal, enhancing recycling technologies and infrastructure, coupled with the EU Sustainable Battery Regulation's targets for recycled content, promotes a circular economy. Standardising battery design and ensuring proper labelling can make recycling more efficient, significantly improving the environmental sustainability of xEV batteries.

TRANSPARENCY AND CONSUMER INFORMATION

When purchasing a car, consumers typically consider criteria such as safety, comfort and fuel efficiency. However, when specifically considering the purchase of an electric vehicle (including making comparisons between electric vehicles) and information to users of electric vehicles to ensure that the use of their vehicle is optimised, consumers desire information on total cost of ownership (TCO); electric range; battery charging times; chargepoint location and usability; battery health and optimisation; and lifecycle assessment (LCA) information.

Existing and forthcoming EU legislation mandates the provision of selected information to consumers that could assist in informing either their purchase decision or vehicle use, including the Car Labelling Directive (tailpipe CO_2 emissions/fuel economy), Vehicle Type Approval / Euro 7 Regulation (Environmental Vehicle Passport, including CO_2 emissions, fuel/electric energy consumption, electric range and engine/electric motor power, battery durability), Sustainable Batteries Regulation (battery passport). Regarding electric vehicles, the forthcoming Environmental Vehicle Passport (EVP) as required by the Euro 7 Regulations may offer potential opportunities for presenting standardised information to consumers regarding the vehicle.

Vehicle manufacturers are a further source of sustainability information aimed at both the consumer and users of (electric) cars. Vehicle manuals tend to provide relatively consistent information on safety and vehicle charging, but limited information on battery range, battery charging times and information relating to vehicle production and environmental impact. In addition to manuals, vehicle manufacturers provide information to owners/users of electric vehicles via original equipment manufacturer (OEM)-developed apps, including estimated electric range, current battery status/charge level and location of charging stations.

Third party tools provide consumers with the ability to compare a range of vehicle models and can include vehicle comparison sites and more detailed LCA. Vehicle comparison sites offer information on aspects such as includes fuel type; electric range; battery type; battery capacity; presence of rapid charging and acceleration capability. In addition, information can include total cost of ownership, tailpipe emissions, bidirectional charging capability, maximum speed, charge time, type of charger.

LCA tools are available from both vehicle manufacturers and third-party sources, which can provide consumers with a more holistic/complete picture of sustainability information regarding vehicles (with most focused on GHG emissions). However, because there is currently no harmonised methodology for vehicle LCA there are differences in lifecycle stages covered/system boundaries, metrics considered and assumptions made, making it still difficult for consumers to be able to compare vehicles on a like for like basis in many cases. However, work is currently ongoing in Europe and internationally to develop a harmonised approach for vehicle LCA, which should help to improve this situation in the future.

POLICY RECOMMENDATIONS

Policy recommendations are presented in the table below.

Policy recommendations

Policy recommendation	Further detail	Related tasks
Advocate for reduced vehicle mass and right-sizing when choosing replacement vehicles (production and vehicle selection)	• Vehicle mass reduction can lead to reduced material consumption and improved sustainability of manufacturing processes. • Requirements for energy storage capacity for a given range objective will also be reduced, due to smaller batteries and H_2 storage vessels • Improved information aimed at consumers incentivising them to choose smaller/lighter vehicles (where these can meet utility needs), countering the current trend towards larger SUVs and enabling consumers to experience benefits relating to better energy efficiency.	Sustainability of manufacturing processes Energy efficiency Transparency and consumer information
Reduce the environmental impact of vehicle manufacturing, through considering material substitutes and increased material circularity	• Incentives are also already in place in the EU for improvement in battery impacts due to provisions in the Battery Regulation on recycled content, end-of-life recycling and recovery, reporting on battery carbon footprints and also additional information in a battery passport. • Manufacturers should also be encouraged to further/continue to consider the full lifecycle impacts of vehicle production and use, in particular focussing on the materials selected and used (including circularity of those materials) to ensure sustainability impacts are minimised.	Sustainability of manufacturing processes Lifecycle analysis
Welcome extending the requirement for increased monitoring and reporting of BEVs' (and FCEVs) on-board energy consumption data, similarly as for ICEVs, HEVs and PHEVs	• The review highlights that real-world data on BEV energy consumption is sparse. To provide robust recommendations on improving the energy efficiency of BEVs, it is first necessary to have a rigorous and sound understanding of the factors influencing BEV energy consumption. • Significant improvements in understanding are being developed for ICEVs, HEVs and PHEVs due to EU mandated monitoring of on-board fuel consumption (via OBFCM), and reporting on this. • Extension of this requirement to BEVs (and FCEVs) would be very welcome, and would create a level playing field and facilitate the development of a richer dataset to analyse and draw conclusions from for policymakers, OEMs and consumers alike.	Energy efficiency
Target future policies towards developments with the greatest potential for improving BEV energy efficiency	• There is large variability in the energy consumption of passenger cars with a similar mass, suggesting there is scope for technical improvements, but these are possible through a large variety of angles, including: improved energy recuperation, decreased coasting resistance,	Energy efficiency

Policy recommendation	Further detail	Related tasks
	the application of light-weight chassis components, reductions in aerodynamic drag, and reductions in charging losses, to name a few Weiss, Cloos, & Helmers, 2020). • The evidence identified in this report suggests a number of approaches could be reasonable avenues to target based on their contribution to total BEV energy consumption (see following suggestions)	
Consider the introduction of incentives or mandates to install improved thermal management systems for BEVs, possibly requiring the installation of heat pumps (at least in cooler regions)	• One of the largest factors affecting BEV energy consumption is ambient temperature and its effect on energy demand from auxiliary heating and cooling components, especially in cold temperatures. • There are large efficiencies still to be gained in BEV thermal management systems (UEA, 2022), and the main source of promise is in the introduction of heat pump air conditioning systems to manage cabin temperatures, replacing traditional single cooling air conditioner and PTC electric heating systems (He, Jing, Zhang, Li, & Gu, 2023). • This requirement could be targeted to certain markets with colder average annual temperatures. Other developments which could be mandated include the increased integration (between cabin, battery and engine) and intelligence (predictive ability and real-time response) of thermal management systems.	Energy efficiency
Consider the introduction of incentives to promote right-sized BEVs and batteries as BEVs consolidate their market position	• The evidence reported highlights that vehicles with greater mass are less energy efficient. • Drivers are favouring increasingly larger vehicles, as indicated by the significant growth of the SUV segment - fleet average BEV mass in the Netherlands rose from 1500kg in 2017 to 1900kg in 2022, resulting in an increase in fleet average energy consumption of ~14%. • Incentives may be needed to limit this trend, a position shared by various authors in emerging literature (Ricardo, 2023; ICCT, 2024; TNO, 2024b). Monetary incentives to address this market failure could include benefits for lighter vehicles (grants, tax breaks), and/or penalties for heavier vehicles (tax increases). • Incentives can be reinforced/complimented also by increased public infrastructure deployment and awareness and will also act to reduce the perceived and actual need for larger batteries.	Energy Efficiency
Consider the introduction of energy efficiency targets for BEVs into future legislation	• The current regulatory regime based on direct emissions of CO_2 from vehicles provides no direct incentive to improve the efficiency of zero emission tailpipe vehicles, like BEVs. • In future regulatory revisions, the potential for inclusion of energy efficiency targets for ZEVs could be considered, to help incentivise future improvement in energy consumption / energy efficiency. The design of these would need some care, however, to provide a suitable balance suitable across different technologies.	Energy efficiency

Policy recommendation	Further detail	Related tasks
Raise awareness amongst consumers and users of BEVs of the conditions that lead to optimal BEV energy efficiency, and the wider sustainability impacts of using these vehicles in urban areas	• Regardless of vehicle size, all evidence points to optimal BEV energy efficiency during journeys that are short (reducing charging losses), mild-temperature (minimising power from auxiliaries), at slow average speeds (reducing engine power demand) and with stop-start activity (maximising energy recovery), which are all more prevalent in urban settings. • Policy should therefore ideally focus first on greater uptake in urban areas to improve fleet-wide real world energy consumption, including raising awareness amongst consumers of the benefits to them as users and local benefits. Such policies also have the benefit of improving local air quality in population-dense areas.	Transparency and consumer information Energy efficiency
Recommend standardising battery designs in the future, and reparability ideally down to the cell-level	• The lack of standardisation in battery pack design complicates refurbishment efforts. • Policymakers should encourage the development of industry standards for battery design, including size, electrode chemistry and format. Standardisation can simplify the refurbishment process, reduce costs and increase the efficiency of second-life applications. • In addition, battery repairability down to at least the module-level and ideally the cell level is needed (especially with newer cell-to-pack designs) to prevent unnecessary full battery replacements, which would also support consumer rights and competition in the repair market.	End of life xEV batteries
Encourage data sharing and collaboration on battery state and performance	• Effective repurposing of xEV batteries also requires extensive data on their current state and performance down to the cell-level. • Enhanced data sharing and collaboration on battery state should ensure that all authorized independent operators have access to relevant data, promoting a level playing field and consumer choice. • Policies should therefore incentivise data sharing and collaboration between industry stakeholders, including battery manufacturers, automotive companies and energy storage providers. • This could be facilitated by the creation of centralised data repositories and collaborative platforms.	End of life xEV batteries
Identify and implement improved testing and certification protocols for second-life batteries	• Predicting the life expectancy of repurposed batteries is challenging due to limited empirical data. • Similarly as for first use, establishing robust testing and certification protocols for second-life batteries can provide more reliable estimates of their performance and lifespan. • This could include establishing dedicated testing facilities and encouraging industry-wide data sharing to build a comprehensive database of battery performance metrics.	End of life xEV batteries

Policy recommendation	Further detail	Related tasks
	• A clear standardised measurement procedure for battery capacity and performance over time needs to be established, to ensure transparency and reliability for consumers.	
Incentivise domestic battery reuse and recycling capacity	• Currently many countries will lack the domestic infrastructure to recycle end-of-life batteries, requiring them to be shipped long distances. Classified as hazardous waste, these batteries require additional safety precautions and increase transport and logistics costs, which can account for up to 63% of total reuse or recycling costs. • Developing local capacity for battery reuse could significantly reduce costs, boost local economies and reduce dependence on global supply chains. Governments could encourage this development through incentive programmes, supportive tax policies, trade regulations and public-private partnerships.	End of life xEV batteries
Continue advocating for mandatory recycling efficiency, material recovery rates and recycled content targets for key battery materials	• The EU Sustainable Battery Regulation sets recycling efficiency and material recovery rate targets for end-of-life batteries. The recycling target for lithium-ion batteries by weight is 70% by the end of 2030 and the material recovery target is 95% for cobalt, copper, lead and nickel and 70% for lithium. • In the regulation, new batteries in the market will be subjected to mandatory minimum levels of recycled content requirements. By 2035, batteries will need to contain minimum recycled content of 20% for cobalt, 10% for lithium, 12% for nickel and 85% for lead. • For recycling efficiency, it is crucial to ensure that these targets are verifiable by independent labs, preventing greenwashing and ensuring true environmental benefits.	End of life xEV batteries
Increase public awareness and education about the benefits and safety of second-life batteries.	• Informing consumers and stakeholders about the environmental and economic benefits of repurposing xEV batteries can increase demand and support for these initiatives.	Transparency and consumer information End of life xEV batteries
Develop a methodology and provide information on total cost of ownership (TCO) of electric vehicles (for new and second hand models)	• Provision of information on **Total Cost of Ownership (TCO)** of electric vehicles – for both new and used – would highlight to consumers the lower running costs, availability of financial incentives and energy costs of electric vehicles compared with ICEs, which could help to alleviate consumer concerns regarding **affordability** and enable more **realistic comparisons** between models. • The methodology for TCO should be tailored to local contexts and applicable to both new and second-hand vehicles, making it more relevant for consumers across different regions. • In terms of how this information could be provided, this could be through OEM manuals/websites, although an agreed approach would be required to ensure appropriate comparisons. There is also an opportunity for TCO information to be included on the Car CO_2 label (or similar).	Transparency and consumer information

Policy recommendation	Further detail	Related tasks
Advocate for information on electric range, recharging speed and battery health status to consumers/users of BEVs	• Information on expected electric range could be provided to consumers during the purchase decision stage (e.g., OEM manuals / websites, comparison sites). Information should be accurate and transparent, ensuring that the conditions that might influence the range achieved are clearly explained/stated. ○ Information could be region/climate specific - HVAC takes up a large share of total energy consumed in colder climates, and some vehicles perform better in colder climates than others ○ More transparency regarding the intended use of vehicles – for example, consumers who intend to drive long distances on motorways should be advised not to purchase a large/heavy BEV if they want to maximise range. • Additional information could be provided via OEM manuals on how users can maximise driving range. ○ This includes through highlighting impacts of aggressive driving and considering effective charging strategies • Highlighting the electric range of vehicles on a revised Car CO_2 label (standardised across all Member States) could also be an option. ○ It is not clear whether electric range is to be included on the EVP (required by the Type Approval Regulations). ○ What is needed is a ‘typical’ range for real-world driving, that consumers can understand and not mistrust – perhaps with variations in the range expected in different conditions (e.g. urban vs highway driving, driving in low temperature conditions, etc). • Information on electric range for users of electric vehicles (in use/on board) tends to be reliable and based on real-world data delivered by the vehicle or associated OEM application. However, it is not currently collected in a standardised way in order to understand the trends in factors affecting energy consumption over the fleet or how this is changing over time. • Battery information (health / status / durability): This is being addressed to some extent through the SBR and the requirement for a battery passport, and Euro 7 Regulations and the Environmental Vehicle Passport (information on battery range and state of health). ○ The new Euro 7 standard also sets requirements for all BEVs and PHEVs registered in the EU to have minimum levels of battery durability, relating to age and mileage, to address consumer concerns on battery durability. ○ The provision of battery passport in EU requires battery manufacturers to disclose information on batteries such as characteristics (e.g. chemistry), SOH and operation	Transparency and consumer information Energy efficiency End of life xEV batteries

Policy recommendation	Further detail	Related tasks
	history. Making this information available will help reduce costs of repurposing and recycling. ○ However, further reliable information needs to be provided to consumers regarding battery durability and impacts (in particular for used EVs and their owners). This could be via information in OEM manuals and OEM applications. • Information on recharging speed: Recharging speed information allows consumers to assess how quickly an electric vehicle can be recharged, which directly impacts convenience and practicality in daily use. OEMs should be required to clearly disclose the recharging speed of their vehicles in all consumer-facing materials.	
Increase awareness of xEV chargepoint location and accessibility amongst potential BEV consumers	• Improvements could be made in raising awareness of recharging infrastructure deployment in Member States to alleviate the perceived lack of provision (contributing to concerns relating to range anxiety). ○ It is acknowledged that considerable progress has been made in terms of the roll-out and provision of recharging infrastructure in the EU – this progress needs to be communicated to consumers to alleviate concerns regarding access to recharging infrastructure. ○ Increased public infrastructure deployment and awareness will also act to reduced the perceived and actual need for larger batteries/range for BEVs (reducing production and operational energy consumption impacts) • In terms of information provision, users of electric vehicles are well-catered for, with many OEM applications and third-party applications providing up to date information on the location, availability and associated use of recharging infrastructure. • Additionally further information on useability of recharging infrastructure (via recharging infrastructure providers, OEM manuals) and battery charging times (via OEM manuals, applications) could be provided.	Transparency and consumer information
Consider the provision of more standardised environmental information to consumers and BEV users, including lifecycle assessment (LCA)	• Although environmental considerations (e.g., CO_2 emissions, air pollutant emissions etc.) feature in the consumer purchase decision process, they are not the primary concern for consumers. • The current Car Labelling Directive addresses the provision of environmental information for new passenger cars through requiring the tailpipe CO_2 emissions of vehicles to displayed at point of sale on a label (and also through other media, including guide, poster and promotional material). However, as sales and shares of electric vehicles continue to increase, the suitability of tailpipe CO_2 emissions as a metric to compare models has become less relevant or appropriate.	Transparency and consumer information Lifecycle emissions Sustainability of manufacturing processes

Policy recommendation	Further detail	Related tasks
	• Depending on how it is implemented, the forthcoming requirements of the Vehicle Type Approval Regulation (Euro 7) to provide information on CO_2 emission, pollutant emission limits and fuel consumption via the Environmental Vehicle Passport will go some way to providing this information for individual vehicles, but it is uncertain how easily this information will be to access or how visible it will be prior to purchase – at the point where it can be taken into consideration in the purchase decisions process. However, as with the Car CO_2 label, provision of information on tailpipe emissions is not an appropriate metric for consumers wanting to make informed comparisons between models (which include electric vehicles). This does, however, create the opportunity to provide additional standardised environmentally-related information to be disseminated to consumers. • Provision of LCA information for electric vehicles (and all other types of vehicles – new and used) could enable comparisons to be made between electric vehicles and ICEVs. However, there are some important considerations to ensure the information provided is effective: ○ Accuracy of data – OEM LCAs tend to be more accurate due to the fact they have access to data from suppliers at the various stages in the value chain. However, they also do not tend to use a standardised methodology (including definition of the various lifecycle stages) and make different assumptions about use (years/km, and energy/fuel use), which means it is not possible for consumers to make accurate comparisons between models. OEM LCAs are also typically only available for selected (often the most popular) models and concerns regarding the testing methodologies used. ○ Conversely, third party LCA interactive tools (e.g., Green NCAP) attempt to present comparable LCA information to consumers providing indicative information on a range of metrics, whilst acknowledging lower real-world accuracy of the data. ○ The European Commission is currently in the process of developing (by the end of 2025) a harmonised European methodology for vehicle LCA as part of the LDV CO_2 regulations (European Commission, 2023), for voluntary reporting by OEMs.	

CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Abbreviation	Definition
AC	Alternating current
ACEA	European Automobile Manufacturers' Association
ADP	Abiotic Depletion Potential
ADPel	Abiotic Depletion Potential Elements
AECC	Association for Emissions Control by Catalyst
AFID	Alternative Fuels Infrastructure Directive
AFIR	Alternative Fuels Infrastructure Regulation
ANEC	The European Consumer Voice in Standardisation
AP	Acidification Potential
ASSB	All-solid-state batteries
AVERE	European Association for Electromobility
BAIC	Beijing Automotive Group
BEUC	European Consumer Organisation
BEV	Battery electric vehicles
BF	Blast furnace
BF-BOF	Blast furnace-basic oxygen furnace
BMK	Austrian Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology
BMS	Battery management system
CAM	Cathode active materials
CBAM	Carbon Border Adjustment Mechanism
CECRA	European Council for Motor Trades and Repairs
CFF	Circular Footprint Formula
CFRP	Carbon-fibre reinforced plastics
CoC	Certificate of conformity
CONG	Congested
COPERT	Calculator of air pollutant emissions from road transport
CRM	Critical Raw Materials
DC	Direct current
DfC	Design for Circularity
DG CLIMA	Directorate-General for Climate Action
DOD	Depth of Discharge
DRC	Democratic Republic of Congo
DRI	Directly Reduced Iron
EAF	Electric arc furnaces

Abbreviation	Definition
EBA	European Battery Alliance
EoL	End of life phase
EP	Eutrophication Potential
EPR	Extended Producer Responsibility
ETP	Ecotoxicity Potential
EVP	Environmental Vehicle Passport
FCEV	Fuel cell electric vehicles
FF	Free flow
FIA	Federation Internationale de l'Automobile
FU	Functional unit
GHG	Greenhouse gases
NCAP	New Car Assessment Program
GW	Gigawatts
GWP	Global Warming Potential
GWP_P	Global Warming Potential of vehicle production stage
$GWP_{P,H}$	Harmonised Global Warming Potential of vehicle production stage
GWP_U	Global Warming Potential of vehicle use stage
$GWP_{U,H}$	Harmonized Global Warming Potential of vehicle use stage
H2-DRI	Hydrogen-Directly Reduced Iron
H2-DRI-EAF	Hydrogen based direct reduction with electric arc furnace
HESS	Home Energy Storage Systems
HEV	Hybrid electric vehicles
HEV-G	Hybrid Electric Vehicle-Gasoline
HORSE	Powertrain component manufacturer
HTP	Human Toxicity Potential
HVAC	Heating, ventilation and air conditioning
ICCT	International Council on Clean Transportation
ICEV	Internal combustion engine
ICEV-D	Internal Combustion Engine Vehicle-Diesel
ICEV-G	Internal Combustion Engine Vehicle-Gasoline
IEA	International Energy Agency
ISO	International Organization for Standardization
JRC	Joint Research Council
$KgCO_2e$	Kilograms of carbon dioxide equivalent
Km	Kilometre

Abbreviation	Definition
LC	Life cycle
LCA	Life Cycle Assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LDV	Light duty vehicle
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
MSW	Municipal Solid Waste
NEDC	New European Driving Cycle
NMC	Nickel manganese cobalt
OBFCM	On-board fuel consumption
ODP	Ozone Depletion Potential
OEM	Original equipment manufacturer
PEF	Product Environmental Footprint
PEMS	Portable Emissions Monitoring Systems
PHEV	Plug-in hybrid electric vehicle
PHEV-G	Plug-in Hybrid Electric Vehicle-Gasoline
PM	Particulate matter
POCP	Photochemical Ozone Creation Potential
POFP	Photochemical Oxidant Formation Potential
PTC	Positive temperature coefficient
PV	Photovoltaics
PVDF	Polyvinylidene fluoride
R&D	Research and Development
RDC	Real driving conditions
RDE	Real Driving Emissions
RDW	Netherlands Vehicle Authority
RE	Renewable energy
RED	Renewable Energy Directive
RWC	Real world cycle
SBR	Sustainable Batteries Regulation
SIB	Sodium-ion battery
SLI	Starting, Light, and Ignition batteries
SOC	State of charge
SOH	State of health
SSMS	Sustainable and Smart Mobility Strategy
SUV	Sport utility vehicle

Abbreviation	Definition
T&E	Transport and Environment
TCO	Total cost of ownership
TTW	Impacts due to emissions from the vehicle during operational use
V2V	Vehicle to vehicle
VKT	Vehicle km travelled
VKT_H	Harmonised vehicle km travelled
VO	Vehicle occupancy
WLTC	Worldwide harmonised light vehicle test cycles
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
WTT	Well-to-Tank fuel/electricity production cycle
xEV	Generic name for electromotive vehicles such as a hybrid electric vehicles, plug-in hybrid electric vehicles and fuel-cell electric vehicles

1. INTRODUCTION

1.1 CONTEXT

Recent data from ACEA (2024) demonstrates that the sales share of battery electric vehicles (BEV) has increased to 14.6% in 2023 (up from 12.1% in 2022) in the EU, with market share continuing to grow. Hybrid electric vehicles also achieved a market share of 25.8% (up from 22.6%), and plug-in hybrid electric vehicles 7.7% (down from 9.4%). For the first time, traditional gasoline and diesel fuelled cars accounted for less than half of EU car sales in 2023, i.e., 48.9% market share compared to 52.8% in 2022, with market share continuing to decline.

Electromobility has a significant role to play in delivering a smooth transition towards climate neutrality, a key focus of the European Green Deal (launched in December 2019), the EU's growth strategy that aims to transform the EU into a fair and prosperous society, with modern, resource efficient and competitive economy. It covers all sectors of the economy (including transport). In the context of the European Green Deal, EU Member States are committed to turning the EU into the first climate neutral continent by 2050. To get there, they have pledged to reduce emissions by at least 55% by 2030 comparted to 1990 levels (as set out in the Commission's 2030 Climate Target Plan, and enshrined in the European Climate Law, 2021). This ambition is aligned with the Paris Agreement to keep global temperature increase below 2°C and work to keep it to 1.5°C.

In the transport sector, the Commission's Sustainable and Smart Mobility Strategy (SSMS) (2021) outlines the ambition for at least 30 million zero-emission cars to be in operation on European roads by 2030, with nearly all cars, vans, buses and new heavy-duty vehicles being zero emission by 2050. The SMSS also states the Commission's ambition to increase the number of electric charging points to 1 million by 2025, rising to 3 million by 2030.

The 2030 ambition is implemented through legislative proposals set out in the Commission's '**Fit for 55' Package**, which was announced in July 2021. Key proposals and updates to legislation relating to the transport sector and the future uptake of EVs include:

- Amendment of the Regulation setting CO_2 emission standards for cars and vans (previously Regulation 2019/631, amended by Regulation (EU) 2023/851). This included the introduction of more demanding EU-wide CO_2 emission reduction targets for 2030 (55% reduction compared to 1990), and a new target of 100% emissions reduction from 2035 onwards. By 2025, the Commission will present a harmonised EU methodology for the calculation of life cycle emissions of cars and vans as well as for the fuels and energy consumed by these vehicles. The reporting of vehicles' lifecycle CO_2e emissions by manufacturers would be on a voluntary basis from 2026, and mandatory from 2028.
- Revision of the Alternative Fuels Infrastructure Directive (AFID) (Directive 2014/94/EU) resulting in the Alternative Fuels Infrastructure Regulation (AFIR) ((EU) 2023/1804). Measures in the Regulation include concrete targets for deploying alternative fuels infrastructure in EU Member States (recharging and refuelling) aimed at road, maritime and aviation modes. Other measures address issues relating to the lack of transparency on pricing, facilitating cross-border payments when charging e-vehicles and the use of common standards.
- Proposal for updated Regulation on Euro 7 emission standards aims to further reduce pollutant emissions from vehicles and improve air quality (supporting the Commission's 'zero pollution' ambition also under the European Green Deal). Whilst the CO_2 emission standards will drive the deployment of zero-emission vehicles, it is anticipated that approximately 20% of cars and vans on the roads in 2050 will continue to emit pollutants from tailpipe, and BEVs will also contribute to pollutant emissions via brakes and microplastics via tyres. The new Euro 7 emission standards will aim to address these impacts.
- The Sustainable Batteries Regulation ((EU)2023/1542) replacing the previous Directive (2006/66/EC) aims to uphold the environmental performance, safety and durability of xEV traction batteries (among batteries for other applications) supporting the placement of batteries with low carbon footprint, using minimal hazardous substances, requiring progressively lesser amount of non-EU derived critical materials, in addition to improving the end-of-life (EoL) management of resources from expired EoL batteries.

These policies and pieces of legislation are expected to further stimulate and support the electrification of the passenger car fleet, pushing consumers to make the transition from fossil fuel cars to electric vehicles, with the ambition to move towards zero and low-emission vehicles, while ensuring that appropriate charging infrastructure is also in place. Another important consideration, in line with FIA's list of policy priorities, is customer protection, i.e., ensuring consumers are able to make informed decisions when purchasing vehicles.

Consumer information relating to electric vehicles is of particular importance, due to the increased policy focus on their continued uptake and importance in contributing to achieving the EU's climate neutrality goals. Consumers must ideally receive relevant information on the sustainability credentials of zero-emission vehicles and their components, communicated via an appropriate channel. Consumers then need to understand the information; only if they successfully reach this stage, will they be able to use the information to inform their purchase decision.

Consumer decisions regarding the purchase of new passenger cars are currently targeted through the 'Car Labelling Directive' (Directive 1999/94/EC). The legislation requires that information on a car's fuel efficiency and CO_2 emissions is provided to consumers via a label that provides this information (amongst other formats). The aims of the Directive are to assist consumers in buying or leasing cars that use less fuel, and thereby emit less CO_2. It also aims to encourage manufacturers to reduce the fuel consumption/CO_2 emissions of new cars. However, as EU battery-electric new car registrations in the EU continue to surge (reaching over 20% market share in August 2023, compared to 11.6% the previous year) it is becoming clear that **comparisons between BEVs based on use-phase direct exhaust CO_2 emissions alone** (as required by the Car Labelling Directive) **are not sufficient for consumers to make an informed decision**. A range of further aspects should be duly taken into consideration in the decision-making process to distinguish between the electric vehicle models on offer, including **overall lifecycle GHG emissions (as CO_2e), comparative sustainability of the manufacturing processes, real-world energy efficiency, and battery life/second-life applications**. This study aims to carry out a review of the available literature evidence on these four important aspects, and thereby provide FIA with an up-to-date summary of the key findings, which will help to better inform consumer decisions and policy recommendations.

1.2 STUDY OBJECTIVES AND SCOPE

The aim of the study is to perform research and analysis into a range of aspects relating to the sustainability of EVs and how this is communicated to consumers, to improve understanding of the factors and the variation in impacts, and to inform the development of suitable policy recommendations. The work has involved conducting a range of research in five key areas relating to EVs:

1. Lifecycle emissions (Section 2)
2. Sustainability of manufacturing processes (Section 3)
3. Real world energy efficiency (Section 4)
4. Battery life and second-life applications (Section 5)
5. Transparency and consumer information (Section 6)

The study has culminated in this summary report on the findings, including the development of potential policy recommendations (Executive Summary).

The scope of the work is focused on passenger cars sold and operated within the EU/Europe.

2. LIFECYCLE EMISSIONS

2.1 INTRODUCTION AND OBJECTIVES

The overall aim of this chapter is to provide an assessment of the net environmental benefits of xEV adoption, based on an assessment of the available evidence from lifecycle assessment. The objective of the analysis by the study team was therefore to review and harmonize available quantitative information on GHG emissions associated with all phases of the life cycle of a range of electric vehicle options (xEVs), collect new updates from the latest literature, and compare to corresponding GHG emissions for more conventional internal combustion vehicles (ICEVs). To achieve this objective, three main sub-tasks were carried out:

- Collection, screening and review of published LCAs
- Harmonisation of literature information on life-cycle emission data
- Quantification of net environmental benefits of xEV adoption, also incorporating LCA modelling results from analyses made by Ricardo as part of our previous work

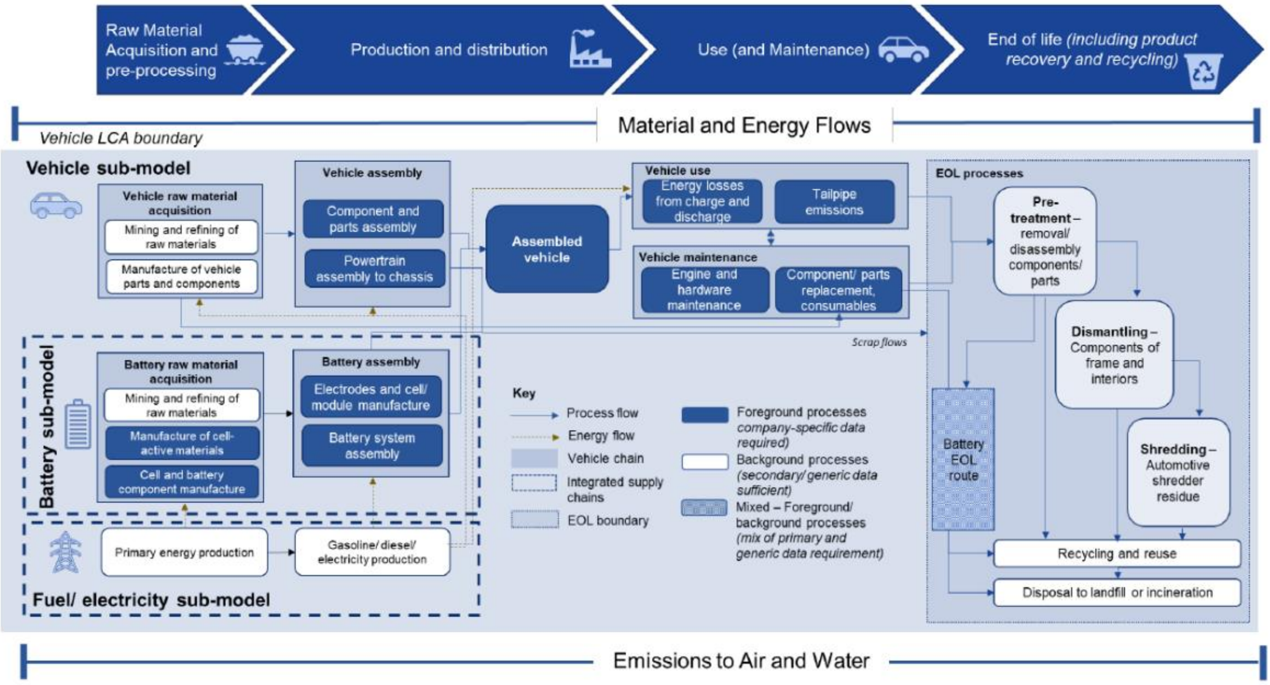
The scope focuses specifically on the xEV options that have emerged as the most significant contenders, namely: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs), as compared to ICEVs (both gasoline and diesel variants). ICEVs running on biofuels or e-fuels were excluded from the scope defined for this review.

2.2 BACKGROUND AND CONTEXT

Lifecycle Assessment (LCA) is a methodology for assessing the environmental impacts of a product or process, across all its life cycle stages. For a passenger vehicle, these stages, as illustrated in Figure 2-1, comprise the following:

- Raw material acquisition and pre-processing
- Material transport (between extraction site, intermediate processing plants and the product manufacturing site)
- Vehicle manufacturing
- Vehicle use and Maintenance (servicing)
- EoL (which may include repurposing, repair, recycling and/or disposal)

Figure 2-1: Lifecycle phases of a passenger vehicle



Source: (Ricardo, 2023)

As defined in ISO standards 14040 and 14044, LCA is undertaken in four stages:

1. **Goal and scope setting**

   At this stage, the purpose and intended audience of the analysis, the product and/or process (system) boundaries and key characteristics, geography and time of analysis, and the system's functional unit (FU, e.g., vehicle·km travelled) are all defined.

2. **Life Cycle Inventory (LCI) analysis**

   At this stage, a complete list of all the material and energy flows that cross the system's boundary is compiled, tracing back all flows to their origin at the interface with the geo-biosphere (i.e., nature).

3. **Life Cycle Impact Assessment (LCIA)**

   At this stage, the input and output flows collected at the LCI stage are classified into separate environmental impact categories (e.g., Global Warming, etc.). Within each category, the results are characterised in terms of equivalent quantities of a reference compound (e.g., CO_2e) and then summed together, to produce category-specific mid-point indicators of potential environmental impact.

4. **Result interpretation**

   At this last stage, the quantified impacts are reviewed and interpreted to inform the assessor and client of the key environmental hotspots across the whole life of the product. Sensitivity analyses may also be carried out to investigate a range of alternative scenarios, or to estimate result susceptibility to data uncertainty.

2.3 COLLECTION AND SCREENING OF THE LITERATURE

A wide range of sources were identified for consideration during the research for this project, also building on Ricardo's previous work. The methodology used for collection, screening and prioritisation of the literature is discussed in detail in Appendix A1. Within the 45 selected literature sources, 87 vehicle data points were identified.

Reviewing papers with a European focus was a priority for the study. Therefore, most data points collected (59%) reflect vehicle LCAs where a European electricity grid mix was assumed for the use phase. Papers from North America and Asia & Australia were also taken into account, with 14% and 26%, respectively.

ICEVs and BEVs were the two powertrain types that were most widely reported on in vehicle lifecycle analyses (with fewer studies including analyses of PHEVs and FCEVs), respectively reflecting the current dominance of ICEVs as the "default" standard, and the growing recognition of the prominent role that BEVs are expected to play in transitioning away from conventional ICEVs.

For all the vehicle data points collected, results were provided for the "current year" (as assumed in the original publications). Additionally, for 14 data points future projections for vehicle lifecycle emissions for a set year in the future were also included. These forward-looking analyses offer insights into the potential environmental impacts of vehicles over time.

2.4 REVIEW OF EVIDENCE FROM THE LITERATURE ON LIFE-CYCLE EMISSIONS OF PASSENGER CARS

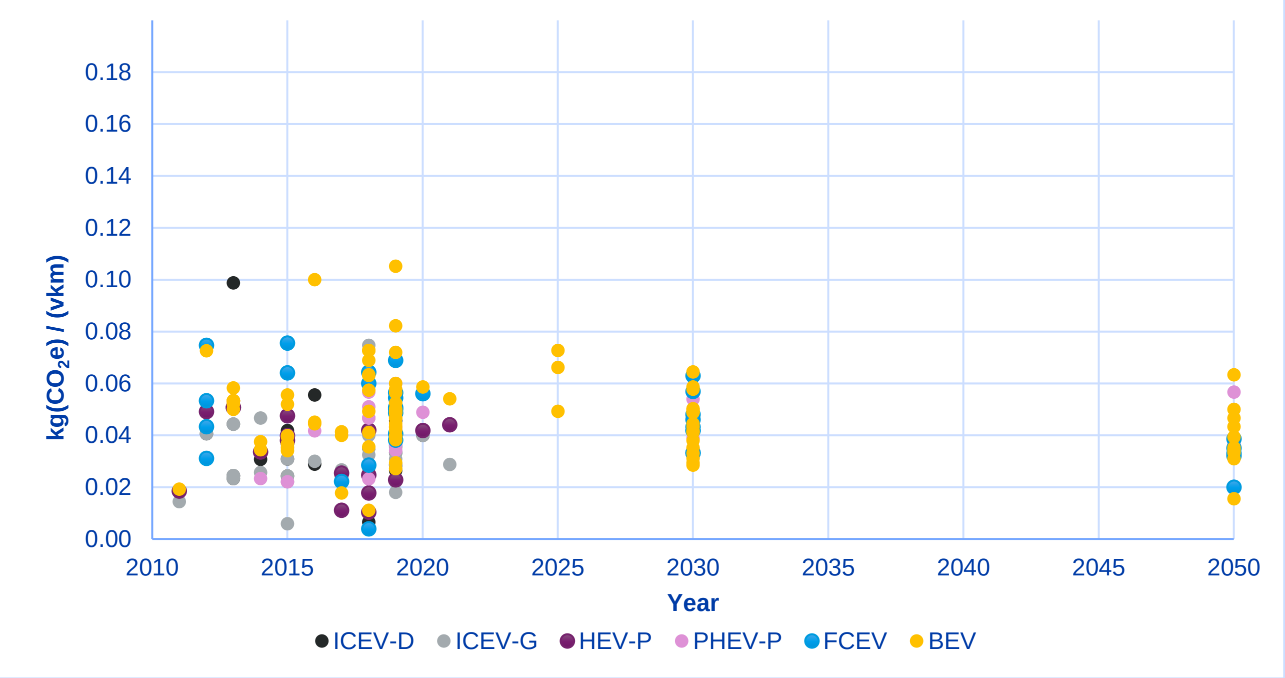
As part of the analysis, Ricardo conducted a harmonisation exercise on the information collected in the literature review, which was essential to ensure consistency and comparability of the results. By standardising the data sources and assumptions across the papers, meaningful comparisons can be made between vehicle types, allowing the identification of emerging trends in environmental impacts. Further information on the harmonisation methodology is provided in Appendix A1.

2.4.1 Production emissions

Figure 2-2 reports all the GHG emission data points extracted from the reviewed literature, post-harmonisation. It should be noted that the horizontal axis indicates the actual vintage of the data used in the calculations and not the year of publication of the LCA.

One significant factor affecting the results of the analyses is the assumed lifetime mileage of the vehicle. In particular, this parameter determines over how many km the initial vehicle production emissions are artificially "spread out" in order to express them per FU (i.e., per vehicle·km). The GHG emissions per vehicle·km during the use phase are instead unaffected by the assumed vehicle lifetime mileage. As outlined in Section A1.2, all data in the study were harmonised to a total lifetime mileage of 225,000km (based on Ricardo's previous analyses on the typical lifetime mileage of Lower Medium Cars in Europe, (Ricardo et al., 2020)). However, a sensitivity analysis was also carried out to determine the impact of different lifetime mileages on the overall vehicle GHG emissions. The results of this sensitivity analysis are reported in Appendix A1.

Figure 2-2: GHG emissions associated with the vehicle production phase



Notes: All data harmonised to: FU = Vehicle·km travelled and 225,000 km lifetime mileage; Key: ICEV-D/G = internal combustion engine vehicle – diesel / gasoline, HEV = hybrid electric vehicle, PHEV = plug-in hybrid electric vehicle, FCEV = fuel cell electric vehicle, BEV = battery electric vehicle.

In general, **production emissions for xEVs tend to be higher than those associated with conventional power train types,** primarily due the battery, fuel cell and H2 storage systems.

In particular, **for BEVs, production emissions are largely influenced by the battery packs used, and current production emissions frequently reported are typically double or more those of similar ICEVs** (depending on vehicle specifications, and particularly location of battery manufacturing). It is important to note that the majority of the impacts from battery manufacturing are directly linked to the amounts of materials used in the batteries, which, in first approximation, are proportional to battery mass, not battery energy storage capacity. Therefore, generally speaking, improvements in battery formulations that are characterised by increased gravimetric energy density tend to directly reduce the environmental impacts of battery manufacturing, per kWh of energy storage. However, battery manufacturing is also a highly energy intensive process, so the energy mix /region of manufacturing particularly the battery cells (and cathode materials), is also highly influential on the overall production impacts. Up to now, this **potential for emission reductions over time (due to newer battery chemistries with increased energy density) has in many cases been offset by a parallel upwards trend in battery capacity per vehicle,** a strategy that OEMs have adopted to increase the electric driving range and thus address one of the main perceived drawbacks of BEVs (often referred to as "range anxiety"). However, it may be expected that in the coming years and decades, once sufficiently long electric ranges are achieved for all vehicles (also considering a wider roll-out of charging infrastructure), increasing battery sizes any further will no longer be a strategy worth pursuing (and/or consumers will less frequently opt to purchase more expensive long-range model variants), and hence **reduced production impacts per vehicle will start to emerge more clearly as a consequence of improved battery energy densities** (as well as other improvements to vehicle efficiency).

Two additional key areas hold particularly significant potential for emission reductions in vehicle manufacturing in the future, namely:

- The expected **decarbonization of the grid mixes** providing the electricity used in vehicle (and battery) manufacturing; and
- The gradual **replacement of conventional blast furnace-basic oxygen furnace (BF-BOF) steel production** (a process that entails significant GHG emissions, both directly due to the carbon coke used as a reducing agent, and indirectly due to the fuels combusted to attain the required high temperatures in the furnaces) **with steel production via the "green" Hydrogen-Directly Reduced Iron (H2-DRI) route, which uses low-GHG renewable electricity in both key stages** (respectively, to electrolyze water and produce the H_2 used to reduce the ore directly, and to power the subsequent Electric Arc Furnace where the iron is converted into steel).

Finally, overarching drivers for reductions in vehicle manufacturing emissions in the future, across all power train types, are represented by environmental policies and legislation. **Europe is at the forefront of this global trend, with multiple pieces of legislation aimed at improving circularity and reducing waste across the entire vehicle supply chain** (ELV Directive, Euro 7 Regulation, proposed Circularity Requirements for vehicles). Of specific relevance to BEVs is then the newly introduced Battery Regulation, which explicitly mandates the use of LCA and life-cycle approaches to the quantification of environmental impacts, and is set to introduce quantitative targets also for both EoL recycling and minimum content of recycled content in battery manufacturing.

2.4.2 Use phase emissions

As illustrated in Figure , the use phase emissions collected in the literature span a wide range. This life cycle phase reports the greatest GHG emissions, up to three times higher than the production phase emissions. ICEV-Gs reported the highest use phase emissions of all the power train types, followed by ICEV-Ds.

The use phase emissions associated with FCEVs varied considerably, depending on the H2 supply chain. In particular, current H_2 production relies for the most part on chemical reforming of natural gas, which entails considerable CO_2 emissions ("grey H_2"). Several literature studies assumed that such grey H_2 will continue be used throughout the use phase of current production vehicles (some also making the same assumption for the 2030 data points), resulting in use phase emissions towards the higher end of the relatively wide range reported in Figure for FCEVs. Conversely, other studies assumed varying proportions of the H_2 use to power the FCEVs to be produced by electrolyzing water using renewable electricity ("green H_2"), leading to markedly lower estimates for the associated use phase emissions. It is also noteworthy that green H_2 was assumed in all studies for the later 2050 datapoints.

For PHEVs, the performance typically falls in-between those of HEVs (non-plug-in hybrids) and BEVs, with a wide variance based on different assumptions on electric range/battery size, as well as how this translates into real-world share of operation in electric (charge depleting) and non-electric (charge sustaining) modes. Recent evidence from real-world fuel consumption monitoring in the EU (European Commission, 2024) suggests that the real-world emissions for PHEVs sold to date are on average far higher than those estimated in even the more conservative LCA studies (with exhaust emissions being on average 3.5 times higher than official figures according to regulatory testing using WLTP). This is likely due to a combination of the real-world electric range being lower than WLTP-basis, and user behaviour (i.e., not charging the vehicle as frequently as anticipated, so operating only on non-electric mode for a much higher share of overall km).

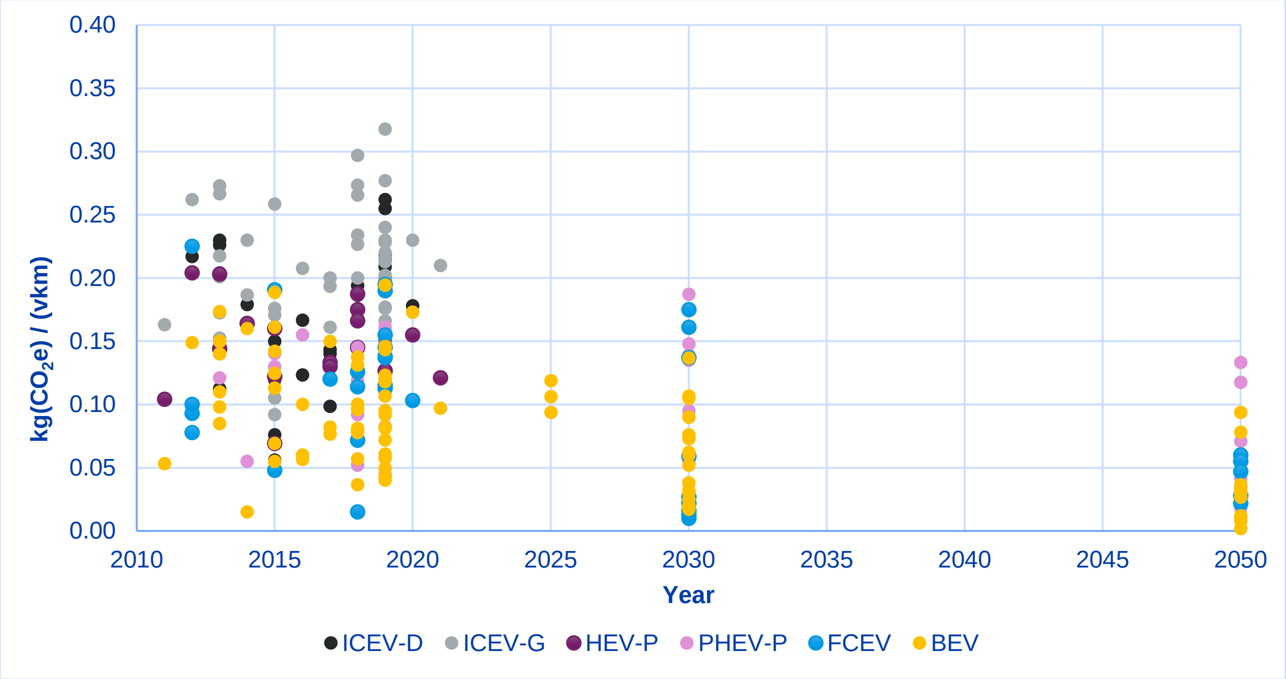
Finally, in broad general terms, **BEVs tend to be characterised by the lowest use phase GHG emissions across all power train types considered** (with isolated exceptions).

BEV use phase emissions vary considerably according to the assumed location and associated electricity grid mix. Given that use phase emissions generally dominate the overall life-cycle emissions of BEVs, the influence of geographic location is then discussed in more detail in Section 2.4.4.

Regardless of location, it is then important to note that **most of the reviewed literature studies made simplistic assumptions on the composition of the electricity grid mix**. Essentially, each data point was calculated while assuming that the grid mix will remain the same as for the year when the vehicle is produced, throughout the entire use phase of the vehicle. Yet, in a world where most countries are actively engaged in efforts directed at decarbonising electricity generation, **such assumptions are overly simplistic and likely overly pessimistic** when reporting on use phase emissions over time.

Some studies address this oversimplification by a way of a sensitivity analysis, repeating the BEV calculations for one or more alternative grid mix compositions, which are deemed representative of corresponding future energy scenarios, at certain static point in time (i.e., 2030 and/or 2050). These values are also reported in Figure .

