STUDY

Requested by the TRAN Committee

European Parliament

Environmental challenges through the life cycle of battery electric vehicles

Study

Policy Department for Structural and Cohesion Policies
Directorate-General for Internal Policies
PE 733.112 - March 2023

EN

RESEARCH FOR TRAN COMMITTEE

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Abstract

This study provides an up-to-date expert assessment and comparison between the life cycle's carbon footprint of battery electric and internal combustion engine passenger cars. It presents evidence from the literature and from life cycle assessment modelling and concludes with policy recommendations. The analysis includes sensitivities, regional variations for six Member States, and also the effects of technical and legislative development on the potential outlook up to 2050.

This document was requested by the European Parliament's Committee on Transport and Tourism.

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LINGUISTIC VERSIONS

Original: EN

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To contact the Policy Department or to subscribe to updates on our work for the TRAN Committee please write to: Poldep-cohesion@ep.europa.eu

Manuscript completed in March 2023

This document is available on the internet in summary with option to download the full text at: https://bit.ly/3ZbZCQG

This document is available on the internet at:
http://www.europarl.europa.eu/thinktank/en/document/IPOL_STU(2023)733112

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Please use the following reference to cite this study:
Hill, N., Raugei, M. et al. 2023, Research for TRAN Committee – Environmental challenges through the life cycle of battery electric vehicles, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels
Please use the following reference for in-text citations:
Hill, N., Raugei, M. et al. (2023) or Ricardo (2023)

DISCLAIMER

CONTENTS

LIST OF ABBREVIATIONS

AFID/AFIR	Alternative Fuels Infrastructure Directive/Regulation
ARD_MM	Abiotic Resource Depletion – Minerals & Metals
AQP	Air Quality Pollutants
B7	7%vol biofuel blend in diesel
BAU	Business As Usual
BEV	Battery Electric Vehicle (fully electric)
CBAM	Carbon Border Adjustment Mechanism
CED	Cumulative Energy Demand
CH_4	Methane
Co	Cobalt
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
CRM	Critical raw material
EC	European Commission
EoL	End-of-Life
ELV	End-of-Life Vehicle
ETS	Emission Trading Scheme
EV	Electric Vehicle
FAME	Fatty Acid Methyl Ester (Biodiesel)
FCEV	Fuel Cell Electric Vehicle (running on hydrogen)
FU	Functional unit

GHG	Greenhouse Gases
GWP	Global Warming Potential
H_2	Hydrogen
HEV-G	Hybrid Electric Vehicle, with Gasoline ICE
HREE	Heavy Rare Earth Elements
HTP	Human Toxicity Potential
HVO	Hydrotreated Vegetable Oil (Renewable Diesel)
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ICEV-D/G	Diesel/Gasoline ICE Vehicle
IEA	International Energy Agency
ISO	International Organisation for Standardisation
kWh	kilo-Watt-Hour
LA	Lifetime Activity
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCV	Light Commercial Vehicle (van)
LDV	Light Duty Vehicle (Car or LCV)
LFP	Lithium-Ion-Phosphate (battery chemistry)
LHV	Lower Heating Value
Li	Lithium
LIB	Lithium-ion battery
Li-ion	Lithium Ion
LMO	Lithium-Manganese Oxide (battery chemistry)

MD	Medium Duty
MJ	Mega-Joule
Mn	Manganese
N_2O	Nitrous Oxide
NCA	Lithium-Nickel-Cobalt-Aluminium Oxide (battery chemistry)
NEDC	New European Drive Cycle
Ni	Nickel
NH_3	Ammonia
NMC	Lithium-Nickel-Manganese-Cobalt Oxide (battery chemistry)
NO_X	Nitrogen Oxides (includes nitrogen monoxide and nitrogen dioxide)
OEM	Original Equipment Manufacturer
PCR	Product Category Rules
PEF	Product Environmental Footprints
PHEV	Plug-in Hybrid Electric Vehicle
PMF	Particulate Matter Formation
POCP	Photochemical Ozone Creation Potential
PtX	Power-to-X (where X can be a variety of hydrocarbon liquid fuels or gases)
PV	[Solar] Photo Voltaic
RE	Renewable Energy/Electricity
REE	Rare Earth Elements
RES	Renewable Energy Sources
REEV	Range Extended Electric Vehicle
RW	Real world
SO_2	Sulphur Dioxide

SO_2e	Sulphur Dioxide equivalent
SoC	Available State-of-Charge percentage for battery
SUV	Sports Utility Vehicle
TCO	Total Cost of Ownership
TTW	Tank-to-Wheel
VO	Vehicle Occupancy
VOC	Volatile Organic Compound
V2G	Vehicle-to-Grid
WLTP	Worldwide harmonised Light vehicle Test Procedure
WTT	Well-to-Tank
WTW	Well-to-Wheel
xEV	Generic term to refer to all electric vehicles (includes BEVs, PHEVs, REEVs and FCEVs)
ZEV	Zero Emission Vehicle (includes BEV and FCEV)

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ACKNOWLEDGEMENTS

The authors of this report would like to acknowledge and thank the following contributors, who also provided reference literature to be included in the review of evidence for this project:

- ifeu (Institut für Energie- und Umweltforschung Heidelberg gGmbH)
- Joanneum Research
- University of Leiden

EXECUTIVE