Figure 2-3: Lifecycle GHG emissions reported associated with the vehicle use phase

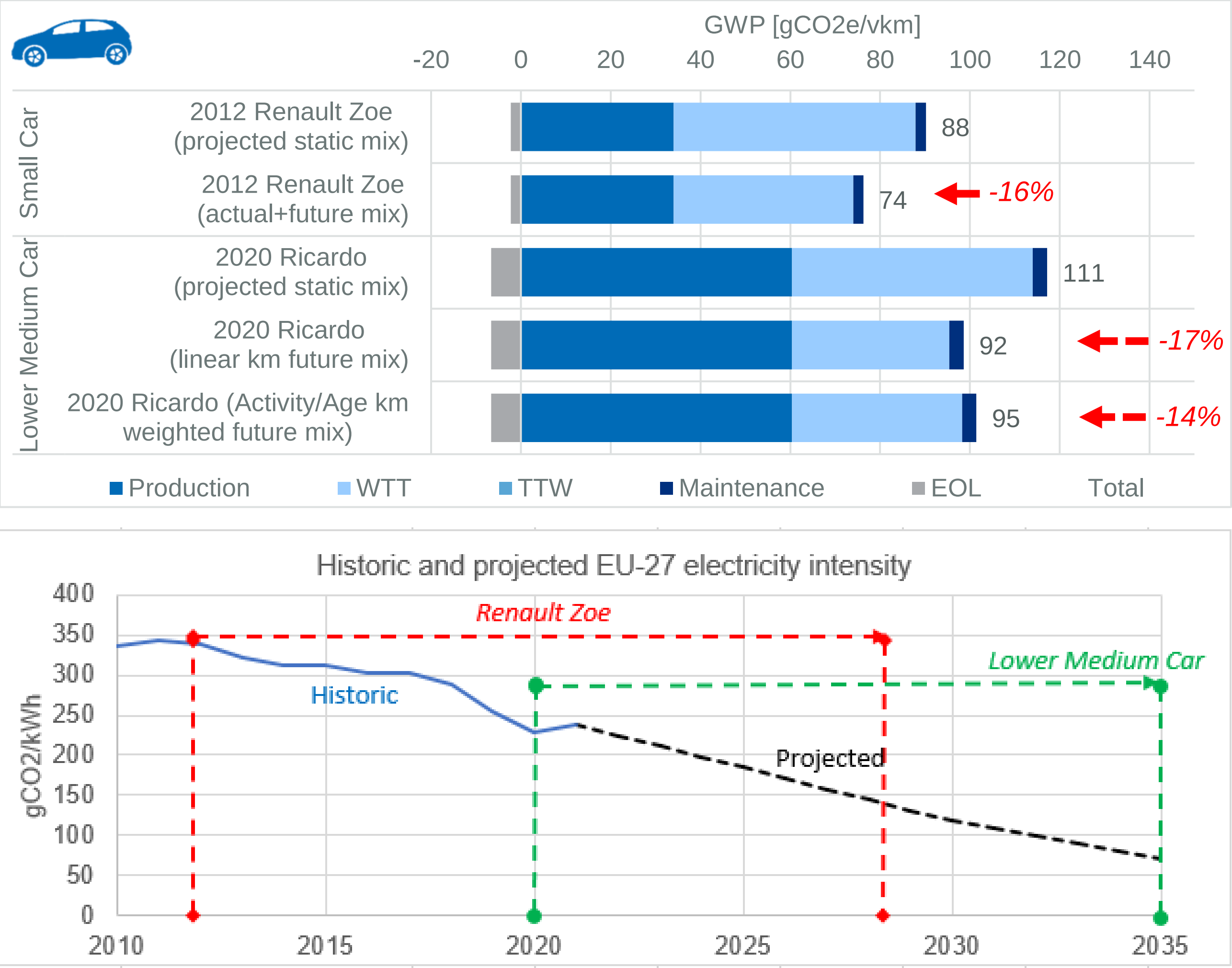


Notes: All data harmonised to: FU = Vehicle·km travelled and 225,000 km lifetime mileage. Key: ICEV-D/G = internal combustion engine vehicle – diesel / gasoline, HEV = hybrid electric vehicle, PHEV = plug-in hybrid electric vehicle, FCEV = fuel cell electric vehicle, BEV = battery electric vehicle.

However, **a different approach is likely to be far more appropriate and conducive to more realistic results, namely assuming a "dynamic" grid mix composition** that is allowed to change over time throughout the expected service life of the vehicle (as has been the case in Europe and many other regions in the historic record). None of the reviewed literature studies applied such a "dynamic" modelling element, with the exception of more policy-focused studies by Ricardo and ICCT, which suggests there is a gap in the literature.

Figure provides an illustration of the effects of these different assumptions for the EU average grid mix, also showing how the results of an LCA of an historic BEV model were over-estimated due to assuming a static grid mix. Within Europe, the GHG intensity of electricity production/supply has decreased consistently since 1990 (from ~500 gCO_2/kWh) and, based on already implemented current policy, is projected to continue decreasing significantly in the future (EEA, 2023). An additional consideration that can also have an effect on the overall assessment is the variation in annual activity of vehicles over their lifetime, with newer vehicles typically being driven more km in their initial years of operation than older vehicles nearing the end of their lifetimes. This effect of this is also illustrated in Figure , where the electricity GHG intensity is higher for those years where annual km is typically also higher.

Figure 2-4: The impacts of assumptions of 'static' or 'dynamic' electricity mix projections on the overall lifecycle GHG emissions of passenger cars



Sources: (1) Adapted by Ricardo from (Renault, 2012); (2) Ricardo vehicle LCA modelling (October 2023); (3) (EEA, 2023): Greenhouse gas emission intensity of electricity generation in Europe.

Notes: 2012 vehicle energy consumption based on NEDC for the Renault Zoe has been adjusted by Ricardo to WLTP-basis (via official data for Wh/km NEDC and WLTP from CO_2 monitoring published by the EEA); Ricardo 2020 generic lower medium car based on WLTP average for segment. All data normalised to 225,000 km lifetime over 15-year life. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. GWP = Global Warming Potential.

Although not always captured by the reviewed literature, a further factor that may be expected to lead to a **decrease in use phase emissions for future BEVs** (and to a lesser extent, also PHEVs and HEVs) is represented by the **on-going improvements in battery technologies**, with concomitant reduced mass per unit of energy storage, which can **enable vehicle lightweighting and hence reduced energy consumption** (assuming that total required energy storage per vehicle stabilizes and is not increased also – as previously discussed in Section 2.4.1).

2.4.3 End of Life emissions

Methodological inconsistencies and lack of sufficient detail and disaggregation in the reviewed literature made it impossible to include EoL GHG emission estimates in our harmonization exercise (discussed further in Appendix A1).

One of the key considerations to this effect is the use of different EoL allocation methods, which particularly affect the treatment of recycled content used in vehicle production and end-of-life recycled materials. Ricardo has previously independently carried out an evaluation of the relative contribution of the EoL phase on the total life-cycle GHG emissions of both conventional ICEVs and BEVs (Ricardo, 2023), also taking into account the possible alternative adoption of three among the most widely employed EoL allocation approaches, namely:

- “Recycled content”: this method allows accounting for secondary (i.e., recycled) material inputs to manufacturing, but it does not address material recycling at EoL.
- “Avoided burden”: in open contrast to the previous option, this method includes EoL material recycling and calculates associated environmental “credits”, but it does not allow accounting for secondary (i.e., recycled) material inputs in product manufacturing.
- “Circular Footprint Formula” (CFF): this third method adopts a “balanced” approach, whereby both the benefits of using secondary materials in vehicle manufacturing and the potential environmental credits ensuing from material recycling at EoL are taken partly into account (European Commission, 2021c).

A more detailed explanation on these three EoL allocation methods and their trade-offs is provided in Appendix A1.4.

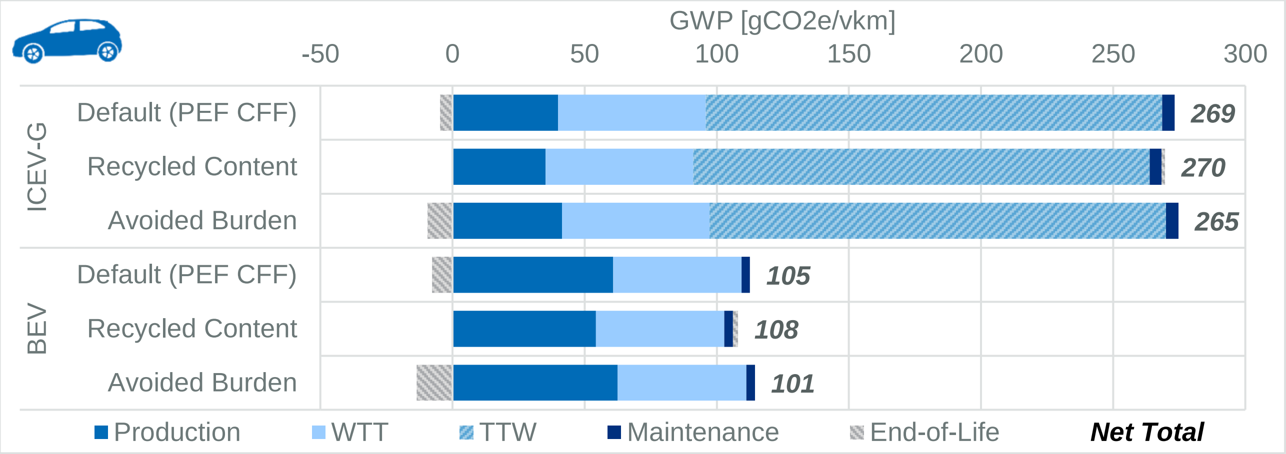
Figure below reports Ricardo’s own modelling results for the life-cycle GHG emissions of an average Lower Medium class passenger vehicle, respectively powered by an internal combustion engine or battery electric power train, broken down by life cycle phase, i.e.: vehicle production, use phase (WTT+TTW), maintenance and EoL, and respectively adopting the three EoL allocation approaches mentioned above.

As can be seen, despite the differences resulting from the alternative EoL methods, the most important result emerging from this exercise is that **whilst the choice of methodology can affect the comparison to a smaller extent, in no case do the EoL emissions significantly affect the overall ICEV vs BEV comparison as a whole**.

This is an important finding, that allows confident discussion in the next sections the overall relative GHG emission benefits of xEV adoption, based on the evidence that has emerged from the systematic literature review and harmonisation, in spite of the inevitable exclusion of the EoL phase from the latter.

As already mentioned in earlier Section 2.3.1, recent **European legislation (such as on the** Circularity Requirements **for vehicles and** Battery Regulation**) is anticipated to greatly reduce the impacts from materials used in vehicles** through improved design, greater use of recycled material and increased (and improved) use of end-of-life recycling processes.

Figure 2-5: Sensitivity on the influence of the end-of-life (EoL) allocation methodology on net life cycle GHG impacts, Lower Medium Car, 2020, EU27



ICEV-G = Internal Combustion Engine Vehicle running on gasoline; BEV = Battery Electric Vehicle.

Source: Sources: Ricardo LCA modelling conducted for the European Parliament, January 2023 (Ricardo, 2023).

Notes: Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. GWP = Global Warming Potential.

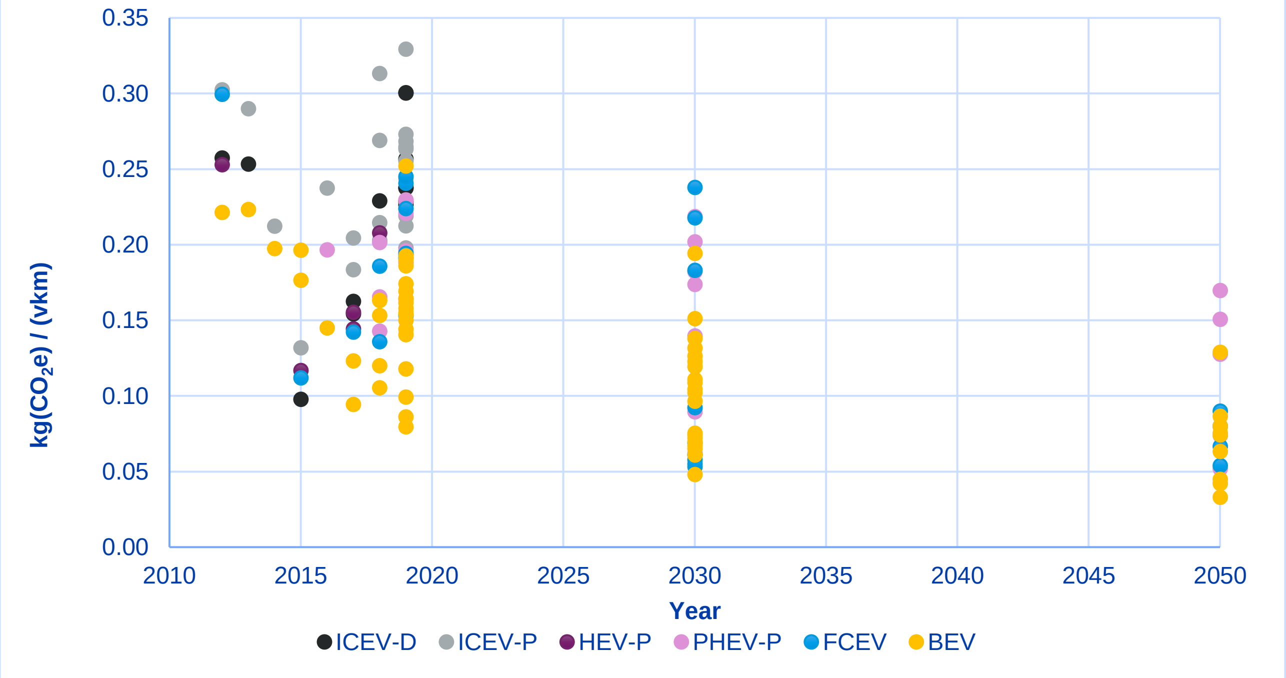
2.4.4 Overall life-cycle emissions

Figure presents the break-down analysis of the full set of data points from the literature review, including GHG emissions from both production and use phases taken together, but excluding the EoL data (as these could not be harmonised – discussed previously).

Production and use phase GHG emissions span a wide range. Regarding ICEVs only, the **use of diesel fuel appears to lead to significantly lower emissions vs gasoline**. While this comparison between ICEV-D and ICEV-G results may in small part be affected by cross-study inconsistencies in terms of associated vehicle size classes, the fact that the statistical distributions of the two sets of results are centred on sufficiently separated values, with comparatively little overlap, points to a likely high degree of robustness for this finding.

Additionally, **HEV with gasoline engines are characterised by consistently lower GHG emissions than their non-hybrid counterparts**. This finding indicates that, on average, the additional complexity and increased up-front carbon intensity of hybrid power trains are justified in light of the ensuing overall lifecycle emission reductions.

Figure 2-6: Total lifecycle GHG emissions reported associated from the vehicle production and use phases, broken down into power train type



Notes: All data harmonised to: FU = Vehicle·km travelled and 225,000 km lifetime mileage. Key: ICEV-D/G = internal combustion engine vehicle – diesel / gasoline, HEV = hybrid electric vehicle, PHEV = plug-in hybrid electric vehicle, FCEV = fuel cell electric vehicle, BEV = battery electric vehicle.

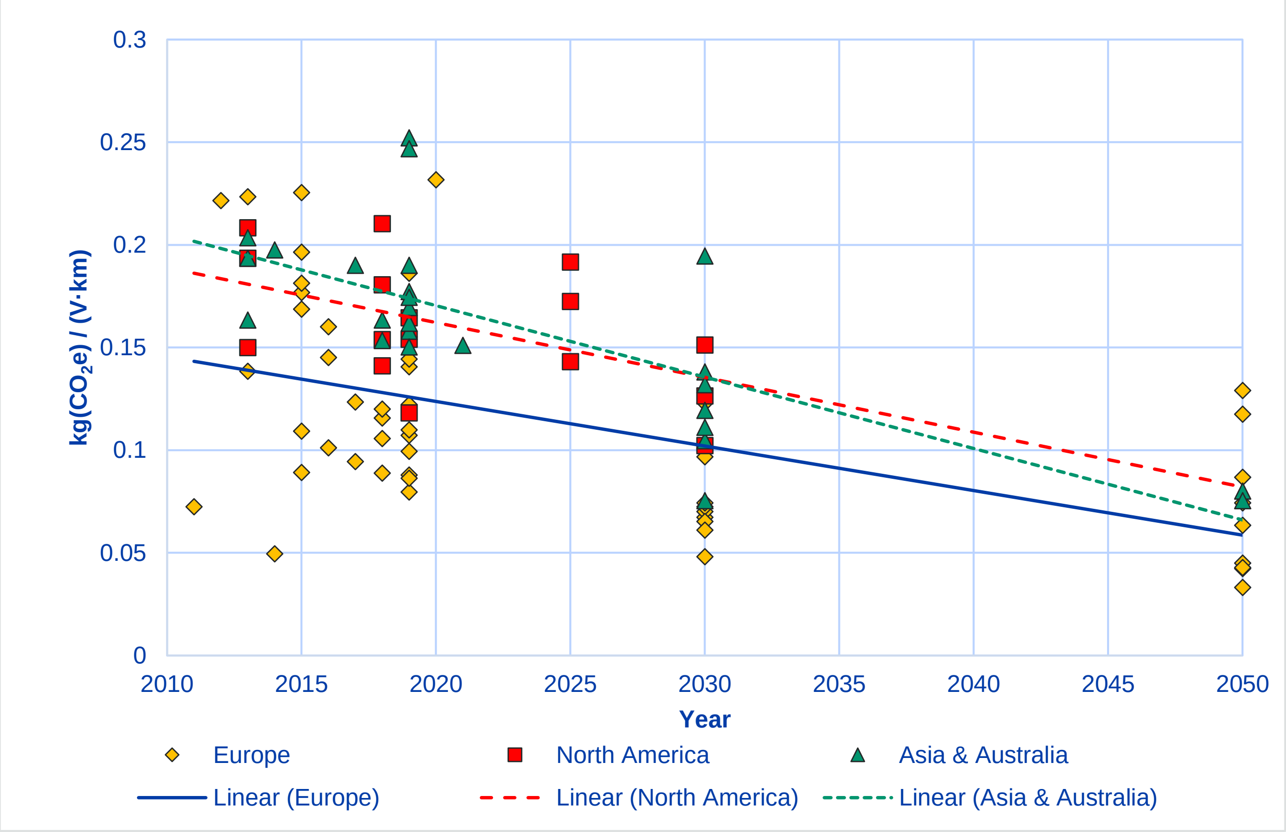
The datapoint distributions in Figure show **BEVs emerging as the least carbon intensive option overall** (even despite a general lack of accounting for future electricity decarbonisation in most of the studies reviewed). **Significantly lower GHG emissions were reported for Europe**, given that the regional grid mix is more decarbonised than the grid mix in North America and Asia Pacific. Figure 2-7 below isolates the GHG emission results for BEVs, once again for the sum of the production and use phases. Datapoints related to each region are reported using region-specific symbol shapes in order to show the variations in results depending on the electricity grid mix.

Figure 2-7 also shows clear downward trends over time (obtained through linear regression), primarily due to **use phase GHG emissions expected to significantly decrease, when the grid mix used for the use phase calculations is adjusted according to the future projections**.

The trendline for European datapoints can be explained by Europe's progressively "cleaner" electricity grid, i.e., Europe is increasing its share of RE sources such as wind, solar, and hydroelectric power. **Policies and investments in Europe are accelerating the integration of renewable energy** into the grid therefore, **electricity consumed by BEVs will increasingly come from low-carbon sources**.

The literature reviewed included projections for vehicle GHG emissions in 2025 and 2030 in North America, and in Asia & Australia, too; however, it is notable that no sources in the review provided estimates for vehicle lifetime emissions in North America for the year 2050. Clear downward trends in GHG emissions emerge for these other regions, too. Notably, the trendlines for North America and Asia & Australia are steeper compared to Europe. This means that, although the initial emissions in these world regions are higher than in Europe, the subsequent expected rates or reduction in GHG emissions are more pronounced in North America and Asia & Australia than in Europe, when comparing current emissions data with future projections.

Figure 2-7: Total lifecycle GHG emissions reported associated with the vehicle production and use phases of BEVs in Europe, North America and Asia & Australia



Notes: All data harmonised to: FU = Vehicle·km travelled and 225,000 km lifetime mileage. Key: ICEV-D/G = internal combustion engine vehicle – diesel / gasoline, HEV = hybrid electric vehicle, PHEV = plug-in hybrid electric vehicle, FCEV = fuel cell electric vehicle, BEV = battery electric vehicle.

2.5 QUANTIFICATION OF NET ENVIRONMENTAL BENEFITS OF xEV ADOPTION

The systematic review and harmonisation of the life cycle GHG emissions of passenger cars produced by these most recent peer-reviewed scientific literature has enabled an understanding of the net environmental benefits of xEV adoption, compared to ICEVs.

Specifically, based on the results of the review, **BEVs stand out as the most promising option to decarbonise the passenger vehicle fleet**, when compared to conventional internal combustion engine vehicles (ICEVs) running on gasoline, and, to a lesser extent, also on diesel. Despite their inherently lower production emissions FCEVs are generally found to offer lower life-cycle GHG emissions savings, due mainly to their much lower overall lifecycle energy efficiency.

Even current **BEVs on the market today are already expected to represent a very significantly lower carbon intensive option than conventional ICEVs**, over their estimate 15-year service life. Specifically, based on the literature review, and without accounting for future electricity decarbonisation, specifically **–43% in Europe, –29% in North America, and -23% in Asia & Australia, when compared to gasoline ICEVs**; and –**34% in Europe, +18% in North America, and -11% in Asia and Australia, when compared to diesel ICEVs**. As mentioned above in Section 2.4.2, however, it must be considered that these result ensue from calculations that assume the electricity grid mix to remain the same throughout the service life of the BEV, which in most cases is an unrealistically pessimistic assumption; hence, the **real-world benefit of early BEV adoption are likely to be even greater than reported**.

The expected further emission reduction trends emerging from the reviewed literature in terms of harmonised LCA modelling results for BEVs operated in Europe and other world regions have been presented and discussed in Section 2.4.4.

Ricardo have conducted a wide range of analyses and sensitivities using our own extensive vehicle LCA modelling tools, which have been used to inform and understand how different vehicles, fuels and powertrains perform currently on consistent basis and how this could change in the future due to changes in technology, the market and policy. In particular, to complement the findings from the literature review and harmonisation presented in the previous sections, and extend the scope of the quantification of the benefits of xEV adoption in the coming decades in Europe specifically, it is worth referring to the results from recent modelling analysis for the European Parliament (Ricardo, 2023), which found that **current BEVs are expected to reduce GHG emissions by as much as 63% compared to gasoline ICEVs over their lifetime**.

The following Figure 2-8 and Figure 2-9 provide a break-down of a range of possible future scenarios for Europe, as assessed by Ricardo. Specifically, Figure 2-8 shows how ICEV-G, FCEV and BEV may be expected to benefit from decreased life-cycle GHG emissions in the future, as well as reduced overall demand for primary energy (CED metric).

It is noteworthy, however, how in the case of ICEVs, the largest calculated reductions in emissions are for theoretical assumptions (“100%Bio-Blend”, and 100% ”e-fuels/RE” with e-fuels produced using only RE) which are not realistic scenarios (respectively primarily due to competition for land and total RE capacity), and which are only provided as “bookends” to illustrate ultimate theoretical limits. Hence, only the “Default Fossil” and “Future Blend” scenarios should likely be considered when comparing the achievable reductions with those for xEVs (with the latter “Future Blend” scenario perhaps also being optimistic in terms of viability and roll-out of bio- and e-fuels, especially without very substantial reduction in fuel demand due to electrification). Additionally, the CED results clearly indicate how inefficient (in terms of total use of primary energy) the e-fuel option is, relatively, with these fuels best reserved for use in applications where direct electrification is not feasible (e.g., for most maritime shipping and aviation). For later periods (i.e., for 2040 onwards) the “Grid electricity” scenario for BEVs also corresponds to what is the expected evolution of the European grid based on Europe meeting its long-term Net Zero commitments. This mix is predominantly renewables and nuclear, and includes some centralised BECCs generation (biomass based electricity generation with carbon capture and storage) by 2050, which offsets some of the impacts from other generation types; hence it has a lower net emission factor. The results for FCEVs sit in-between those of ICEVs and BEVs, due to the additional energy losses associated with the production and use of hydrogen compared to electricity used in directly BEVs.

Figure 2-9 extends the scope of the future projections and comparisons to all considered power train options, i.e., ICEV-G, ICEV-D, HEV-G, PHEV-G[3], FCEV and BEV, while adopting, respectively, power-train specific combinations of the “Future Blend” scenario (for fuels) and “Grid electricity” scenarios (for electricity), as described above. The figure also provides a breakdown of impacts across the lifecycle, with reductions in impacts in the production phase due to a combination of improvements in battery (and other) technology, as well as decarbonisation of key materials (particularly steel, aluminium and plastics production). The analyses also factor in potential future improvements to vehicle operational energy consumption (for all powertrains) based on technical improvements in the powertrains and in other areas (e.g., through mass reduction).

With these caveats in mind, what emerges from Ricardo’s analysis in Figure 2-9 is that, in Europe, even **assuming a non-negligible and as yet uncertain roll-out of bio- and e-fuels, the maximum reductions in life-cycle GHG emissions for ICEVs and HEVs/PHEVs by 2050 are -50%** (relative to the present), whereas for **BEVs the expected/conservatively estimated reductions are almost -80%. FCEVs also show large potential for GHG emission reductions (-75%); however, such potential relies on assumptions on “green” H2 availability** which remain somewhat more uncertain in terms of their feasibility, especially when considering the competition for RE from other sectors, and the fact that **the same RE would be used far more efficiently if directly fed to BEVs, instead of being used to produce “green” H_2**.

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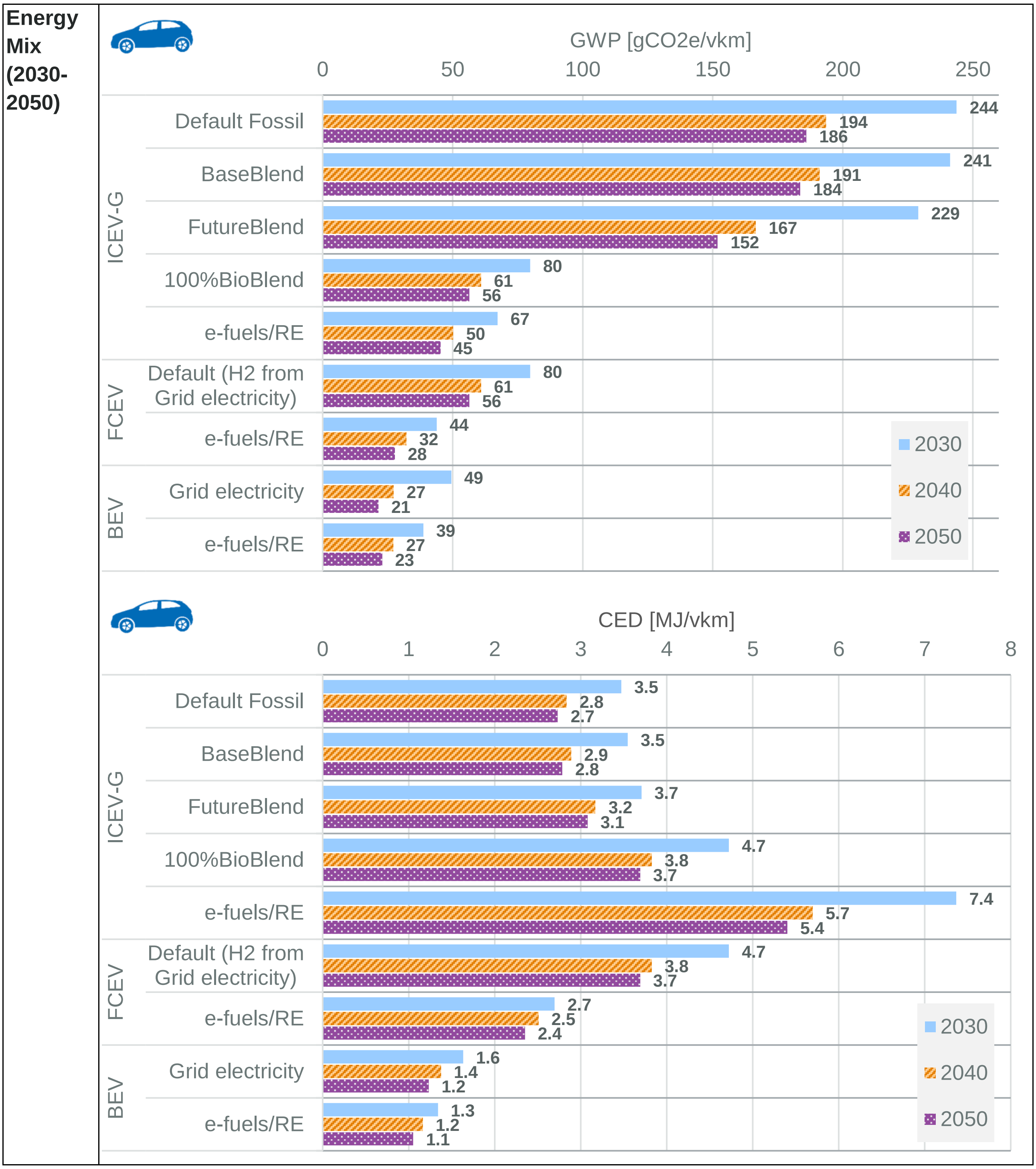
[3] Note: the analysis for the European Parliament does not account for more recent evidence now available that suggests the real-world electric operation share is lower than previously assessed; this is also being reflected in updates to regulatory certification using WLTP which will be introduced from 2025 reflecting an amended utility function for % electric operation vs electric range capability of the vehicle.

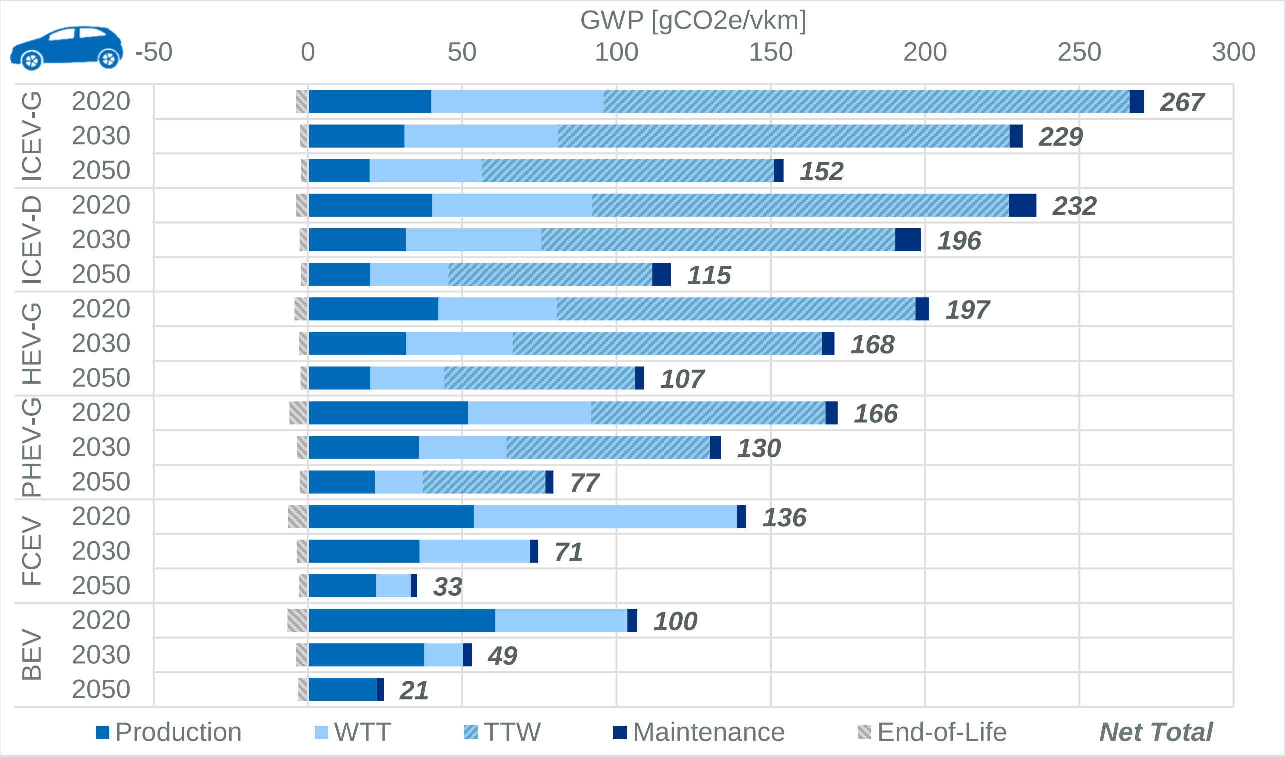
Figure 2-8: Breakdown of the future outlook for life cycle GHG impacts for a Lower Medium Car, 2020 / 2030 / 2050, EU27 (Ricardo analysis for the European Parliament, 2023)



Sources: Ricardo LCA modelling conducted for the European Parliament, January 2023 (Ricardo, 2023) (updated).

Notes: Default electric range for a BEV in 2030 is assumed to be 440 km with a 50 kWh battery. Low range is assumed to be 360 km (with a 41 kWh battery), and high range is 600 km (with an 81 kWh battery). Best- and worst-case scenarios are based on combination of low range with high future battery energy density, and high range with low battery energy density. The 'FutureBlend' is the updated projection based on increased share of low carbon fuels based on the Fit for 55 package modelling for 2030, and the previous Tech1.5 scenario projections to 2050 from (Ricardo et al., 2020). *For 'e-fuels/RE', for ICEVs this means e-fuel produced using renewable electricity, for FCEVs this means hydrogen produced from renewable electricity (i.e. 'green hydrogen'), and for BEVs it means just using the renewable electricity directly. Renewable electricity is defined as from solar, wind or hydro generation (i.e. excluding centralised combustion of biomass). Grid electricity is assumed to include a share of BECCs (biomass based electricity generation with carbon capture and storage) by 2050, which offsets some of the impacts from other generation types; hence it has a lower net emission factor.*

Figure 2-9: Breakdown of the future outlook for life cycle GHG impacts for a Lower Medium Car, 2020 / 2030 / 2050, EU27 (Ricardo analysis for the European Parliament, 2023)



Sources: Ricardo LCA modelling conducted for the European Parliament, January 2023 (Ricardo, 2023).

Notes: Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. GWP = Global Warming Potential.

2.6 SUMMARY

Ricardo's research highlights that while production emissions for electrified vehicles (xEVs), particularly Battery Electric Vehicles (BEVs), are currently higher than those for conventional Internal Combustion Engine Vehicles (ICEVs) due to the additional mass and energy-intensive battery manufacturing process, BEVs emerge as the most promising technology for reducing overall greenhouse gas (GHG) emissions. BEVs typically have the lowest use phase emissions, which can vary based on regional electricity grid mixes, and are expected to see significant future reductions in total life cycle emissions as battery efficiency improves, and grids become greener. By 2050, in Europe, BEVs could achieve nearly an -80% reduction in life cycle GHG emissions, surpassing the potential reductions for ICEVs and hybrid vehicles (-50%). Although Fuel Cell Electric Vehicles (FCEVs) also show potential for large emission reductions (-75%), this depends on the availability of "green" hydrogen availability. Its availability remains somewhat more uncertain in terms of feasibility, especially when considering the competition for RE from other sectors. Additionally, the same RE would be used far more efficiently if directly fed to BEVs, instead of being used to produce “green” H_2. Overall, based on the analysis of evidence on lifecycle emissions impacts, BEVs stand out as the most effective option for decarbonizing the passenger vehicle fleet over the long term.

3. SUSTAINABILITY OF MANUFACTURING PROCESSES

3.1 INTRODUCTION AND OBJECTIVES

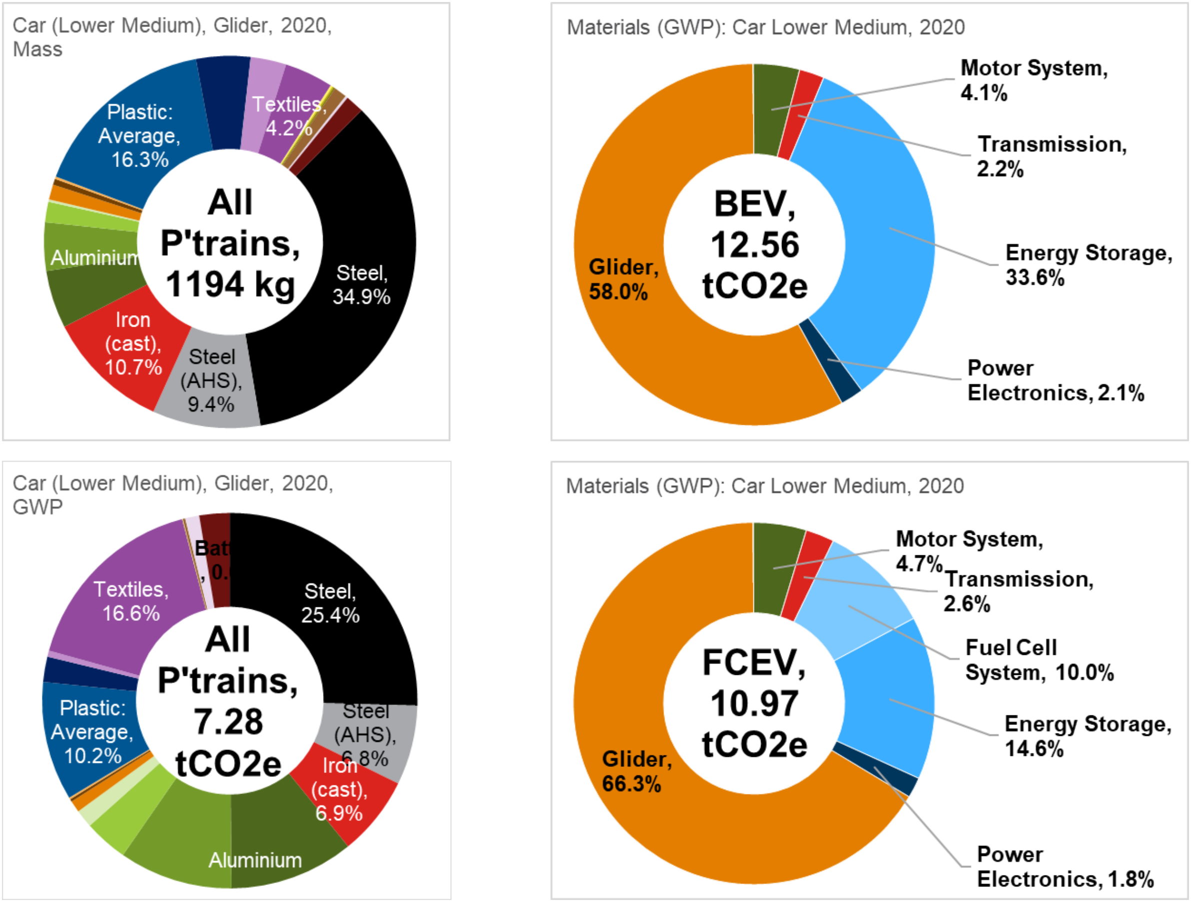
The previous chapter provided an overall assessment of evidence on the environmental performance of xEVs over their lifetime; this illustrated the significant impacts due to manufacturing, compared to conventional ICEVs. This chapter presents the key challenges faced in shifting present day automotive manufacturing to ever-increasingly sustainable processes, and the potential for future improvements. These issues are explored based on a review of published evidence on the main sources of impact in xEV manufacturing, distilling this information into the most viable strategies for improvement. This therefore includes a focus on the extraction of raw materials, importance of supply chains, energy sources used in manufacturing, and design for circularity.

3.2 OVERVIEW OF KEY SOURCES OF IMPACT IN XEV MANUFACTURING

This section provides an overview of the key sources of environmental impact within xEV manufacturing.

Figure 3-1 illustrates the relative contributions to the total production GHG emissions, broken down by vehicle sub-assembly (i.e., glider, motor, transmission, energy storage, and power electronics).

Figure 3-1: Breakdown material GHG impacts by system and glider mass for a Lower Medium Car, 2020, EU27



Source: Ricardo analysis for the European Parliament, (Ricardo, 2023)

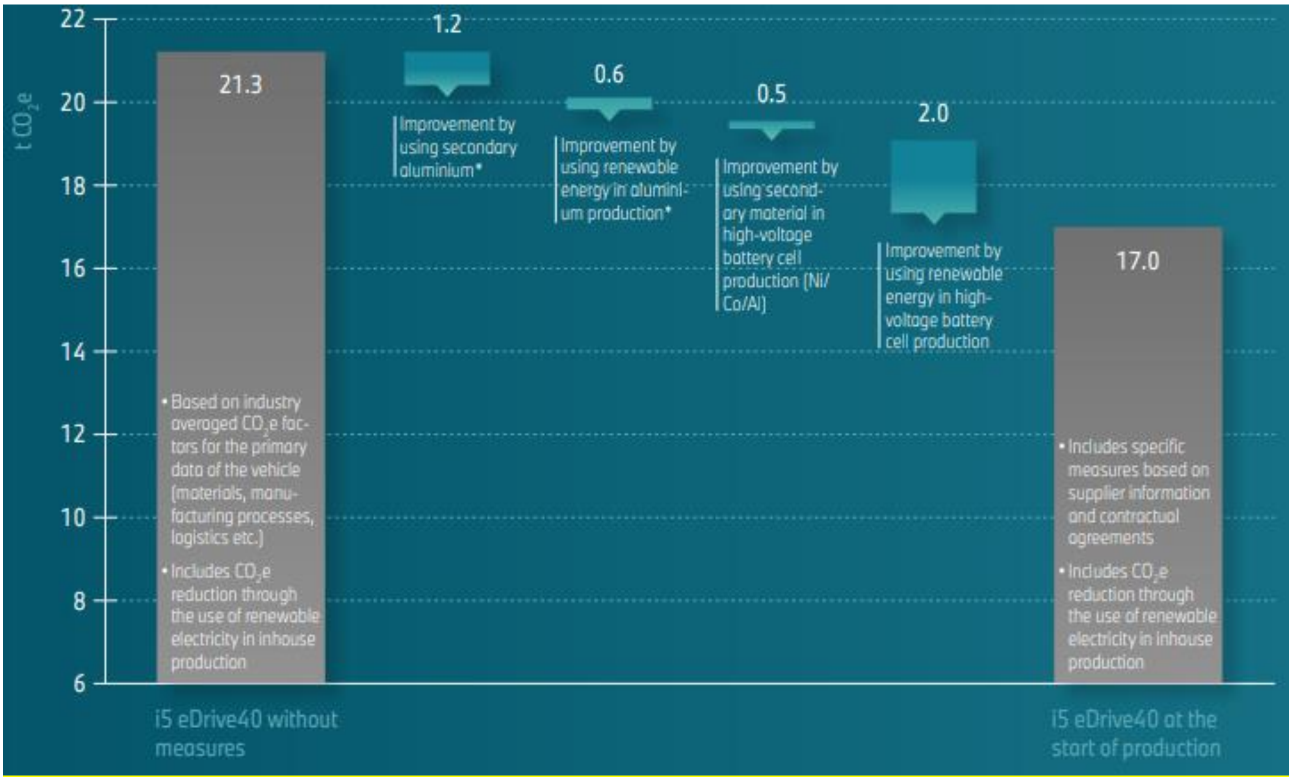
In current-production xEV manufacturing, the largest contributor to GHG emissions is the vehicle's glider (non-powertrain components, comprised primarily of the body-in-white, chassis, interior, etc). **In most vehicles, almost two thirds of the mass of the glider is comprised of steel and aluminium, and consequently these two materials are in turn responsible for a sizeable share of the vehicle's overall production GHG emissions** (*cf*. Sections 3.2.3 and 3.2.4).

The xEV's energy storage system represents a close second-largest contribution to its total production GHG emissions. In BEVs (and PHEVs), the energy storage system consists of a battery pack (at present, almost without exception one of the Li-ion types), whereas in FCEVs, it is composed of a pressurised vessel for the on-board storage of H_2, supplemented by a small battery pack. These two components and their associated emissions are discussed in more detail in Sections 3.2.1 and 3.2.2, respectively.

When considering the expected future trends in xEV manufacturing, **significant improvements are expected in battery technologies, and to a lesser extent also in on-board H2 storage options**, both in terms of reduced manufacturing emissions (i.e. principally through a shift to lower GHG energy) and improved gravimetric energy densities (*cf*. Section 3.2.1). As a result, the GHG emissions associated to energy storage systems are expected to shrink on a per-vehicle basis. Conversely, in absolute terms, much more limited emission reductions are likely to be easily attainable for the other vehicle powertrain components, thereby leaving the vehicle glider in a comparatively even more prominent position as the largest contributor to the vehicle's overall production GHG emissions.

Examples of some quantitative estimates of the most readily implementable strategies to decarbonize xEV manufacturing in the short term are provided in a recent Carbon Footprint study produced by BMW (reproduced here as Figure 3-2) for the i5 eDrive 40 (BEV model). According to that study, **the most substantial improvement in terms of GHG emission reductions may be achieved by using RE in battery production** (use of RE in manufacturing is discussed on more detail in Section 3.2.5). After that, increasing the share of recycled aluminium in the vehicle's glider composition is shown to have the second-largest potential for emission reductions, followed by a shift to RE use in virgin aluminium smelting (*cf.* also Section 3.2.4), and finally, by improvements in closed-loop recycling of LIB metals (cf. Sections 3.2.1 and 3.2.7).

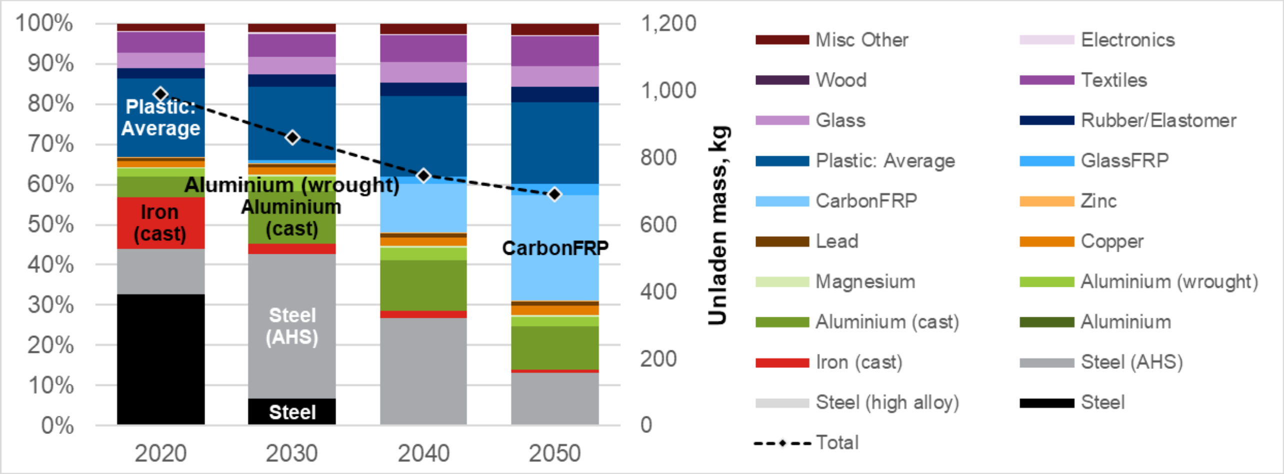
Figure 3-2: Indicative potentials for GHG emission reductions in vehicle manufacturing (BMW estimates)



Source: *BMW GROUP VEHICLE FOOTPRINT - BMW i5 eDrive40 (BMW Group, 2023)*

Based on Ricardo's previous analysis, as illustrated in Figure 3-3, in the coming decades, the material composition of the vehicle's glider may also shift towards more intensive use of other advanced lightweight materials, beyond aluminium, such as e.g., carbon-fibre reinforced plastics, as part of a holistic push towards reduced use-phase energy consumption. However, this may have mixed consequences in terms of GHG emissions, depending on the specific carbon-intensity of those materials' supply chains (*cf.* Section 3.2.6).

Figure 3-3: Breakdown of mass by glider material – projection 2020-2050, Lower Medium Car



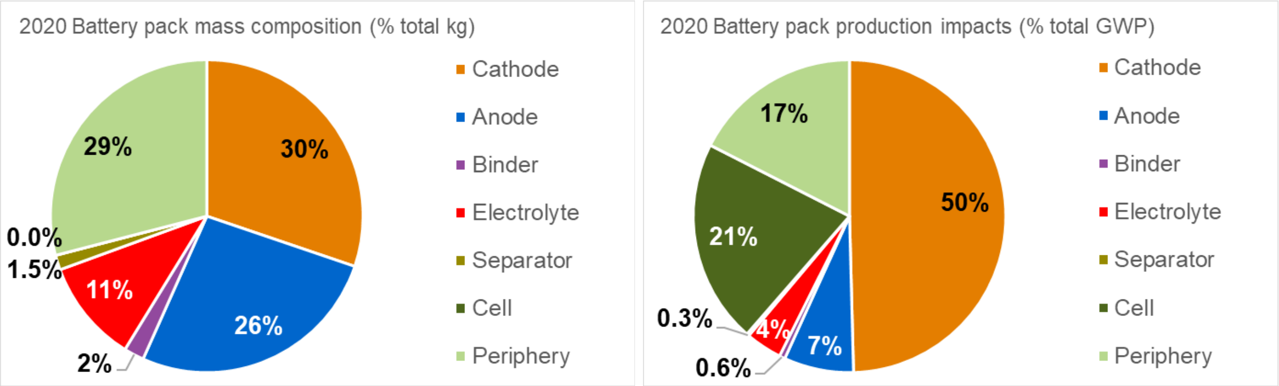
Source: (Ricardo et al., 2020)

The following sub-Sections (3.2.1 to 3.2.7) will address in more detail all these key sources of impact, and provide a discussion of the most promising strategies to address them.

3.2.1 Batteries (BEVs)

As shown in Figure 3-4, the main components of a LIB are the cathode (the chemical formulation of which has a particularly strong impact on the battery's overall gravimetric energy density), the anode, the liquid electrolyte and the separator, and finally the periphery – i.e. outer casing and electronics (including the battery management system - BMS). The figure provides a breakdown in terms of mass of materials and their corresponding contribution to the total GWP impact, with 'Cell' representing the additional impacts from cell manufacturing itself (i.e. mainly energy consumption), besides the individual components.

Figure 3-4: Indicative break-down of mass and production GHG emissions of a typical BEV Li-ion battery pack



Source: Ricardo analysis for the European Parliament, (Ricardo, 2023)

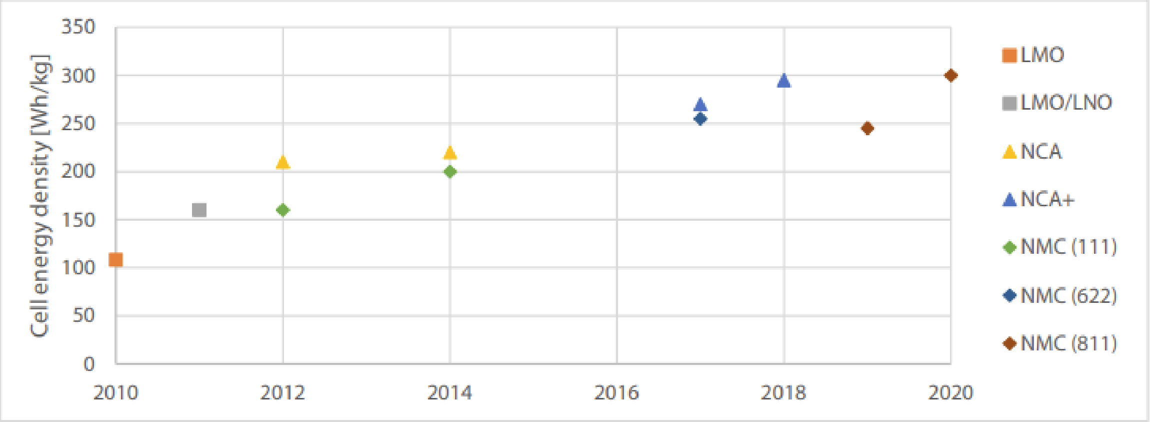
Note: Cell = additional impacts from cell manufacturing (i.e. excluding cell components), mainly energy consumption.

As shown in this chart, the **two principal sources of GHG emissions at the battery cell level are the production of the cathode active materials (CAM) and the energy consumption for cell manufacturing itself.** These impacts are due to a combination of the energy used in manufacturing (both CAM and the cells), and the **upstream emissions from the supply chains** of the required materials (i.e., lithium for the cathode, plus cobalt, nickel, manganese and/or aluminium, iron and phosphorus in various proportions depending on the formulation).

One general, high-level trend that applies across the board of all battery chemistries and which has, broadly speaking, led to a gradual decrease in emissions per unit of battery energy storage capacity is that of progressive improvements in the batteries' gravimetric energy densities over time (*cf.* Figure 3-5). This is due to the fact that, by and large, GHG emissions correlate with battery mass, and therefore higher [Wh/kg] specifications result in lower emissions per Wh.

Although difficult to accurately predict in quantitative terms, **such trend in terms of increasing battery energy densities is commonly expected to continue to extend into the coming decades,** thereby potentially leading to further expected reductions in GHG emissions per vehicle (provided that on-board energy storage capacities stabilise at levels compatible with sufficient electric driving ranges, and assuming that such trend is not countered by further unnecessary increases in overall vehicle sizes).

Figure 3-5: Time series of commercial battery-cell energy densities



Source: BNEF (Bloomberg New Energy Finance) from (CleanTechnica, 2020), reproduced by Ricardo.

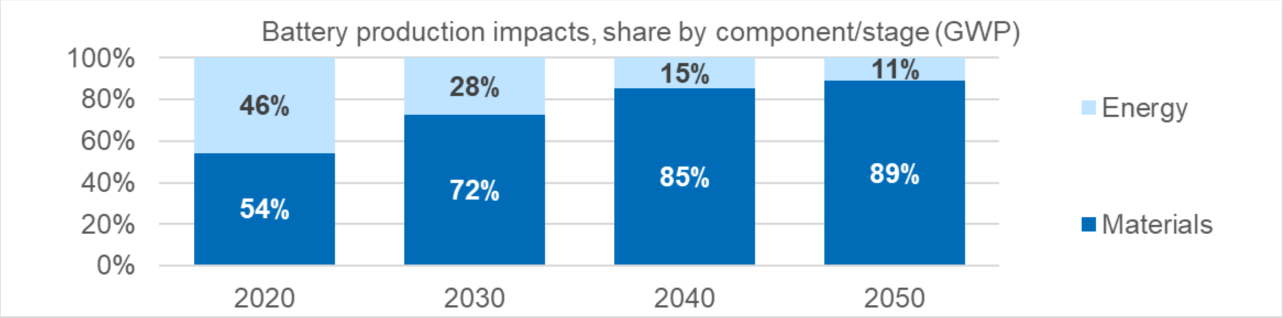
As already mentioned, all current LIB chemistries rely (to different degrees) on a range of metals that have significant other environmental consequences, including, but not limited to, GHG emissions. For instance, mining activities, particularly for lithium and cobalt, are frequently associated with habitat destruction, water pollution and high GHG emissions. Also, water depletion in arid areas is a significant concern where lithium extraction is carried out via the brine route.

Ricardo's modelling (Figure 3-6), informed by battery industry roadmaps and electricity grid mix scenarios for Europe, has shown that the relative shares of emissions due to, respectively, energy and materials used in LIB manufacturing were estimated to be almost evenly matched in 2020.

However, **the impacts due to energy inputs to battery manufacturing are expected to be comparatively easy to reduce in the coming decades,** via a combination of cell manufacturing improvements and on-going decarbonisation of the electricity supply chain. Among the former improvement strategies are: further direct electrification of cell manufacturing, thereby dispensing with gas-fired electrode drying lines; and the potential introduction of dry coating (reducing or removing drying/solvent removal requirements in cell manufacturing) or switching from conventional binders such as polyvinylidene fluoride (PVDF) to less carbon-intensive water-soluble alternatives (McKinsey & Co., 2023).

Conversely, the **impacts associated to the key battery materials supply chains are expected to be comparatively harder to reduce, with the consequence that these are projected to represent almost 90% of the total GHG emissions by 2050,** if these improvements are achieved.

Figure 3-6: Energy vs. materials shares of total production GHG emissions LIBs, EU27 supply mix

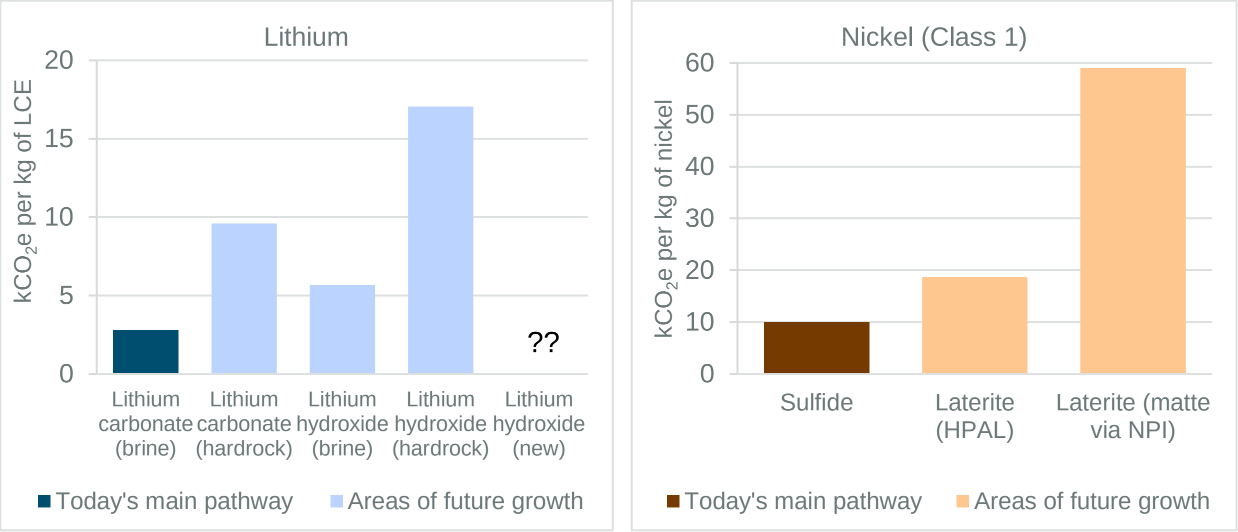


Source: (Ricardo, 2023)

In fact, the **emissions associated to the battery metals are rather variable, depending on the specific geologic deposits used and related supply chains involved**. For instance, Figure 3-7 reports two ranges of GHG emission estimates, respectively for Li and Ni sourced from a range of different kinds of deposits.

Specifically for lithium, one potentially promising (but still to be evaluated) strategy for decarbonising its supply chain is shifting from (or at least supplementing) the more conventional supply chains based on either spodumene (Li carbonate) rocky deposits (principally located in Australia) or concentrated Li brines (primarily from Latin America), to newly discovered geothermal sources (Cornish Lithium, 2022), or possibly clay deposits (USGS, 2018). However, none of these new sources of lithium has so far shown the potential to supplement or displace conventional sources at a global scale.

Figure 3-7: GHG impacts for two key battery materials (Li and Ni) by resource type and processing route

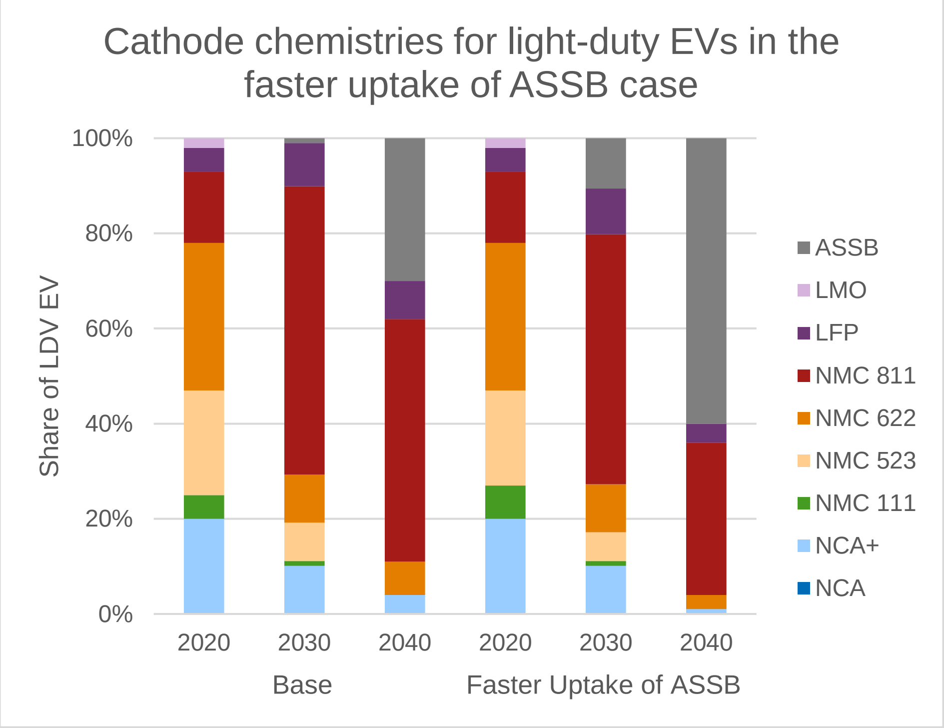


Source: (Ricardo, 2023)*; charts partially reproduced by Ricardo using data from* (IEA, 2021a) *for material GHG impacts.*
Notes: LCE = lithium carbonate equivalent.

In the medium-to-long term, **mitigating the impacts related to key battery materials can also be pursued via the development of alternative battery chemistries** that reduce the dependence on these materials.

The International Energy Agency (IEA) has produced future scenarios indicating a possible gradual shift to new battery chemistries such as all-solid-state batteries (ASSB) (cf. Figure 3-8), characterised by reduced reliance on these critical metals.

Figure 3-8: Scenarios of future evolution of xEV battery technology mix



Source: (IEA, 2021a)

Additionally, over the past three to five years **there has been an increased uptake of cobalt-free lithium-ion battery chemistries (mainly lithium iron phosphate - LFP) in the automotive industry**, as well as at least one pledge by a major battery manufacturer to start sodium-ion battery (SIB) manufacturing on a large, commercial scale (Electrive, 2024). If sustained, these new trends may be expected to have a positive impact in terms of GHG emission reductions, both at the battery pack and, consequently, at the whole vehicle level.

3.2.2 Hydrogen storage (FCEVs)

On-board compressed hydrogen storage is required as hydrogen has a high energy content by weight, but not by volume, thereby creating a storage challenge. Hydrogen gas is typically stored at high pressures (350-700 bar) to reduce the volume required, but this necessitates heavy, large and robust tanks, which impacts on vehicle design and efficiency. These high-pressure tanks are made predominantly with carbon-fibre reinforced plastics (CFRP), which are highly GHG intensive (as well as having currently limited potential for recyclability).

Strategies to reduce hydrogen storage impacts are therefore likely best focused on (i) lowering GHG intensity of CFRP, and (ii) developing (and implementing) recycling processes for CFRP. The former can be pursued by optimising the general efficiency of the CFRP manufacturing process, as well as, potentially, by turning to the use of bio-based substrates (however, see caveats on bio-materials in Section 3.2.6). **Fully closing the loop on CFRP recycling, instead, is still a somewhat elusive target, due to performance and safety concerns** if the recycled material is to be re-used for high-pressure H_2 storage vessels.

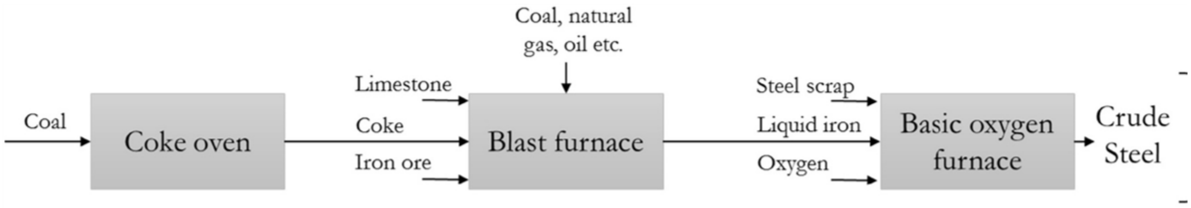
In the longer term, the use of **metal hydrides as an alternative to compressed storage may hold some promise, but development of these storage solutions is still at the very early stages** (Gomez & Santos, 2023). These materials absorb hydrogen gas and form a solid compound, allowing hydrogen to be stored at lower pressures; hence, in principle, they have the potential to address issues such as low energy density and safety. However, there is little information on the environmental impacts of their production.

3.2.3 Steel

As already introduced in Section 3.2, steel is one of the materials that are responsible for the largest overall shares of the manufacturing GHG emissions of an xEV, as well as for conventional and hybrid vehicles.

Conventionally, primary steel production is done via the so-called “integrated” BF-BOF route, which is schematically illustrated in Figure 3-9. This route relies heavily on coal as the key input, which is used both as a source of energy and heat, and – critically – as a reagent to chemically reduce the iron ore to “Pig” iron. This causes direct (as well as indirect) GHG emissions, when the coal coke is oxidised to CO_2 in the BF.

Figure 3-9: Conventional “integrated” BF-BOF steel production route

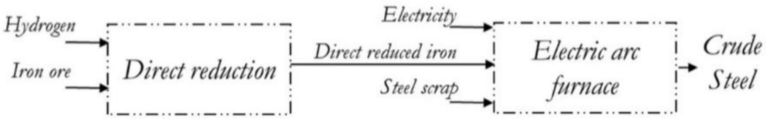


In 2022, actual steel production in Europe was split between 44% of production capacity processing steel scrap into recycled steel using electric arc furnaces (EAF), with around 56% of steel produced via the primary “integrated” BF-BOF route to produce virgin steel, and steel production totalled 136 million metric tonnes (WorldSteel, 2023).

Producing secondary (recycled) steel via EAF emits around 85% less CO_2 than via BF-BOF, and uses existing infrastructure and production processes; as such, minimal investment is required and cost competitiveness can be achieved with primary steel. There is also an abundance of scrap steel in the EU, with automotive steel recycling rates reaching around 90% (WorldAutoSteel, 2023). Therefore, **the first go-to strategy to reduce the GHG intensity of the steel inputs to xEV manufacturing should be to increase the share of secondary (recycled) steel use.** The automotive industry has been somewhat reluctant to do so in the past, due to the recycled steel failing to meet the requisite technical quality standards for some specific applications. However, many OEMs are now setting objectives to increase recycled content in their material supply agreements, where this is possible whilst maintaining critical standards.

A second possible strategy to reduce the GHG emissions associated to the steel input to xEV manufacturing is to **gradually shift primary (i.e., virgin) steel production from the conventional “integrated” BF-BOF route to a range of possible lower carbon alternatives**. Among the latter, the most promising one is widely reported to be the so-called H_2-DRI-EAF steel route, which is illustrated in Figure 3-10.

Figure 3-10: Low-GHG “green” steel manufacturing route



In this supply chain, the iron ore is first pelletized and then fed to a “Direct reduction” reaction chamber, where it is reduced to metallic iron by a flow of H_2 gas (which replaces the role conventionally played by carbon coke, and results in harmless water vapour emissions instead of CO_2). The “Directly Reduced Iron” (DRI) thus produced is then fed to an EAF like the ones already commonly employed to recycle steel scrap (and in fact, DRI and steel scraps can be mixed in all proportions).

In order **for this DRI-EAF steel production route to achieve its maximum GHG emission reduction potential, though, it is imperative that the H2 gas used be sourced via the “green” route**, i.e., produced by splitting water in an electrolyser powered entirely by RE. In this case, it has been calculated that the GHG emission reduction vs. the conventional BF-BOF route would be approx. 98% (Berger, 2021). Conversely, the use of an electrolyser with the 2021 global grid electricity mix would produce 23.5 $kgCO_2e$ emissions per kg of H_2, (IEA, 2023b), hence significantly limiting the GHG emission reduction potential of DRI-EAF steel vs. BF-BOF, to approx. 40% only (IEA, 2020b).

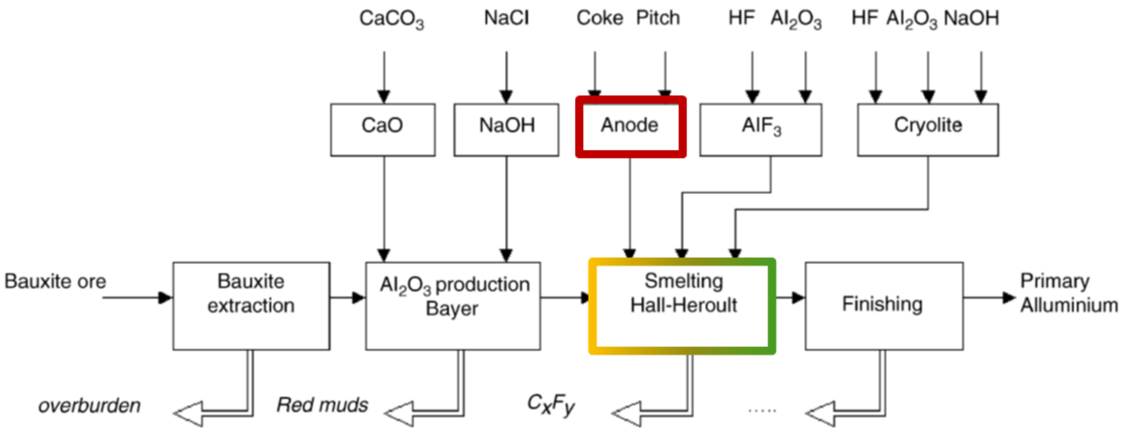
The main hurdle that needs to be overcome for this steel decarbonization strategy to become viable at scale is therefore to do with ensuring a sufficiently abundant and affordable supply of “green” H_2 produced using RE. Currently, “green” H_2 is not economically competitive with “grey” H_2 produced via natural gas steam reforming, but according to some projections, its price may drop from >4€/kg to below 2.5 €/kg by as early as 2025, and eventually to €1/kg by 2050 (McKinsey, 2020) (McKinsey, 2022), thereby making “green” DRI-EAF steel fully competitive on a global scale, outside of those initial niche markets where it is already viable today due to an abundance of cheap RE (e.g., hydropower in Sweden). A number of OEMs have already announced strategic agreements or objectives for the use of "green" DRI-EAF steel, with more currently anticipated (Ricardo, 2024).

3.2.4 Aluminium

Aluminium is also a significant component of the environmental impacts of passenger cars, with xEV models typically utilising higher shares of this material also to reduce vehicle mass, with benefits for battery sizing / range.

The primary aluminium supply chain entails three main production stages, as illustrated in Figure 3-11, namely: bauxite extraction, alumina (Al_2O_3) production, and metallic aluminium production via smelting (Hall-Heroult process). Among these, the most energy intensive stage is smelting, where very large quantities of electricity are required. Depending on the technology or mix of technologies used to generate such electricity, this can also be the most carbon-intensive step of the primary aluminium supply chain (globally, approximately 65% of total emissions in Al production come from the generation of electricity (MPP, 2023)).

Figure 3-11: Production route for primary aluminium



Aluminium is – at least in principle – an infinitely recyclable material. With the recycling process emitting only 0.5tCO_2e per tonne of recycled aluminium, shifting from primary to secondary represents a 97% GHG emission reduction potential, vs primary production (MPP, 2023). Global collection rates of EoL aluminium are around 73% (WEF, 2021), with 90% of aluminium scrap from vehicles being recycled in Europe (European Aluminium, 2022). However, **an important consideration is that different aluminium alloys are combined in the recycling process, and there is also contamination** (e.g., due to steel rivets used to join aluminium panels together in car manufacturing). This has so far therefore impeded the re-use of recycled Al in closed-loop applications (i.e., in new vehicle manufacturing). However there are a range of active research into ways for closing the loop with end-of-life vehicles (ELVs) including using a single alloy family for designing components for easier sorting as well as improved sorting and processing of ELVs (Krall et al., 2024; Light Metal Age, 2023),. Close cooperation across the automotive lifecycle supply chain for production and EoL is needed to unlock the potential.

The second most viable approach to decarbonise aluminium production is articulated along two complementary strategies. The first one consists of switching to 100% RE to power the smelting process. The second one entails a replacement of the carbon anodes that are conventionally used in the same process, as conventional smelting facilities emit a further 2 tCO_2e per tonne of alumina input (MPP, 2023), due to the oxidation of the anodes. However, **inert anodes are a promising substitute, producing no process CO2 emissions and offering a longer operational lifetime compared to conventional carbon anodes**. This technology is mature with widespread commercial deployment expected by 2030 with industry-scale demonstrators of inert anode technology being led by Rusal (Light Metal Age, 2021) and Elysis joint venture (Rio Tinto, 2021).

3.2.5 Direct energy inputs in vehicle manufacturing

Direct energy inputs to vehicle manufacturing are mainly supplied in the form of electricity; this applies both to battery production and to wider vehicle component manufacturing and assembly as a whole. Therefore, where possible, **improvements in manufacturing efficiency, whereby less energy is required to perform specific tasks, represent the first strategy worth pursuing.** European OEMs have made some progress on reducing manufacturing energy consumption according to (ACEA, 2023a). There was a reported improvement in energy consumption per vehicle by 15% per vehicle 2005-2019. However, there was a significant increase after this, likely due to reduced volumes/demand during the COVID pandemic, and efficiency has improved since a peak in energy consumption per vehicle 2022. The overall trend since 2005 is currently only 6% reduction to 2023.

Actively switching to less carbon-intensive electricity is the next viable strategy to reduce the production GHG emissions of xEVs. Similarly, relocating battery manufacturing to regions already served by larger shares of RE in the grid mix will also have a positive impact.

The most straightforward way of accomplishing a reduction in electricity-related GHG emissions is, of course, generating RE directly on site (e.g., using rooftop PV or wind turbines on company-owned land). Where this is not viable, RE can be sourced from the grid via suitable Renewable Energy Certificates (also referred to as Guarantees of Origin, in Europe). However, when doing so, a potential issue arises if the RE is subtracted from the pre-existing location-based grid mix, so that in practice less RE ends up being available for other users. In such cases, it is next to impossible to completely prevent any instances of external double-counting of the GHG emission reductions afforded by the purchased RE, as the same RE may simultaneously end up being double-counted as forming part of the grid mix input to other processes (whether within the same system boundary, or externally by other simultaneous users of electricity). **The only way to prevent that from happening is to ensure that the RE used for xEV production is generated ad hoc, i.e., that it is additional to the pre-existing mix.** This is the case when the RECs are bundled with dedicated Power Purchase Agreements (PPAs), which specify the source of the RE and clearly state that it comes from new (additional) installed renewable generation capacity.

3.2.6 Material substitution

Production emissions can be reduced through the use of alternative low(er) carbon-intensity virgin materials to displace high(er) carbon-intensity conventional materials. Two clear examples of this strategy have already been discussed in Sections 3.2.3 (“green” steel) and 3.2.4 (low-GHG aluminium).

However, **there may be potential trade-offs between emission reductions in manufacturing and energy savings (and hence emission reductions also) in use phase**, in those cases where the use of higher carbon-intensity materials is a key enabler of vehicle lightweighting. Hence, the importance of not assessing manufacturing impacts in isolation, but always retaining a holistic full life cycle perspective.

The incorporation of bio-materials (e.g. natural textile fibres, wood, etc.) in vehicle production is being discussed with increasing support (Demirel, 2023) with qualities such as strength, durability and lightweight properties combined with being biodegradable helping to distinguish them from traditional materials. The aim to use these materials for the production of components without endangering quality or safety is framed as a step towards more sustainable production practices with no major compromise. However, **caution should be exercised when considering a pivot towards bio-materials as may bring only smaller GHG benefits**, while depending on supply chains that entail large direct and indirect emissions including from irrigation, soil erosion and land use change. In addition, mixed material use has the potential to further complicate end-of-life processing and recyclability potential. This consideration warrants a detailed LCA assessing supply chain sustainability to be carried out to provide a detailed understanding to inform the extent of their uptake.

3.2.7 Material circularity

Increased use of recycled materials in manufacturing – where possible and compatible with the technical requirements dictated by the specific application of the material – is almost invariably conducive to lower GHG emissions.

Additionally, the implementation of careful “Design for Circularity” (DfC) strategies in manufacturing can lead to significant reduction of waste at EoL through easier disassembly and increased re-use of vehicle parts and/or easier recycling of the associated materials. These strategies deserve careful consideration even in those instances where they may potentially increase up-front cost and/or energy use and hence emissions.

Once again, this underlines **the importance of not assessing manufacturing impacts in isolation, but always retaining a holistic full life cycle perspective**.

With the exception of plastics, composites and polymers, most studies indicate that foundation materials in vehicle production are predominantly 100% recyclable. Despite this, current technical recycling methods and limitations associated with recycled materials lead to difficulties in their closed-loop use – particularly for multi-assemblies where material separation is not really feasible. Open-loop recycling has benefits by retaining materials in the general consumption loop, however challenges to closed-loop must be addressed to reap full environmental benefits.

In order to allow the full uptake of circular practices, implementing DfC strategies to the maximum extent possible is crucial (e.g. to facilitate disassembly and material separation, as well as using materials more readily recyclable). The disassembly, re-conditioning and re-use of vehicle parts will deliver a net emission reduction.

3.3 SUMMARY

Before summarising the findings of this Chapter, it is imperative to reiterate that **the most effective overarching strategy to reduce a vehicle's life-cycle GHG emissions, across all vehicle and power train types, remains mass reduction**: this should ideally be accomplished first and foremost, through vehicle downsizing.

Reduced vehicle size and mass (also aided by improved battery energy densities and increased powertrain efficiency) is also conducive to a reduction in the requirement for energy storage capacity (i.e., smaller batteries for BEVs and smaller H_2 storage vessels for FCEVs), resulting in further reductions of GHG emissions during production.

Secondarily, improvements may also be achieved through the use of lower GHG production processes for key materials (such as 'green' steel and aluminium), or through improved components and/or lightweight materials; however, these latter approaches **should be carefully evaluated on a full life-cycle basis, to avoid incurring in possible emission trade-offs and impact shifting**, as discussed in Section 3.2.6.

The following production-focused strategies have emerged as clear pathways to GHG emission reductions:

- Improvements in battery technology leading to greater battery energy density and/or lower GHG materials used in battery cell manufacturing, and improved manufacturing energy efficiency (including e.g. switch to dry electrode coating).
- Decarbonization of primary steel inputs, by shifting from conventional BF-BOF to "green" H_2-DRI-EAF steel.
- Decarbonization of primary aluminium inputs, by using more RE and switching to inert anodes in alumina smelting.
- Increased direct use of RE in manufacturing (both at battery and whole vehicle levels), either by on-site RE generation, or via renewable energy certificates (RECs) where additionality is ensured by power purchase agreements (PPAs).
- Enabling increased material circularity through DfC strategies.

Finally, incentivising increased public reporting of LCA for vehicles by OEMs is deemed helpful to provide greater transparency and enhanced accountability on production impacts (and also other LC stages).

4. REAL WORLD OPERATIONAL ENERGY EFFICIENCY

4.1 INTRODUCTION AND OBJECTIVES

The overall aim of this chapter is to present information on the factors contributing to differences in the real-world energy consumption of electric vehicles in the use-phase (i.e. operation, and not an assessment of end-to-end lifecycle efficiency) and compare the energy efficiency of different BEV models available on the market.

To achieve this objective, three main sub-tasks were carried out, shown below. The first two are contained within this chapter, while the last is contained within Section 0.

- A review of the factors impacting energy consumption of EVs in the real-world, and also how this differs compared to conventional vehicles.
- A comparison of the energy efficiency of different BEV models
- An assessment of the potential policy implications for improving the energy efficiency of BEVs

The scope focuses mainly on BEVs, but comparisons are made against traditional internal combustion engine vehicles (ICEVs) where informative to highlight the policy implications of a fleet-wide transition towards electric vehicles.

4.2 BACKGROUND AND CONTEXT

The energy efficiency of a vehicle is typically measured by the fuel or energy consumed per unit distance travelled. This is an important metric for the environmental performance of vehicles because it is a significant determinant of 'use phase' emissions as described in Section 2.

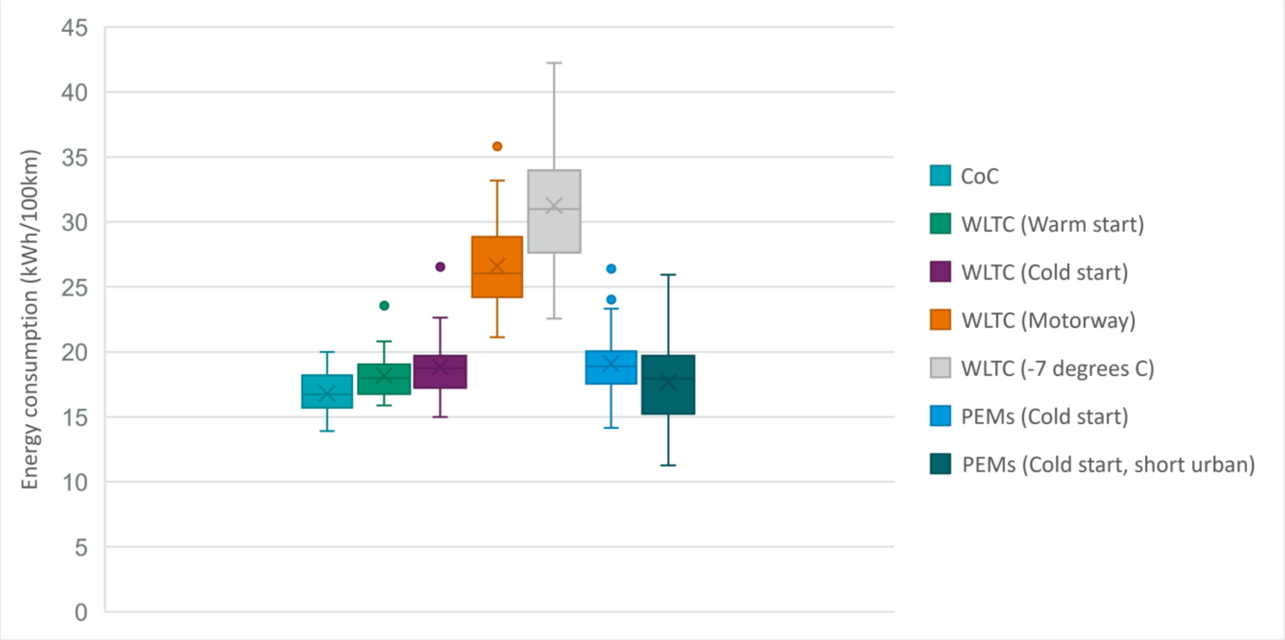
Energy efficiency is tested in laboratories using standardised testing protocols during vehicle certification and must be reported by vehicle manufacturers in their Certificate of Conformity (CoC). However, laboratory-tested energy consumption figures are often markedly different to those reported out on the road, or in the 'real world', as they are not able to capture all aspects of real-world usage. Therefore, in recent years new tests have also been developed to better monitor vehicle fuel and energy consumption in real driving conditions (RDC).

As part of their programme of independent vehicle testing, Green NCAP conducts a range laboratory and on-road testing under different conditions to help also capture some further elements affecting real-world performance (but not all). Figure 4-1 below illustrates the differences between manufacturer-reported energy consumption (CoC) and those recorded under six alternative test procedures run in the Green NCAP testing programme for a number of popular BEV models. The tests performed via PEMS, which monitor energy consumption of vehicles while driving on-road/in the real world rather than in a laboratory, are largely comparable with those performed via the Worldwide harmonised light vehicle test cycles (WLTC), albeit with slightly higher variance. Together these tests are more representative of 'real-world' energy consumption in different conditions.

When compared with CoC values, both mean energy consumption and variance appear higher in the 'real world' tests, with the least energy-efficient vehicles clocking 26kWh/100km when starting the battery from cold (cold-start). Moreover, the WLTC tests show that real-world energy consumption could be even higher in colder ambient environments and when vehicles are driving more consistently at high speeds. These differences highlight the importance of distinguishing between 'real world' and 'certified' energy consumption figures. This chapter therefore focuses on real-world energy consumption as a more representative reflection of the use phase energy consumption of BEVs.

For PHEVs, the overall combined energy consumption is also very strongly influenced by both the electric range of the vehicle and user behaviour. The resulting share of operation in charge depleting and charge sustaining modes is typically accounted for by a utility factor in regulatory testing. Recent evidence on typical operation and analyses of real-world fuel consumption monitoring from PHEVs (European Commission, 2024), (CleanTechnica, 2024) has shown in-use emissions over 3.5 time higher and that the share of operation in electric mode is far lower than is defined in previous regulatory testing protocols. Amendments to the utility function used in such testing in the EU using WLTP will be implemented from 2025, which are expected to improve this aspect. Otherwise, most of the other real-world factors that affect BEV energy consumption are also relevant for PHEVs (and also for FCEVs due to their electric powertrains), so these are not further discussed in detail in the rest of this chapter.

Figure 4-1: Comparison of BEV energy consumption (kWh/100km) in manufacturer certifications against a variety of alternative test cycles.



Source: Green NCAP test data, including charging losses.

Notes: values are split into three broad categories of test - worldwide harmonized light vehicle test cycle (WLTC), Portable Emissions Monitoring Systems (PEMS), and those printed on the certificate of conformity (CoC). Within WLTC and PEMS categories, tests are differentiated by the state of the engine when the test starts (cold versus warm), speed (mostly motorway driving versus a more balanced mix of motorway and slower driving), ambient temperature (at -7^{o}C versus more moderate temperatures) and distance travelled (short versus long).

4.3 FACTORS AFFECTING REAL-WORLD ENERGY CONSUMPTION OF BEVS

The objective of this subchapter is to address the following questions related to real-world energy consumption of BEVs:

- What are the main factors contributing to real-world energy consumption of BEVs?
- How do these differ compare to conventional vehicles?

Factors affecting ICEVs have been thoroughly researched in the literature and draw on a rich dataset from real-world driving. Evidence on the factors affecting BEVs is more limited. The literature findings presented below rely heavily on the following: analysis of individual vehicles in a range of test conditions; analysis in individual geographies; and/or efforts to predict energy consumption via models or simulations. The sample size is therefore relatively small compared to an ‘ideal’ situation where real-world data is available across a range of vehicles and across various geographies. However, this limited sample can still provide a good indication on the extent to which individual factors contribute to total BEV energy consumption.

There are some common factors contributing to energy consumption between BEVs and ICEVs, but they also differ in some key areas. Contributing factors are many and inter-dependent, but are categorised broadly in this report into vehicle-, environment-, and driver- related factors, as also in (Zhang et al., 2020).

4.3.1 Vehicle-related factors

This section summarises literature findings on factors contributing to vehicle energy consumption relating to the characteristics of the vehicle itself, i.e. its size, shape and propulsion mechanics.

Table 4-1 below lists several important contributing factors to vehicle energy efficiency for both BEVs and ICEVs, for comparison. Evidence for the factor’s importance for ICEVs is taken largely from a comprehensive literature review performed by the European Joint Research Council (JRC, 2016), but is supplemented by other sources.

Table 4-1: Summary comparison of vehicle-related factors impacting energy consumption of BEVs and ICEVs

Factor	Impact on BEVs	Impact on ICEVs
Speed	Increases in energy consumption follows a u-shaped curve, rising with speed beyond an energy-optimal speed of around 30 kph. This energy consumption profile favours lower-speed drive cycles.	Like BEVs, energy consumption follows a u-shaped curve. However, ICEVs are less efficient at lower speeds, with the energy-optimal speed at around 75 kph. This energy consumption profile favours higher-speed drive cycles.
Aerodynamics	A reduction in aerodynamic drag reduces energy consumption in BEVs by up to 6-7%. This benefit is greater at higher speeds.	Aerodynamic improvements have slightly less potential to reduce energy efficiency in ICEVs. Various aerodynamic improvements such as properly designed spoilers and vortex generators could reduce fuel consumption by 0.4 % (JRC, 2016). Removing roof boxes and keeping windows shut could have larger impacts.
Battery capacity	Where larger battery size is not accompanied by a reduction in battery density, vehicle mass will increase, leading to greater rolling resistance (see ‘Mass’). While a larger battery will lead to fewer rapid recharging events and improve battery losses, these are not likely to outweigh the increase in charger losses.	ICEVs only have a small on-board battery that does not contribute significantly to fuel consumption.
Vehicle mass	For each 10% increase in vehicle mass, evidence suggests that energy consumption tends to increase by 3-6%. This impact is likely to be somewhat (but not wholly) mitigated by the impact of regenerative braking.	There is a similar relationship for ICEVs; a 3-6% increase in energy consumption for each 10% increase in vehicle mass (JRC, 2016).
Engine power	Holding vehicle mass constant, evidence suggests that engine power is a small contributing factor – increasing energy consumption by 6% for each doubling of rated power output (typically expressed in kilowatts).	By contrast, engine power is an important, if not the most important, driver of fuel consumption for ICEVs. Literature suggests that each doubling of rated engine power tends to increase fuel consumption by around 30–50% (Weiss et al., 2020).
Regenerative braking	Evidence in urban settings suggests that the application of regenerative braking can help to save up to 7-29% of total energy consumption. Savings in non-urban settings (with longer drive cycles and less deceleration time) are likely to be smaller.	Only applies to hybrid engines.

Speed

Like ICEVs, the relationship between speed and energy consumption follows a u-shaped curve for BEVs, with consumption generally rising with speed after a certain energy-efficient point (Janpoom et al., 2023; Qi et al., 2018; Fiori et al., 2019)

Figure 4-2 below shows speed-energy consumption curves derived by Ricardo for the UK Department for Transport in 2023.[4] **BEV energy consumption is lower than all other powertrains at all speeds. However,**

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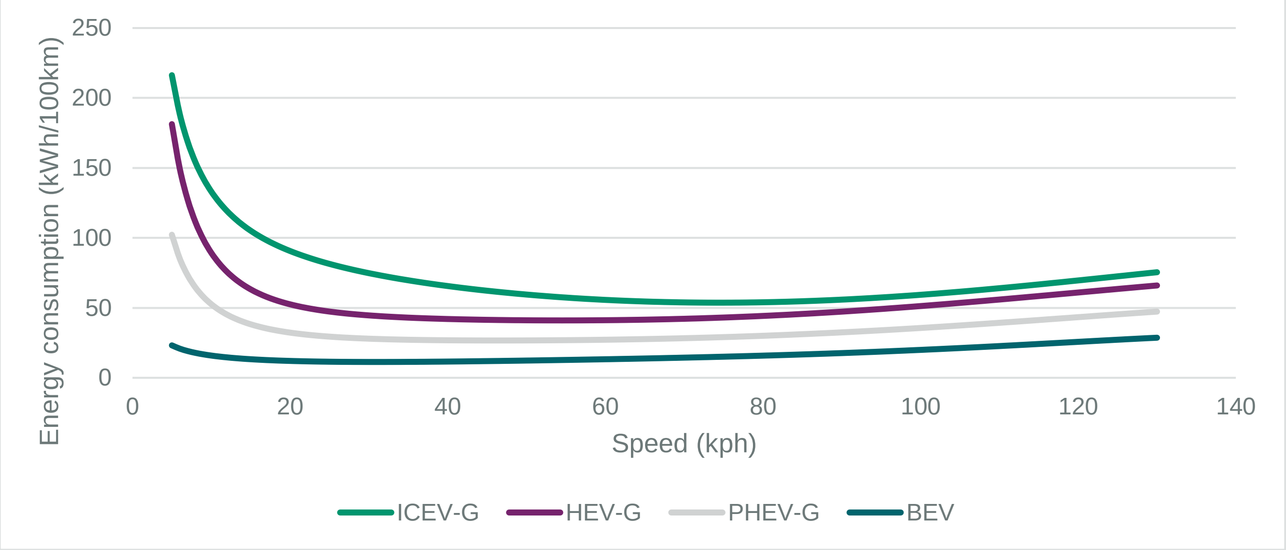
[4] Speed emission curves were produced from simulated energy consumption factors provided by TU Graz and are consistent with HBEFA 4.2.

there are notable differences in the shape of the curve between BEVs and other powertrains. While the energy-optimal speed for BEVs is around 30-40kph, for ICEVs this is around 75kph. This means that while BEV energy consumption is still low, relative to ICEVs it is proportionally much higher at motorway speeds than urban speeds. Using the below energy consumption profiles, motorway driving at 110kph consumes 84% more energy than at 50kph in BEVs, whereas for ICEVs this difference is only 8%. Real-world testing of vehicles under the Green NCAP programme corroborates this relationship: motorway test cycles recorded 58% higher energy consumption than CoC values in BEVs (see Figure A2.1-1 in Appendix A2 for more information), while for ICEVs the difference was only 38%.

Figure 4-2: Comparison of speed-energy consumption curves between various passenger car powertrains.



Source: Ricardo study for the UK Department for Transport, 2023

Note: the PHEV energy consumption curve has been derived assuming that it drives 50% of the distance in 'electric mode'.[5]

Aerodynamics

Making changes to the shape of a vehicle can influence how much resistance it encounters when moving through air. Vehicles that can cut through the air more efficiently will therefore reduce aerodynamic drag and allow the vehicle to consume less energy for a given speed. This is typically measured in vehicles by a coefficient of drag (Cd). **Evidence from previous Ricardo studies suggest that while both BEVs and ICEVs experience lower energy consumption when aerodynamic improvements are made, BEVs can experience even greater benefits than ICEVs** – a reduction of 6-7% when the Cd is improved by 10%, compared to 4.5-6% in ICEVs (Ricardo et al., 2018), (Ricardo et al., 2021 forthcoming). This effect is likely due to the heavier average mass of BEVs compared to ICEVs, which has a proportionally greater effect at higher speeds. Notably, two of the top five most energy-efficient BEVs in the Green NCAP testing programme - the Tesla Model S and the Hyundai Ioniq 6, with Cd's of 0.208 and 0.210 respectively - also appear in the top five list of most aerodynamically efficient BEVs on sale in the UK.[6] This suggests that aerodynamics play a large part in the energy consumption of BEVs.

Battery capacity

There are two effects to be aware of when it comes to the impact of battery capacity on energy consumption:

- effects on vehicle mass (assuming no change in battery density), and
- range / charging behaviour effects.

On the former, it should be evident that if the overall mass of the vehicle increases, then so too should vehicle energy consumption due to an increase in rolling resistance. Figure 4-4 below shows the results of Green NCAP test data for around 30 BEVs. This shows that **for a doubling in battery capacity from the sample**

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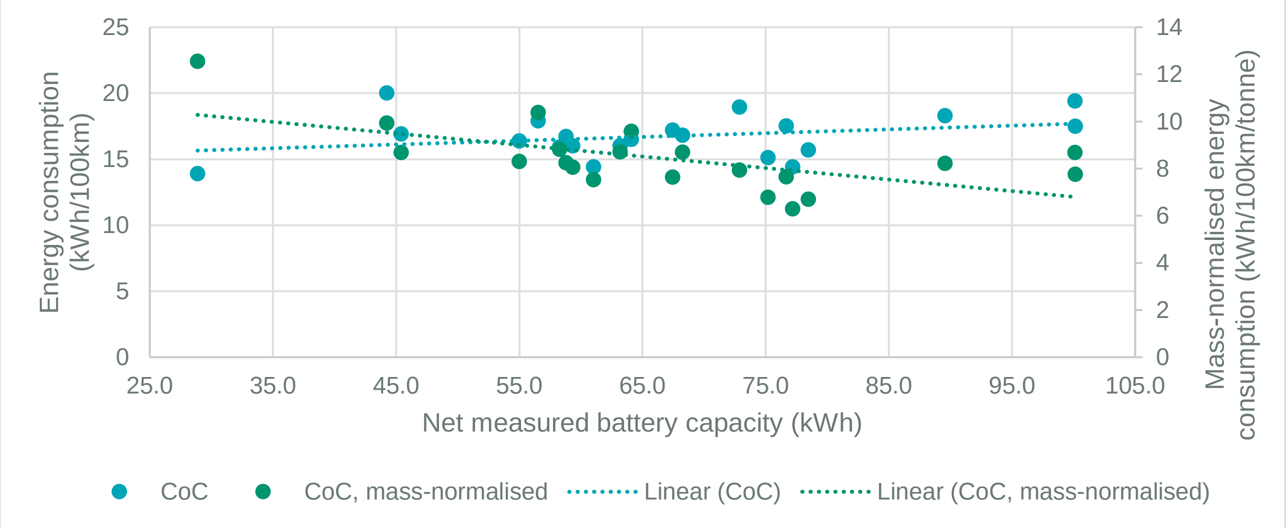
[5] This 50% utility factor assumption is consistent with that made for the study for the UK Department for Transport. However, it is worth noting that more recent estimates reflect that in the real world, as little as 20% of distance driven could be in 'electric mode' (TNO, 2024b).

[6] https://www.topgear.com/car-news/electric/these-are-12-most-aerodynamically-efficient-evs-sale-today

average of 68 kWh, manufacturer-certified average energy consumption increases by 14%. However, once these figures are adjusted for the impact of vehicle mass, this positive relationship disappears. This finding is important as the assumption of no change in battery density is not reflective of global trends. Increasingly, Chinese OEMs producing lower capacity batteries are favouring lower energy density LFP packs – which are cheaper – while currently cars produced in Europe and America with higher capacity batteries more often use lithium nickel manganese cobalt oxide (NMC) (IEA, 2024)[7]. The battery packs can be a much more similar mass as a result, limiting the impact on energy consumption further. Since vehicle mass is considered separately in a later section, most of the impact of battery capacity is attributed to the second effect above.

Figure 4-3: BEV average energy consumption (kWh/100km) against battery capacity.



Source: Ricardo analysis of Green NCAP test data

On charging behaviour effects, it is worth noting that an increase in battery capacity increases the vehicle's effective range, holding all else constant. Fewer recharging events are needed, and more can be done at home rather than topping up on the road using fast chargers. Recent analysis by the ICCT simulates the impact of a larger battery (116kWh vs 58kWh) on energy consumption for a VW ID.3 (ICCT, 2024a). The research showed that with increasing driving range, fewer en-route DC charging stops are required, and hence a larger share of the total energy is charged using AC charging. AC charging has two contrasting impacts: on the one hand, there are slightly lower battery losses[8], but on the other there are greater on-board charger losses[9]. The former cannot outweigh the latter and, therefore, net charging losses are higher for the larger battery, with a variation in the losses of 11-29% depending on assumed drive cycle (commuter versus long distance drivers). However, the change in charger losses from a larger battery are far smaller in absolute magnitude (0.4-0.9 kWh/100km) than the changes in driving energy demand which result from increased vehicle mass (2.1-2.9 kWh/100km).

It is also worth noting the implications of battery size on battery lifetime – for further explanation see Section 5.1.2. In short, smaller batteries need to be recharged more often, and hence reach a greater depth of discharge (DoD) more often, reducing battery lifetime. However, they also have lower maximum charging rates, because they typically exhibit the same ratio of capacity to maximum charge rate (or C-rate). Lower maximum charge rate typically extends battery lifetime. The net impact of these two effects is unclear and will likely depend on the charge management of the battery and the battery chemistry. In some BEV models, different battery chemistries are used for the standard and long-range vehicles. For example, the Volve EX30 uses a 51kWh LFP lithium ion battery for the standard range, and a 69 kWh NMC lithium ion battery for the long-range option. The lower capacity LFP pack is slightly heavier than the higher capacity NMC pack, and there is only a small difference in the overall vehicle mass (and energy consumption). Since LFP battery packs typically have better cycle life/durability compared to NMC chemistries, the more frequent cycling required for

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[7] Examples include the Polestar 3 and the Volvo EX30.

[8] Battery losses refer to the internal battery charging and discharging.

[9] Charger losses correspond to the external charger during DC charging and the on-board charger during AC charging.

the smaller capacity pack is unlikely to reduce the overall battery lifetime. This shows that care must be taken in making assumptions between different BEV versions, models and manufacturers on the effects of battery capacities on overall vehicle energy consumption.

Engine power

The effect of engine power on energy consumption is difficult to disentangle from battery size and vehicle mass since these are quite often correlated. However, one study analysing charging event data from 211 BEVs attempts to separate the impact of engine power from the impact of vehicle mass by modelling them as two separate independent variables in a multivariate regression. This study shows that, when regressed against real-world energy consumption, each doubling of vehicle power would correspond to an increase in energy consumption of 6% when holding vehicle mass constant (Weiss et al., 2020). Considering that the authors find a doubling of vehicle mass leads to a 46% increase in real-world energy consumption, this indicates that mass is a more important determinant than battery power.

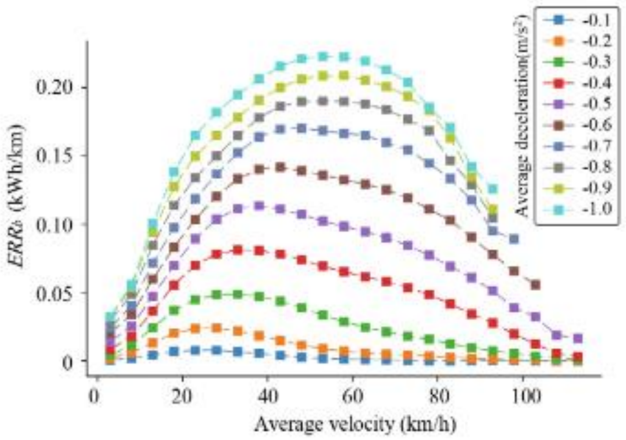
Brake regeneration

One key differentiator between traditional ICEVs and many BEVs and/or hybrids is the ability for the vehicle to recover energy during braking. This is achieved by the wheels turning the electric motor in reverse once the accelerator pedal is lifted, inducing a current and returning energy to the battery.

Available information on the magnitude of regenerative braking is limited to urban settings, making it less representative for longer drive cycles. However, it provides an upper estimate of the energy that can be recovered given the short trip durations and congestion experienced in a busy urban area.

One study estimates this through the collection of real-world driving data from 55 electric BAIC taxis in Beijing city. The authors extract a profile of energy regeneration against vehicle speed and state of deceleration, shown below. In general, this figure shows that energy recovery increases with both vehicle speed at the point of deceleration (average velocity) and braking force (average deceleration), but only up to a certain speed – around 50kph. At speeds greater than 50kph energy recovery starts to fall, likely as more energy is lost as heat. For this specific vehicle and urban taxi drive cycle combination, the authors found that **regenerative braking can help to save as much as 7.6–28.7% of total energy consumed during a trip** (Zhang et al., 2020).

Figure 4-4: Energy recovered through regenerative braking (ERRb) at various velocities and rates of deceleration.



Source: (Qi et al., 2018)

Important also to note is the relationship between increasing battery capacity and regenerative braking. Increasing battery capacity without improving energy density results in a higher vehicle mass, therefore requiring higher energy demand to overcome mass-related resistance. Recent ICCT analysis states that only part of the higher energy demand can be recuperated through regenerative braking. For a simulated urban commuter driving a VW ID.3, annual average energy consumption increases by 3.5 kWh/100km when switching from a 58kWh battery to a 116kWh battery (or +17%), while energy recovery only increases by 1.6 kWh/100km. This indicates that larger batteries result in larger net energy consumption (ICCT, 2024a).

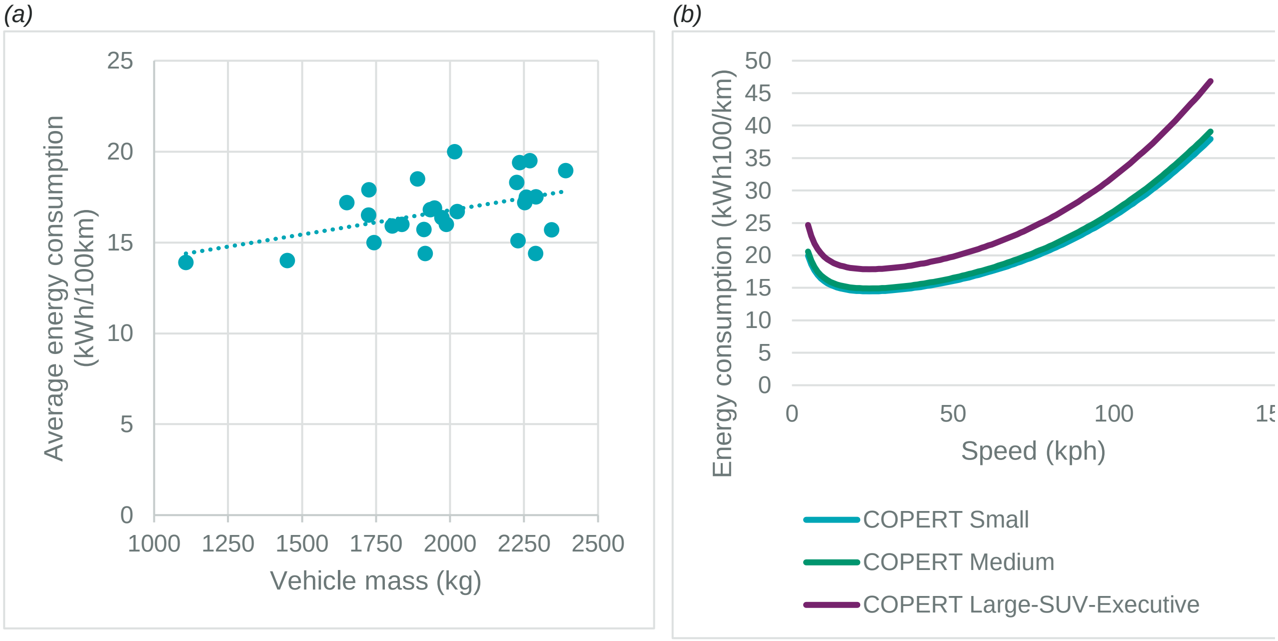
Vehicle mass

An increase in vehicle mass increases the demand being put on the engine to generate enough power to move that mass. **Analysis of charging event data from Travelcard covering 22,000 BEVs suggest trends in fleet average vehicle weight closely match trends in fleet average energy consumption, suggesting a high degree of correlation (TNO, 2024b).**

Figure 4-5 (a) below shows Green NCAP test data for around 30 BEVs - for a doubling of vehicle mass from the sample average of 2000kg, results suggest that manufacturer certified average energy consumption increases by 30% (although there will be other factors also affecting this trend). Compared to other literature, regression analysis of charging event data from 211 BEVs suggests that a doubling of mass from a sample average of 1689 kg would increase manufacturer certified average energy consumption 60% (Weiss et al., 2020), which is also consistent with previous vehicle simulation based analysis on the effects of mass reduction on energy consumption of vehicles from (Ricardo et al., 2021 forthcoming).

Figure 4-5 (b) shows COPERT speed emission curve factors for a range of passenger car segments. This shows that the gap in energy consumption between small/medium cars and large SUVs increases slightly with speed, indicating that mass has a larger effect on energy consumption at higher speeds. This is because SUVs are both heavier and have greater drag coefficients.

Figure 4-5: (a) BEV average energy consumption (kWh/100km) against vehicle mass, and (b) comparison of speed-energy consumption curves between passenger cars of different sizes and masses



Source: Ricardo analysis of Green NCAP test data

Source: COPERT 5.7[10]

4.3.2 Environment-related factors

This section summarises literature findings on factors contributing to vehicle energy consumption relating to the environment around the vehicle, i.e. temperature and contextual traffic conditions.

Table 4-2: Summary comparison of environment-related factors impacting energy consumption of BEVs and ICEVs

Factor	Importance for BEVs	Importance for ICEV
Ambient temperature / auxiliary components	BEVs are most energy-efficient at around 21ºC. Efficiency reduces at both colder and warmer temperatures due to required conditioning of the battery and cabin but	Auxiliary systems comprise a much smaller part of ICEV fuel consumption. Air conditioning increases fuel consumption by 9%, steering assist systems increase it

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[10] COPERT | Calculations of Emissions from Road Transport (emisia.com)

Factor	Importance for BEVs	Importance for ICEV
	reduces significantly more rapidly moving towards colder temperatures.	by up to 4.5 %, and other auxiliaries together contribute an addition of 6.5 % (JRC, 2016). In addition, ICEVs can use waste heat to help provide supplementary heating in colder conditions.
Traffic conditions	BEVs are more energy efficient in congested traffic, because there are lower average speeds and more time is spent decelerating/ braking to allow for energy recovery (see 'Speed' and 'Regenerative braking' above).	Congestion will lead to slower speeds, increased idle time and more start/stop activity. ICEV are less fuel-efficient at lower average speeds, leading to greater fuel consumption. This could be as much as 30% higher than free-flow traffic (JRC, 2016), however this is reduced for hybrid vehicles with regenerative braking.

Ambient temperature / Auxiliary components

Vehicle propulsion systems operate most efficiently at moderate temperatures, and drivers prefer cabin temperatures closer to room temperature for their own thermal management. Therefore, vehicles are designed with additional auxiliary components to maintain engine temperatures at their most efficient operating temperature and to maintain cabins at around room temperature. Heating, ventilation and air conditioning (HVAC) components work hard in extreme high or low temperatures to maintain this optimal temperature environment.

There are also increasingly more electrified components in vehicles as vehicles modernise that raise the power demand from components that aren't related to temperature variation, including sensors and steering assist. Temperature and auxiliary component demand are therefore highly, but not perfectly, correlated. In a detailed study, UEA list and estimate the annual energy usage of 26 different components in BEVs (UEA, 2022). The top 5, and their estimated share of auxiliary component energy demand, are: air conditioning (36%), actuator control units (12%), sensors (7%), power steering pump mechanism (7%), and headlights (7%).

Authors have used various methods to investigate the impact of ambient temperature and/or auxiliary components on energy demand in BEVs. One study aims to simulate the effect of ambient temperature separately from auxiliary power demand, finding that auxiliary power demand is the more important determinant - in low-speed trips, energy consumption is of the same magnitude as propulsion energy consumption (see Figure A2.1-2 and commentary for further information) (Komnos et al., 2022). By monitoring vehicle energy consumption while stationary (<0.5kph), TNO estimated that for urban use at average speeds of 30kph, non-propulsion related energy demand could comprise up to 50% of total energy consumption (TNO, 2024a). A study for JRC compared energy usage when HVAC is turned on with when it is turned off. They find an increase in distance specific energy consumption of approximately 12% for a test at 25 ºC and 71% for a test at -10 ºC due to the energy demand of the auxiliary systems (JRC, 2019). Comparison of test cycles performed at different temperatures can also directly point to temperature's effect on BEV energy consumption (see Figure A in Appendix A2 for more information).

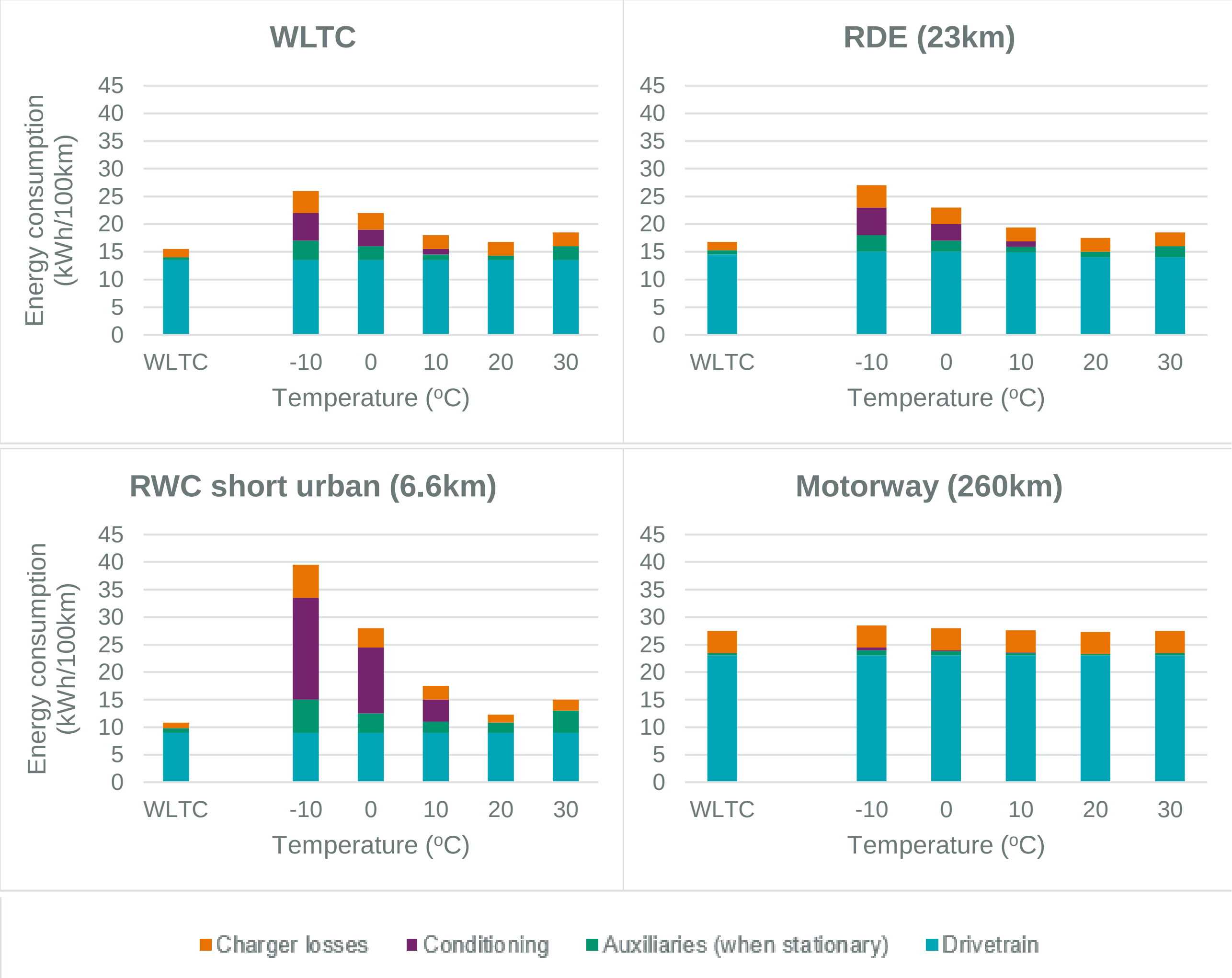
Finally, the 2022 UEA study mentioned above uses real-world energy consumption data to simulate auxiliary component energy demand at the component level (UEA, 2022). The findings are explored in more detail as follows. Figure 4-9 below shows the breakdown of vehicle energy use in a variety of cycles, environmental conditions, and HVAC settings. The 26 components are grouped into two categories (air conditioning, and other components), and compared with energy demand from engine drive and charging losses. Some key interpretations of the charts are provided below.

- **The effect of temperature on energy consumption in BEVs is u-shaped, with a more pronounced effect at lower temperatures.** The WLTC (top left), RDE (top right) and RWC (bottom left) charts all show optimum energy performance around room temperature, rising at both colder and hotter temperatures.
- **Per kilometre energy consumption is highest in cold urban drive cycles, and lowest in moderate-temperature urban drive cycles.** Comparing all four charts, the greatest extremes are found in the RWC short urban chart (bottom left). BEV powertrains are most efficient at slower average

speeds, as found in urban areas (see Section 4.2.1 for more information), but these efficiency gains can be offset by large temperature demand from auxiliary systems in cold temperatures.

- **Cold temperatures have more of an effect on energy consumption in short drive cycles compared to long ones.** The main differences between the RWC (bottom left) and Motorway (bottom right) charts are that in the former, the test cycle is shorter and contains more stop-start activity. The large amount of energy required to get the battery and cabin to temperature are spread over relatively fewer kilometres, creating a higher average figure. By contrast on motorways, average energy consumption stays fairly flat across all temperatures. Most energy demand comes from the drivetrain.

Figure 4-6: Calculated energy consumption values for the average compact BEV for different drive cycles, environmental conditions, and HVAC settings



Source: Adaptation of Figure 15 from (UEA, 2022)

Notes: WLTC – worldwide harmonized light vehicle test cycle, RDE – real driving emissions, RWC – real world cycle. All simulations run at WLTC test weight.

Traffic conditions

One study directly compares the energy performance of electric passenger cars to ICEVs in different traffic conditions – it combines real traffic trajectory data and simulated trajectory data across a number of geographies and timeframes to demonstrate differences in energy consumption between congested (CONG) and free flow traffic (FF). Each dataset represents a different level of congestion, and they simulate alternative congestion levels by varying the average speed of vehicles – higher for free flow, and slower for congested. They find that **for EVs, congested conditions are characterized by between 0-18% lower energy consumption if compared with free flow conditions, depending on the dataset consulted** (see Figure A2.1-4 in Appendix A2.1 for a graphical representation). By contrast, for ICEVs congested conditions lead to

0-65% *higher* energy consumption (Fiori, et al., 2019). The authors explain that this can be explained rather straightforwardly because of the combined effect of:

a) higher and more constant efficiency of electric motor/generator and electric devices (inverters, batteries etc) with respect to ICEVs, and
b) the energy recovered during braking, that allows reducing energy consumption especially when congested.

The impact of both vehicle speed and regenerative braking as factors determining energy consumption are explored further in Section 4.2.1. The impact of traffic conditions is likely to constitute the combination of these two impacts, with the total effect being caused by the interaction between the contextual traffic environment and the performance of the vehicle. ybridisation of ICEVs will probably reduce the differential to EVs in the future, but it is likely that they won't bring the same level of benefits as for EVs, as only part of the powertrain is electrified and the rate (and amount) of energy storage will be limited by the much smaller battery for hybrids versus BEVs.

4.3.3 Driver-related factors

Finally, this section summarises literature findings on factors contributing to vehicle energy consumption which are directly in the control of the driver, i.e. how they drive the vehicle and, in the case of BEVs, how and where they charge.

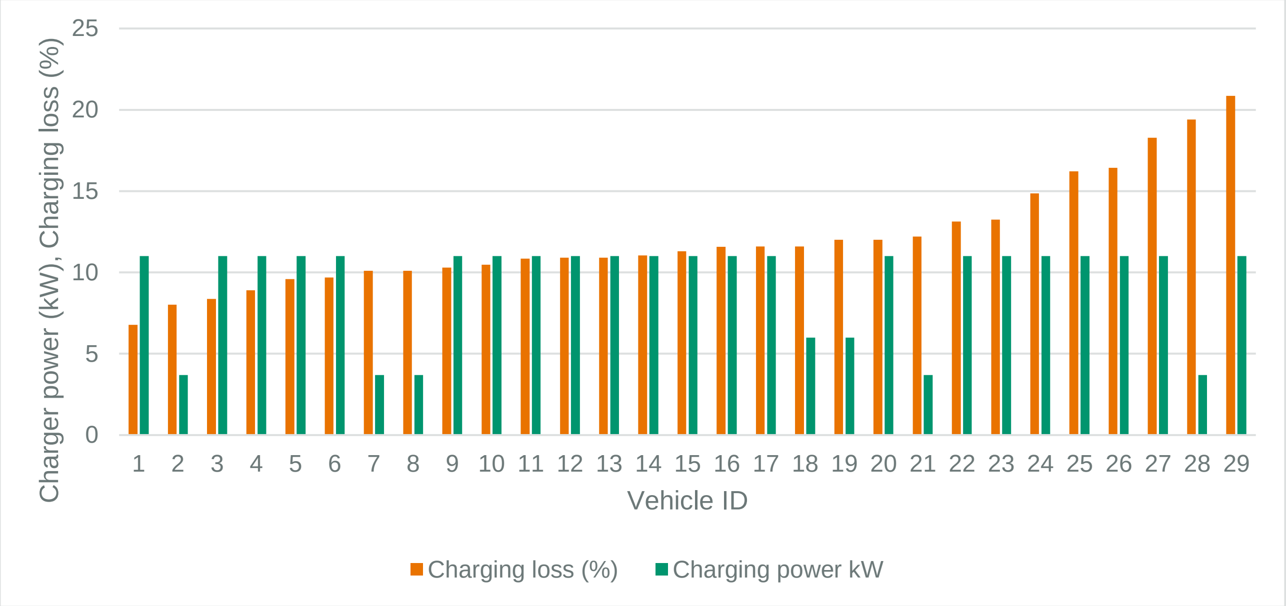
Table 4-3: Summary comparison of driver-related factors impacting energy consumption of BEVs and ICEVs

Factor	Importance for BEVs	Importance for ICEVs
Use of public / ultra rapid chargers	One ICCT simulation suggests that greater use of rapid or ultra-rapid charging leads to slightly higher annual average energy consumption, in the region of 3-5% depending on the size of the battery.	N/A
'Harshness' of acceleration and braking	One study based in Beijing, China suggests that a 'low acceleration, low deceleration' driving pattern reduces energy consumption in BEVs by around 9% compared to a 'high acceleration, high deceleration' pattern.	Evidence suggests that ICEV fuel consumption is more sensitive to driver behaviour. Aggressive driving can increase fuel consumption by +24 %, while eco-driving can reduce it in the order of 6-8 % (JRC, 2016).

Use of public / ultra rapid chargers

Charging losses can be substantial in BEVs even when slow AC charging is used. Analysis of Green NCAP's test data relating to charging losses is shown in the diagram below. Each individual BEV is shown along the x axis, while a dual-purpose y-axis shows both the Charging loss (%) and charging power (kW). Vehicles are ordered by charging loss from lowest (left) to highest (right). Within slow chargers, there seems to be no apparent relationship between these two variables – charging losses for a 3kW charger range from 8-19%, while for a 7kW charger they range from 7-21%.

Figure 4-7: Plot of AC charger losses (%) against charger power (kW) for each BEV tested within the Green NCAP programme.



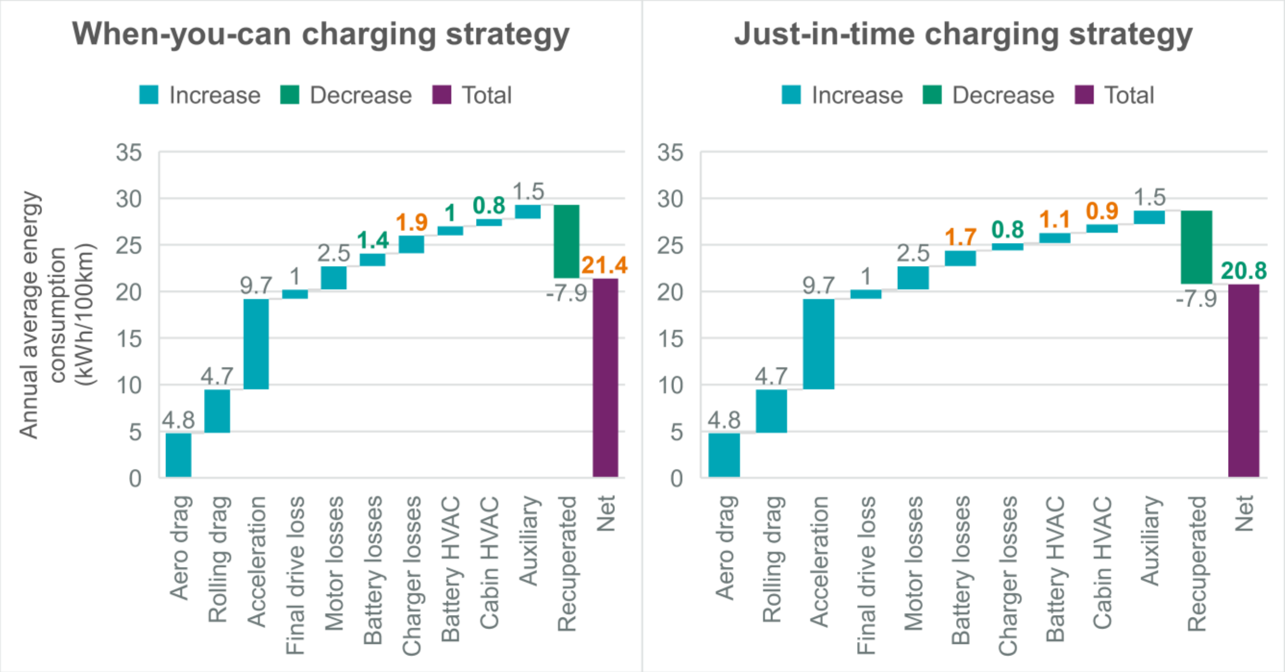
Source: Ricardo analysis of Green NCAP data

However, recent analysis by the ICCT highlights the impact of using more DC chargers within two realistic charging strategy scenarios (ICCT, 2024a):

- **Just-in-time**: the battery is recharged by DC charging when the SOC drops below 20%. Additionally, AC home charging is performed by the rural commuter and the long-distance driver if the SOC is below 80% when reaching home.
- **When-you-can**: the driver utilizes AC charging during all planned stops if the SOC is lower than 80%. If the SOC drops below 20% during driving and the distance to the next stop is higher than the remaining battery range, the battery is replenished by DC charging.

Figure 4-13 below is an adaption of a figure from the ICCT's report, which highlights the source of differences in energy consumption in a VW ID.3 with a 58kWh battery. When moving from the left chart (Just-in-time) to the right chart (When-you-can), there are some key differences in energy consumption. **Battery losses** fall by 19%, because of the lower average charging power associated with the when-you-can strategy. However, **charger losses** rise by 133% because a less efficient on-board charger is used more often. This is somewhat mitigated by a reduction in **battery HVAC** energy consumption (-11%) because less frequent temperature conditioning of the battery with fewer DC fast charging events, and a reduction in **cabin HVAC** (-3%) because less heat is generated through DC charging events. However, **the net effect is a 3% increase** in annual average energy consumption, because **charger losses outweigh other factors.**

Figure 4-8: Effect of charging strategy on energy consumption for the urban commuter



Source: Adaptation of Figure 9 from (ICCT, 2024a)

Notes: Simulations refer to a VW ID.3 with a 58kWh battery in urban settings. Battery losses refer to the internal battery charging and discharging. Charger losses correspond to the external charger during DC charging and the on-board charger during AC charging.

The above findings highlight the agency that drivers can exert in managing their charging behaviour to limit losses associated with charging.

‘Harshness’ of acceleration and braking

There is limited evidence on the impact of driver behaviour on BEV energy consumption. However, one study estimates this through the collection of real-world driving data from 55 electric BAIC taxis in Beijing city. The authors observe that **average energy consumption is 9% higher in ‘HaHd’ (hard acceleration, hard deceleration) behaviours than in ‘LaLd’ (light acceleration, light deceleration) behaviours**, which could indicate the effect of different styles of driving on energy consumption (Zhang et al., 2020). It should be noted though that this relates to one vehicle in one geography, and so the representativeness of these results are limited.

4.4 COMPARISON IN THE REAL-WORLD ENERGY CONSUMPTION OF AVAILABLE BEV MODELS

The objective of this subchapter is to address the following questions related to real-world energy consumption of EVs:

- How do different BEV models currently available on the market compare in terms of their energy consumption?
- How is the real-world energy consumption of BEVs changing over time?

As stated in the introduction to this chapter, it is important to consider the real-world energy consumption of available BEV models rather than values reported by manufacturers in laboratory conditions. The challenge in providing one figure for energy consumption lies in properly defining what a ‘representative’ test cycle is, i.e. what average driving profiles are like in the real world. This will vary significantly by environment (temperature) and usage patterns (shorter vs longer drives, charging behaviour, etc.). Whilst there are no extensive high-quality robust datasets available that provide a full assessment of true ‘real-world’ performance, testing by Green NCAP provides an approximation of this, accounting for a wider range of ‘real-world’ effects than for the standard regulatory protocol through a range of laboratory tests/settings, and on-road testing with PEMS.

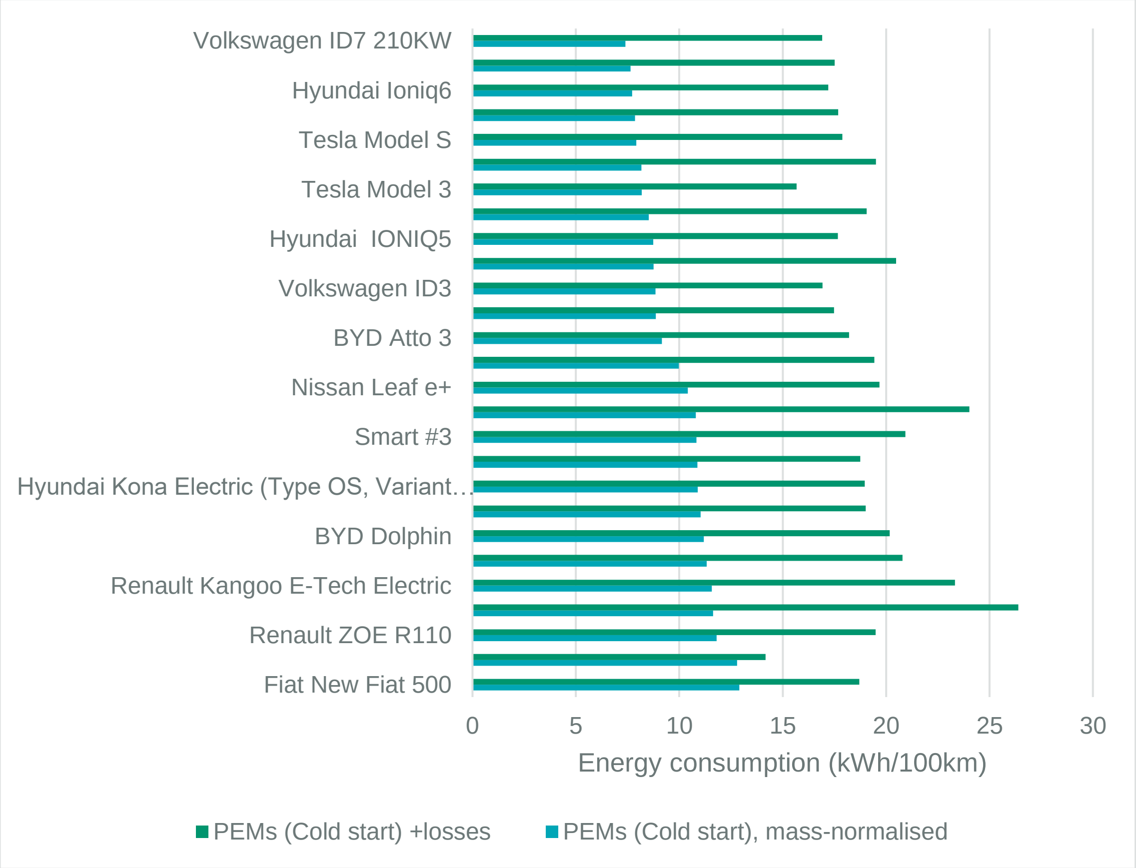
4.4.1 Current snapshot based on available datasets

Here analysis of Green NCAP test data for 27 BEVs registered between 2022 and 2024 is presented. This dataset contains 7 of the top 10 selling BEVs on the European market in 2023, which together comprise around 30% of total European BEV sales (ICCT, 2024b).

The green lines in the graph below show that there is a wide range of energy consumption values in popular BEV models. **Ignoring differences in vehicle size/mass, according to the Green NCAP testing the Dacia Spring appears to consume the least energy per unit distance travelled (14.2 kWh/100km), while the Ford Mustang Mach-E consumes the most (26.4 kWh/100km).** Cross-referencing this with online information available via the EV Database which covers a much larger range of 260 EVs, real world energy consumption (as estimated by the authors[11]) ranges from the most energy efficient Tesla Model 3 (13.8 kWh/100km) to the least efficient Lotus Electre R (24.3 kWh/100km). Due to the wide range of driving conditions and behaviour, and lack of detail on the specific data, it is extremely difficult to make fully objective comparisons. However, the findings suggest that the Green NCAP dataset may be reasonably representative of models available on the market.

The models in the Green NCAP test data sample range from a 3-door Smart car to a large SUV. Comparing average energy consumption between vehicle segments would unfairly bias smaller vehicles, so to compensate for this to an extent mass-normalised energy consumption values are also presented in blue. Mass-normalisation is a simplistic method of comparison since it implicitly assumes all variation in consumption is related to mass, which the previous section highlights is far from the case. It is therefore recommended that the total energy consumption figures are not ignored. **After normalisation, the evidence shows that per kg mass, the VW ID7 is the most energy efficient, while the New Fiat 500 displays the lowest energy consumption**. All vehicles are ordered by mass-normalised energy consumption, from lowest to highest.

Figure 4-9: Energy consumption of popular BEV models based on Green NCAP PEMS testing (n=27).



Source: own elaboration based on Green NCAP test data.

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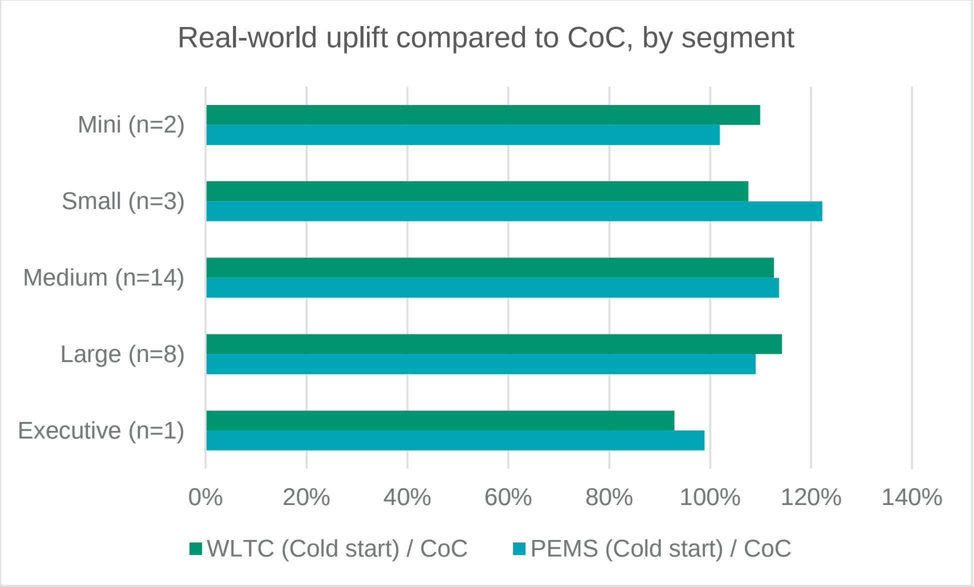
[11] The authors report WLTP energy consumption and 'real' energy consumption separately, where real energy consumption is calculated by them "based on moderate drive style and climate".

Figure 4-16 below shows that **the difference between Green NCAP testing under more real-world representative conditions and the certified energy consumption may decrease as vehicle size increases**, although it is worth noting that there is a very small sample size for both Mini (A-segment) and Executive (E-segment) vehicles.

Green NCAP laboratory testing WLTC energy consumption values from cold engine start are generally closer to CoC values (93-114%) than PEMS energy consumption values (99-122%), as would perhaps be expected (as the WLTC is used as part of the regulatory testing protocol – WLTP – used to produce the CoC values). The exception is the NIO ET7 as the one Executive vehicle – here, the CoC value seems more representative of energy consumption testing under more real-world conditions, with only a 1% difference against the PEMS test.

Figure 4-10: Difference in Green NCAP testing of energy consumption in real-world approximated conditions, as indicated by PEMS and WLTC tests, against manufacturer-reported energy consumption (CoC)



Source: own elaboration based on Green NCAP test data

Notes: Segmentation in the chart follows European terminologies. These are replicated here along with American terminologies for clarity, in the fomat EU/US: A-segment – Mini / Minicompact, B-segment – Small / Subcompact, C-segment – Medium / Compact, D-segment – Large / Mid-size, E-segment – Executive / Large.

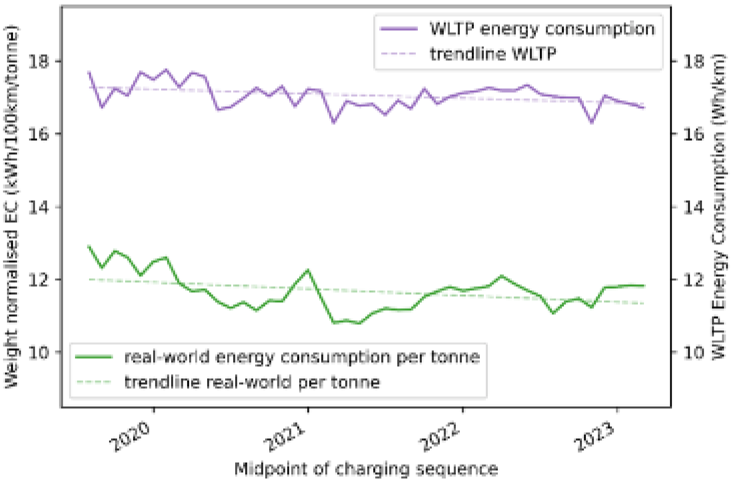
4.4.2 Trends in BEV energy consumption over time

There is limited time series data to be able to draw strong conclusions on how BEV real world energy consumption is changing over time. However, since 2014 there has been a requirement in the Netherlands for manufacturers to register personal and light company vehicle car odometer readings, and an open-access dataset is now managed by the Netherlands Vehicle Authority (RDW). TNO have cross-referenced this data with charging event data from Travelcard to produce an indicative time-series dataset (TNO, 2024b). This dataset spans 22,000 BEVs in Europe over the period 2020-2023. They report the following trends:

- **WLTP energy consumption has fallen slightly.** Values measured in laboratory tests suggest that the average energy consumption of new BEVs has reduced over time.
- **Real-world energy consumption is rising relative to CoC.** In combination with the above, the authors claim that the percentual gap between real-world and WLTP energy consumption has trended from about 15% at the beginning of 2020 to roughly 25% at the beginning of 2023.
- **Vehicle mass is rising.** Consumer are increasingly favouring SUVs, and as such there have been a lot of bigger electric SUVs introduced, many of which have higher energy consumption due to their mass. TNO's data suggests that the average BEV mass has risen from around 1500kg in 2017 to 1900kg in 2022. This changes the fleet composition, raising the fleet average electricity consumption.
- **Mass-adjusted real-world energy consumption is falling.** This indicates that there may be reductions in energy consumption over the past few years within vehicle segments (in aerodynamics,

powertrain efficiency etc.). However, since real-world energy consumption is still rising, the mass effect of a changing vehicle composition outweighs these small changes.

Figure 4-11: Monthly average real-world energy consumption per tonne of empty mass and WLTP energy consumption.



Source: (TNO, 2024b)

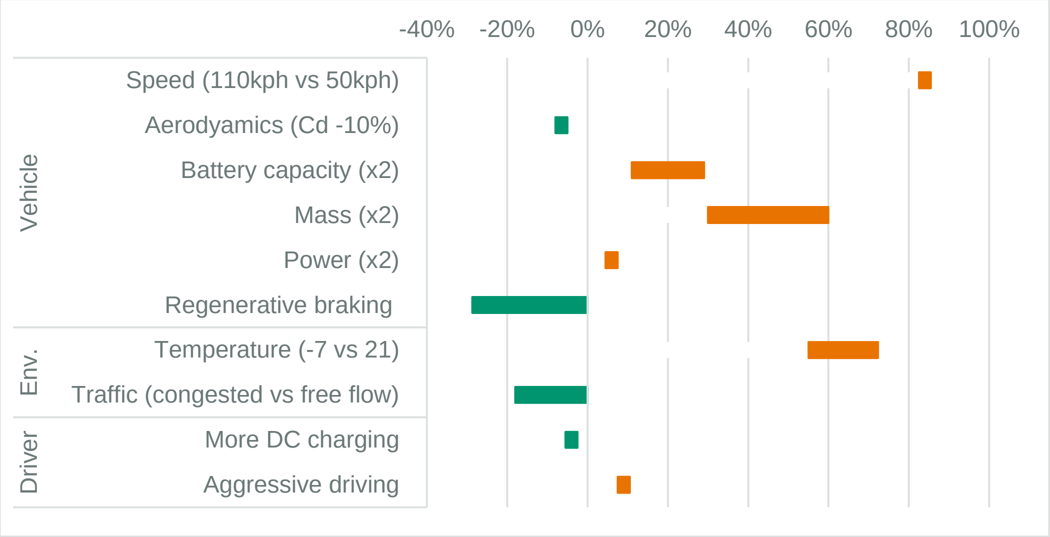
Note: real world energy consumption only appears lower than WLTP energy consumption because it is normalised for weight (and plotted on a different axis).

It is not clear whether the Netherlands fleet is fully representative of the European fleet, however, the important takeaway from these findings is that it is critical to monitor (a) real-world energy consumption of BEVs going into the future, as they differ significantly from manufacturer-certified values, and (b) the market composition of the BEV fleet in terms of mass and/or segmentation, since in combination with (a) this allows us to see whether improvements are being made, or whether this is just due to a changing fleet mix.

4.5 SUMMARY

Figure 4-10 below shows a brief summary of the literature review conducted to show the relative importance of the factors explored in determining the real world energy consumption of BEVs. **Driving in cold temperatures, at high speeds, or bearing significant load all increase real world energy consumption to a significant degree.** Using larger batteries, more powerful engines, and aggressive driving increase energy consumption to a more limited extent. **Regenerative braking (more prevalent in congested traffic conditions) can recover large amounts of energy in urban areas. Improvements to aerodynamics can also reduce energy consumption, especially at higher speeds.** It is worth noting that the aerodynamic changes represented here are proportionally small (-10% in drag coefficient) compared to other factors like battery capacity, mass and power where the associated metrics are doubled, meaning that the relative gains are significant – and for significantly lower cost. A change in charging strategy to favour on-the-go charging is unlikely to reduce energy consumption significantly.

Figure 4-12: Relative importance of each factor in determining energy consumption of BEVs, as summarised from available evidence.



Sources: own elaboration from analysis and literature review.[12]

Notes: impacts of regenerative braking and traffic in the chart above are likely to overlap. Ranges indicate uncertainty from a single author, or a range of values reported by different authors.[13]

Analysis of Green NCAP testing data suggests that real world energy consumption of available BEV models varies from 14.2 kWh/100km (Dacia Spring) to 26.4 kWh/100km (Ford Mustang Mach-E). Mass-normalised energy consumption estimates suggest that the most efficient vehicle tested per kilogram of mass was the VW ID7, while the least efficient was the Fiat 500.Manufacturer-reported energy consumption could be further away from actual (real world) energy consumption for small A/B-segment vehicles (102%-122%) than large E-segment vehicles (93%-98%), although this finding could be due to a limited sample size.

Fleet average vehicle energy consumption in the real world is rising over time, largely because vehicles are getting heavier. However, this is concealed by the fact that fleet average manufacturer-reported energy consumption is falling slightly over time. TNO suggests that the gap between these two has risen from about 15% at the beginning of 2020 to roughly 25% at the beginning of 2023. There are clearly some improvements being made in vehicle energy efficiency over time and manufacturers want to highlight this, but because vehicles are getting heavier, total fleet average energy consumption is still rising.

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[12] Speed - *(Ricardo, 2023 forthcoming)*. Aerodynamics - *(Ricardo et al., 2018)*, *(Ricardo et al., 2021 forthcoming)*. Battery capacity – *(ICCT, 2024a)*. Mass - *(Green NCAP, 2024)*. Power - *(Weiss et al., 2020)*. Regenerative braking - *(Qi et al., 2018)*. Temperature - *(UEA, 2022)*, *(Green NCAP, 2024)*. Traffic - *(Fiori et al., 2019)*. Charging - *(ICCT, 2024a)*. Aggressive driving - *(Zhang et al., 2020)*.

[13] Small ranges are single-source estimates, enlarged for visibility. Large ranges indicate values from various sources, with the exception of (a) Regenerative braking, where the only literature value available refers to urban settings (impacts likely lower in other settings), and (b) Battery capacity / Traffic, where one source itself indicates a range.

5. BATTERY LIFE AND SECOND-LIFE APPLICATIONS

This chapter focuses on batteries of electric passenger cars covering their performance/degradation, end-of-automotive life applications and environmental implications. The chapter is based on scientific literature, empirical evidence from data aggregators, OEM publications and publicly available evidence from research projects. The three subchapters cover a high-level review of:

- Battery degradation rate data for different xEV models and strategies for extending battery life of xEVs
- Feasibility of repurposing used xEV batteries for energy storage applications
- Opportunities to reduce the environmental implications of battery production, usage, and disposal

The scope of the study is limited to commonly used lithium-ion battery chemistries, i.e., Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP), unless otherwise specified. In subchapter 5.2, the use-case for repurposing of used EV batteries is limited to energy storage applications.

5.1 REVIEW OF XEV BATTERY DEGRADATION RATES AND STRATEGIES FOR EXTENDING BATTERY LIFE

The objective of this subchapter is to address the following questions related to battery degradation:

(a) What is xEV battery degradation?

(b) What are the common factors influencing xEV battery health?

(c) What is the common value/range of battery degradation and battery durability from empirical evidence (for consumer information), vehicle battery warranties and regulations?

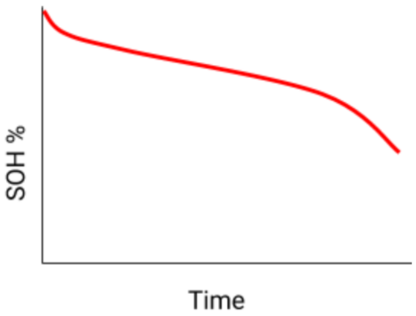
(d) What are the different strategies for xEV users to extend the battery life?

5.1.1 Introduction to battery degradation

xEV batteries degrade due to both usage (cycle life) and age (calendar life) which leads to a loss of energy storage capacity (impacting range) and power over time. The degradation is caused by various chemical and physical reactions that affect the key components within xEV batteries, such as the electrodes and the electrolyte.

The available energy storage capacity of an xEV battery as a percentage compared to its initial storage capacity when it's new is referred to as its state of health (SOH). New batteries start off with 100% SOH, which reduces with time as the battery degrades. For example, a 60 kWh battery with an SOH of 90% would have an effective capacity of 54 kWh. Similarly, the xEV's range would reduce. For example, a new BEV with a 300 km range would lose around 30 km of range once the battery has reached an SOH of 90%. This reduction in range is unlikely to have a noticeable impact on most drivers' daily driving needs (Geotab, 2024), except perhaps in very cold weather where range is further reduced due to additional heating needs. However, for high-usage scenarios such as commercial fleets, this slight loss in range may need to be considered for operational planning (Geotab, 2024).

Figure 5-1 Non-linear degradation profile of xEV batteries.



Battery degradation is non-linear, generally following the s-shaped profile shown in Figure 5-1. The degradation profile can be broken down into three stages (Liu, et al., 2020), as shown in Figure A3.1-1 in the Appendix. During the first stage, the battery experiences an initial drop in SOH. This is followed by a more linear and moderate decline during the second stage, which accounts for most of the battery's lifetime. In the third stage, as the battery approaches the end of its life, a final rapid decrease in performance is experienced. A BEV battery is generally no longer considered appropriate for traction purposes when they reach 70% - 80% of its initial capacity or state of health (SOH) (Al-Alawi, 2022), (Lluc Canals Casals, 2019), (Eric Wood, 2011). PHEV and HEV batteries often retain more SOH at their end-of-life.

5.1.2 Common factors influencing battery health

Vehicle batteries respond differently under different conditions. The common factors influencing battery health or degradation rate can be broadly categorised into:

(a) **Vehicle make and model:** The two key potential factors are battery chemistry and thermal management. While most xEVs use lithium-ion batteries, there are many different variations of lithium-ion chemistries. A battery's chemical make-up will influence how it responds to stress and aging. In addition to cell chemistry, temperature control techniques differ across vehicle models. A major distinction is whether the battery pack is cooled and/or heated by air or liquid; better thermal management can keep the battery closer to ideal operating conditions, and therefore reduce aging.

(b) **Environmental conditions and operating modes:** There are several factors such as voltage, current and temperature under different conditions and operating modes having varying impacts on xEV battery health as summarised in Table 5-1. In more extreme temperature conditions, it is harder for the battery thermal management systems to maintain optimal battery internal conditions.

Table 5-1: Factors influencing battery health for different operating modes

Operating mode	Factors impacting battery degradation	Type of impact	Degree of impact
Charging	SOC / Voltage	• Slight overcharging to above the nominal SOC value increases capacity but accelerates degradation (Liu et al., 2020). However, xEV battery management systems (BMSs) prevent overcharging, so this is unlikely to occur in practice. • Undercharging to lower SOC reduces capacity but lowers degradation (Mathieu, Briat, Gyan, & Vinassa, 2021).	Low
	Charging current / C-rate	• Higher charging current rates generally lead to faster degradation; however, the trend can vary between different chemistries (Guo et al., 2021).	Medium-high
	Temperature	• Charging/discharging at either very low or high temperatures accelerates degradation (Guo et al., 2021). Further evidence is presented in Figure A3.1-2 in the appendix.	High
Driving	Temperature		
	Voltage: Depth of Discharge (DOD)	• Over-discharging or reducing the cut-off voltage of the battery can accelerate degradation (Guo et al., 2021). While xEV BMSs prevent over-discharging, higher levels of DOD (within BMS limits) are associated with increased degradation (Liu et al., 2020).	High
	Discharge current (driving speed and acceleration)	• Higher discharge currents can accelerate degradation; however, current intensity has a smaller influence than DOD (Simolka et al., 2020).	Medium
Standby (Parked)	SOC / Voltage	• High standby SOCs (over 70%) accelerate capacity fade due to lithium plating (Guo et al., 2021).	High
	Temperature	• Battery capacity fade increases at higher standby temperatures compared to moderate temperatures (Guo et al., 2021).	Medium

5.1.3 Review of battery degradation rate data for different xEV models

Battery durability is a key concern for consumers, therefore, it is important to review available degradation data to better understand what range of degradation may be expected in practice. This information can help increase consumer confidence and reduce hesitancy related to adoption of xEVs. In this exercise, we aim to assess what might be a common value/range of EV battery degradation and a potential minimum life of xEV battery. The following evidence have been studied to inform this assessment:

(a) **Empirical evidence** – This includes evidence from data aggregators, scientific publications, and OEM claims. These sources of data can provide an accurate representation of battery degradation rates. However, the rates vary based on several factors mentioned earlier.

(b) **Vehicle battery warranties** – This includes a summary of various OEM battery warranties. While warranties aren't explicitly a representation of battery lifespan, they do set the expectation from OEMs that the vast majority of xEV batteries should retain a certain minimum capacity over a fixed distance or period (unless there is a fault) over a wide range of operating conditions/usage.

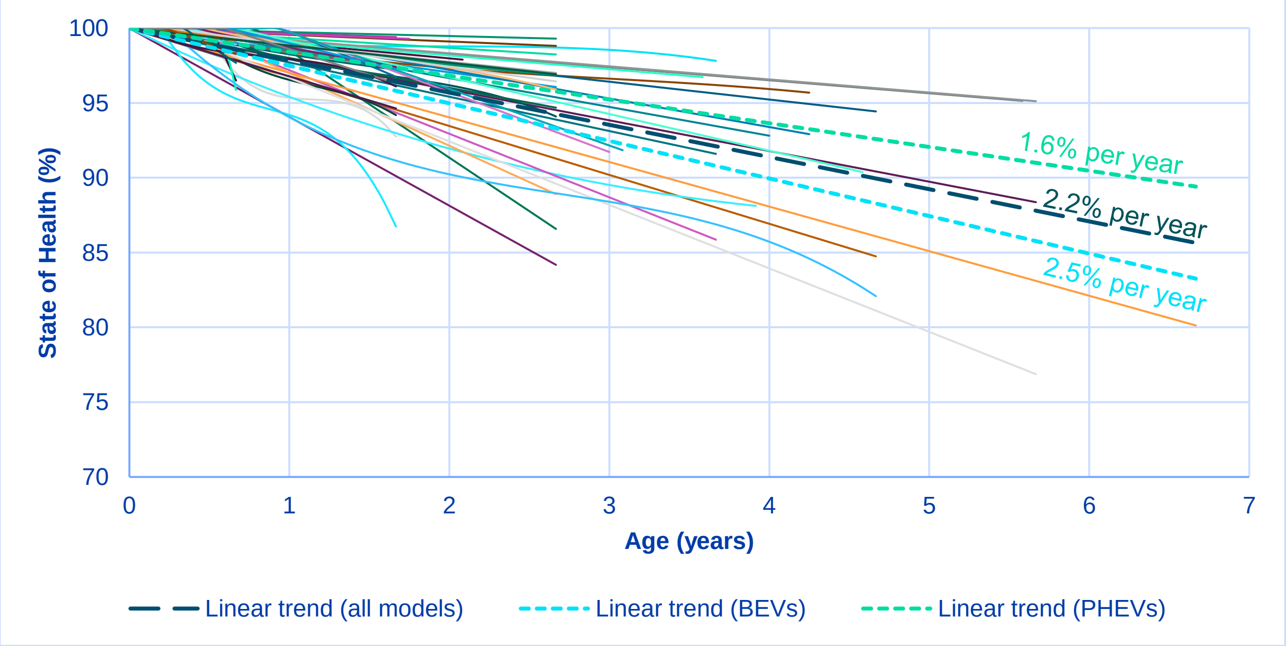
(c) **Regulations** – A brief overview of existing and planned regulations relating to battery degradation and durability requirements is presented.

5.1.3.1 (a) Empirical evidence

There is currently a limited number of publicly available battery degradation datasets available. However, as xEV batteries become a more mature technology over time, more datasets are likely to become available. We have identified and collected data from three different types of sources for our review of empirical evidence – datasets, publications, and OEM claims. The key datasets are from companies that provide fleet analytics based on vehicle telematics data (Geotab, 2024) (Recurrent Auto, 2024). Evidence is supplemented with further information from publications and OEM claims. An overview of the data sources and their limitations is provided in Table A1.1-1 in the Appendix.

An overview of Geotab's battery State of Health data (Geotab, 2024) for 64 different model-year variations of BEVs and PHEVs is shown in Figure 5-2, along with an average for all models. Each curve shows the aggregated average degradation data for a specific make, model and year. The chart shows that SOH values differ between different models and years as the vehicles get older, with an average SOH of 89% after 5 years. **This equates to an average of approximately 2.2% degradation per year if assumed to be linear**.

Figure 5-2: SOH vs Age for 64 model-year variations (BEVs and PHEVs).

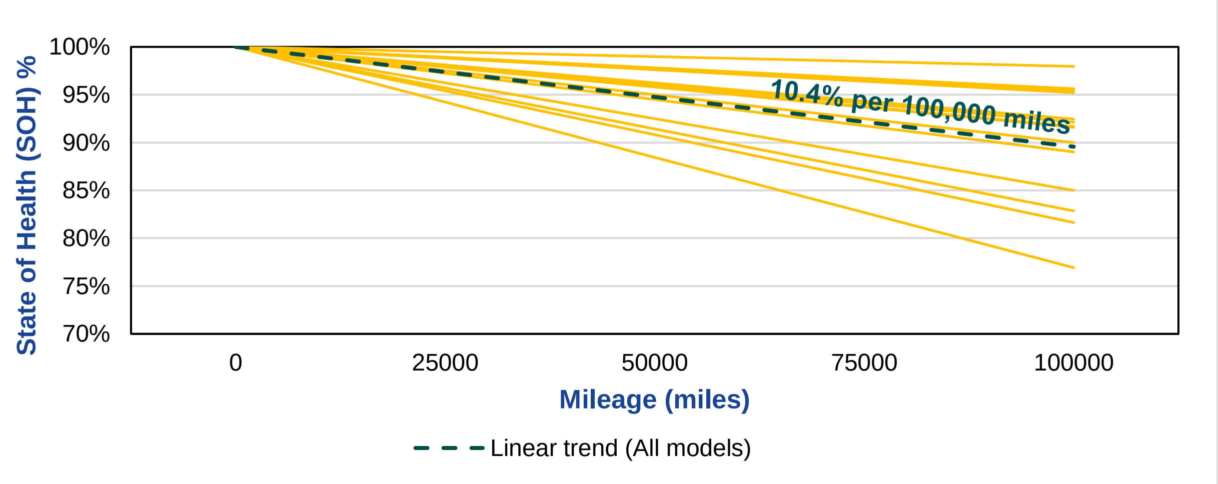


Source: (Geotab, 2024)

Notes: Individual model labels not shown. Each of the curves displayed shows the average aggregated trend line for a model from Geotab's analysed data. Of the 64 different model-year variations, 35 were BEVs and 29 were PHEVs. As *shown by the varied length of the individual curves, models in the dataset only have data up to the age of the vehicle at the time the data was collected by Geotab, with less trends available for vehicles with higher ages.*

Recurrent Auto claim that data from their community of 15,000 vehicles has shown battery degradation is generally in the range of 1-2% per year (Witt, 2023). A liner plot of the degradation of 14 model variations of Recurrent's data (Recurrent Auto, 2024) is shown in Figure 5-3. **The chart shows an average degradation rate of approximately 1% per 12,600 miles (25,100 km) for a maximum odometer reading of 100,000 miles.**

Figure 5-3: State of Health (SOH) vs vehicle mileage 14 model-year variations (BEVs)



Notes: These BEV battery degradation rates are calculated for odometer readings up to 100,000 miles. The percentage degradation rates for the next 100,000 miles are expected to be higher. The degradation trend is plotted to be linear because of unavailability of the intermediary data points (for example SOH at 25,000 miles). While the degradation SOH at 100,000 miles will be accurate, the rate of actual degradation will be non-linear.

A few comparisons have been drawn studying differences in battery degradation across vehicles such BEVs vs PHEVs; newer and old vehicle models; and fast charging vs slow charging.

BEVs vs PHEVs:

Figure 5-2 also shows how the change in SOH trends differ between battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs), based on trends for the 35 BEV and 29 PHEV model-year variations in the Geotab dataset. **The trendlines show PHEVs tend to experience lower degradation rates than BEVs** in this dataset, with around 92% SOH after 5 years compared to 87%, and a degradation rate of approximately 1.6% per year compared to 2.5% per year if assumed to be linear. The battery degradation in a PHEV is most likely slower compared to a BEV because of several reasons, such as the following according to (Battery University, 2019) (GreenCars, 2023):

- *Usage patterns and depth of discharge:* PHEVs operate within a more constrained state of charge (SOC) window to maintain battery health, prevent deep discharges, and efficiently manage the transition between electric power and the ICE (Nigel, 2022). It is also because they are not under constant load and are charged at low power ratings (slow charging).
- *Battery size and thermal management:* The smaller battery packs in PHEVs are easier to manage thermally, helping to keep the battery within optimal temperature ranges. Reduced thermal stress leads to slower degradation.

Newer vs older xEV models

Newer xEVs are showing improvements in battery life due to advances in battery technology, such as and changes in battery chemistry, and also improved battery management systems (BMS), thermal management (passive air-cooling vs liquid cooling). Newer xEV models also tend to have higher capacity batteries, which means that there are fewer charge/discharge cycles needed to travel the same km. For example, in the available Geotab dataset, the 2016 Nissan Leaf model (with a 30 kWh battery) showed 6.9% degradation by the third year, whereas the older 2013 model (with a 24 kWh battery) showed 8.9-percent degradation by the third year. The effect of improved thermal management can also be seen in one example from Geotab's data, where a passive air-cooled BEV model from one OEM is compared to a liquid cooled BEV model from a different OEM of the same year (Geotab, 2024). The passive air-cooled battery showed a higher average degradation rate of 4.2% per year compared to the liquid cooled battery, which had a rate of 2.3%.

Fast charging vs slow charging

A study on the implications of fast charging on lithium-ion xEV batteries performed testing on two 2012 Nissan Leaf 24 kWh battery packs (Tanim et al., 2018). The study performed 13 months of cycling on the batteries, equivalent to approximately 50,000 miles. **The battery pack that experienced the slow charging (AC Level 2) charging protocol showed 23.2% loss in capacity, while the fast charged (DCFC 50 kW) battery pack showed a higher level of degradation, with 28.1% capacity loss.** However, these results are for earlier battery technology and more recent batteries are expected to experience lower levels of degradation (CARB, 2022). More recent data from Recurrent's fleet of 13,000 Tesla vehicles showed that frequent[14] rapid charging may not speed up degradation as significantly compared to slow charging (Witt, 2024). However, their data is skewed towards newer vehicles so the data may not reflect any potential longer term cumulative effects of fast charging (Witt, 2024).

In addition to these empirical data, very few OEMs, such as Tesla, have released data regarding the real-world degradation rate of its electric vehicle batteries. Tesla has provided information related to battery retention against mileage for two sets of models, i.e., Tesla Model S/X and 3/Y, as shown in Figure A3.1-4 and Figure A3.1-5 respectively in the Appendix. **Tesla stated that after 200,000 miles (322,000 km) their Model S/X lose around 12% of their original capacity on average while their Model 3/Y lose around 15% of their capacity on average.** These values equate to approximately 1% loss in battery capacity every 13,300 miles (21,400 km) and 16,700 miles (26,900 km) respectively. It is worth noting that Tesla models often have the leading battery capacity (electric range) compared to other models, requiring fewer charge/discharge cycles to travel the same distance. Thus, it is likely that the degradation for lower battery capacity (electric range) will be higher.

To summarise the empirical evidence, we conclude the following:

- The data from Geotab for 56 model-year variations shows an approximate battery degradation rate of 2.2% per year. This translates to a vehicle with a 400 km (250 mile) range losing 44 km (27.5 miles) of range after 5 years. At this average degradation rate of 2.2% per year, an EV battery would take 15 years to decline to 70% maximum charge.
- The data from Recurrent for 16 model variations shows an approximate range loss rate of approximately 1% per 15,600 miles. They also report an average rate of 1-2% degradation per year. At this average degradation rate of 2.2% per year, an EV battery would take 15 years to decline to 70% maximum charge.
- Very few OEMs have published real-world battery degradation rate of their EV batteries. Tesla's Model S/X and 3/Y have a degradation rate of 12% and 15% respectively per 200,000 miles (322,000 kms). These values equate to approximately 1% loss in battery capacity every 13,300 miles (21,400 kms) and 16,700 miles (26,900 kms) respectively.
- Newer xEV batteries degrade slower due to advances in battery technology such as battery chemistry, battery management systems and thermal management systems.
- Analysis of Geotab's data showed that the trend of battery degradation in the PHEV models was less than the BEV models. This is likely due to differences in usage patterns, battery size and thermal management.
- Frequent fast charging has been shown to increase rates of battery degradation in older xEV models. Some data from newer xEV models does not show a very significant impact, however, there is some uncertainty around the longer-term effects of frequent fast charging.

5.1.3.2 (b) Battery warranties offered by OEMs based on xEV battery age, mileage and degradation

Manufacturer warranties aren't explicitly a representation of battery lifespan; however, they do set the *expectation* that xEV batteries should retain a certain minimum level of capacity over a fixed distance or period of time. **Most OEMs offer warranties for xEV batteries in the range of 7-8 years and 100,000-120,000 miles (~160,000-200,000 km), generally covering a minimum of 70-75% of original storage capacity.** A detailed list of battery warranties in presented in Table A3.1- in the Appendix.

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[14] Fast charging more than 70% of the time.

The life of xEV batteries generally far exceeds the warranty periods, except in certain cases of battery faults or damage. **In total, 2.5% of approximately 20,000 drivers in the Recurrent community had reported battery replacement, and the majority of these occurred while the vehicles were under warranty** (Recurrent, 2024). **Excluding official battery recalls, battery replacements have been reducing with newer models.** Further evidence on xEV battery replacements by model year is presented in Figure A3.1-3 in the Appendix. Recurrent (2024) reported that 13% of their community's vehicles from 2015 or older have reported battery replacements, whereas less than 1% of their vehicles from 2016 and newer have replaced their batteries.

5.1.3.3 *(c) Regulatory provisions on EV battery durability and degradation*

Regulations play a crucial role in establishing minimum battery durability requirements for manufacturers and ensuring these standards align with consumer needs.

The new Euro 7 standard will set requirements for all BEVs and PHEVs registered in the EU to have minimum levels of battery durability, relating to age and mileage (whichever is reached first) (Dornoff & Rodríguez, 2024). The methodology is harmonized with other regions, based on work from the UNECE on UN GTR No. 22.[15] For passenger cars (category M_1), batteries will need to retain an energy storage capability of 80% after 5 years or 100,000 km, and 72% after 8 years or 160,000 km. This requirement is expected to come into force towards the end of 2026 for cars and vans that require a new type approval, and all new vehicle from a year after (Inficon, 2024). Similarly, light-commercial vehicles (category N_1) will need to retain 75% and 67% battery capacity for the same usage periods, expected to come into force around mid-2028. **Additionally, the Euro 7 proposal also sets requirement for manufacturers to include user viewable SOH monitors in new vehicles (categories M_1, M_2, M_3, N_1, N_2 and N_3), which will make it visible to vehicle users.**

Manufacturers of PHEVs are currently required to provide battery warranties of 10 years or 150,000 miles (~240,000 km) in the US as part of existing emission control warranty requirements (CARB, 2022). However, no minimum level of battery capacity or degradation is specified in this requirement. As part of California's Advanced Clean Cars II (ACC II) Regulations (CARB, 2022), there has been a proposal that *"BEV and FCEV test groups must be designed to maintain 80% or more of the original (as new) certified combined city and highway test range for 10 years or 150,000 miles, whichever occurs first"* from 2026 onwards. In terms of warranty, California mandates that BEVs and PHEVs models years from 2026 to 2030 must have a minimum warranty of 8 years or 100,000 miles (~160,000 km) for batteries falling below 70% SOH (LLI, 2022). It also mandates an increase in the SOH limit from 70% to 75% from 2031 onwards. The US Environmental Protection Agency (EPA) has designated the high-voltage battery as a specified major emission control component for BEV and PHEV model years from 2027 onwards, requiring the batteries to have warranties for a period of 8 years or 80,000 miles (~130,000km) (Environmental Protection Agency, 2024).

5.1.4 Strategies for extending battery life of xEVs

While battery degradation cannot be avoided entirely, there are some strategies that could be used to extend the battery life of xEVs, as summarised in Table 5-2 below. These strategies are available for xEV users wanting to maximise their battery life and should only be implemented when it is practical and convenient to do so.

Table 5-2: Summary of strategies for extending the battery life of xEVs, split by operating modes and degradation factors.

Operating mode	Factors affecting battery life	Strategy to reduce impact of factors affecting battery degradation
Charging	Voltage	• Minimise charging to above 70-80% unless necessary (i.e., if maximum range is required for a long trip) and never fast charge to above 80% (Recurrent, 2024).
	Charging current / C-rate	• Only use fast charging occasionally or when necessary, such as for long trips (Recurrent, 2024). While some high-use duty cycles may

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[15] United Nations Economic Commission for Europe, "Addendum 22: United Nations GTR No. 22," ECE/TRANS/180/Add.22 § (2022), https://unece.org/sites/default/files/2022-04/ECE_TRANS_180a22e.pdf.

Operating mode	Factors affecting battery life	Strategy to reduce impact of factors affecting battery degradation
		require a faster charge, level 2 charging should be sufficient for most drivers if the vehicle remains parked overnight.
	Temperature	• Avoid fast charging when the battery is very cold or hot (Recurrent, 2024). • Before charging at low or high temperatures, pre-conditioning (heat up or cool down) the battery ensures that it is at optimum temperature (Cotta, 2023). Most modern xEV batteries have built in thermal management systems that allow pre-conditioning, however, some older or less expensive models may not. Depending on the system, the BEV or PHEV may need to be plugged in for pre-conditioning (to run on grid power), or in some cases can be started while driving towards a charger (some models may do this automatically if a fast charge is scheduled) (Cotta, 2023). • In addition to pre-conditioning, the timing of charging can also be chosen to optimise the temperature of the battery before charging (Cotta, 2023). During times of low temperatures, charging directly after a trip can take advantage of the warmer battery. During hotter periods, delaying charging after returning from a trip can allow the battery to cool down before charging begins.
Driving	Temperature	
	DOD	• If possible, minimise the DOD (how much energy you use in between charging) when driving by charging more regularly. For example, instead of using 50% of the battery before recharging, a driver could use about 30%, then charge before using another 20% (Recurrent, 2024).
	Discharge current (driving speed and acceleration)	• Minimise sudden starts and stops while driving (Woodya et al., 2020).
Standby (parked)	SOC	• Avoid time spent at full (100% SOC) or empty (0% SOC) charge. Ideally, keep the SOC between 20-80%, especially when parking the vehicle for long periods (Woodya et al., 2020).
	Temperature	• Minimise exposure to high temperatures during standby (Woodya et al., 2020): ○ Avoid parking in the sun on hot days. ○ Plug the BEV or PHEV in on hot days to allow the battery cooling system to run as needed.

5.2 FEASIBILITY OF REPURPOSING USED XEV BATTERIES FOR ENERGY STORAGE APPLICATIONS

The objective of this section is to address the following questions related to battery repurposing:

- What is battery repurposing, its stages, benefits and lifespan?
- What are the potential use-cases and examples of repurposed xEV battery in energy storage applications? What is the energy potential (GWh/year) of end of automotive life batteries?
- What is the feasibility of repurposed batteries in energy storage applications?
- What are the policy recommendations to address barriers associated to use of repurposed xEV batteries for energy storage applications?

5.2.1 Introduction to xEV battery repurposing

The expanding production of batteries brings forth concerns regarding the potential escalation of waste, particularly involving critical minerals that possess a high pollution potential when disposed in landfills or water bodies. An important aspect of battery circularity is extending the length of their useful life. An xEV battery is no longer considered appropriate for traction purposes when they reach 70% - 80% of its initial capacity or SOH (Al-Alawi, 2022; Casals et al., 2019). PHEV and HEV batteries often retain more SOH at their end-of-life. As batteries from the electric vehicles reach their end of automotive life, they can either be repurposed, recycled or disposed. At the time these xEV batteries complete their automotive life, they are still capable of storing energy. After the automotive life, depending on its state of health and how much capacity remains after its initial use, a battery can be repurposed to be used for a different application, for example as a battery energy storage system.

Repurposing means the use of retired xEV batteries in a different application than the battery was originally designed for. These include less strenuous use-cases such as stationary energy storage applications. Once an xEV battery reaches their definite end-of-life, having lost a significant proportion of its original capacity, it can then be recycled. Figure A3.2-1 in the Appendix depicts the life cycle of an xEV battery, where repurposing comes higher in circularity hierarchy compared to recycling and disposal.

Repurposing presents several benefits such as:

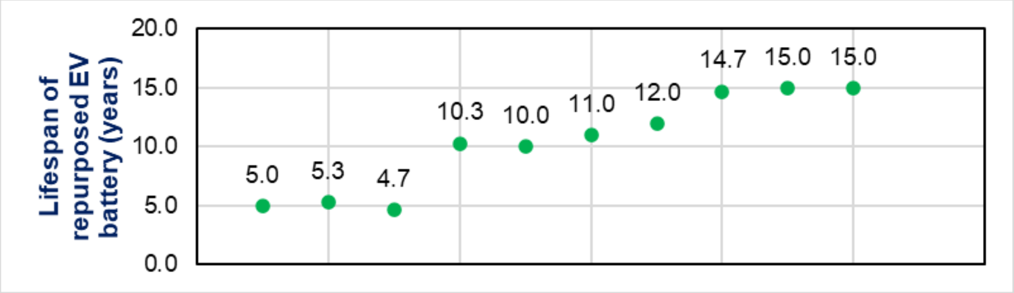
- Helping reduce the total lifetime cost of electric vehicles as repurposing could increase the end-of-life value of batteries
- Providing services at a reduced cost, i.e., the production cost of repurposed batteries is below 25% of the production cost of new batteries (European Commission, 2019)
- Supports roll-out of renewable power plants and reduces the need for short-term peak plants
- Reducing primary supply requirement of critical minerals, i.e., up to 8% annually by 2040 for minerals such as lithium, nickel, cobalt and copper (IEA, 2021a)
- Reducing dependence on specific suppliers or imports of battery materials, which can create supply chain vulnerabilities and geopolitical tensions

It should be noted that not all electric vehicle (xEV) batteries can be repurposed, and their potential for second-life applications depends on several factors including their physical condition, disassembly feasibility, safety, and economic viability. One study suggests that 85% of the batteries can be repurposed at end of vehicle application life, and that the remaining 15% being are damaged beyond repair (Foster et al., 2014).

The lifespan of repurposed xEV batteries is dependent on several influencing factors such as the initial health of the battery, second life duty cycle, weather, specific application and management of the battery system. **A general estimate for lifespan of repurposed EV batteries for energy storage applications is 5 to 15 years.** Figure 5-4 illustrates lifespan figures collected from several pieces of literature mentioned in

Table A3.2-1 in the Appendix.

Figure 5-4: Lifespan of repurposed xEV batteries

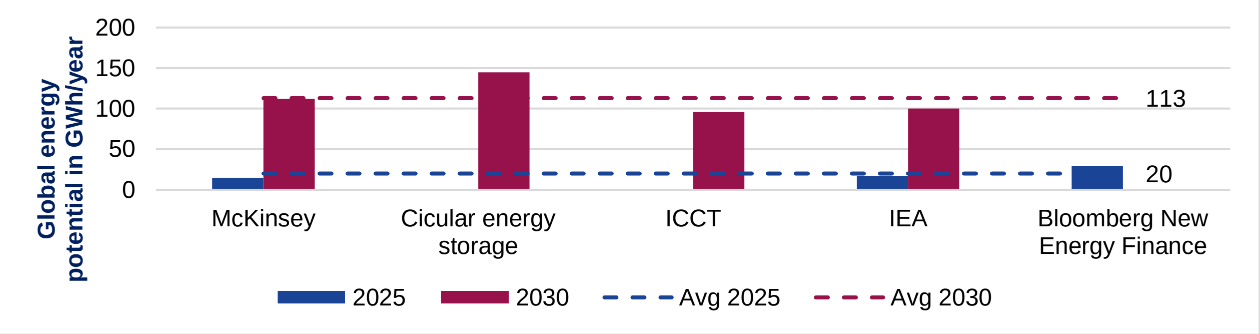


5.2.2 Potential use-cases of repurposed xEV batteries in energy storage applications and potential of end of life batteries globally

The potential energy storage use-cases for repurposed EV batteries is presented in Figure A3.2-2. A list of applications and the corresponding pilots, demonstrations, and ongoing projects in the EU where xEV batteries have been repurposed for second-life energy storage is illustrated in Table A3.2-2 in the Appendix.

According to the IEA Global EV Outlook 2024, there are around 45 million electric vehicles in the world (BEV and PHEVs combined) in 2023. According to the Alternative Fuel Observatory, there are 4.99 million BEVs and 3.60 million PHEVs on the road in the European Union. Currently, the availability of used xEV batteries is low but is expected to grow significantly. The following table shows the potential GWh available from end-of-life batteries for repurposing/reuse globally based on a number of alternative sources/analyses. The average global energy potential of end-of-life xEV batteries for repurposing/reuse is 113 GWh/year by 2030. To put this in context of global demand for xEV batteries, i.e., 4.3 TWh by 2030, that is a significantly small proportion.

Figure 5-5: Global energy potential of end-of-life xEV batteries for repurposing/reuse



Sources: own elaboration based on (McKinsey, 2019; ICCT, 2023; IEA, 2020a; Circular Energy Storage, 2021; BloombergNEF, 2024)

5.2.3 Feasibility of repurposed xEV batteries for energy storage applications

This subsection analyses the feasibility of xEV battery repurposing for energy storage from a technological, economic and environmental standpoint to understand their full impact and potential scalability. The key literature collected and reviewed are listed in Table A3.2-4 in the Appendix.

(a) Technical considerations

From a technical perspective, it is generally believed that second life batteries from xEVs can be used for stationary applications such as battery energy storage system. As of 2024, the real-world application and regulations of xEV batteries for repurposing are limited and technical challenges persist. Some of these challenges are listed below:

- **Lack of design uniformity and obsolescence**: Large number of battery-pack designs on the market that vary in size, electrode chemistry and format (cylindrical, prismatic, and pouch). Each battery is designed by the battery manufacturer and automotive OEM to be best suited to a given xEV model, which increases repurposing complexity due to lack of standardization and fragmentation of volume (GAIA, 2024). In addition, manufacturers are pushing towards vehicle-integrated battery design which causes battery removability a concern during collection (ICCT, 2023). Development of new battery chemistries could also cause the current generation of xEV batteries being unfit for repurposing.
- **Uncertain life expectancy:** Predicting the life expectancy of repurposed batteries is challenging. Due to the limited use cases to test the degradation of these batteries, estimations for second-life batteries' life expectancy must be performed through simulations and not based on empirical testing, which causes them to be a riskier alternative. Currently, no warranties or insurance exist regarding second-life battery quality or performance, and few industry standards focus on battery-management systems or state-of-health disclosures (Little, 2024).
- **Lack of battery traceability and liability:** Several countries do not have mechanisms to ensure that the battery can be traced over their lifetime and is collected when the vehicles reaches its EoL (Earthworks, 2021). Additionally, many jurisdictions do not have regulations that clearly define who is responsible for the battery once it reaches its end of life. Most markets do not have regulations on

delineation of battery responsibility between the producer and the consumer once the vehicle reaches its EoL.

- **Lack of data about xEV battery characteristics and state**: Most markets do not require electric vehicle manufacturers to make the information readily available to third-party repurposing centers about battery's initial technical characteristics (nominal voltage, capacity, chemical composition), level of degradation and remaining capacity, which will determine its suitability for second-life application. This creates inefficiencies as the third-party repurposing centre needs to test all these aspects.
- **Battery safety concerns**: There are a few hazards associated to disassembling of a battery pack such as high voltage, explosion risks and electrolyte fumes. These have been identified as a key area for improvement in stakeholder consultation and the use of artificial intelligence and advanced robotics will lead to substantial changes in safety, reliability and efficiency of the process (European Commission, 2019).

  In addition, in lithium-ion batteries, a critical point, known as the "knee" at 50-60% SoH occurs when deterioration accelerates, leading to potential hazards, which is difficult to predict. Current research is insufficient to confidently determine the likelihood or impact of age-related failures. (Office for Products, Safety & Standards, 2023) suggested that extensive stakeholder consultations resulted in opposing viewpoints. One viewpoint advocated for need for safety framework to allow use of repurposed xEV batteries as long as the full history of batteries in their first life applications is known and can be tested. The other more radical viewpoint suggested that the repurposed xEV batteries should not be employed for storage as their safety can never be guaranteed.

Some of the key technical strengths and opportunities for EU on repurposing of xEV batteries are:

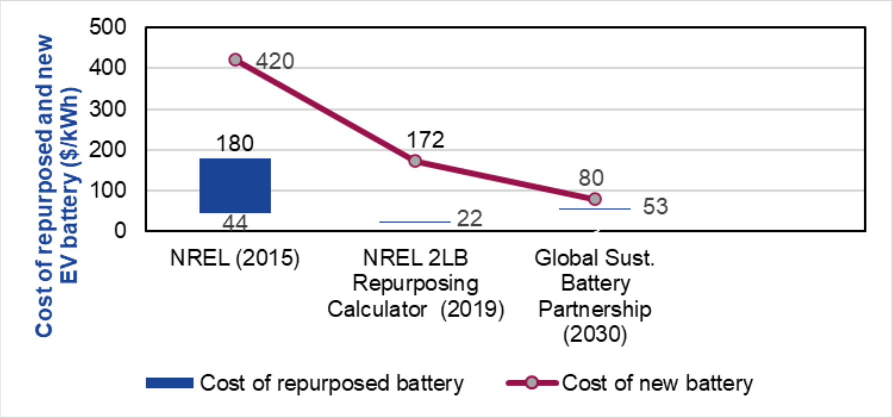
- **Significant projects in Europe investigating repurposed batteries for energy storage**: Several stakeholders in EU are actively involved in the repurposing xEV batteries as illustrated in Table A3.2-2 in the Appendix. Companies such as AUDI, Renault and B2U Storage Solutions are pioneering projects that use end-of-life batteries for various energy storage applications.
- **Established industry in EU on battery energy storage systems**: Europe's total battery energy storage capacity reached 36 GWh as of 2023 and the energy storage power requirements are expected to be 200 GW by 2030 (SolarPower, 2024). Repurposed xEV batteries can strengthen possibilities for EU to meet the 2030 targets.
- **New policies address challenges related to xEV battery purposing in EU:** An update to the 2006 Battery Directive, a Sustainable Battery Regulation was adopted in 2023, which plays an important role in setting standards for battery lifecycle management, including repurposing. This regulation includes a digital record system, called Battery Passport, which will include information about technical characteristics, state of health and operation history of batteries. In parallel, the provision on Extended Producer Responsibility (EPR) makes manufacturers responsible for the collection of end-of-life batteries.

(b) Economic considerations

Several literatures consider repurposing of end-of-life xEV batteries as an attractive economic opportunity due to the reasons mentioned below:

- **Cheaper purchase price of repurposed xEV batteries usually:** Repurposed xEV batteries are usually cheaper compared to new xEV batteries. However, this is subjected to the repurposing cost, transportation cost, cost of battery acquisition and several other factors covered later. The figure below represents the price comparison of repurposed and new xEV battery packs across different timelines, which showcases that repurposed xEV batteries remain usually cheaper compared to new batteries even with the reduction in lithium-ion battery pack prices. The assumptions of new EV battery pack prices are taken from (BloombergNEF, 2022). This demonstrates that the purchase price of repurposed xEV batteries is 10-66% of the new xEV battery cost. However, several of this research assumes zero or low resale value for acquisition of these xEV batteries for repurposing, which is expected to increase as secondary battery markets mature. That will increase costs for repurposed batteries.

Figure 5-6: Cost of repurposed and new xEV battery (USD/kWh)



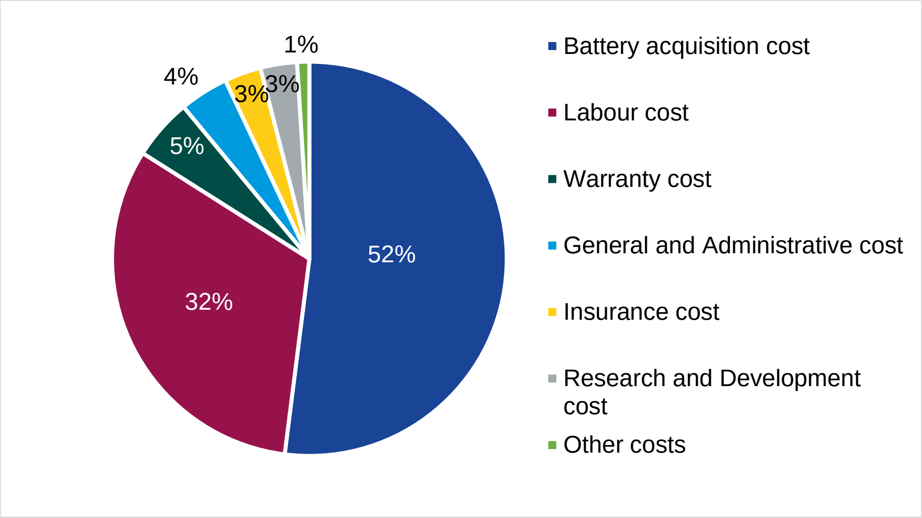
Source: Ricardo analysis of (NREL, Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries, 2015), (NREL, 2019) , and (GSEP, 2021)

- **Savings in cost of raw material for battery manufacturers:** Repurposed xEV batteries will lead to savings in cost of raw materials, resulting from reduction in overall demand for new raw materials. Lithium commodity prices have increased over 1,000% since 2020, resulting in a notable uptick in Li-ion battery pack prices (Little, 2024). Prices for other raw materials used in battery manufacturing have also surged in the recent past. This has been caused by the expanding demand for xEVs coupled with the inelastic nature of the mining industries (i.e., limited ability of supply expanding when prices increase).
- **Additional revenue for OEMs and reduced EV cost for consumers:** OEMs can collect and sell the end-of-life xEV batteries to repurposing centres and increase the “dollar per kilowatt-hour” value of their product. In parallel, higher value of the end-of-life battery would in turn reduce the cost of xEV purchase for buyers.

However, there are a few economic challenges that remain, some of which are highlighted below:

- **Competition from battery recycling**: For battery owners, the decision to repurpose rather than recycle hinges on the relative revenue generated by each option. Recycling focuses on recovering valuable metals such as lithium, cobalt, and nickel, which can be highly profitable given the growing demand for these materials in battery production. Some sources consider battery recycling as the near-term favoured route over battery repurposing due economics (BCG, 2020).
- **Expensive acquisition and labour cost:** Battery repurposing involves processes that are time and labour intensive. The critical cost components of repurposing an EV battery are shown in Figure 5-7. The high acquisition cost results from a high xEV battery logistics cost. The Sustainable Battery Regulation classifies EoL batteries as hazardous material which pose electrical, chemical and fire risk (Reneos, 2022). This requires special certification and packaging for its transportation, which makes it further expensive. In addition, the multiple stage processes involving repurposing such as assessment, disassembly, clustering and reassembly add significant costs too (Al-Alawi, 2022).

Figure 5-7: Cost components of repurposing an xEV battery



Source: Guidehouse + NREL + McKinsey

- **Cost differential between used and new is reducing:** From 2013 to 2023, the global average price of lithium-ion batteries was reduced by 82% (BloombergNEF, 2022) and that trend is expected to continue in the long term. As new batteries become cheaper, the cost differential between used and new diminishes, unless there are cost optimisations in the battery repurposing processes.

Several studies support the conclusion that the economic feasibility of xEV battery's repurposing for energy storage applications depends upon several parameters such as the purchase price of the end-of-life battery, its lifespan for second-life application and cost of electricity.

(c) Environmental considerations

Repurposing EV batteries for energy storage applications offers significant environmental benefits, such as reducing waste and conserving resources. Here are some of the drivers:

- **Extending batteries usable life and improving it carbon intensity:** Repurposed xEV batteries can extend a battery's usable life by 72 percent, thus resulting in a 42 percent reduction of greenhouse gas emissions attributable to the xEV battery on a per-kilometer basis (ICCT, 2018).
- **Material efficiency:** Obtaining one ton of lithium-ion necessitates mining 250 tons of spodumene ore or 750 tons of mineral-rich brine, as referenced in studies (Haram, 2023). Repurposing reduce the need of "dirty" mining materials for the production of batteries.
- **Reducing hazardous waste:** End-of-life xEV batteries are disposed of as Municipal Solid Waste (MSW) which would cause large undesirable waste to enter landfills. Discarding these batteries could potentially cause irreversible damage to the environment since they are made of heavy metals and chemicals (Al-Alawi, 2022).
- **Help lower the need for additional power production:** Repurposed xEV batteries can be used to mitigate the effects of RE sources intermittent characteristics. Several studies identify peak-load shaving—charging batteries while grid demand is low and drawing power from those batteries when demand is high— as the most promising application for repurposed xEV batteries.

However, several environmental barriers must be addressed to fully realise the previous benefits:

- **Significant energy consumption for repurposing**: Reconditioning and testing processes for second-life batteries, along with transportation during acquisition, can consume significant amounts of energy, which may diminish the overall environmental benefits (Bobba, 2018)
- **Uncertain state of health**: The uncertain state of health of used batteries complicates the prediction of their performance and environmental impact" (Casals et al., 2019)

5.2.4 Policy recommendations to address barriers associated to use of repurposed xEV batteries for energy storage applications

Taking into account the main drivers and challenges, a comprehensive set of policy recommendations can help to overcome the above-mentioned barriers and exploit the opportunities offered by xEV battery repurpose.

- **Standardisation of battery designs and repairability ideally down to the cell-level**: The lack of standardisation in battery pack design complicates refurbishment efforts. Policymakers should encourage the development of industry standards for battery design, including size, electrode chemistry and format. Standardisation can simplify the refurbishment process, reduce costs and increase the efficiency of second-life applications. In addition, battery repairability down to at least the module-level and ideally the cell level is needed (especially with newer cell-to-pack designs) to prevent unnecessary full battery replacements, which would also support consumer rights and competition in the repair market.
- **Encouraging data sharing and collaboration:** Effective repurpose of xEV batteries requires extensive data on their current state and performance. Policies should incentivise data sharing and collaboration between industry stakeholders, including battery manufacturers, automotive companies and energy storage providers. This could be facilitated by the creation of centralised data repositories and collaborative platforms. Enhanced data sharing and collaboration on battery state should ensure that all authorized independent operators have access to relevant data, promoting a level playing field and consumer choice.
- **Improved testing and certification protocols**: Predicting the life expectancy of repurposed batteries is challenging due to limited empirical data. Establishing robust testing and certification protocols for second-life batteries can provide more reliable estimates of their performance and lifespan. This could include establishing dedicated testing facilities and encouraging industry-wide data sharing to build a comprehensive database of battery performance metrics. A clear standardised measurement procedure for battery capacity and performance over time needs to be established, to ensure transparency and reliability for consumers.
- **Encourage innovation and collaboration**: Encourage collaboration between battery manufacturers, automotive companies, research institutions and policy makers. The European Battery Alliance (EBA) is an example of such a collaborative framework that can drive innovation and compliance. Providing grants and subsidies for research and development of advanced dismantling and repurposing techniques can improve the safety, reliability and efficiency of the repurposing process.
- **Incentivise domestic battery repurposing**: Many countries lack the domestic infrastructure to recycle end-of-life batteries, requiring them to be shipped long distances. Classified as hazardous waste, these batteries require additional safety precautions and increase transport and logistics costs. Developing local capacity for battery repurpose could significantly reduce costs, boost local economies and reduce dependence on global supply chains. Governments could encourage this through incentive programmes, supportive tax policies, trade regulations and public-private partnerships.
- **Public awareness and education**: Increase public awareness and education about the benefits and safety of second-life batteries. Informing consumers and stakeholders about the environmental and economic benefits of repurposing xEV batteries can increase demand and support for these initiatives.

With these recommendations, we can overcome the current barriers to the reuse of xEV batteries and fully exploit the opportunities they present. This will contribute to a more sustainable and resilient energy future, reducing waste, lowering costs, and increasing energy security while supporting economic growth and innovation in the battery industry.

5.3 ASSESSMENT OF IMPROVEMENT OPPORTUNITIES TO REDUCE THE ENVIRONMENTAL IMPLICATIONS OF EV BATTERIES

The objective of this subchapter is to address the following questions related to environmental implications of xEV batteries:

- What is the current state, opportunities and challenges across the battery value chain in Europe?
- What are the environmental implications and improvement opportunities across EV battery production, usage and disposal?

- How does the EU Sustainable Battery Regulation impact the environmental implications of EV batteries?

5.3.1 Summary of the European EV battery value chain in Europe

There are three stages of xEV value chain, i.e., battery production (*cf.* sections 2.4.1 and 3.2.1), battery usage (*cf.* section 2.4.2) and battery disposal (*cf*. section 2.4.3). To understand the environmental implications and improvement opportunities across the xEV battery value chain in Europe, it is important to understand the major challenges and opportunities in relation to each stage from a European perspective.

Table 5-3: Summary of xEV Battery Value Chain in Europe

Stage	Key element	- Challenges and + Opportunities
Battery production	Raw materials - Lithium	- Lithium is not extracted on a major scale in Europe. Demand for lithium will grow globally >40-fold by 2040 compared to 2023 (IEA, 2021b) + The largest European reserves are found in Germany, Czechia, and Serbia which has an estimated 1.2 million tonnes (Green European Journal, 2023) + Breakthroughs in sodium ion batteries could replace lithium demand in the long-term, but this scenario is extremely uncertain (Acuity, 2024) + Lithium extraction from salt water has a much lower environmental impact than projects at salt deserts and mines; Vulcan is setting up a lithium extraction optimisation plant aiming to use geothermal heat from the Upper Rhine Valley brine deposit (Balkan Green Energy News, 2023)
	Raw materials - Cobalt	- By 2050 the demand for cobalt is expected to increase up to 350%, mainly driven by the uptake of electric mobility (CobaltInstitute, 2022) - The EU imports most of the refined cobalt needed for batteries from countries such as China and the Democratic Republic of Congo (DRC). (Resources Policy, 2022). Non-formalised mining practices raise significant transparency and human rights concerns + In Europe ,104 deposits have been identified and are being explored for cobalt, of which 79 are in Finland, Norway and Sweden (British Geological Survey, 2021)
	Raw materials - Nickel	- In Europe, mining capacities can fulfil up to 16% of the anticipated future demand for nickel in batteries (Nickel Institute, n.d.). Major European producers of nickel include Finland, France, Norway + In Europe, nickel recycling rates are remarkably high. The recycling of nickel-cadmium cells in EU countries ranges from 75% to nearly 100% (Gaz GMBH, 2022) + There is already a large and liquid market for Nickel in Europe due to its use in steel manufacturing, i.e.,17 kilo tonnes in 2020 (JRC, 2021)
	Cell manufacturing and battery assembly	- xEV batteries require significant energy to be produced, which is often sourced from non-renewable sources
Battery usage	Application and integration	- Trends towards larger vehicle sizes and SUVs are being exhibited across many economies within Europe. Larger vehicles require heavier batteries thereby requiring higher energy during use

Stage	Key element	- Challenges and + Opportunities
Battery disposal	Recycling and second life	- Waste management poses significant challenges due to hazardous components and the risk of improper handling and disposal. Inefficient recycling processes and lack of recycling infrastructure can lead to landfilling of xEV batteries and the loss of valuable materials + Stakeholders in Europe are increasingly focusing on developing efficient recycling technologies and establishing a robust set of practices to support a more circular economy of the growing volume of used EV batteries. Hydrovolt, Europe's largest xEV battery recycling plant is based in Norway (Hydro, 2022) + The end of the first wave of electrification will be associated with increases in recyclable material availability reducing pressure on virgin material extraction (PwC, 2023)

5.3.2 Review of environmental implications of xEV batteries

This subsection reviews the environmental implications and focuses on improvement opportunities of xEV batteries across the three stages of battery production, battery usage and battery disposal. From the extraction and processing of raw materials to the manufacturing and assembly of cells, to charging, maintenance and finally disposal, each stage has a considerable impact on the overall environmental outcomes of xEV batteries. Detailing the multifaceted current challenges in the sector also provides important context for the exploration of improvement opportunities.

5.3.2.1 Battery Production

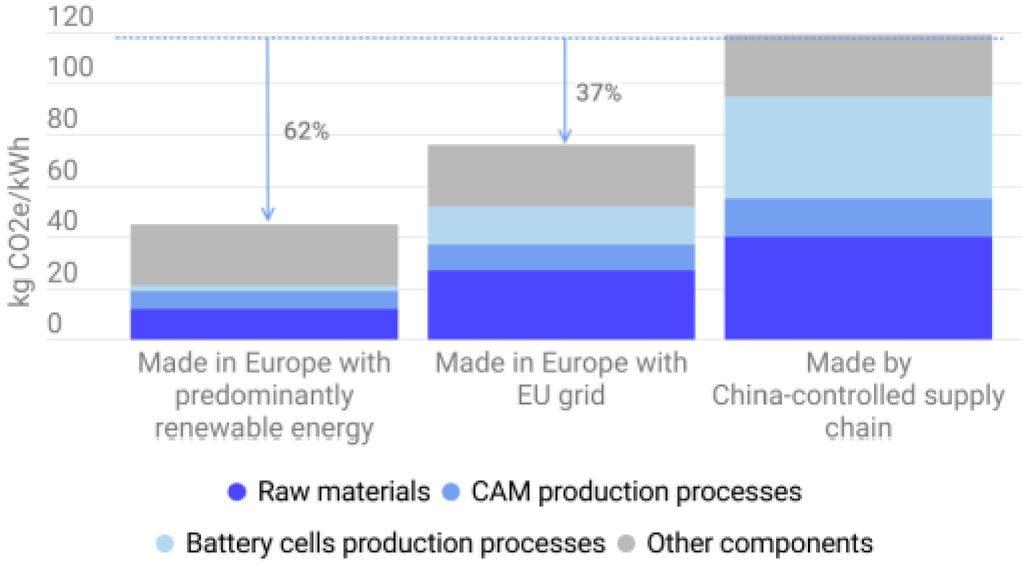
The highest GHG emissions for batteries are generated in the production phase (*cf*. section 3.2.1). This is due in part to the energy intensity of the extraction and processing of raw materials, complex manufacturing processes, and global supply chains, in addition to the frequently high carbon intensity of the grid in the intermediate steps from mining to processing to assembly. In Table 5-4, the key environmental implications that result from xEV battery manufacturing processes is summarised.

Table 5-4: Environmental implications and improvement opportunities of EV battery manufacturing

Environmental implication	Improvement opportunity
• The production of an xEV battery in a higher emissions intensity (CO_2e/kWh) grid leads to higher carbon footprint • T&E (T&E, 2023b) estimates that a lithium-ion battery produced in EU grid in 2022 have a 78 gCO_2e/kWh carbon footprint while that produced in Chinese grid will have 105 gCO_2e/kWh (35% higher) (*cf.* Figure 5-8, below). A greater share of EV batteries could come from China over time, considering the increasing battery production there for its burgeoning electric vehicle market	• Sourcing electricity from renewable sources during manufacturing or decarbonisation of grid • Incentivising locating battery production facilities near low carbon energy source is crucial. The production of an xEV battery in Sweden has a carbon footprint of 64 gCO_2e/kWh while that in Poland is 109 gCO_2e/kWh • Improved vehicle/powertrain efficiency and improvements in manufacturing efficiency, processes and yields reduces requirement for energy storage capacity
• Of the two main xEV battery chemistries currently used, NMC and LFP, the emissions per kWh of LFP batteries are about one-third lower than NMC batteries at the pack level (IEA, 2024). • Critical minerals processing accounts for 55% of total emissions for NMC, compared to 35% for LFP.	• Stringent carbon tariffs or eligibility rules for xEV subsidies based on lifecycle emissions. This will incentivise battery producers to rely more on LFP batteries, which today are almost exclusively produced in China, rather than the more emissions intensive NMC batteries • Strategies to reduce emissions from high-nickel-cobalt chemistries by focussing on critical minerals processing

Environmental implication	Improvement opportunity
• The trend towards larger vehicles magnifies the demand for bigger batteries, thus resulting in increased need for critical minerals and increased carbon footprint • In 2023, the sales-weighted average battery electric SUV in Europe had a battery almost twice as large as the one in the average small electric car	• Introduction of regulations that limit the permissible weight of xEVs for certain incentives or to qualify for urban access privileges. This can help discourage the production and purchase of heavier, larger xEVs.
• Electric range anxiety and lack of confidence about reported range lead to greater demand for bigger batteries, thus larger carbon footprint	• Transparency about more accurate estimates of range and charging speeds reduce the real or perceived need for bigger batteries • Wider roll-out of charging infrastructure, and better information on availability

Figure 5-8: Climate benefits of onshoring the battery production to Europe



Source: (T&E, 2024a)

5.3.2.2 *Battery Usage*

The GHG impacts associated to the use phase of the electric vehicles (powered through batteries) tends to be lower for BEVs compared to ICEVs (*cf.* section 2.4.2). This is because of the higher energy conversion efficiency of electric powertrain and the lower carbon intensity per unit of energy delivered to the powertrain of electricity compared to fossil fuels employed in ICEVs. The latter factor is highly variable depending upon the electricity grid mix used to charge the batteries.

Table 5-5: Environmental implications and improvement opportunities of xEV battery usage

Environmental implication	Improvement opportunity
• xEV charging from grid electricity powered by fossil fuels during the use-phase contributes to GHG emissions	• Sourcing electricity from renewable sources for xEV charging or decarbonisation of grid
• Faster battery degradation during use due to several factors mentioned in 5.1.2, could cause a faster retirement of xEV batteries	• Using strategies to extend battery lifespan as captured in 5.1.4

Environmental implication	Improvement opportunity
• Higher energy consumption in xEV batteries	• Battery density (Wh/kg) improvement causing smaller batteries to deliver similar range • Higher charging and discharging efficiencies will lead to lower energy consumption during the use phase of the vehicle battery

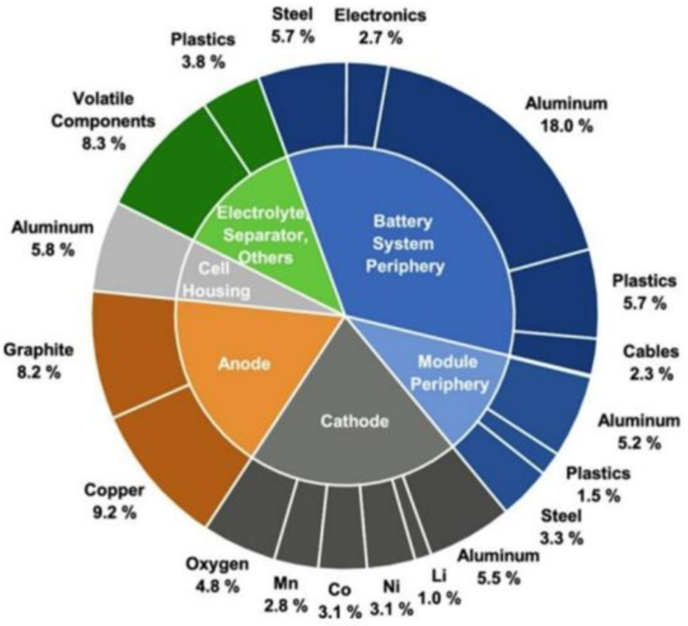
5.3.2.3 *Battery Disposal*

By reducing the demand for raw material, the recycling of electric vehicle batteries contributes to mitigating the negative environmental and social impact of mining. According to the waste management hierarchy, re-use/repurposing is recommended over recycling or disposal (FIA, 2022).

Table 5-6: Environmental implications of EV battery disposal

Environmental implication	Improvement opportunity
• The general composition of an xEV battery system is illustrated in Figure 5-9 • With the expected significant uptake of xEVs in this decade, there will be increased demand for raw material mining	• Setting targets on mandates for battery recycling and recycled content will encourage recycling of xEV batteries • Production of recycled aluminium creates approximately 95% less greenhouse gas emissions compared to producing aluminium from natural sources • The Sustainable Battery regulation targets 65% of the average weight of lithium-based batteries to be recycled by 2025 • Similarly, the EU Sustainable Battery Regulation sets targets for lithium ion batteries with a capacity larger than 2 kWh, at least 16% of the cobalt, 6% of the lithium, and 6% of the nickel used in the battery cell are recycled material (ICCT, 2023) • Implementation and enforcement of battery recycling and recycled content targets will be key • For recycling efficiency, it is crucial to ensure that these targets are verifiable by independent labs, preventing greenwashing and ensuring true environmental benefits
• However, EoL recycling is not yet economical for some critical raw materials due to variability of battery chemistry, structure and design	• Standardisation of battery chemistry, structure and production, and the creation of regulations on labelling and monitoring batteries could bolster the commercial viability of recycling as the electric vehicle industry grow
• Recycling processes of battery packs use substantial amounts of electricity	• Incentivising locating battery recycling facilities near low carbon energy source is crucial
• When an end-of-life xEV battery arrives at a recycling centre, information on its chemistry composition and other technical characteristics is often hard to access. • Several different recycling pathways require information about battery chemistry and design. The uncertain state of health of used batteries complicates the prediction of their performance and environmental impact	• Accessible information on the battery chemistry and design are thus a precondition to an efficient assignment of end-of-life batteries to the respective recycling plants

Figure 5-9: General composition of an xEV battery system as a percentage of total battery pack mass



Source: (Jan Diekmann et al., 2017)

5.3.3 EU's Sustainable Batteries Regulation implications on environmental impacts of xEV batteries

The EU Sustainable Batteries Regulation aims to ensure the environmental sustainability of batteries throughout their lifecycle. In this section we explore how the regulatory landscape of xEV batteries is impacted by the major themes within this legislation.

Replacing the previous Batteries Directive (2006/66/EC), the new Sustainable Batteries Regulation (SBR) (EU 2023/1542) has introduced new sustainability and transparency requirements covering the design, production and EoL management of all types of batteries manufactured or sold in the EU (European Commission, 2023a), making it the first piece of EU legislation that takes a full life cycle approach.

The regulation encompasses four main areas. Firstly, **carbon footprint** declarations; carbon footprint performance classes and maximum carbon thresholds for batteries are to be phased-in, as well as an indication of levels of recycled cobalt, lead, lithium and nickel in battery production. This has been designed to facilitate the improvement in environmental performance of batteries.

Secondly, **due diligence** obligations have been set, adopting internationally recognised standards such as the OECD Due Diligence Guidance (OECD, 2016). This states that the source of critical raw materials (CRM), including the supply of cobalt, natural graphite, lithium, nickel and other chemical compounds, must be verified by operators, except for SMEs. The purpose of this change is to manage the serious social and environmental risks that exist along battery supply chains.

Thirdly, **labelling requirements** to enhance transparency have been set, including the introduction of battery passports which will be required to specify the battery model, specific battery and its use, which will need to be QR code enabled and printed or engraved on batteries. Other labelling requirements apply to recycled content and battery components. This requirement ensures information covering the sustainability impacts of batteries will be available and accessible.

Finally, changes to **EoL management** have been made, including the definition of collection rate targets as well as mandatory levels of recycled CRM for industrial, SLI and xEV batteries, initially set at 16% for cobalt, 85% for lead, 6% for lithium and 6% for nickel. These measures aim to ensure greater levels of recycling and higher-quality recycling of batteries.

This legislation has been introduced in the face of continuously rising demand for batteries and is expected to become the global benchmark. The goal of this regulation is to foster a more environmentally sustainable lifecycle for batteries in the EU. While some obligations are designed to be phased in over time, requirements will generally be applied to xEV batteries first before other battery types.

5.4 SUMMARY

There are several factors that influence battery health such as make and model (battery chemistry and thermal management), operating modes and environmental conditions. Battery durability is an uncertainty and a key concern for consumers that is being addressed through technology development and regulations. While battery degradation cannot be avoided entirely, there are some strategies that could be used to extend the battery life of xEVs that users can be made aware of. Repurposing of xEV batteries for stationary applications are technically feasible and there are ongoing pilots across EU, however, there are several persisting technical, economical and environmental challenges, some of which can be addressed through policies. Similarly, there are several improvement opportunities for reducing the environmental impact of xEV batteries across the production, usage and disposal stages. A summary of policy measures to address barriers related to battery life, repurposing and environmental implications is covered in Section 7.

6. TRANSPARENCY AND CONSUMER INFORMATION

6.1 INTRODUCTION AND OBJECTIVES

The aim of this chapter is to assess the comprehensiveness and accuracy of environmental labels, energy consumption ratings and lifecycle assessments provided by manufacturers. This task considers the information that is required to enable such comparisons to be made, the extent to which relevant information is currently available and recommendations regarding how to address any gaps identified.

The subchapters include a review of the following:

- Background and context
- Information required by consumers to inform vehicle purchasing decisions
- Review of information available to consumers
- Assessment of gaps and summary

6.2 BACKGROUND AND CONTEXT

The 2023 FIA study (Steer, 2023) identified a number of **key barriers to xEV uptake,** including affordability, range anxiety, vehicle performance, charge point provision, charge point useability, and xEV availability. It was concluded that provision of clear, concise and transparent information to consumers could help to mitigate some of these barriers. The key findings, and conclusions regarding how provision of consumer information could reduce these barriers, are summarised below:

- **Affordability:** Although EV affordability is often quoted as one of the main barriers to xEV uptake, it can be considered a perceived barrier, in that when total cost of ownership is factored in and the progressively cheaper xEV models that are entering the market, EVs can be considered affordable when compared with ICEs.
    - A Consumer Monitor study performed in 2023 in the EU asked participants to identify the five most relevant disadvantages of driving BEVs. 65% of respondents identified the cost of BEVs as a barrier (EAFO, 2023), with the median price that all EU respondents are willing to pay for a new or used BEV being €20,000.Analysis by ACEA revealed that those European countries with the highest shares of electric vehicles are also those where net annual income exceeds €32,000, in comparison to those countries with the lowest shares of EVs, who have a net annual average income of €9,000, indicating affordability does impact on choice and purchase criteria (ACEA, 2023).
    - Whereas consumers of new electric vehicles tend to be concerned about high purchase prices and potentially high levels of depreciation in value during the first few years of ownership, opportunities exist for buyers of second-hand electric vehicles who are more likely to be able to purchase vehicles for a much reduced price. Approximately 80% of EU citizens buy their vehicle second hand (TML, 2016). It has been estimated that at the current rates of electrification, 33 million EU households will have access to second hand electric cars until 2035, which could increase significantly if the leasing sector accelerates its uptake of EVs (up to 51 million) (T&E, 2023). When comparing the ownership costs between used electric and petrol cars, a study calculated that households could be €6,000 better off over seven years when purchasing electric (BEUC, 2021).
    - A report by the Institute for Energy Research (IEA) also revealed that insurance costs are higher for EVs than they are for ICE vehicles. In the UK, insurance premiums for EVs were found to be twice that of an ICE. This was concluded as being due to the higher frequency and cost of claims, and the shortage of skilled technicians with the skills to make repairs which lengthens repair times (IER, 2024).
    - **Information highlighting lower running costs, availability of financial incentives and energy costs of electric vehicles in comparison to ICEs could help to alleviate this barrier, in addition to the increased financial benefits of purchasing a second-hand electric car (rather than a second-hand petrol car).**

- **Range anxiety and vehicle performance:** Most recent electric vehicle models have vehicle ranges in excess of 300km, which make them suitable for the majority of journeys, although the relatively novel nature of EVs leads consumers to consider range and battery life to be insufficient.
    - As discussed in Section 3 (factors affecting energy efficiency), there are a range of factors that will affect the real-world range/performance of electric vehicles. Factors significantly increasing energy consumption of EVs include cold ambient temperatures and average travel speeds above 30kph, while improvements to vehicle aerodynamics and greater utilisation of regenerative braking can reduce xEV energy consumption. Real-world consumption tends to be higher than figures reported by vehicle manufacturers, and this can contribute to range anxiety if consumers experience real ranges that are less than they were expecting.
    - Battery durability is a concern to consumers, particularly in relation to the used car market as range will deplete over time. A study focusing on the used xEV market found that the largest barrier preventing the used xEV market from taking off was fear of poor battery health (of those drivers who would not buy a used EV, 62% cited concerns about battery lifespan[16]) (Green Finance Initiative, 2023). Additionally, nearly 75% of the dealerships involved also identified battery lifespan as one of the main consumer concerns for used xEVs. Linked to the affordability concern above, depleted range of used xEV owners is therefore likely to be a concern for lower income households that tend to purchase used vehicles.
    - **Reliable information about battery range and how EV users can optimise it for everyday and long-distance trips could help to relieve this barrier**
- **Chargepoint provision:** Availability of reliable public (and private) chargepoints is of concern of consumers and acts as a barrier to xEV uptake.
    - To some extent, the provision of reliable chargepoints can be a barrier. Concerns over recharging BEVs are identified by EU respondents as the second most common challenge to the uptake of EVs in the Consumer Monitor survey (EAFO, 2023). However, as identified in a recent report by T&E (T&E, 2024), the number of public electric vehicle chargers in the EU has increased three-fold in the past three years, with the majority of EU countries[17] meeting their EU targets for 2024 relating to provision of public charging infrastructure (under the Alternative Fuels Infrastructure Directive – AFID). Based on growth rates considered in the analysis, it is projected to meet the EU's milestone target of 1 million chargers by 2025. The Alternative Fuels Infrastructure Regulation (AFIR) has also since come into force in 2024, which now includes targets for both highway coverage and overall number of chargers.
    - The provision and availability of private recharging stations is also important. The EAFO consumer monitor and survey 2023 revealed that only 18% of BEV users regularly use public slow recharging stations on the street or public parking, and only 10% use fast recharging stations. This indicates a strong preference for private recharging and the need for information and support in their installation.
    - Furthermore, while 60% of BEV users reported that recharging while travelling abroad was (very) easy, the main issue identified by users was the lack of recharging stations along the way. Provision and availability of recharging points along travel routes is therefore important (EAFO, 2023).
    - **Robust and accurate information on chargepoint provision could help to alleviate this barrier, in addition to provision of reliable chargepoint infrastructure.**
- **ChargePoint usability:** Chargepoint usability concerns include the time taken to charge vehicles, functionality (ease of use), and etiquette. Variable pricing schemes and insufficient interoperability between chargepoint operators When comparing to refuelling of ICEs, consumers are expecting five-minute charge times, which are not possible.
    - Important characteristics for public recharging were identified by EU BEV drivers. Among the most important was the availability of clear and transparent price information, short to no waiting time to access the charging point, the need for the charging station to be fully operational upon arrival, and easy access and payment options (EAFO, 2023).

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[16] Survey of 2,000 drivers in the UK, conclusions from 35 car dealerships, motor finance lenders and lease companies.

[17] Eight EU Member States yet to meet the 2024 target

  - **Consistent information at chargepoints and when consumers purchase a vehicle could help to alleviate this barrier**
- **xEV availability:** Wait times for purchasing new electric vehicles may be in excess of 12 months and can be considered long in comparison for those of conventional ICE vehicles.
  - However, there are also perceived issues with supply of second-hand electric vehicles, with suggestions that consumers are looking for smaller vehicles in the second-hand car market, whereas the new vehicle car market is dominated with larger models (Euractiv, 2024), implying supply may be an issue.
  - **Better information and management of expectations could help to alleviate this barrier**

In summary, there is scope to improve information relating to electric vehicles across a range of aspects, whereby consumers do not understand the capabilities of electric vehicle technology and there is limited information on driving range, chargepoint availability, access and payment methods. This could contribute to consumers being less likely to purchasing electric vehicles due to limited knowledge.

This task considers the information that is required by consumers when making a purchasing decision, and which could potentially support the uptake of electric vehicles, with a view to alleviating any perceived barriers.

6.2.1 Ability to compare electric vehicle models

Where consumers have made the decision to purchase an electric vehicle, there are potentially further barriers, exacerbated by lack of relevant and consistent information that will enable them to make objective comparisons between models across their priority criteria.

An example of this relates to the Car Labelling Directive (EC 1999/94/EC) which requires the provision of information on emissions of CO_2 and fuel economy at point of sale for all new passenger cars. The Directive is concerned with tailpipe emissions of passenger cars and therefore all electric vehicles fall into the zero-emission category. Whilst this is a positive signal to potential consumers in terms of the overall environmental/GHG emission impact of a vehicle, it does not provide consumers with information to enable comparisons between electric vehicle models, nor also a more holistic and encompassing comparison between vehicles of all powertrain types based on their full lifecycle. As electric vehicles become a more significant share of the overall new passenger car fleet, this issue will only be exacerbated further.

Additionally, although a variety of information is provided to consumers via OEM manuals and apps and other sources, it is often in an inconsistent and non-standardised format (see Section 6.3) which makes reliable comparisons difficult.

6.3 INFORMATION REQUIRED BY CONSUMERS TO INFORM VEHICLE PURCHASING DECISIONS

The objective of this subchapter is to address the following questions:

- What factors do consumers take into account when making purchasing decisions?
- What information is desired by consumers when considering the purchase of electric vehicles and/or enabling comparisons?
- What information is desired by consumers to ensure the use of electric cars (once purchased) is optimised?

In the introduction to this task, the key barriers to electric vehicle uptake were identified, including affordability, range anxiety, vehicle performance, charge point provision, charge point useability, and xEV availability. In all cases, the provision of clearer, more consistent and robust information to consumers can help to alleviate these barriers. This section considers this and other information that may be required by consumers when making passenger car purchasing decisions.

Regarding the elements that consumers take into account when making their purchasing decisions more widely (not just cars), 'quality and price' of products tend to be the two most important aspects, with 97% of Eurobarometer survey respondents indicated quality is 'very' or 'rather important, with 94% responding the same regarding price. However, 73% of respondents in the EU consider the environmental impact of a product to be 'very' or 'rather' important (European Commission, 2023c). Another survey focusing on identifying lifestyle priorities for European consumers revealed that they tend to prioritise purchasing more sustainably in

2023 (48%), followed by a switch to e-mobility (37%) and reductions in household budget (37%) (France, Germany, Italy, Spain and UK) (Hyundai, 2023).

There have been a number of studies and surveys performed that consider the characteristics or criteria that are taken into account by consumers in the car purchasing decision. One study (Codagnone et al., 2016) identified the main issues characterising car purchasing as follows:

- **Eco-friendly attributes** play a secondary role and are dominated by other attributes such as price, performance and safety.
- Car purchasing tends to be a two-stage process; whereby the **class of car is initially determined, followed by consideration of attributes**, including eco-friendliness and fuel economy, when selecting a particular model in the preferred segment.
- Indications that **fuel economy is considered more important than CO_2 emissions** and other environmental attributes.

More recently, a Statista survey revealed the key characteristics that citizens considered to be especially important to them when they make decisions regarding the purchase of a new car (from a pre-determined list) in European Member States (Statista, 2024). Attributes presented included safety; suitability for everyday use; high quality; fuel efficiency; high driving comfort; low price; good warranty and customer service; environmental friendliness; design; propulsion type; spaciousness; good driver assistance systems; preferred make; good connectivity with devices; sportiness; good multimedia system. Answers varied between Member States, with examples of the top three attributes as follows[18], including an indication of where ‘environmental friendliness’ ranked in their purchase criteria:

Table 6-1: Purchase criteria for cars in selected EU Member States, 2024

Member State	First characteristic	Second characteristic	Third characteristic	Environmental friendliness
Finland	High comfort (59%)	Safety (56%)	Suitability for everyday use (55%)	24% (11th criterion)
France	Safety (48%)	Low price (40%)	High driving comfort (36%)	29% (6th criterion)
Germany	Safety (54%)	Suitability for everyday use (48%)	High quality (45%)	30% (9th criterion)
Italy	Safety (59%)	Low price (42%)	Fuel Efficiency (40%)	28% (10th criterion)
Netherlands	Fuel efficiency (53%)	High quality (53%)	Safety (48%)	25% (9th criterion)
Poland	Fuel efficiency (62%)	Safety (61%)	High Driving Comfort (51%)	26% (11th criterion)
Spain	Safety (64%)	Fuel efficiency (50%)	High Driving Comfort (47%)	34% (10th criterion)
Sweden	Safety (52%)	High Quality (44%)	Fuel Efficiency (43%)	29% (8th criterion)

Source: Statista 2024

In the majority of cases presented here, safety tended to be the most popular answer, with comfort, quality and price also featuring highly. Environmental/sustainability factors were not neglected, with fuel efficiency being cited as being one of the top car purchase criteria in Netherlands, Poland, Spain, Sweden and Italy, although it can also be viewed as an economic consideration. ‘environmental friendliness’ as a criterion varied between 24 and 34% (between 6th and 11th criterion).

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[18] Not confirmed if this applies to both new and used passenger car purchases

Referring to the 2018 car buyers survey performed in the UK (LowCVP & TEPR, 2018), respondents were asked how important information on CO_2 and fuel (and electricity consumption) were in their decision-making, with 24% stating fuel/electricity consumption being 'most important' (followed by 42% 'very important'), and 16% stating CO_2 emissions being 'most important' (followed by 31% 'very important'), 16% stated CO_2 emissions were not important. Additionally, there was a divergence in responses for CO_2 emissions when car fuel type was considered, with electric and plug-in hybrid customers placing higher importance on them (38% and 35% of respondents respectively considering this factor to be 'most important'). Among existing BEV drivers who took part in the consumer monitor survey in 2023, 45% reported that they did not know the origin of the electricity used to charge their vehicle (EAFO, 2023). This highlights the importance of environmental information being communicated at recharging stations.

In a study focused on electric vehicles, a survey was conducted focusing on consumers intending to purchase a new car within the next five years (EVForward Europe, 2023)[19]. In this context, purchase **price** was identified as one of the top four criteria considered when purchasing new vehicles (41% considered it to be most important). Environmental benefits were cited as the top criteria for only 20% of consumers. Conversely, 16% of respondents claimed that **driving range** of electric vehicles is the most prominent barrier and was the main reason for not purchasing an electric vehicle.

A research study (Mandys, 2021) used a stated preferences dataset combining survey answers from a survey run between 2014 and 2015 (UK Data Service Catalogue, specifically the Electric Vehicles Module of the Opinions and Lifestyle Survey) to understand consumer choices in relation to electric vehicles. The results suggest that the propensity of being a potential xEV early adopter increases with youth, education, being a student, living in the more southern parts of UK, being married and, to a lesser extent, income. Additionally, purchase cost, performance, maximum range and environmental friendliness are found to be important vehicle attributes for the potential buyers. Furthermore, two key barriers to wide xEV adoption are identified – high purchase cost and low maximum range of the vehicle. "*The direct costs of the vehicle, such as the purchase cost and recharging costs, were found to be of more significant concern, compared to other variables such as comfort, interior size, the width of the vehicle choice, reliability, technology establishment, maintenance costs, vehicle taxies, resale value, and insurance costs*".

Green Finance Initiative published a study on the used xEV market where they surveyed more than 2,000 UK drivers and received contributions from other lead companies in the sector (e.g., Octopus EV and EVA England). In this study, they found that more than a quarter (25%) of respondents would not buy a used EV over concerns of battery health, cost and charging infrastructure. It was suggested that further assurance and information on battery health, the number one barrier, would be the most effective solution to encourage drivers to purchase second-hand EVs (Green Finance Initiative, 2023). Similar concerns over battery health were noted in a report by the UK House of Lords, where they determined that the most significant factor stopping the sale of used EVs was concern over battery health; they called for a cross-industry battery health testing standard (UK House of Lords, 2024). Improving information and dissuading concerns over battery health, should therefore be a priority in the provision of future BEV customer information.

The European Commission (DG CLIMA) recently launched a Call for Evidence[20] supporting the evaluation of the Car Labelling Directive (Directive 1999/94/EC). The revised Passenger Car CO_2 Regulations currently require the Commission to review the Car Labelling Directive by the end of 2024 "*considering the need to provide consumers with accurate, robust and comparable information on the fuel and energy consumption,* CO_2 *emissions and air pollutant emissions of new passenger cars placed on the market, including under real-world conditions, as well as evaluate the options for introducing a fuel economy and* CO_2 *emissions label for new light commercial vehicles*" (European Commission, 2023b). Responses to this Call were received from a range of stakeholders.[21] In relation to the need to provide 'accurate, robust and comparable' information on fuel and energy consumption, CO_2 emissions and air pollutant emissions to consumers, feedback was provided relating to the relevance of the existing Directive considering the change (increase) in the number and share of electric vehicles and the subsequent decrease in suitability of the existing labelling requirements (and other associated tools) in relation to this trend.

In terms of information that stakeholders consider to be important to provide to consumers (via the label or other information tools), **charging capability, electric driving range, battery health and energy efficiency**

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[19] Based on survey of 10,182 respondents, 18-80 years, in five countries (France, Germany, Italy, Spain and UK)

[20] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14141-Car-labelling-evaluation_en

[21] 46 responses received in total.

were all identified. However, more than that, a number of stakeholders called for an alternative approach to be taken, moving away from the focus on tailpipe emissions (including CO_2) and towards a **Life Cycle Assessment (LCA) approach**. Stakeholders recognise that the current tailpipe emission approach does not enable effective comparisons between electric (zero emission) vehicles beyond the fact that they emit zero tailpipe emissions. However, a LCA approach would enable other aspects to be taken into account in vehicle comparisons, including the resourcing and use of raw materials, manufacturing, in-use and EoL processes. The European Commission is also required to develop (by the end of 2025) a harmonised European methodology for vehicle LCA as part of the LDV CO_2 regulations (European Commission, 2023), for voluntary reporting.

The following summarises the key information that is desired by consumers considering the purchase of electric vehicles (and also enabling comparison), and in addition, users of electric vehicles to ensure their use is optimised.

- **Total cost of ownership (TCO**) – addressing affordability concerns, but also longer-term battery durability issues
- **Electric range** – addressing range anxiety concerns, but also battery durability/capacity loss
- **Battery charging times** – addressing range anxiety and practicality concerns
- **Chargepoint location and useability** – addressing range anxiety and usability concerns
- **Battery health / optimisation** – addressing concerns relating to battery durability, but also total cost of ownership and range
- **Lifecycle analysis information** – addressing concerns relating to the comparison of xEV models (and xEV with ICE models)

6.4 REVIEW OF INFORMATION AVAILABLE TO CONSUMERS

The objective of this subchapter is to address the following questions:

- What are the mandatory regulatory requirements for manufacturers relating to provision of vehicle sustainability information?
- What other vehicle sustainability information is made available to consumers by manufacturers?
- What vehicle sustainability information is made available to consumers by other sources?

The answers to these questions are provided in more detail in the following sections.

6.4.1 Summary of regulatory requirements for manufacturers– vehicle sustainability information

A review was undertaken of the regulatory requirements (mandatory) for providing sustainability information on passenger cars / xEVs in EU Member States aimed at manufacturers. The findings are summarised in Table 6-1.

Table 6-2: Regulatory requirements for manufacturers – Vehicle sustainability information (mandatory)

Regulatory instrument	Requirement / Article
Car CO_2 labelling Directive (1999/94/EC)	• A **label** showing **fuel economy and CO_2 emissions** on all new cars or displayed nearby at the point of sale; • A **poster** or display prominently showing the official f**uel consumption and CO_2 emissions** data of all new car models displayed or offered for sale or lease at point of sale; • A yearly **guide** on **fuel economy and CO_2 emissions** from new cars, produced in consultation with manufacturers. The guide should be available free of charge at the point of sale and from a designated body within each Member State; • All **promotional literature** to contain the official **fuel consumption and CO_2 emissions** data for the car models to which it refers.

Regulatory instrument	Requirement / Article
Certificate of Conformity (2013/168/EC)	• Obliges **manufacturers** to issue a **Certificate of Conformity** for each vehicle produced in accordance with the type-approval. • Assures compliance with EU safety and environmental standards; manufacturers must share test results of **noise levels, exhaust emissions and fuel consumption**.
Alternative Fuels Infrastructure Regulation (2023/1804)	• Primarily related to the provision/roll-out of infrastructure for alternatively fuelled vehicles in EU Member States (e.g., distance-based deployment targets) • Includes requirement for manufacturers and vehicle distributers that relates to the provision of **information with regards to vehicles that are capable of being regularly recharged or refuelled**: o Relevant, consistent and clear information - Made available via Vehicle manuals, and on motor vehicles when placed on the market (manufacturers) – Can include colour coding scheme/graphical expression (existing/future requirements) o At recharging and refuelling points (by operators) o In motor vehicle dealerships (distributers) • Requirement by mobility providers/operators of recharging/refuelling points: o Full information through electronic means on the availability, waiting time or price at different stations o Provide full price transparency
Renewable Energy Directive (2023/2413)	• Renewable Energy Directive (RED) is primarily aimed at achieving a minimum share of RE sources in EU final energy consumption in a range of sectors, including transport, by 2030 • It refers to a **potential voluntary labelling scheme** aimed at manufacturers for products produced using RE – which could support consumer-driven uptake of products
Sustainable Batteries Regulation (2023/1542)	• Every industrial or electric vehicle battery on the EU market with a capacity of over 2kWh will require a **battery passport –** whereby batteries are labelled to provide end-users with transparent, reliable and clear information about batteries and waste batteries. • This includes all the necessary information concerning their main characteristics, including their capacity and the amount of certain hazardous substances present. • To ensure the availability of information over time, that information should also be made available by means of QR codes which are printed or engraved on batteries or are affixed to the packaging and to the documents accompanying the battery and should respect the guidelines of ISO/IEC Standard 18004:2015. The QR code should give access to a battery's product passport. Labels and QR codes should be accessible to persons with disabilities, in accordance with Directive (EU) 2019/882 of the European Parliament and of the Council.
Vehicle Type Approval Regulation (Euro 7) (2024/1257)	• The regulation states that "environmental data about vehicle types should be made available to vehicle users. An EVP should therefore be made available for each vehicle. Vehicle users should also have access to up-to-date information about **fuel consumption, the state of health of traction batteries, pollutant emissions and other relevant information generated by on-board systems and monitors**". • The EVP is defined as "a record in digital form that contains information on the environmental performance of a vehicle at the moment of registration, including the level of **pollutant emission limits, CO_2 emissions, fuel consumption, electric energy consumption, electric range and engine or electric motor power, and battery durability and other related values**". • In terms of manufacturer obligations, they will be required to issue an EVP for each vehicle and deliver that passport to the purchaser together with the vehicle, extracting

Regulatory instrument	Requirement / Article
	the relevant data from sources, such as the certificate of conformity and the type-approval documentation. Manufacturers shall ensure that EVP data are available for display in the vehicle electronic systems or through a QR code, or any similar method, and that EVP data can be transmitted from on- to off- board.

6.4.2 Other vehicle sustainability information provided by manufacturers

Vehicle manufacturers (OEMs) provide vehicle sustainability information to consumers via a variety of means, often on a voluntary basis, including via their vehicle manuals and LCAs. This section considers currently available vehicle sustainability information provided by manufacturers in more detail.

6.4.2.1 Lifecycle analysis

Vehicle manufacturers can prepare and provide lifecycle analysis (LCA) reports for selected models, accessible via their websites or available from dealerships. Due to the nature of the information provided, vehicle LCAs are assumed to be used by consumers prior to owning a vehicle, in order to provide information on sustainability aspects of a vehicle's life cycle. **Currently there is no established harmonised vehicle LCA methodology, which makes it difficult to compare vehicle models from different manufacturers consistently**.

The ***TranSensus LCA study*** (www.lca4transport.eu) aims to develop a European-wide harmonised, commonly accepted and applied single lifecycle assessment approach for road vehicles. Initial deliverables under the study included a review of current practices on LCA approaches in the electromobility value chain (including those produced by OEMs and other LCA studies) (TranSensus, 2023). The review identified a number of key findings, including the following:

- **Data:** Source of data and assumptions made tend to differ widely across LCA studies. Primary data is not always possible to obtain, although is desirable when developing LCA. Access to primary data often depends on where the LCA practitioner is within the value chain, with OEMs more likely to be able to obtain relevant primary data from their own operations and suppliers.
- **Vehicle use phase:** LCA methodologies can use regulatory energy consumption in the calculation of the use phase (typically used by OEMs) – which is often underestimated, although other studies attempt to take account of real-world operation, including electricity supply (which can make a significant difference). Future grid mixes are a further aspect that could be taken account of as rapid decarbonisation of grids occurs. However despite the clear historical trends and future policy and regulatory targets many OEMs are reluctant to use even conservative future electricity mix projections, due to concerns over the potential for litigation over green claims (as anything occurring in the future cannot be proven). Lifetime assumptions also vary significantly between approaches (both years and vehicle km), in addition to battery maintenance/replacement.
- **Focus on greenhouse gas emissions:** This tends to be the main focus of many LCA studies, justified through climate change being a main driver for electrification. However, there are a range of other impact categories that could be considered (such as abiotic resource depletion, dissipation and circularity of materials).

For this study, a further high-level review of LCA assessments produced by OEMs was undertaken, identifying the lifecycle stages defined in the assessment, metrics considered, assumptions used, information on circularity and any other information provided (see Table A4.2.1-1– Appendix A4). It was identified that defined **lifecycle stages** and the system boundary itself do vary between the OEM assessments, typically including material production and logistics; vehicle battery manufacture; usage; and EoL/recycling. The **impact categories and indicators used** tend to vary considerably between the OEMs, including those relating to climate change (global warming potential / tonnes or grams CO_2e), but also additional impacts and indicators. The **assumptions used** underpinning the LCA study analysis also vary (sometimes significantly). Of those reviewed, lifetime vehicle km examples were provided between 100,000 and 300,000km total distance, and other variables including number of passengers, lifetime years used, and critically the electricity mix).

However, what is clear from the review of the lifecycle assessments is that **they are not standardised between OEMs and tend to provide a comparison with one of their own models only**. Although consumers will be able to obtain detailed information on the individual models, **it will not be easily possible**

for them to make comparison between models/brands due to the variances in the lifecycle stages considered, impact categories/metrics used and the assumptions used relating to lifetime use (distance and time).

Further information on vehicle lifecycle assessments from other sources is provided in Section 6.3.2.1.

6.4.2.2 OEM manuals

A recent study for FIA (Steer, 2023) reviewed selected manufacturer manuals in terms of the following information provided to consumers on electric vehicle models:

- General xEV information
- Charging information
- Vehicle performance and range
- Safety
- Environmental impact and battery disposal

Six operator manuals were reviewed to explore the quality of information provided by OEMs to consumers. The review focused on xEV specific information across five broad themes considered to represent a comprehensive overview of xEV-related information. The summary in Table A4.2.2-1 (Appendix A4) provides an assessment of the quality of the information provided in the manuals for each of the identified themes.

Across the manuals, **information relating to charging and safety was found to be relatively consistent, and to some extent environmental impact//battery disposal**. However, areas where there was **limited or no information for the majority of manuals included battery range, battery charging times and vehicle production and environmental impact**. To some extent, information on these aspects are provided by OEMs but via other reports/formats.

6.4.2.3 Information provided to owners/users of electric vehicles

The ongoing provision of and access to information for owners and users of electric vehicles is also important to support optimal use and maintenance of vehicles. A review of such information provided by OEMs post-purchase was undertaken, focussing on a selection of applications offered to owners and the information that is accessible to them, often via online apps/apps for smartphones. A high-level assessment and summary of the information provided to owners via selected OEM apps is provided in Table A4.2.3-1 (Appendix A4).

The most common information provided to users via OEM applications includes estimated electric range, the current battery status/charge level and ability to locate charging stations (and associated information on their availability, price etc.). A wide range of additional information is also provided to users via the apps, including location of the vehicle, charging status, cost savings, service history and remote features (unlock/lock, start, defrost etc.). Information is specific to the vehicle and its real-world use, and available to the user, therefore supporting optimal use and maintenance of the vehicle. However, as an information source it is not accessible to prospective consumers and therefore unlikely to affect purchase decisions/comparisons.

In addition, there have been instances where such apps being discontinued for older xEV models, or certain important functionality removed (e.g. (BBC, 2024)). It is unclear whether this is to become a more widespread trend for future xEV models, also where fleet uptake is expected to be orders of magnitude higher. However similar issues also occur in other smart consumer electronic products, where updates become less frequent or services become unavailable in older products due to difficulties in maintaining compatibility with new platforms.

6.4.2.4 Other information and sources to consider

In addition to the information discussed above, there may be other information related to electric vehicles that will become important for consumers to be aware of in the future.

One such issue is information on **bidirectional charging**, whereby energy can be sent from the vehicle for use by other devices, rather than just in one direction from power source to a car’s battery. In the case of one-directional charging, where AC electricity is passed to the electric vehicle and converted to DC energy to be stored in the battery. The conversion happens either in the charger or the vehicle, depending on where the convertor is located. In the case of bi-directional charging, a vehicle’s DC energy can be converted back into AC electricity and passed to another device/recipient, with the most common recipients being returning the energy to the electricity grid (vehicle to grid – V2G), home (vehicle to home – V2H), loads – such as tools or appliances within the vehicle or from the charging point via an adapter (vehicle to load – V2L) or to another vehicle (vehicle to vehicle – V2V) (EV Connect, 2024).

There are a range of benefits of using bidirectional charging, which include the following:

- **Saving money on energy use:** Using bidirectional charging with smart charging technology can enable users to charge vehicles during off-peak hours or when renewable sources are available and subsequently use the energy in the home (or elsewhere) during other periods of the day. Alternatively, energy can be sold back to utility companies for redistribution (via vehicle to grid).
- **Storage of power for home or business:** The vehicle can be used for energy storage during periods the main energy source is unavailable.
- **Portable power source:** The energy stored in the vehicle can be used as a portable power sources for a range of devices, or other vehicles.

As bidirectional charging develops and more vehicles (and chargers) become equipped with the necessary convertors, there are considerations for the information that could be provided to consumers and users of electric vehicles. Raising awareness of bidirectional charging amongst potential consumers, and its uses and benefits as described above, could assist in overcoming some of the remaining barriers to electric vehicle uptake, potentially influencing purchasing decisions. Awareness of V2G is currently low, with 34% of EU respondents of the consumer monitor survey reporting they had never heard of it, and 22% reporting they knew very little about it (EAFO, 2023). There is therefore a need to inform consumers about bidirectional charging capabilities of electric vehicle models, ensuring that both the vehicle and the chargers that are being considered are capable of two-way charging. Post purchase, information will be required to be provided to the user to ensure they are able to optimise bidirectional charging to their advantage, making the most of smart technology and ensuring cost savings are achieved. OEM apps are the main candidate for provision of this information (EV Connect, 2024).

However, despite these benefits there are a number of other considerations for consumers relating to bidirectional charging, which is still a relatively new technology. Batteries are made by OEMs with an expectation of achieving approximately 1,000 or more charges (based on a rough calculation of 480km per charge, which could equate to 480,000km over a lifetime – varying depending on the battery capacity, operational efficiency and charging regime of the user). However, battery warranties are typically limited to around 160,000 km or 8 years (whichever comes first). Introducing bidirectional charging could mean that batteries degrade more quickly than they might have done under traditional mobility-only usage, reducing their lifespan (although the user may accept this trade-off due to the benefits achieved). This reinforces the need for information on battery status and health for the user (Baca & Sperling, 2023).

6.4.3 Vehicle sustainability information provided by other sources

This section considers vehicle sustainability information provided by other sources / third parties.

6.4.3.1 Third party LCA comparison tools

Typical information provided via OEM vehicle LCAs was discussed in section 6.3.2.1. However, it was observed that it is difficult for consumers to make comparisons between models due to the differences in the life cycle stages used, the metrics considered and the assumptions made. Methodologies are being developed that attempt to overcome some of these issues and that will enable consumers to make comparisons.

T&E's LCA tool[22] allows users to compare the lifetime CO_2 emissions of an electric car with petrol, diesel, or other electric cars. In this way, the methodology enables users to make comparisons between types of vehicles and understand better the environmental impact of each type. The tool enables consumers to input the following information:

- Where the battery was made (EU Average, Sweden, China, or Germany)
- Where the car is driven (Country)
- Battery supply chain (Standard or Low impact)

The user then selects what vehicle type to compare against (Gasoline, Battery Electric, Plug-in Hybrid, or Diesel). The tool then calculates the CO_2 emissions per km of both of the selected vehicles, while also

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[22] T&E Life Cycle Analysis for Electric Vehicles

generating graphs that display the tonnes of CO_2 emitted over a lifetime by lifecycle stage (e.g., Use phase, recycling etc.). This is an example of a 'light touch' interactive tool that allows users to make a basic comparison between types of vehicles and gain high-level understanding of their environmental impact.

IEA LCA Calculator is another tool that allows consumers to make comparisons between conventional and electric cars. The tool enables consumers to distinguish between vehicle type (ICE, plug-in hybrid and electric vehicle) in selected world regions and countries. For each vehicle, further tailoring can be made, including size, annual driving distance, lifetime, powertrain-specific assumptions (e.g., battery size) and information about the energy supply such as the emissions intensity of electricity production, or the vehicle's fuel consumption. The calculator then outputs the following information:

- Cumulative emissions (tCO_2e)
- Breakdown of total lifetime emissions
    - Car production
    - Battery production
    - Energy production (well-to-tank)
    - Fuel combustion (tank-to-wheel)

The calculator also summarises the presented information in the form of easy-to-understand statements. It will provide percentages comparing the tons of CO_2e produced by each vehicle relative to an ICE based on the information provided (e.g., "*Battery EV will produce 23.2t, 16% less over its lifetime than an ICE vehicle")*.

Green NCAP (a development from the European New Car Performance ratings - Euro NCAP - focusing on vehicle safety) is another initiative that has been developed to rate vehicles in terms of their environmental performance. Green NCAP is an independent initiative promoting the development of cars that are clean, energy efficient and cause as little harm to the environment as possible. The aim of Green NCAP is to improve air quality, minimise use of resources and reduce global warming. It aims to do this through providing information to consumers (via a star rating and index system) regarding the following:

- Clean air index (NMHC, NOx, NH_3, CO, PM)
- Energy efficiency index (kW / 100km, consumption and driving range)
- Greenhouse gases (CO_2, N_2O, CH_4)
- Average score

Green NCAP conducts a combination of both laboratory tests (using regulatory testing protocols) and on-road testing of some of the most popular European vehicle models to provide an independent assessment of the energy consumption and emissions performance. This testing has highlighted differences in performance compared to official OEM published regulatory values for a wide range of vehicle and powertrain types (i.e. for conventional ICEV, HEV, PHEV and BEV models), which could also have implications for the accuracy of data that is presented to consumers. These are also discussed further in Section 5.

Green NCAP also collates and provides European **Life Cycle Assessment** (LCA) results for a range of manufacturers and models, based on high-level publicly available data using a methodology developed for this purpose (presented in LCA information factsheets). Common assumptions are used, including:

- 16 year lifetime
- 240,000km mileage
- Current forecast about changing average energy mix of 27 EU Member States and the UK.

This enables vehicles to be compared on the European market tested under the same (Green NCAP) conditions. In addition, the same high level publicly available data for all vehicles is used, but this helps the consumer to identify the main factors for different life cycle outcomes rather than allow an LCA comparison system.

In addition to the LCA factsheets, Green NCAP have developed a **LCA interactive tool**, which enables users to select and compare up to three vehicles. This can be any vehicle, or vehicles that have also been tested by Green NCAP – which include a measurement on the best, average and worst results. The user is able to customise the LCA parameters to take into account local and personal circumstances including miles driven, RE mix and country of use.

There are aspects that are not yet fully taken account of in the methodology, including environmental effects of NOx, SOx and particulate matter emissions, and related consequential impacts such as acidification, ozone formation and toxicity to humans. Full life cycle impacts of transport system on other aspects including water demand, pollution of water, soil or air are also missing.

Specific manufacturer or model data is not used, instead utilising publicly available scientifically accepted generic information about vehicle production and recycling processes – therefore manufacturers conducting their own LCA will have calculated results in a much more detailed way using in-house/primary data for their specific vehicles, manufacturing processes and supply-chains. Green NCAP are exploring potentials ways to increase the specificity of the assessment and use more OEM/model-specific data in calculating production emissions as part of the LCA. However, the current approach enables an indicative comparison to be made between different models using a consistent methodological basis.

6.4.3.2 Electric Vehicle comparison sites

There are many vehicle comparison sites available across Europe, including both ICE and EVs enabling consumers to compare a range of metrics, potentially informing purchasing decisions. A review was undertaken of selected national and European level vehicle comparison sites to understand the type of information that is typically provided (see Table A4.2.5-1– Appendix A4). **Information that is typically provided includes fuel type; electric range; battery type; battery capacity; presence of rapid charging and acceleration capability. In addition, information can include total cost of ownership, tailpipe emissions, bidirectional charging capability, maximum speed, charge time, type of charger**. Similarly to OEM manuals, **information provided by comparison sites is not standardised, and key assumptions used in analyses may not be fully transparent**.

6.4.3.3 ChargePoint locations, availability and use

Although not directly related to the vehicle use, provision of information regarding chargepoint location, availability and use is of interest to both consumers considering purchasing an electric vehicle (potentially reducing barriers to uptake through raising awareness), but also users/owners of electric vehicles.

In addition to information provided to users/owners via OEM apps (see Table A4.2.4-1 – Appendix A4), there are numerous third-party website applications and websites that provide information on chargepoint location, availability and use. A high-level review was undertaken of selected European applications to evaluate what information is typically provided. Of those reviewed, **information on the location, number of ports, live availability, charger type and speed and price information is provided**. Other information provided varies depending on the application, but can include opening times, popular times, when the charger was last used, payment options, how long other vehicles have been charging, and facilities nearby.

6.5 ASSESSMENT OF GAPS

The objective of this subchapter is to address the following questions:

- What are the gaps relating to vehicle sustainability information currently provided by manufacturers/other sources and information required by consumers in the purchasing decision?

Using the information collated in the previous sub-sections, an assessment of the gaps has been performed, in particular between the information that is provided to consumers (both information that is required to be provided via European legislation and other information that is typically provided by manufacturers), and the information consumers require to make an informed purchasing decision.

Table 6-3: Assessment of gaps (Information that is not currently provided but is forthcoming (e.g. through agreed legislation) is displayed in *blue italics*)

Information required by consumers / xEV users	Discussion	**Stage at which information is used**	**Currently provided (format)**	**Status of provision**	**Analysis / Gaps**
Affordability (vehicle price / total cost of ownership)	Information on the purchase price of EVs (new and used) can be identified directly from OEMs/dealerships/private sellers. However, the perceived high purchase costs of electric vehicles (particularly new) can act as a barrier to their uptake (often when compared to purchase price of ICE vehicles) However, clear information on the total cost of ownership (TCO) is often more difficult to identify and could potentially be a more useful metric for consumers when making their purchase decision or comparisons between models, particularly where affordability is concerned.	Purchase decision	Car CO_2 labelling Directive	Voluntary	**Total cost of ownership** is occasionally included on the Car CO_2 label for new cars, but not as a mandatory requirement (at the discretion of the national competent authority). Assumptions are made regarding electricity mix/cost and vehicle use (km). Information is not standardised across Member States.
		Purchase decision	Vehicle comparison site	Voluntary	Assumptions are made regarding electricity mix/cost and vehicle use (km). Information is not standardised across third parties.
Electric range (and battery health / status)	'Range anxiety' and vehicle/battery performance has been identified as one of the key barriers to xEV uptake. It is important to provide information on range capability of EVs during the purchase decision stage, upon which consumers can make comparisons between models.	Purchase decision / In-use	OEM manuals	Voluntary	Across the manuals previously reviewed, limited information was provided on **electric range** of the models concerned. However, manuals were found to tend to include information on how users can maximise driving range. Information is not standardised across OEMs.
		Purchase decision	Vehicle comparison site	Voluntary	Information on electric range provided via comparison sites. Unverified source of the electric range information. Information is not provided in a standardised format.

Information required by consumers / xEV users	Discussion	**Stage at which information is used**	**Currently provided (format)**	**Status of provision**	**Analysis / Gaps**
	Information on electric range status is also important during the in use phase, keeping consumers informed of remaining range of their vehicle before it requires recharging. Similarly, information on the battery's health and status is required, both during the purchase decision and in use stages (and costs associated with this – see also affordability). Information and advice on how to optimise the performance of their vehicle and its battery is also of benefit to owners of electric vehicles in order to get the most out of their vehicles.	In-use	OEM applications	Voluntary	Information provided to users via OEM app related to real-world data, including the **estimated electric range** remaining and battery status/health. Information is not standardised across OEMs.
		In use	*Vehicle Type Approval Regulation (Euro 7) - EVP*	*Mandatory*	*Forthcoming requirement whereby the manufacturer is required to provide access to up to date information on electric range and state of health of batteries via the EVP*
		Purchase decision / In-use	*Sustainable Batteries Regulation – Battery passport*	*Mandatory*	*Forthcoming requirement whereby the battery manufacturer is required to provide transparent, reliable and clear information about batteries and waste batteries to users via the battery passport*
Chargepoint location and useability (including battery charge time)	Linked to range anxiety, the availability, location and useability (how to recharge, time taken to charge and payment) of chargepoints can also be an important factor in the purchase decision-making process, in addition to transparency/ information relating to the type of charger and instructions on how to charge to raise awareness for those unfamiliar with electric vehicles.	Purchase decision / in-use	Chargepoint applications and maps	Voluntary	Information is currently provided to consumers / users via online apps related to real-world data, including the location of chargepoints (via maps), and additional information on live availability, pricing etc.
		Purchase decision / In-use	OEM manuals	Voluntary	OEM manuals generally provide good information relating to how to charge vehicles, information relating to the charging components, and descriptions of the chargepoint types. Whilst manuals do provide information on **battery charge times**, it tends to be limited. Information on battery optimisation was mixed between the different OEMs, with some providing comprehensive information and other extremely limited/no information. Information is not standardised across OEMs.

Information required by consumers / xEV users	Discussion	Stage at which information is used	Currently provided (format)	Status of provision	Analysis / Gaps
		In-use	OEM applications	Voluntary	Information is currently provided to users via OEM app related to real-world data, including the current battery status / charge level and time remaining to charge. Information is not standardised across OEMs.
		In-use	OEM applications	Voluntary	Information is currently provided to users via OEM app related to real-world data specific to the model being used, including the location of chargepoints (via maps), and additional information on availability, pricing etc.
		Purchase decision / In-use	*Alternative Fuels Infrastructure Regulation*	*Mandatory*	*Forthcoming requirement whereby the manufacturer is required to provide information on which vehicles can be regularly recharged or refuelled (manuals and on vehicles)* *Information (by mobility providers/operators) on availability, waiting times and price.*
Environmental information (e.g., CO_2 emissions, air pollutant emissions)	The current Car Labelling Directive is focused on providing information to the consumer on tailpipe emissions of passenger cars (CO_2 emissions / fuel consumption). Whilst this results in electric vehicles being categorised as the cleanest vehicles (zero tailpipe emissions), it does not enable the consumer to differentiate between xEV models.	Purchase decision	Car CO_2 Labelling Directive (CO_2 emissions)	Mandatory	Not appropriate for the comparison of xEV models
		Purchase decision	Car Labelling Directive (air pollutant emissions)	Voluntary	**Tailpipe air pollutant emission information** is occasionally included on the Car CO_2 label, but not as a requirement (at the discretion of the national competent authority). Information is not standardised across Member States. Not appropriate for the comparison of xEV models.
		Purchase decision	*Vehicle Type Approval Regulation*	*Mandatory*	*Forthcoming requirement whereby the manufacturer is required to provide information on pollutant*

Information required by consumers / xEV users	Discussion	Stage at which information is used	Currently provided (format)	Status of provision	Analysis / Gaps
			(Euro 7) – Environmental Vehicle Passport (EVP)		*emission limits,* CO_2 *emissions, fuel consumption via the EVP*
		In use	*Vehicle Type Approval Regulation (Euro 7)*	*Mandatory*	*Forthcoming requirement whereby the manufacturer is required to provide access to up to date information on pollutant emissions via onboard systems and monitors.*
Vehicle lifecycle analysis / information	As described above, the current Car Labelling Directive is only focused on providing information to the consumer on tailpipe emissions of passenger cars, which does not enable the consumer to differentiate between xEV models. More detailed information is required to compare modes, such as LCA.	Purchase decision	OEM LCA	Voluntary	Use accurate OEM data on the materials and processes used in the supply chain. Due to different lifecycle stages used, different impact categories/metrics used and assumptions made regarding vehicle use (years and distance) and electricity mix, difficult for consumers to make comparisons between models. Generally, only available for a limited number of vehicle models, and only for the most popular configuration.
		Purchase decision	Third party LCA (e.g., Green NCAP)	Voluntary	Common data sources used on the materials and processes used in the supply chain (not accurate to individual OEMs). A common approach used in terms of life cycle stages considered, impact categories/metrics used and assumptions made (with the ability to tailor to regional circumstances). Enables the consumer to make an indicative generic high-level comparison between models.

6.6 SUMMARY

Information is desired by consumers when comparing and purchasing electric vehicles, information on total cost of ownership; electric range; battery charging times; chargepoint location and usability; battery health and optimisation; and lifecycle analysis information.

It is mandated that selected information is provided to consumers that could assist in informing either their purchase decision or vehicle use. However, further sources of vehicle sustainability information include vehicle manufacturers and third parties, including vehicle manuals, OEM-developed and owned apps, vehicle comparison sites, and LCAs. These tools offer a range of information, but not in a standardised format and differing levels of accuracy/detail.

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APPENDICES

A1 Additional material on lifecycle emissions for Chapter 2

A1.1 LCA LITERATURE REVIEW – DATA COLLECTION METHODOLOGY AND SOURCES INCLUDED

A wide range of literature sources were identified, screened and reviewed, including reports and scientific papers from governmental and non-governmental organisations, non-profits and NGOs, consultancy firms, and industry associations, as well as independent papers published in peer-reviewed scientific journals.

Databases such as Elsevier's Science Direct and Google Scholar were used to search for relevant literature. The following key words and *Boolean operators* were used for searching in the "title, abstract or author-specified keywords" field: "Life cycle assessment" *OR* "LCA" *AND* (EV OR BEV OR ZEV OR ICEV OR FCEV OR HEV OR PHEV)".

Initial screening of the papers involved defining the scope according to the following preliminary criteria:

1. **Temporal scope**

   The study must have been published within the last decade, i.e., from the year 2013 onwards. This was to ensure that the collected information was not unduly affected by obsolete assumptions and data sources. Given that we already had a pre-existing knowledge base of relevant LCA sources, the main focus was to review more recently published papers and reports, from 2020 onwards.

2. **Geographic scope**

   The study preferably has a European focus; however, other geographies may be included depending on their relevance, including North America, Asia, and Australia, and other more global perspectives.

Subsequent screening involved refining the scope further via a manual review. This involved reading all sources that met the temporal and geographic criteria to determine their relevance according to more specific factors. Sources were retained upon meeting the following criteria:

1. **Vehicle size classes**

   The study must address one or more of the main passenger vehicle size classes: compact, medium-size, and large or sports utility vehicles.

2. **Emission types and mid-point impact categories**

   The study must report the Global Warming Potential (GWP) of the vehicles. Other emission types and mid-point life cycle impact assessment (LCIA) indicators considered in some of the studies included: Acidification Potential (AP), Ozone Depletion Potential (ODP), Photochemical Oxidant Formation Potential (POFP), Human Toxicity Potential (HTP), Ecotoxicity Potential (ETP), and Abiotic Depletion Potential Elements (ADPel).

3. **Cradle to grave model**

   The study must apply a full "cradle-to-grave" model (i.e., not "well-to-tank" or "well-to-wheel" dealing with the fuel or energy carrier only) to ensure that the entire vehicle life cycle is considered.

4. **Functional unit**

   The study must be transparent about the adopted functional unit (FU), which may be defined as either the whole vehicle, or a suitable unit of transport such as vehicle·km or passenger·km.

5. **Vehicle mileage / occupancy**

   The study must indicate the assumed total vehicle mileage (as well as the average vehicle occupancy, should passenger·km be chosen as the FU).

A total of 45 sources were retained following the screening process. A full account of the sources included in the review is included in Table A1.1-1 below.

Table A1.1-1: List of sources used in literature review

Year	Authors	Lead author affiliation	Title
2022	Wang, N.; Tang, G.	Xi An Jiao Tong Univ. China	A Review on Environmental Efficiency Evaluation of New Energy Vehicles Using Life Cycle Analysis
2022	Shafique, M.; Luo, X.	Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong	Environmental life cycle assessment of battery electric vehicles from the current and future energy mix perspective
2022	Smit, R.; Kennedy, D. W.	Transport Energy Emiss Res TER, Australia	Greenhouse Gas Emissions Performance of Electric and Fossil-Fueled Passenger Vehicles with Uncertainty Estimates Using a Probabilistic Life-Cycle Assessment
2022	Buberger, J.; Kersten, A.; Kuder, M.; Eckerle, R.; Weyh, T.; Thiringer, T.	Universität der Bundeswehr München	Total CO_2-equivalent life-cycle emissions from commercially available passenger cars
2022	Koroma, M. S.; Costa, D.; Philippot, M.; Cardellini, G.; Hosen, M. S.; Coosemans, T.; Messagie, M.	Electrotechnical Engineering and Energy Technology, MOBI Research Group	Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management
2022	Shafique, M.; Azam, A.; Rafiq, M.; Luo, X. W.	City Univ Hong Kong	Life cycle assessment of electric vehicles and internal combustion engine vehicles: A case study of Hong Kong
2022	Tang, B. W.; Xu, Y.; Wang, M. Y.	Hubei Univ Technol, Sch Elect & Elect Engn, China	Life Cycle Assessment of Battery Electric and Internal Combustion Engine Vehicles Considering the Impact of Electricity Generation Mix: A Case Study in China
2022	Buberger, J.; Kersten, A.; Kuder, M.; Eckerle, R.; Weyh, T.; Thiringer, T.	Renewable and sustainable energy reviews	A global comparison of the life-cycle greenhouse gas emissions of combustion engine and electric passenger cars
2021	Piptone, E.; Caltabellotta, S.; Occhipinti, L.	Department of Engineering, University of Palermo, 90128 Palermo, Italy;	A Life Cycle Environmental Impact Comparison between Traditional, Hybrid, and Electric Vehicles in the European Context
2021	Zheng, G.; Peng, Z. J.	Univ Essex, UK	Life Cycle Assessment (LCA) of BEV's environmental benefits for meeting the challenge of ICExit (Internal Combustion Engine Exit)
2021	Zeng, D.; Dong, Y.; Cao, H. J.; Li, Y. K.; Wang, J.; Li, Z. B.; Hauschild, M. Z.	Chongqing University, China	Are the electric vehicles more sustainable than the conventional ones? Influences of the assumptions and modeling approaches in the case of typical cars in China
2021	Yang, L.; Yu, B. Y.; Yang, B.; Chen, H.; Malima, G.; Wei, Y. M.	Beijing Inst Technol, China	Life cycle environmental assessment of electric and internal combustion engine vehicles in China
2021	Petrauskiene, K.; Galinis, A.; Kliaugaite, D.; Dvarioniene, J.	Kaunas University of Technology, Lithuania	Comparative Environmental Life Cycle and Cost Assessment of Electric, Hybrid, and Conventional Vehicles in Lithuania
2021	Benitez, A.; Wulf, C.; de Palmenaer, A.; Lengersdorf, M.; Roding, T.; Grube, T.; Robinius,	Forschungszentrum Jülich, Institute of Energy and Climate Research	Ecological assessment of fuel cell electric vehicles with special focus on type IV carbon fiber hydrogen tank

Year	Authors	Lead author affiliation	Title
	M.; Stolten, D.; Kuckshinrichs, W.		
2021	Ternel, C.; Bouter, A.; Melgar, J.	IFP Energies nouvelles	Life cycle assessment of mid-range passenger cars powered by liquid and gaseous biofuels: Comparison with greenhouse gas emissions of electric vehicles and forecast to 2030
2021	Yugo, M.; Gordillo, V.; Shafiei, E.; Megaritis, A.	Concawe	A look into the life cycle assessment of passenger cars running on advanced fuels
2021	Bieker, G.	ICCT	A global comparison of the life-cycle greenhouse gas emissions of combustion engine and electric passenger cars
2021	Hill, N.; Amaral, S.	Ricardo, UK	Lifecycle Analysis of UK Road Vehicles
2020	Helmers, E.; Dietz, J.; Weiss, M.	University of Applied Sciences Trier, Germany	Sensitivity Analysis in the Life-Cycle Assessment of Electric vs. Combustion Engine Cars under Approximate Real-World Conditions
2020	Koroma, M. S.; Brown, N.; Cardellini, G.; Messagie, M.	Vrije Universiteit Brussel, Belgium	Prospective Environmental Impacts of Passenger Cars under Different Energy and Steel Production Scenarios
2020	Desantes, J. M.; Molina, S.; Novella, R.; Lopez-Juarez, M.	Universitat Politècnica de València, Spain	Comparative global warming impact and NOX emissions of conventional and hydrogen automotive propulsion systems
2020	Bouter, A.; Hache, E.; Ternel, C.; Beauchet, S.	IFP Energies Nouvelles, France	Comparative environmental life cycle assessment of several powertrain types for cars and buses in France for two driving cycles: worldwide harmonized light vehicle test procedure cycle and urban cycle
2020	Ambrose, H.; Kendall, A.; Lozano, M.; Wachche, S.; Fulton, L.	University of California, Davis, USA	Trends in life cycle greenhouse gas emissions of future light duty electric vehicles
2020	Belmonte, B. B.; Esser, A.; Weyand, S.; Franke, G.; Schebek, L.; Rinderknecht, S.	Technische Universität Darmstadt, Germany	Identification of the Optimal Passenger Car Vehicle Fleet Transition for Mitigating the Cumulative Life-Cycle Greenhouse Gas Emissions until 2050
2020	Petrauskiene, K.; Skvarnaviciute, M.; Dvarioniene, J.	Kaunas University of Technology, Lithuania	Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania
2020	Helmers, E.; Dietz, J.; Weiss, M.	University of Applied Sciences Trier, Germany	Sensitivity Analysis in the Life-Cycle Assessment of Electric vs. Combustion Engine Cars under Approximate Real-World Conditions
2020	Evtimov, I.; Ivanov, R.; Stanchev, H.; Kadikyanov, G.; Staneva, G.	University of Ruse, Bulgaria	LIFE CYCLE ASSESSMENT OF FUEL CELLS ELECTRIC VEHICLES

Year	Authors	Lead author affiliation	Title
2020	Hill, N.; Amaral, S.; Morgan-Price, S.; Nokes, T.; Bates, J. (Ricardo Energy & Environment); Helms, H.; Fehrenbach, H.; Biemann, K.; Abdalla, N.; Jöhrens, J. (ifeu); Cotton, E.; German, L.; Harris, A.; Ziem-Milojevic, S.; Haye, S.; Sim, C.; Bauen, A. (E4tech).	Ricardo, UK	Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA
2019	Wu, Z. Y.; Wang, C.; Wolfram, P.; Zhang, Y. X.; Sun, X.; Hertwich, E.	Tsinghua University, China	Assessing electric vehicle policy with region-specific carbon footprints
2019	Kim, S.; Pelton, R. E. O.; Smith, T. M.; Lee, J.; Jeon, J.; Suh, K.	Seoul National University, South Korea	Environmental Implications of the National Power Roadmap with Policy Directives for Battery Electric Vehicles (BEVs)
2019	Bekel, K.; Pauliuk, S.	University of Freiburg, Germany	Prospective cost and environmental impact assessment of battery and fuel cell electric vehicles in Germany
2019	Rosenfeld, D. C.; Lindorfer, J.; Fazeni-Fraisl, K.	Johannes Kepler Universität Linz, Austria	Comparison of advanced fuels-Which technology can win from the life cycle perspective?
2019	Kawamoto, R; Mochizuki, H; Moriguchi, Y; Nakano, T; Motohashi, M; Sakai, Y; Inaba, A	Mazda Motor Corporation, Japan	Estimation of CO2 Emissions of Internal Combustion Engine Vehicle and Battery Electric Vehicle Using LCA
2018	Kawamoto, R.; Mochizuki, H.; Moriguchi, Y.; Nakano, T.; Motohashi, M.; Sakai, Y.; Inaba, A.	University of Ontario Institute of Technology	Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles
2018	Burchart-Korol, D.; Jursova, S.; Folega, P.; Korol, J.; Pustejovska, P.; Blaut, A.	Silesian University of Technology, Poland	Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic
2018	Wu, Z. X.; Wang, M.; Zheng, J. H.; Sun, X.; Zhao, M. N.; Wang, X.	China Automotive Technology & Research Center, China	Life cycle greenhouse gas emission reduction potential of battery electric vehicle
2018	Concawe	Concawe	Life-cycle analysis—a look into the key parameters affecting life-cycle CO2 emissions of passenger cars
2017	Renault	Renault	Renault Megane IV - 2017 - Life Cycle Assessment Results - Renault LCA Methodology
2017	Lombardi, L.; Tribioli, L.; Cozzolino, R.; Bella, G.	Niccolò Cusano University, Tor Vergata University (Rome, Italy)	Comparative environmental assessment of conventional, electric, hybrid, and fuel cell powertrains based on LCA
2017	Van Mierlo, J.; Messagie, M.; Rangaraju, S.	Vrije Universiteit Brussel, Brussels	Comparative environmental assessment of alternative fueled vehicles using a life cycle assessment
2016	Tagliaferri, C.; Evangelisti, S.; Acconcia, F.; Domenech, T.; Ekins,	Chemical Engineering Department,	Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach

Year	Authors	Lead author affiliation	Title
	P.; Barletta, D.; Lettieri, P.	University College London	
2016	Ager-Wick Ellingsen, L.; Singh, B.; Hammer Strømman, A.	Norwegian University of Science and Technology (NTNU)	The size and range effect: lifecycle greenhouse gas emissions of electric vehicles
2016	DelPero, F.; Delogu, M.; Pierini, M.	University of Florence	Life Cycle Assessment in the automotive sector: a comparative case study of Internal Combustion Engine (ICE) and electric car
2015	Bauer, C.; Hofer, J.; Althaus, H.-J.; Del Duce, A.; Simons, A.	Paul Scherrer Insitut, Empa	The environmental performance of current and future passenger vehicles: Life Cycle Assessment based on a novel scenario analysis framework
2015	Tong, F.; Jaramillo, P.; Azevedo, I. M. L.	Carnegie Mellon University	Comparison of life cycle greenhouse gases from natural gas pathways for light-duty vehicles
2013	Nanaki, E. A.; Koroneos, C. J.	University of Western Macedonia	Comparative economic and environmental analysis of conventional, hybrid and electric vehicles – the case study of Greece

Figure A1.1-1 reports the paper count per year of publication, from 2013 to 2022. LCAs of passenger vehicles appears to have peaked in 2021, with a total of 19 papers published between 2020 and 2021. These 45 sources then became the object of the harmonisation task described in Section 2.4.

Figure A1.1-1: Number of papers included in the review per year of publication

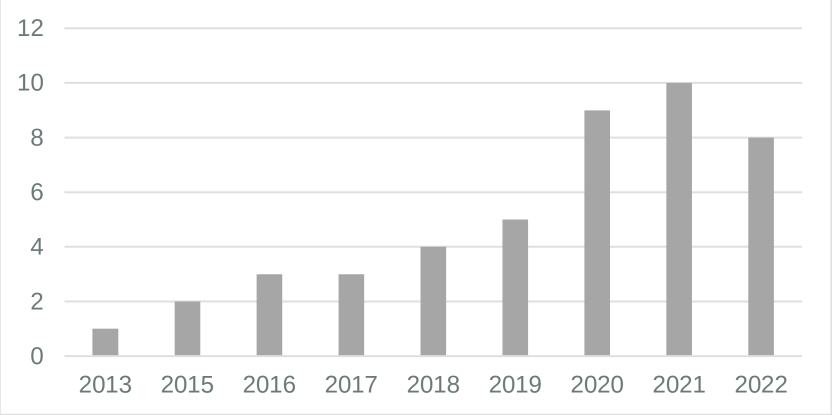


Figure A1.1-2 reports the number of data points that refer to each of the three main vehicle size classes (compact, mid-size, and large or sports utility), or an average “fleet mix”.

Figure A1.1-2 Number of data points addressing each vehicle size class

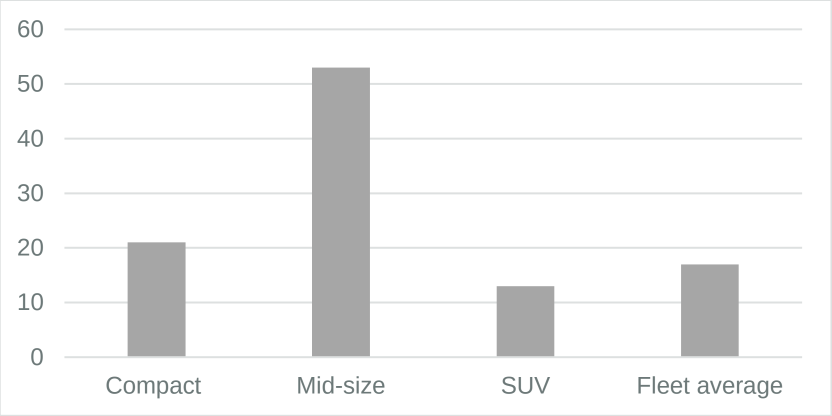


Figure A1.1-3 shows the number of data points per geographic region.

Figure A1.1-3 Number of data points per geographic region

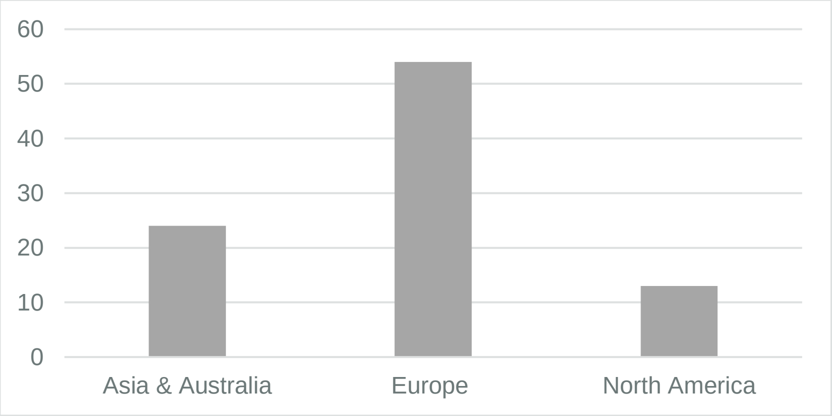
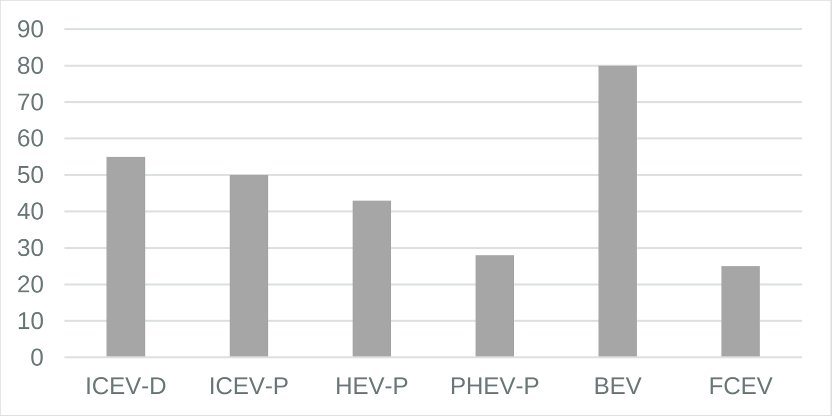


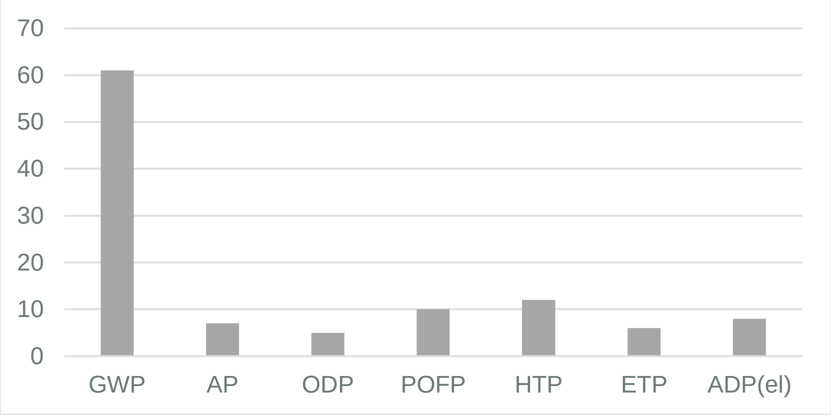
Figure A1.1-4 indicates the number of data points collected and reviewed per vehicle power train type.

Figure A1.1-4 Number of data points addressing each vehicle category (by power train type)



The review focused primarily on papers reporting GWP. However, other mid-point impact indicators were also taken into account by some of the authors, among which: Acidification Potential (AP), Ozone Depletion Potential (ODP), Photochemical Oxidant Formation Potential (POFP), Human Toxicity Potential (HTP), Ecotoxicity Potential (ETP), and ADPel. Figure A1.1-5 indicates the number of data points collected reporting on each mid-point impact category.

Figure A1.1-5 Number of data points addressing each mid-point impact category



A1.2 LCA LITERATURE REVIEW – HARMONISATION METHODOLOGY

The harmonisation of the LCA results from the reviewed literature was carried out based the criteria outlined below:

1. **Common functional unit**

   Results are to be expressed in terms of the same FU. The choice was made to complete the harmonisation process based on vehicle·km. It was the preferred option as this FU arguably strikes the best balance between significance (it refers to a better identifiable unit of service than just "vehicle") and accuracy (it avoids additional assumptions on average vehicle occupancy, which may vary significantly across time and different geographies).

2. **Common assumption on the total vehicle mileage**

   A common assumption on total vehicle mileage was made. This was set at 225,000. This value was recently reported to be statistically representative for Europe[23]. Alternative values were also considered by way of Sensitivity Analysis (see Section 2.5)

3. **Common system boundary**

   The literature varied in terms of methodological treatment of the EoL phase. Some studies reported EoL emissions by adopting the "cut off" approach, whereby no emission credits were assigned to recycling. Other papers, instead, reported EoL emissions according to the "avoided burden" approach, with recycling credits. Finally, some papers excluded EoL entirely from the scope of the analysis. For this reason, it was important to determine a common system boundary in order to clearly define which stages of the vehicle life cycle were to be included. This review therefore excludes EoL emissions from the harmonisation process.

From a numerical standpoint, the harmonization of the published GHG emission results was carried out using Equations (1) and (2) as described below.

Eq. (1) - Harmonisation of GHG results for vehicle production stage:

$$\begin{cases} IF\ (FU = vehicle)\ THEN\ GWP_{P,H} = \frac{GWP_P}{VKT_H} \\ IF\ (FU = vehicle\cdot km)\ THEN\ GWP_{P,H} = \frac{GWP_P\cdot VKT}{VKT_H} \\ IF\ (FU = passenger\cdot km)\ THEN\ GWP_{P,H} = \frac{GWP_P\cdot VO\cdot VKT}{VKT_H} \end{cases}$$

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[23] Hill, N.; Amaral, S.; Morgan-Price, S.; Nokes, T.; Bates, J.; Helms, H.; Fahrenbach, H.; Bieman, K.; Abdalla, N.; Joehrens, J.; et al. Determining the Environmental Impacts of Conventional and Alternatively Fuelled Vehicles through LCA. European Commission, DG Climate Action. Available online: https://ec.europa.eu/clima/system/files/2020-09/2020_study_main_report_en.pdf (accessed on 14th May 2024).

where:

$GWP_{P,H}$ = Harmonised Global Warming Potential of vehicle production stage;

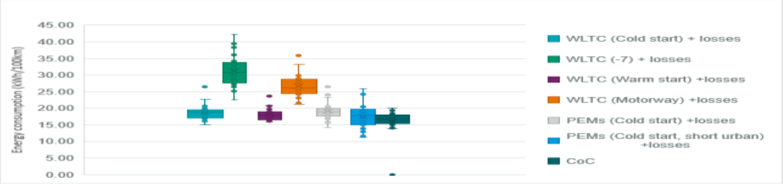
GWP_P = Global Warming Potential of vehicle production stage, as originally published;

VKT_H = harmonised vehicle km travelled (i.e., lifetime mileage);

VKT = vehicle km travelled (i.e., lifetime mileage), as assumed in original study;

VO = vehicle occupancy, as assumed in original study.

Eq. (2) - Harmonisation of GHG results for vehicle use stage:



where:

$GWP_{U,H}$ = Harmonized Global Warming Potential of vehicle use stage;

GWP_U = Global Warming Potential of vehicle use stage, as originally published;

VKT = vehicle km travelled (i.e., lifetime mileage), as assumed in original study;

VO = vehicle occupancy, as assumed in original study.

The total harmonized life-cycle GHG emissions ($GWP_{LC,H}$, excluding EoL stage) were then simply calculated as the sum of the two previous terms:

$$GWP_{LC,H} = GWP_{P,H} + GWP_{U,H}$$

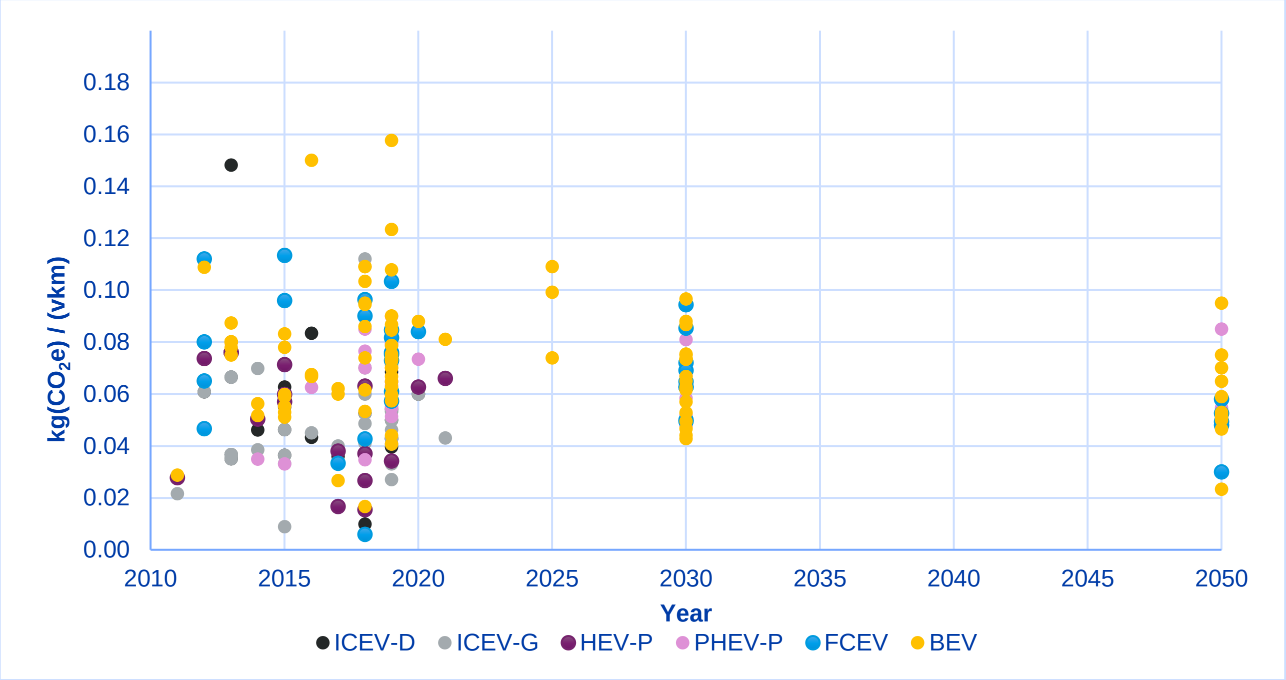
A1.3 LCA LITERATURE REVIEW – SENSITIVITY ANALYSIS

A sensitivity analysis was conducted on the harmonised literature results to assess the influence of assumed vehicle lifetime mileage on its production GHG emissions. Specifically, two alternative values were considered for total vehicle lifetime mileage, namely:

- 150,000 km, representing the ‘lower’ value = “worst case”
- 340,000 km, representing the ‘higher’ value = “best case”

Figure A1.3-1 shows the results, applying a total vehicle lifetime mileage of 150,000km. In comparison to Figure 2-2, the results show an increase in vehicle production GHG emissions, across all vehicle types.

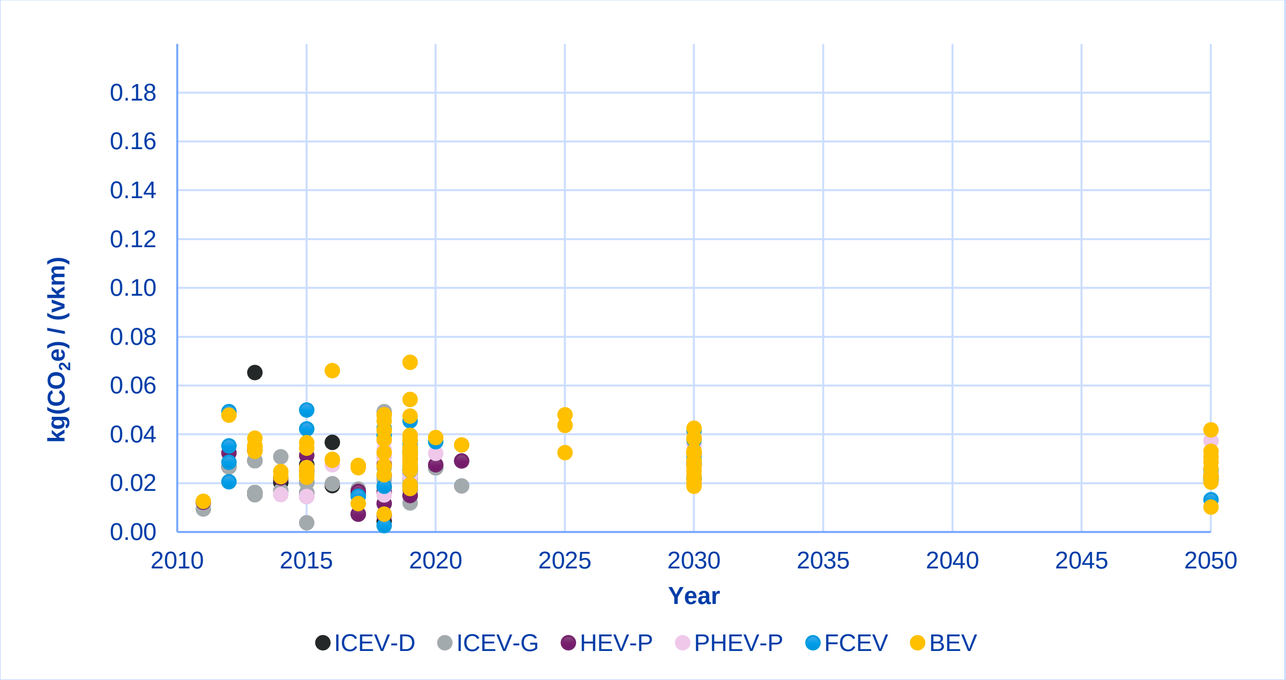
Figure A1.3-1 Sensitivity analysis: GHG emissions associated with the vehicle production phase, assuming a total lifetime mileage of **150,000km**.



All data harmonised to: FU = Vehicle·km travelled and 150,000 km lifetime mileage

In contrast, with a greater total lifetime mileage of 340,000km, the total GHG emissions associated with vehicle production are reduced, when expressed per FU (i.e., per vehicle·km). This is because the GHG emissions associated with vehicle production are distributed over a larger distance. Figure A1.3-2 illustrates the results.

Figure A1.3-2 Sensitivity analysis: GHG emissions associated with the vehicle production phase, assuming a total lifetime mileage of **340,000km**.



All data harmonised to: FU = Vehicle·km travelled and 340,000 km lifetime mileage

A1.4 LCA – END OF LIFE ALLOCATION METHODS

The three most widely employed EoL allocation approaches in LCA differ in significant ways, and have numerous associated implications and trade-offs, are briefly illustrated below:

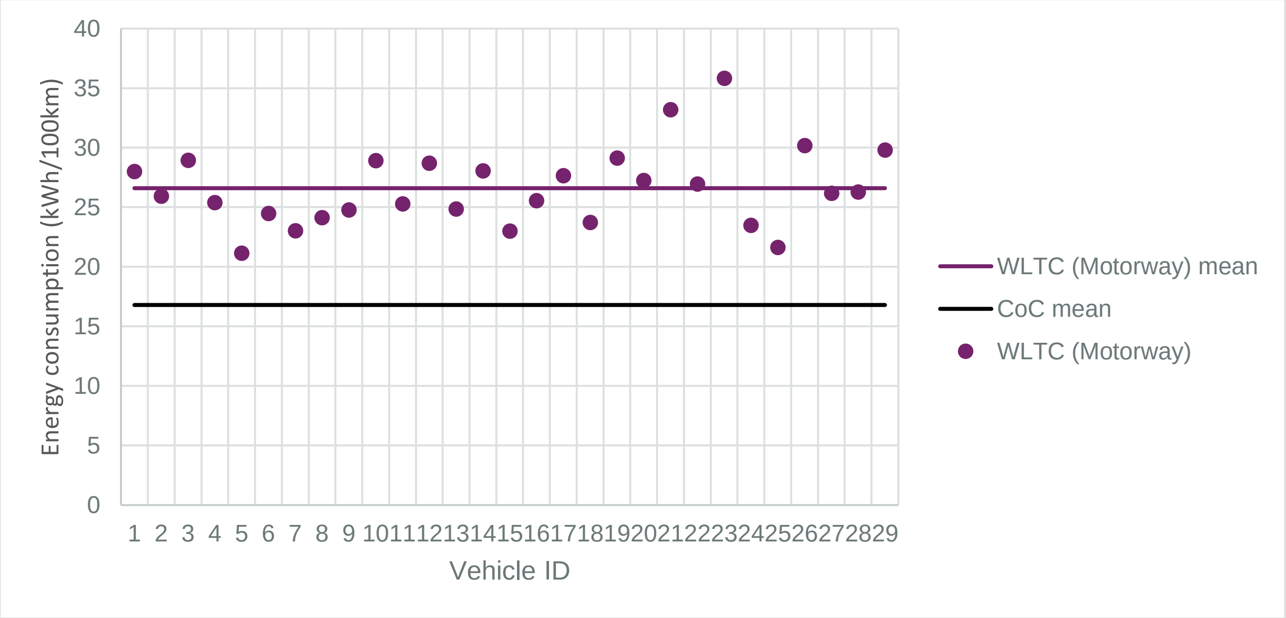
- "Recycled content" (also referred to as "Cut-off", or 100:0). In this approach, both recycling and any associated credits are excluded from the system boundary. Specific emissions and resources consumed for other disposal processes (including those with energy recovery) are instead included, but no credits are given for energy recovery. This approach promptly accounts for those environmental impacts that are caused by the consumption of primary material feedstocks, irrespective of whether or not the materials may end up being recycled in the future. As such, it is a more risk-averse approach, and it can be seen as aligned with a "strong sustainability" concept.
- "Avoided burden" (also referred to as "EoL recycling", or 0:100). In this approach, recycling and energy recovery are included in the system boundary, together with the associated emissions and resource use credits. However, to ensure the avoidance of any external double counting, under this approach the material input to the product under analysis is always assigned the specific emissions and resources consumed for its primary (i.e., virgin) production, irrespective of whether or not any secondary (i.e., recycled) feedstock is used in manufacturing. This approach assumes that the materials will still be in demand by the time the product has reached its EoL, and therefore it can be regarded as "borrowing" an "environmental loan" from the future. As such, it is a more risk-tolerant approach, and it can be seen as aligned with a "weak sustainability" concept.
- "Circular Footprint Formula" (CFF). This approach was originally introduced in Annex V of the Product Environmental Footprint (PEF) Guide, and later modified in the 2021 revision of the same guide. It was devised to strike a balance between the two aforementioned approaches, and to model EoL recycling within an internally consistent whole-life-cycle framework that also includes the material inputs to the system under study (which can be partially virgin and partially of secondary origin themselves), as well as other EoL waste management options (such as incineration with energy recovery and landfilling). However, this approach is more complex to implement, and it is also less clear-cut in terms of its conceptual implications, and it relies on two key allocation parameters that have to be set for each material specifically, which entails a degree of subjectivity.

A2 Additional material on real world energy consumption for Chapter 4

A2.1 FACTORS EFFECTING REAL-WORLD ENERGY CONSUMPTION OF BEVS

Speed

Figure A2.1-1 Comparison in BEV energy consumption (kWh/100km) in WLTC test cycles between an average test cycle (CoC) and a motorway test cycle



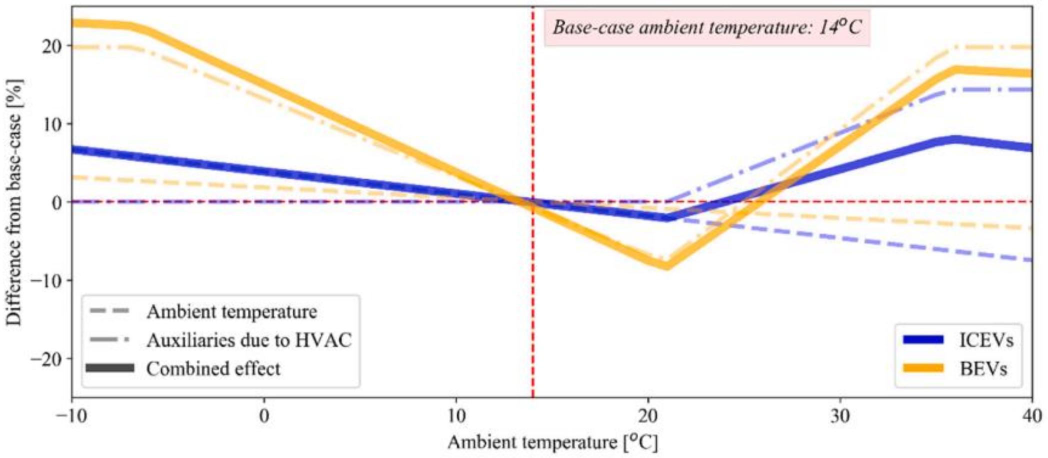
Source: Ricardo analysis of Green NCAP test data

Notes: energy consumption values include charging losses. Values are split into two broad categories of test - worldwide harmonized light vehicle test cycle (WLTC), and those printed on the certificate of conformity (CoC). The WLTC test represents driving mostly at motorway speeds. The dots represent datapoints of individual vehicles, while the line represent the average of the sample.

Ambient temperature / auxiliary components

Evidence from simulations of 6 ICEVs and 4 BEVs in Europe suggests the best efficiency for both ICEVs and BEVs appeared in an ambient temperature of 21 ◦C. The simulated gap between certified and real-world energy consumption is higher during cold conditions (ambient temperatures below 14 ◦C) than warmer conditions (temperatures above 14 ◦C) for both ICEVs and BEVs (Komnos, Tsiakmakis, Pavlovic, Ntziachristos, & Fontaras, 2022).

Figure A2.1-2 Vehicle efficiency losses due to ambient conditions, HVAC auxiliaries, and their combined effect on the gap between certified and real-world energy efficiency, as a function of ambient temperature.



Source: direct extract from (Komnos, Tsiakmakis, Pavlovic, Ntziachristos, & Fontaras, 2022).

Notes: HVAC stands for heating, ventilation and air conditions.

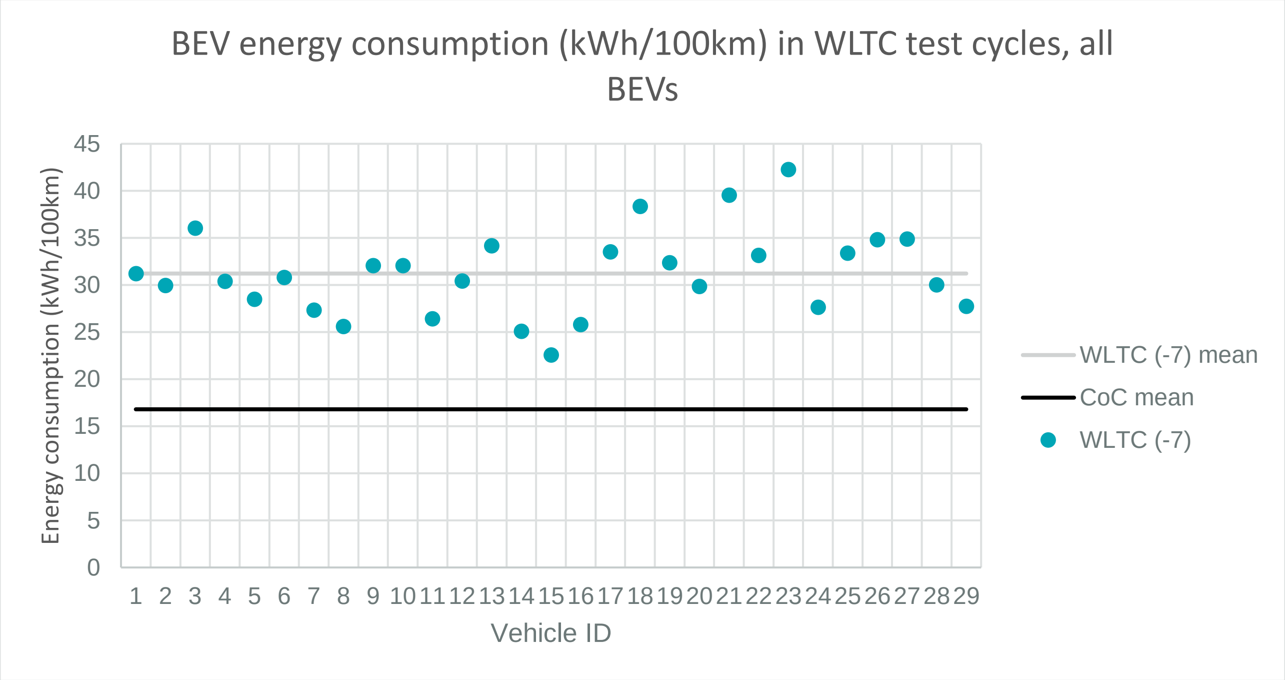
The authors explain that ambient temperature in isolation (the dashed line in the figure above) has a greater effect of ICEVs for two reasons: (a) it takes more energy to get the ICEV engines up to temperature during cold starts, and (b) BEVs have on average better aerodynamics, meaning that changes in air density caused by temperature variations have less of an impact.

However, the impact of auxiliary demand (the dash-dot line above) is higher in BEVs, leading also to a larger total combined effect (the bold line). They explain that auxiliary power demand in low-speed trips is of the same magnitude as propulsion energy consumption, and these trips are more common in real-world driving when compared to certification test cycles.

The above commentary is corroborated in (ICCT, 2024) - "Energy consumption by the urban commuter varies more with the ambient temperature, while the long-distance driver's energy consumption related to the [thermal management system] remains almost constant during the year."

Greater BEV battery energy consumption in cold temperatures is supported by Ricardo analysis of Green NCAP's BEV test data. The figure below shows a comparison between energy consumption reported via the manufacturer's certificate of conformity (CoC) with the WLTC test cycle performed at -7°C. Average energy consumption was 86% higher in the cold ambient test, suggesting that heating equipment was drawing a large amount of energy from the battery.

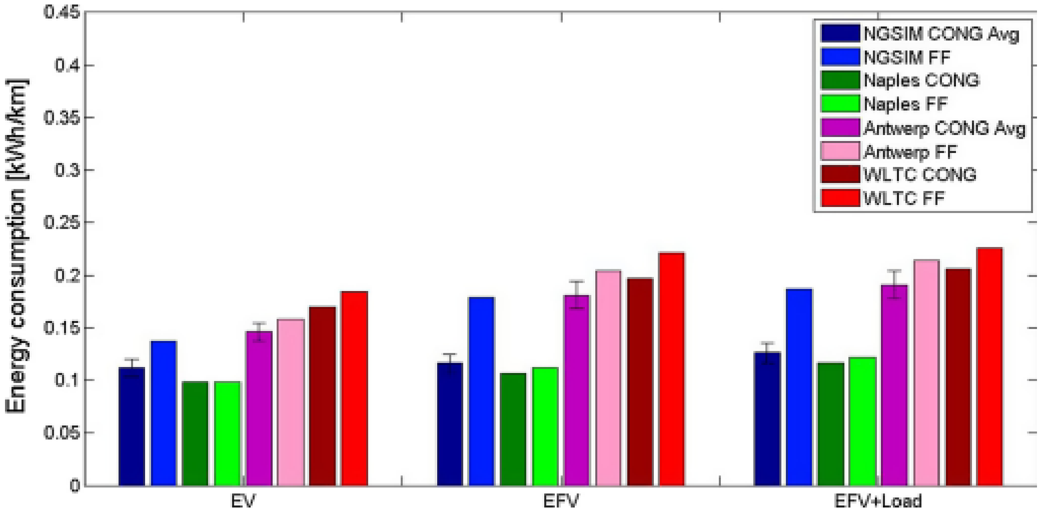
Figure A2.1-3 Comparison in BEV energy consumption (kWh/100km) in WLTC test cycles between an average test cycle (CoC) and a cold ambient test cycle at -7ºC.



Source: Ricardo analysis of Green NCAP test data

Traffic conditions

Figure A2.1-4 Simulated average energy consumption of electric passenger cars (EV) and electric light commercial vehicles (EFV) in a range of datasets and traffic conditions.



Source: (Fiori, et al., 2019)

Notes: Graph displays results for four datasets (NGSIM, Naples, Antwerp, WLTC) in two different traffic conditions (CONG – congested, FF – free flow) and for a range of vehicle types (EV = Electric Vehicle, EFV = Electric Freight Vehicle (light commercial), EFV + Load = Electric Freight Vehicle +300kg)

A3 Additional material on battery life and second-life application for Chapter 5

A3.1 BATTERY LIFE AND DEGRADATION

Table A3.1-1: Overview of battery degradation data sources

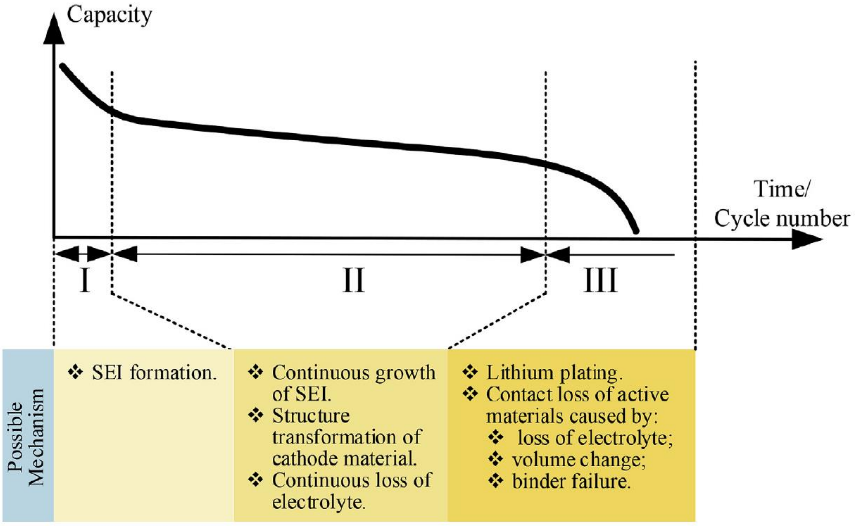
Data Source		Overview	Limitations

Datasets	**Geotab**
	(6,300 EVs)
	(Geotab, 2024)
		• **Battery state of health vs age**
		• Based on telematics data
		• 14 vehicle OEMs
		  ○ 21 models
		    ▪ 11 BEVs
		    ▪ 10 PHEVs
		  ○ 64 model-year variations
			• Latest models not included (most recent model year is 2019)
			• Geographies of vehicle operation unknown

	Recurrent
	(15,000 EVs)
	(Recurrent Auto, 2024)
		• **Projected range at 100% charge vs odometer reading (mileage)**
		• Based on telematics data)
		• 6 vehicle OEMs
		  ○ 7 models
		    ▪ 6 BEVs
		    ▪ 1 PHEV
		    ▪ 16 model variations
			• Data only available as chart figures, individual data points not available for analysis
			• Model years unknown
			• Geographies of vehicle operation unknown

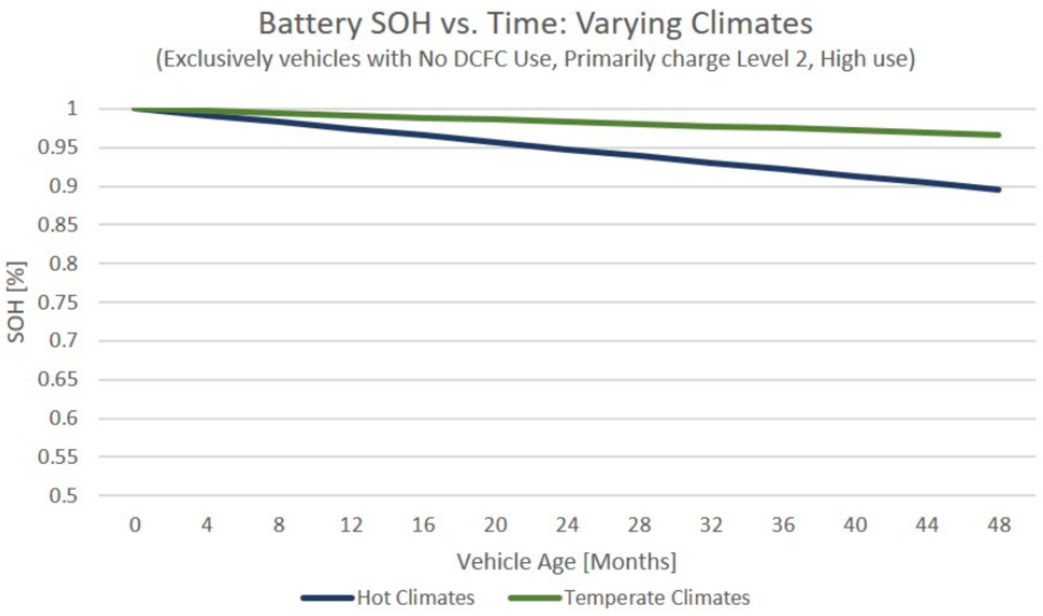
OEM claims	**Tesla**
	(Tesla, 2023)
	(Tesla, 2022)
		• **Battery retention vs mileage**
		  ○ Model S/X
		  ○ Model 3/Y Long range
			• Only available for Tesla models
			• Geographies of vehicle operation unknown

Figure A3.1-1 Overview of battery capacity fade and possible internal mechanisms in different stages



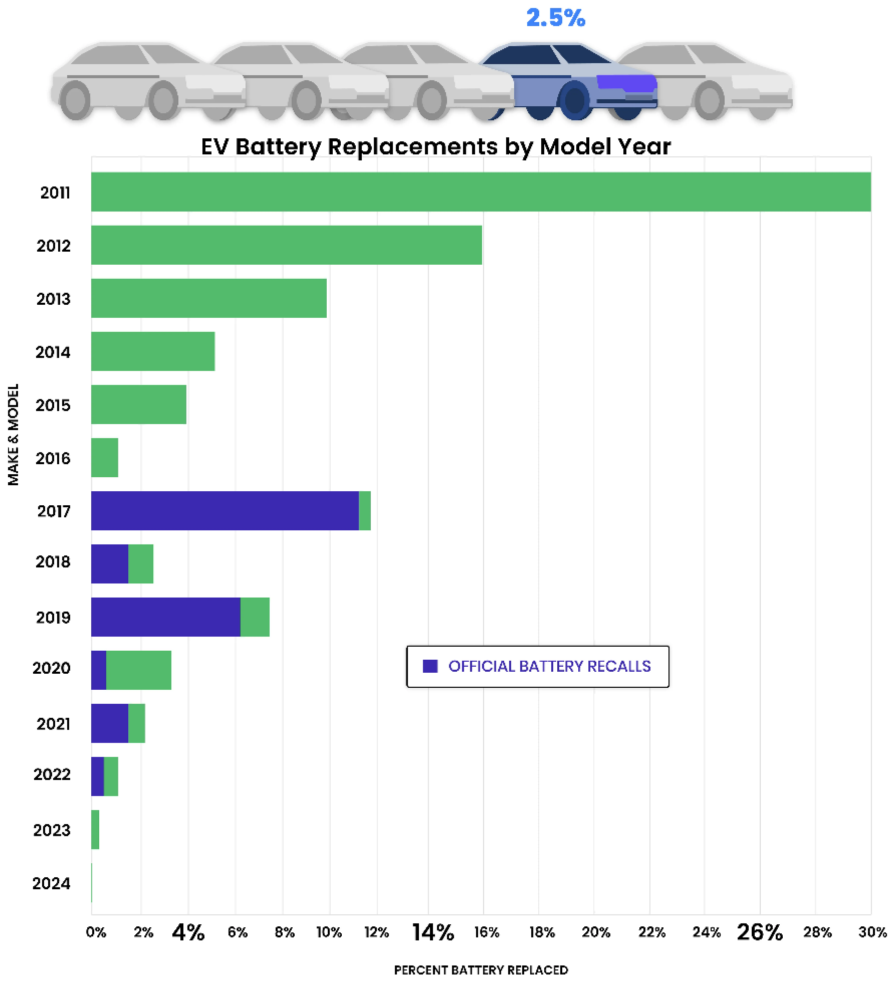
Source: (Han et al., 2019)

Figure A3.1-2 Batteries exposed to hot days degrade faster than those in temperate climates



Source: (Geotab, 2024)

Figure A3.1-3 xEV Battery Replacements by Model Year

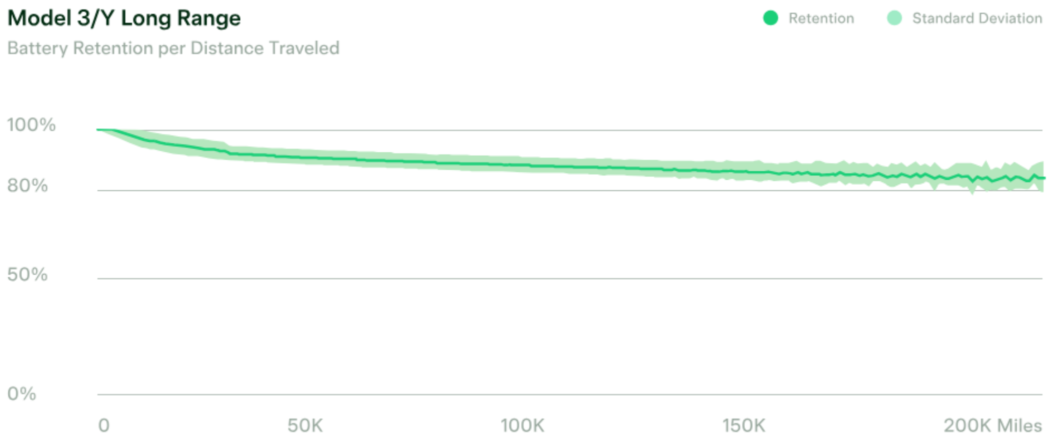


Source: (Recurrent, 2024)

Figure A3.1-4 Tesla Model S/X Battery Retention vs Mileage

Source: (Tesla, 2022)

Figure A3.1-5 Tesla Model 3/Y Long Range Battery Retention vs Mileage



Source: (Tesla, 2023)

Table A3.1-2: Overview of battery warranties for various xEV makes and models

Make and Model	Battery Warranty	Capacity Coverage	Make and Model	Battery Warranty	Capacity Coverage
Audi e-tron	8 years/100,000 miles	70%	Nissan e-NV200 / Leaf	8 years/100,000 miles	75%[24] (approx.)
BMW i3	8 years/100,000 miles	70%	Renault Zoe	8 years/100,000[25] miles	70%
Hyundai Ioniq / Kona Electric	8 years/100,000 miles	70%	Seat Mii Electric	8 years/100,000 miles	70%
Hyundai Nexo (hydrogen)	8 years/100,000 miles	70%	Smart EQ ForTwo / ForFour	8 years/125,000 miles	70%

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[24] Approximately 75%. The high-voltage battery can be replaced under warranty if the capacity reduces to less than 9 bars out of 12.

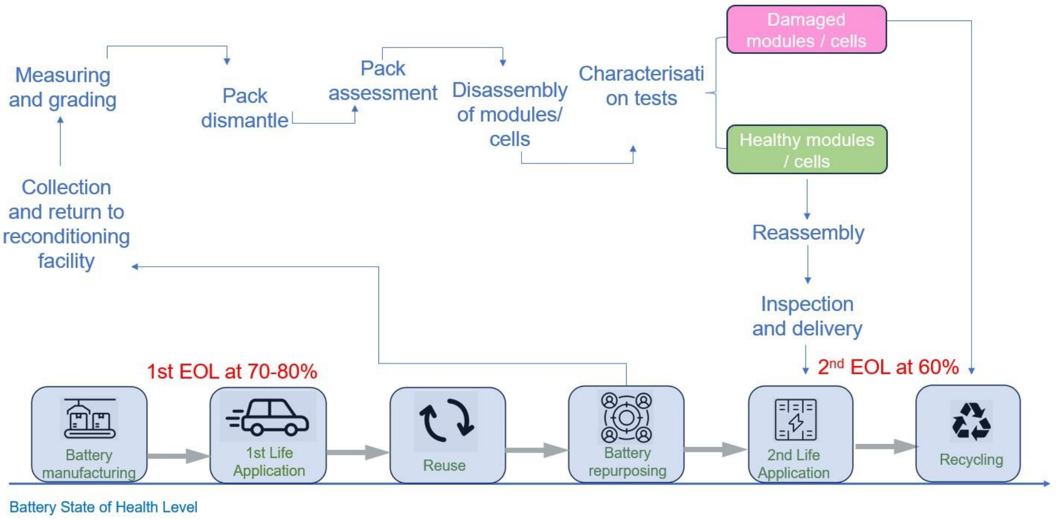
[25] Unlimited mileage for the first 2 years.

Make and Model	Battery Warranty	Capacity Coverage	Make and Model	Battery Warranty	Capacity Coverage
Jaguar I-Pace	8 years/100,000 miles	70%	Tesla Model S/X/Cybertruck	8 years/150,000 miles	70%
Kia e-Niro / Soul EV	7 years/100,000 miles	70%	Tesla Model 3/Y Long Range/ Performance	8 years/120,000 miles	70%
Mercedes B-Class ED	8 years/62,000 miles	70%	Tesla Model 3/Y Rear-Wheel Drive	8 years/100,000 miles	70%
Mercedes EQC	8 years/100,000 miles	70%	Toyota Mirai (hydrogen)	10 years/100,000 miles	–
MG ZS EV	7 years/80,000 miles	70%	Volkswagen ID range	8 years/100,000 miles	70%

Source: (Wilson, 2024) updated with Ricardo research

A3.2 BATTERY SECOND-LIFE

Figure A3.2-1 Electric vehicle battery life cycle



Source: own elaboration (Adapted from source[26])

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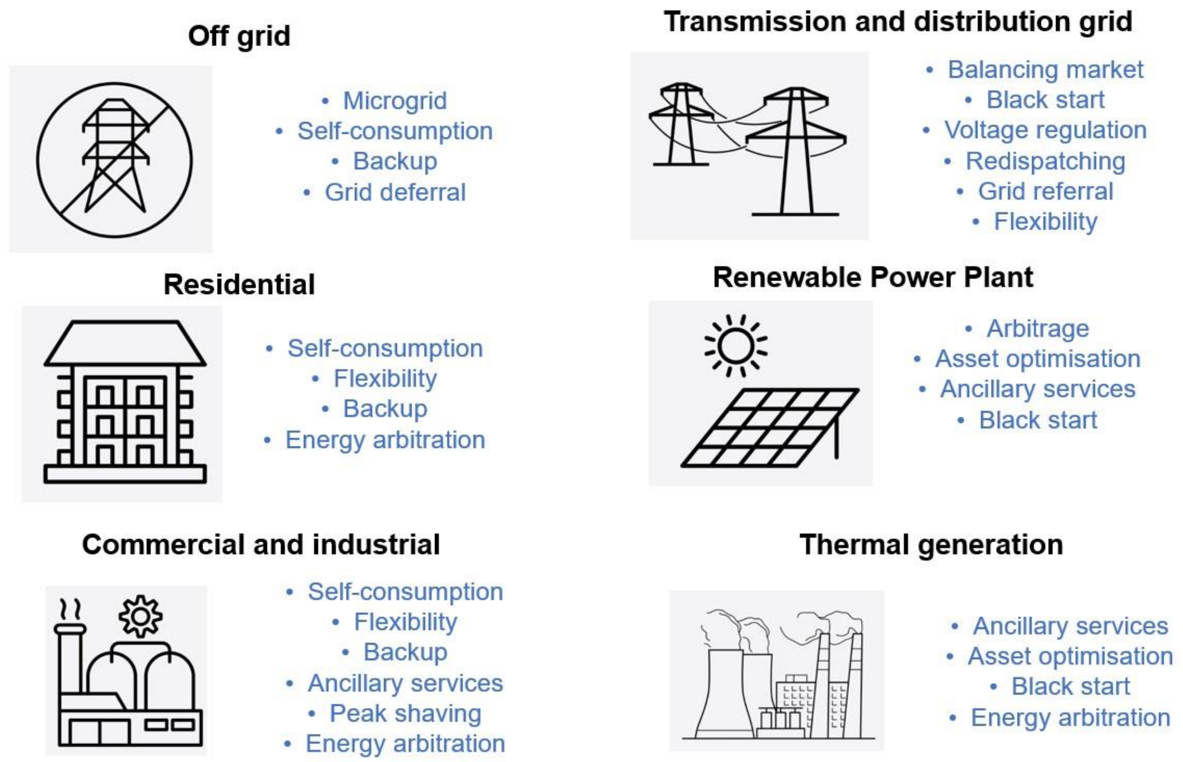
[26] https://www.sciencedirect.com/science/article/pii/S1110016821001757?via%3Dihub

Figure A3.2-2 Main energy storage applications for second-life batteries



Source: own elaboration based on (Reid, 2016)

Table A3.2-1: Sources for lifespan of repurposed xEV battery

Year	Author	Organisation	Title
2024	Seyedreza Azizighalehsari, Prasanth Venugopal, Deepak Pratap Singh, Thiago Batista Soeiro, Gert Rietveld	MDPI	Empowering Electric Vehicles Batteries: A Comprehensive Look at the Application and Challenges of Second-Life Batteries
2023	Huma Iqbal, Sohail Sarwar, Desen Kirli, Jonathan K. H. Shek & Aristides E. Kiprakis	Carbon Neutrality	A survey of second-life batteries based on techno-economic perspective and applications-based analysis
2023	Jinyu Chen, Haoran Zhang, Pengjun Zhao, Zhiheng Chen, Jinyue Yan	Elsevier	Repurposing EV Batteries for Storing Solar Energy
2022	Cameron Murray	Energy Storage News	Repurposing EV batteries into ‘third life’ energy storage and beyond
2021	Mohammed Hussein Saleh Mohammed Haram, Jia Woon Lee, Gobbi Ramasamy, Eng Eng Ngu, Siva Priya Thiagarajah, Yuen How Lee b	Elsevier	Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges
2017	Leila Ahmadi, Steven B. Young, Michael Fowler, Roydon A. Fraser & Mohammad Ahmadi Achachlouei	The International Journal of LCA	A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems
2015	J. Neubauer, K. Smith, E. Wood, and A. Pesaran	NREL	Identifying and Overcoming Critical Barriers to Widespread

Year	Author	Organisation	Title
			Second Use of PEV Batteries

Table A3.2-2: Possible repurposed battery use-cases and examples of demonstrations

Application	Use	Description	EU Examples
Off grid	-Micro grid -Self-consumption -Back-up -Grid deferral	In remote or rural areas without access to the main grid, repurposed xEV batteries can provide reliable electricity for homes, schools, and businesses. Repurposed xEV batteries can serve as backup power sources for critical infrastructure, such as hospitals, emergency response centers, and communication facilities during power outages	In 2019, AUDI commissioned the largest multi-use storage facility in Germany. The company used 20 used lithium-ion batteries for the project, all of which came from Audi's test vehicles. Audi claims that the 1.9MWh storage system is large enough to provide charging services for around 200 electric vehicles. It also said the installation is capable of supplying electricity to the entire 5.5-hectare EUREF campus for just under two hours. THRT1de1.pdf Enel X, for instance, participates in notable second-life batteries initiatives, including collaborations with Nissan in Melilla (maximum stored energy capacity of 1.7 megawatt hours [MWh]) and at Rome-Fiumicino International Airport. Enel launches innovative "Second Life" storage system for used electric car batteries in Melilla, Spain | Enel Group Announced by Renault in 2018, the Advanced Battery Storage project is taking place at different sites in Europe. It uses a combination of used and new electric vehicle batteries to provide up to 50 MWh of energy storage capacity to balance the electricity supply from renewable energies (Hampel, 2020).
Transmission and distribution grid	-Balancing market -Black start -Voltage regulation -Redispatching -Grid referral - Flexibility	The first major commercial application for batteries is the provision of ancillary services, in particular fast services and in particular fast response power to the primary reserve market for for frequency regulation. Future applications in this domain	JLR has partnered with Wykes Engineering Ltd, a leading RE company, to develop one of the UK's largest energy storage systems to harness solar and wind power using second-life Jaguar I-PACE batteries. JLR CREATES NEW RENEWABLE ENERGY STORAGE SYSTEM FROM USED CAR BATTERIES | JLR Media Newsroom (jaguarlandrover.com)

Application	Use	Description	EU Examples
		likely to be related to mitigating the impacts of RE and peak demand	
Residential	-Self-consumption -Flexibility -Back-up -Energy arbitrage	Retired EV batteries find a new purpose in Home Energy Storage Systems (HESS). This entails integrating these batteries into a system designed to store excess energy generated from renewable sources like solar panels or wind turbines. The stored energy can then be utilized during periods of high energy demand or low RE generation.	ECO STOR has developed a solution that repurposes used electric vehicle batteries to provide affordable energy storage for homes. ECO STOR's solution uses the entire battery as is, avoiding costly disassembly and reassembly, new wiring and electronics, and maintaining strict automotive standards. ECO STOR repurposes used EV batteries for home energy storage (businessnorway.com)
Renewable Power Plant	-Arbitrage -Asset optimisation -Ancillary services -Black start	The opportunities for EV batteries in RE power plants are similar to those mentioned above. They can store excess energy for later use, increasing the efficiency of these power stations.	B2U Storage Solutions has built its first facility outside Los Angeles using 1,300 retired batteries from Honda Clarity and Nissan Leaf EVs. This facility can store 28 megawatt hours of electricity, enough to power approximately 9,500 homes. Millions of EV Batteries Could Retire to Solar Farms | WIRED
Commercial and industrial uses	-Self-consumption -Flexibility -Ancillary services -Back-up -Peak shaving -Energy arbitrage	Industries can reduce their reliance on the grid by integrating RE systems with reused batteries, improving energy security. Rechargeable batteries can store energy generated from renewable sources such as solar and wind, which are intermittent in nature. This helps to stabilise the energy supply and ensure a consistent power flow, which can be of particular interest to businesses.	Nissan formalized a partnership with Sumitomo Corporation to reuse battery packs from the Nissan Leaf for stationary distributed and utility-scale storage systems. Nissan gives EV batteries a second life | Nissan Stories | Nissan Motor Corporation Global Website (nissan-global.com) Renault is supplying the £31m SmartHubs Project in West Sussex with over 1000 batteries that have finished their useful lives in EVs and will now be used in energy storage. Connected Energy, which is heading up the scheme, is using what is effectively a massive power bank to balance the supply and demand of the grid in the county. Renault reveals two new second-life battery programmes (discoverev.co.uk)
Thermal generation	-Ancillary services -Asset optimisation -Black start -Energy arbitrage	Batteries enable conventional power plants to increase revenues from the balancing market and improve operational flexibility. In addition, batteries enable conventional power plants to help restore the grid during	In Herdecke, North Rhine-Westphalia, RWE installed in 2021 an energy storage system using recycled lithium-ion batteries from Audi electric vehicles. With 60 of these battery units, this innovative storage technology makes it possible to temporarily store around 4.5 megawatt hours of electricity at RWE's pumped

Application	Use	Description	EU Examples
		potential blackout scenarios. The integration of both conventional power plants and batteries improves overall system efficiency by optimising power plant operations and enhancing the provision of ancillary services.	storage power plant near the Hengsteysee reservoir. Second life for EV batteries: RWE and Audi create novel energy storage system in Herdecke

Table A3.2-3: Sources for energy potential of EoL EV batteries

Year	Author	Organisation	Title
2019	Hauke Engel, Patrick Hertzke, Giulia Siccardo	McKinsey	Second-life EV batteries: The newest value pool in energy storage
2023	Alexander Tankou, Georg Bieker, Dale Hall	ICCT	Scaling up reuse and recycling of electric vehicle batteries: Assessing challenges and policy approaches
2020	Several	IEA	Global EV Outlook 2020
2021	Hans Eric Melin	Circular Energy Storage	The lithium-ion battery life cycle report
2024	Several	Bloomberg New Energy Finance	Electric Vehicle Outlook 2024

Table A3.2-4: Sources for feasibility of repurposed batteries

Year	Author	Organisation	Title
2023	Alexander Tankou, Georg Bieker, Dale Hall	ICCT	Scaling up reuse and recycling of electric vehicle batteries: Assessing challenges and policy approaches
2024	Seyedreza Azizighalehsari, Prasanth Venugopal, Deepak Pratap Singh, Thiago Batista Soeiro, and Gert Rietveld	Batteries	Empowering Electric Vehicles Batteries: A Comprehensive Look at the Application and Challenges of Second-Life Batteries
2019	Nikolas Hill, Dan Clarke, Laura Blaire, Hetty Meandue	European Commission	Circular Economy Perspectives for the management of batteries used in electric vehicles
2022	Mohammed Khalifa Al-Alawi, James Cugley, Hany Hassanin	Energy and Climate Change	Techno-economic feasibility of retired electric-vehicle batteries repurpose/reuse in second-life applications: A systematic review
2020	Wei Wu, Boqiang Lin, Chunping Xie, Robert J.R. Elliott, Jonathan Radcliffe	Energy Economics	Does energy storage provide a profitable second life for electric vehicle batteries?
2017	Qiangqiang Liao, Miaomiao Mu, Shuqi Zhao, Lizhong Zhang, Tao Jiang, Jilei Ye, Xiaowang Shen, and Guoding Zhou	International Journal of Hydrogen Energy	Performance assessment and classification of retired lithium ion battery from electric vehicles for energy storage

A4 Additional material on transparency and consumer information for Chapter 6

A4.1 INFORMATION REQUIRED BY CONSUMERS TO INFORM VEHICLE purchasing decisions

Table A4.1-1: DG CLIMA Call for Evidence – In support of the evaluation of the Car Labelling Directive (1999/94/EC) – Selected stakeholder feedback regarding electric vehicle information

Stakeholder	Evidence/response	Implications for information related to EVs
BEUC	“Other datasets are specifically important for electric cars: data related to charging capability, the variation of range (and soon the OBFCM data required by Euro7) or the battery state of health should be included.”	Charging capability Electric driving range Battery health
BEUC	“The class system should clearly show the environmental advantage of electric vehicles vis-à-vis conventional cars. The latter should only be given the lowest scores or class categories to reflect their greater environmental impact. However, not all EVs should score "A". Within the label, it is important to make room for more efficient EVs and those produced sustainably. BEUC supports the introduction of an "eco-score" for electric vehicles which should be integrated in the Car Label. The methodology of such eco-score should be rather simple to encompass the main sources of emissions in a simple and understandable way.”	Eco score
CECRA	To account adequately for the various technologies needed for a successful transition, the car labelling directive should be based on well-to-wheel emissions or life-cycle emissions.	Well-to-wheels or LCA
HORSE (ES)	While we recognize the importance and growing popularity of electric vehicles (EVs) as a benefit to the environment, we believe it's equally important for consumers to be aware of next-generation powertrain solutions that offer comparable environmental benefits across the entire supply chain of manufacturing and consumption. In addition, numerous obstacles hinder the widespread adoption of EVs in the EU. These barriers include concerns about limited driving range, high initial purchase expenses, inadequate availability of charging infrastructure in various regions and Member States, and a general lack of awareness and understanding among consumers regarding electric vehicles.	
	Education and awareness: Alongside labelling requirements, efforts should be made to educate consumers about the environmental impact of different powertrain options. This could include public awareness campaigns, educational materials, and incentives to encourage the adoption of low emission vehicles.	
Austrian Ministry for Climate Action, Environment, Energy, Mobility, Innovation and	Efficiency criteria for electric vehicles (kWh/100m)	Efficiency criteria for electric vehicles (kWh/100m)

Stakeholder	Evidence/response	Implications for information related to EVs
Technology (BMK)		
Repsol (ES)	The starting point should not penalise vehicles with internal combustion engines fed with renewable fuels, such as biofuels and synthetic fuels (efuels). At this regard, tail-pipe emissions targeted do not reflect accurately the origin of the CO_2 emitted by a vehicle, ignoring the fact that CO_2 previously removed from the atmosphere does not contribute to climate change. Furthermore, we would like to emphasize that vehicles equipped with an internal combustion engine fed with renewable fuels should be considered as zero-emission vehicles since the CO_2 emitted through the tailpipe has been previously removed from the atmosphere.	
ANEC – The European Consumer Voice in Standardisation	Adapt the label to electric cars, identifying a relevant approach for communicating and comparing the performance and environmental impact of these vehicles.	
AECC – Business Association (Belgium)	The label is based on tailpipe measurement procedure, which does not give the full picture of the vehicle's emissions. The carbon footprint of a vehicle is determined by its entire life cycle, not only the use phase of the vehicle. The label should provide information about this entire vehicle life cycle. This can be linked to the Life-Cycle Assessment (LCA) methodology to be developed by 2025 according to Regulation (EU) 2023/851. For example, for a conventional or hybrid vehicle, it should differentiate between the footprint for the vehicle running on a CO_2-neutral fuel vs. fossil-based fuel.	Lifecycle emissions / Assessment
Westport Fuel Systems	We recommend adding a Life Cycle Assessment (LCA) model for car labelling, as it would provide consumers with a comprehensive view of the environmental impact of vehicles, from production through to disposal, beyond the current operational emission metrics. Such holistic information would empower consumers and EU citizens to make more informed and responsible choices, recognizing the true environmental cost of their vehicle over its lifespan. Furthermore, we propose that this LCA-based car labelling should be adapted to the individual circumstances of each Member State, utilizing national data. This granular approach allows for the peculiarities of each market — be it energy mix, infrastructural variances, or policy directives — to be factored into the making of the new labelling system, thus reinforcing the accuracy of the information provided to the end consumer. The emphasis on market-specific labelling ensures that the Directive remains highly relevant and efficient in addressing the particular challenges and opportunities within each Member State. It respects the diversity within the EU and aligns with the principle of subsidiarity, leveraging national insights to drive consumer behaviour towards more sustainable choices. Adding a life cycle perspective into car labelling, supported by a market-specific assessment, not only steers consumers towards lower-emission vehicles but also promotes transparency in the market. This is essential for nurturing a market that values	Lifecycle assessment

Stakeholder	Evidence/response	Implications for information related to EVs
	sustainability and is in line with the European Green Deal and the sustainable and smart mobility strategies.	
Swedish Energy Agency (SE)	The guidelines should also include air pollution and take into account the vehicles entire life cycle…. Electric vehicles have no tailpipe emissions, and a significant part of their environmental impact arises during production. Given the current pace of developments of electric vehicles and their batteries, much of which had barely started in 1999, as well as the legislative progress in the areas of circularity and material efficiency, there is a pressing need to update the rules governing consumer information on vehicles environmental performance as a whole. The Swedish Energy Agency has endeavoured to identify information points that are relevant for the context of today, and that enable the consumer to more easily compare vehicles emissions (from a lifecycle perspective) and energy efficiency during use phase, as well as their environmental impact during production and end-of-life.	Lifecycle assessment Energy efficiency
AVERE	The Directive only focuses on fuel efficiency and CO_2 emissions and does not consider the advantages of EVs. To address these shortcomings and make the Directive fit for the new reality of European mobility, AVERE calls on the European Commission to review the current framework to ensure that electric vehicles are not only being represented fairly but are able to display their levels of energy efficiency and range.	Energy efficiency Electric driving Range
T&E	For electric cars an ‘environmental score’ should be used to rank their environmental performance. By 2030 the majority of new cars sales will be electric but not every electric vehicle has the same environmental credentials. To support a responsible shift to e-mobility, the label for BEVs should be updated to include a score based on the efficiency of the electric vehicle as well as the climate and resource impact of its production. This will enable consumers to easily choose BEVs based on their total environmental impact, supporting a responsible transition to electromobility. Additionally, providing this information will help improve trust in the environmental benefit of switching to BEVs.	Eco-score (based on efficiency and resource impact)
TESLA	Currently, the Car Labelling Directive mandates the disclosure of fuel economy of CO_2 emissions and fuel consumption data, under which all electric vehicles are categorised as having 'zero emissions'. This classification, although technically accurate in terms of tailpipe emissions, it does not offer the necessary level of information to customers that want to buy the most sustainable electric vehicle. This will be an important measure to future-proof existing regulations, such as the Car CO2 standard ((EU) 2019/631), which mandates a phaseout of internal combustion vehicles by 2035. Proposal for an EU-wide Eco-Score: We propose the introduction of an Eco-Score exclusively for zero-emission vehicles that would be pan-European and have the same values in every Member State. This scoring system would be similar to the eco-design requirements currently used for household appliances. Vehicles would be rated from A (most sustainable) to G (least sustainable), equally weighted based on only existing criteria for vehicle manufacturers:	Eco-score

Stakeholder	Evidence/response	Implications for information related to EVs
	• Energy efficiency of the vehicle, as measured under Worldwide harmonised Light-duty vehicles Test Procedure (WLTP) under Regulation (EU) 2017/1151; • The carbon footprint of the battery and its associated performance class, as required by article 7 of Regulation (EU) 2023/1542 (EU Batteries Regulation); • The embedded carbon emissions of steel and aluminium used in the vehicle, calculated in accordance with the CBAM regulation; • The levels of recycled content present in vehicles, as required by Article 10 of ELVR, OR the levels of recycled content in the battery, as required by Article 8 of Regulation (EU) 2023/1542 (EU Batteries Regulation). This score would empower consumers to make more informed decisions by providing a clearer picture of the overall sustainability of each vehicle, beyond just CO_2 emissions at the point of use. In addition to the direct benefits for consumers, an Eco-Score would incentivise vehicle manufacturers for a race to the top in producing the most sustainable zero-emission vehicle, going beyond the pass/fail requirements set out by EU legislation. Furthermore, this Eco-Score should be used by Member States modulating their national purchase incentives and Extended Producer Responsibility (EPR) fees. The most sustainable zero-emission vehicles would benefit from the highest purchase incentive and lowest EPR fee. In contrast, if an EU-score was applied nationally and not on a pan-European level, Member States will have different requirements and methodologies for calculating an Eco-Score, which would confuse consumers that are comparing products in different Member States. Furthermore, this will also create administrative burdens for manufacturers to provide the different information to 27 different authorities.	
ACEA	LCA could be a potential option in the long-term for labelling based on the agreed methodology, but further analysis would be necessary to derive a meaningful and fair instrument for OEMs and customers in all member states. In any case it needs to be ensured that a future labelling scheme does not lead to market distortion due to different carbon intensity per energy carrier and member state – both in terms of energy used for vehicle production and during usage. This is an issue which cannot be influenced by OEMs as there are many responsible parties that influence the overall LCA results. A clear split concerning responsibilities is needed and has to be kept as it is the case today with tank-to-wheel CO2 emissions.	Lifecycle analysis

A4.2 REVIEW OF INFORMATION AVAILABLE TO CONSUMERS

A4.2.1 Lifecycle analysis

Table A4.2.1-1: Summary of information provided to consumers via OEM lifecycle analysis reports

Manufacturer	Vehicle	Compared with	Lifecycle stages	Metrics considered	Assumptions	Source
Volvo	EX30 (BEV)		• Materials production and refining • Li-ion battery modules • Inbound logistics • Volvo Cars manufacturing • Use phase emissions • End of life	tCO_2e lifetime mileage / kg CO_2e per vehicle km Climate impact ($kgCO_2e$) by fossil GHG emissions, emissions from land use change. Biogenic GHG emissions, aircraft emissions.	200,000km total distance Sensitivities: Comparison data for 150,000, 250,000 and 300,000km lifetime mileage (total $kgCO_2e$/vkm) Number of passengers – 1 to 5 Battery type – Nikel Manganese Colbalt (NMC) and Lithium Iron Phosphate (LFP)	https://www.volvocars.com/images/v/-/media/Project/ContentPlatform/data/media/sustainability/volvo_ex30_carbonfootprintreport1.pdf
BMW	BMW i5 eDrive 40	BMW 520i (ICE)	• Production and logistics • BMW production • Usage • Recycling/EoL	Materials used in vehicle (%) Production and water demand (sites, annual water consumption – m3 per new vehicle) Global warming potential over the lifecycle (tCO_2e) Abiotic depletion potential (kg Sbe) Acidification potential (kg SO_2e) Eutrophication potential (kg PD_4e)	200,000km total distance EU electricity mix Green electricity	https://www.bmwgroup.com/content/dam/grpw/websites/bmwgroup_com/responsibility/downloads/en/2023/230905_BMWG_LCAAnalyse_G60_BEV_V4.pdf

Manufacturer	Vehicle	Compared with	Lifecycle stages	Metrics considered	Assumptions	Source
				Photochemical ozone creation potential (kg C_2H_4e) Nitrogen oxide (NOx) (kg) Particles (kg) Primary energy demand from non-renewable sources (GJ) Primary energy demand from renewable sources (GJ)		
Polestar	Polestar 2	XC0 ICE (petrol)	• Materials production • Li-ion battery modules • Manufacturing • Use Phase • End-of-life	Fossil GHG emissions (gCO_2e) Emissions from land use change (dLUC) (gCO_2e) Biogenic GHG removal (gCO_2e) Biogenic GHG emissions (gCO_2e) Air craft emissions (gCO_2e) Materials used in the vehicle (%)		https://www.polestar.com/dato-assets/11286/1711466586-polestar-3_lca_report_2024_final_2024-03-26.pdf
Audi	Audi Q4 40 e-tron		• Production & Logistics • Tailpipe Emissions • Recycling • Fuel & Energy supply • Maintenance	Global warming potential (GWP)	EU electricity mix in use Green Electricity	https://www.audi.com/content/dam/gbp2/downloads/Environmental-declaration/EN/LCA_Audi_Q4_40_e-tron_en.pdf
Toyota	Mirai	Gasoline vehicle and hybrid vehicle	• Materials production • Vehicle production (in-house parts and outsourced parts)	Abiotic Depletion Potential (ADP) Fossil Fuels Abiotic Depletion Potential (ADP) Elements	Sensitivity Analysis (100,000km for Japan and 150,000km for Europe)	https://global.toyota/pages/global_toyota/sustainability/esg/challenge2050/challenge2/life_cycle_assessment_report_en.pdf

Manufacturer	Vehicle	Compared with	Lifecycle stages	Metrics considered	Assumptions	Source
			• Use (fuel production and driving) • Maintenance • End of Life	Photochemical Ozone Creation Potential (POCP) Global Warming Potential (GWP) Acidification Potential (AP) Eutrophication Potential (EP)		

A4.2.2 **OEM** manuals

A2 Key	Description
1 🟩	Clear information provided /category criteria is clearly provided
2 🟨	Basic Information provided / category criteria is addressed but with limited detail
3 🟥	Limited to no information provided / category criteria is not addressed or provided with very limited detail

Table A4.2.2-1: Manual Review – Summary table comparing each of the six OEM model manuals

Theme	Sub-Theme	Renault Zoe	Tesla Model Y	Volkswagen ID.4	Fiat 500e	Peugeot e-208	Kia e-Niro
General xEV information	xEV introductory/Summary information	🟩	🟥	🟥	🟩	🟨	🟩
	Visuals/schematics	🟩	🟨	🟨	🟩	🟩	🟩
Charging	How to charge your vehicle	🟩	🟩	🟩	🟩	🟩	🟩
	Graphic showing charging components	🟩	🟩	🟩	🟩	🟩	🟩
	Difference in chargepoint types (AC, DC)	🟩	🟩	🟨	🟩	🟩	🟩
	Battery charging times	🟨	🟨	🟨	🟨	🟥	🟩
	Battery optimisation	🟩	🟩	🟩	🟥	🟥	🟨
Battery performance and range	Battery range	🟥	🟥	🟥	🟥	🟥	🟥
	Maximising driving range	🟩	🟩	🟩	🟩	🟥	🟩
	Range warning indicators	🟩	🟩	🟩	🟩	🟩	🟩
	Weather considerations	🟩	🟩	🟩	🟩	🟥	🟨
Safety	Battery/ charging heat warnings	🟩	🟩	🟩	🟩	🟩	🟩
	Electric shock warnings	🟩	🟩	🟩	🟩	🟩	🟩
	Battery modification settings	🟩	🟩	🟩	🟩	🟩	🟩
Environmental impact and	Vehicle production and environmental impact	🟩	🟥	🟥	🟥	🟥	🟥

Theme	Sub-Theme	Renault Zoe	Tesla Model Y	Volkswagen ID.4	Fiat 500e	Peugeot e-208	Kia e-Niro
battery disposal	Environmental user guidance	🟩	🟩	🟩	🟩	🟩	🟩
	Battery disposing practicalities	🟩	🟧	🟩	🟩	🟥	🟩

A4.2.3 **Information provided to owners of electric** vehicles

Table A4.2.3-1: Summary of information provided to owners of electric vehicles via OEM applications.

Manufacturer (OEM)	Application	Estimated electric range	Current battery status / charge level	Identify location of charging stations	Other information provided to vehicle owner
Renault[27]	My Renault App (smart phone / remote dashboard / dashboard)	✓	✓	✓	• Total mileage • Vehicle location • Range in miles • Battery charge level • Car connection status • Charging history (day and time of charge, duration, battery percentage at the start and at the end of charge, charged energy in kw/h). • Vehicle's reachable zone based on the state of charge of the vehicle's battery • Location and availability of charging stations in real time • Prepare an optimal route by finding charging stations along the way
BMW[28]	My BMW app	✓	✓	✓	• Current battery status and estimated range with the maps feature. • Locate and navigate to nearby charging stations. You can also see whether they're in use and the cost of charging. • Access the BMW Charging Network to see your previous charging history, costs and account details. • Pre-condition your car while it's still charging to take its battery to the ideal temperature. This means it will work at its full efficiency as soon as you're ready to set off, while saving battery power for heating or cooling the cabin as you drive.

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[27] https://renault.com.cy/100-electric-e-tech/battery/#1692691370480-434d9647-f687

[28] https://www.bmw.co.uk/en/topics/owners/bmw-apps/my-bmw-app-overview.html

Manufacturer (OEM)	Application	Estimated electric range	Current battery status / charge level	Identify location of charging stations	Other information provided to vehicle owner
Volvo[29]	Volvo cars app	✓	✓	✓	• Location and security • Available range – fuel/battery level and remaining mileage (real-world electric miles) – calculated on recent driving behaviour • Charging status – confirming when charging/active • Clear navigation. • Charging station finder • Battery status and range • Schedule off-peak charging • Save charging locations • Get charging reminders
Tesla[30]	Tesla App	✓	✓	✓	• Estimated electric range • Set charge limit • View charging history • Identification of charging stations • Manage charge payments • Understand charge behaviour, including costs, cost savings • Car location
Hyundai[31]	MyHyundai	✓	✓	✓	• Distance travelled • Estimated electric range • Fuel Consumption • Charge level • Option to start and stop charging

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[29] https://www.volvocars.com/uk/volvo-cars-app/

[30] https://www.tesla.com/ownersmanual/model3/en_pr/GUID-F6E2CD5E-F226-4167-AC48-BD021D1FFDAB.html

[31] https://www.hyundai.com/uk/en/owners/owning-a-hyundai/myhyundai.html

Manufacturer (OEM)	Application	Estimated electric range	Current battery status / charge level	Identify location of charging stations	Other information provided to vehicle owner
					- Vehicle service history - Maps with Hyundai Dealerships, and Fuel/Charge Stations - Charge Management for xEV vehicles - Location - Vehicle health and information
Ford[32]	Fordpass	✓	✓	✓	- Vehicle information and service needs - Charge levels (max charge, preferred charge times) - Range activities - Find charging stations on the go
Genesis USA[33]	Genesis Intelligent Assistant	✓	✓	✓	- Vehicle Information - Charge level - Charge Management (e.g., start charging, charging schedule) - Current range in miles - Locate nearest charge stations in Maps - Battery pre-conditioning
KIA[34]	Kia Access	✓	✓		- Vehicle Information - Charge management (e.g., start charging, or scheduled charge for off-peak times) - Charge level - Trip Data (e.g., average speed, distance travel, time taken)
Nissan[35]	Nissan Connect	✓	✓	✓	- Charge management (e.g., start charging, or scheduled charge for off-peak times)

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[32] https://www.ford.co.uk/technology/connectivity/fordpass

[33] https://owners.genesis.com/us/en/resources/getting-started/exploring-the-genesis-intelligent-assistant-app.html

[34] https://www.kia.com/uk/electric-hybrid-cars/technolo gy/kia-connect-app/

[35] https://www.nissan.co.uk/owners/nissan-connect-services-apps/nissan-connect-services-detailed.html

Manufacturer (OEM)	Application	Estimated electric range	Current battery status / charge level	Identify location of charging stations	Other information provided to vehicle owner
					• Charge level

A4.2.4 **Chargepoint** availability

Table A4.2.4-1: Summary of information provide to consumers via chargepoint availability tools

Tool	Number of ports	How many are available	Charger type / speed	Price	Coverage	Format	Other information
Chargepoint	✓	✓	✓	✓	Europe & North America	App / Map	Station info; Last used; Popular times
Octopus Electroverse	✓	✓	✓	✓	Europe & UK	App / Map	Payment (with app)
Zap-Map	✓	✓	✓	✓	Europe & UK	App / Map	Payment (with app), opening times
Chargemap	✓	✓	✓	✓	Europe, UK & International	App / Map	Payment (with app/card)
Plugshare	✓	✓	✓	✓	Europe/UK/ International	App / Map	Opening hours, facilities nearby
ACP Electric	✓	✓	✓	✓	Portugal	App	Lets user know how long any car at the charging station is charging for

A4.2.5 Electric vehicle comparison sites

Table A4.2.5-1: Summary of information provided to consumers via selected vehicle comparison sites

	Fuel type	Electric range (km)	Battery type	Battery capacity (kWh)	Rapid charge	Acceleration (seconds)	Other
Electric Vehicle Database (Germany, Netherlands, UK)		✓ (miles)		✓	✓	✓ (0-62)	Top speed Efficiency (Wh/m) Rapid charge rear/four-wheel drive; towing capacity (kg); safety rating; charging available (bidirectional / vehicle to home bidirectional / vehicle to grid bidirectional); price £/mile of range
Sustainable Energy Authority Ireland – Compare cars	✓	✓					Price Total cost of ownership Tailpipe emissions
DriveK (EU-wide)		✓		✓	✓		Power (kW) Combined electricity consumption Type of charger
Guide de l'auto web (France)		✓	✓	✓			Couple (N.m) Power Charge time
Catalogue.eu (EU-wide)		✓	✓	✓		✓ (0-100)	Max speed

RICARDO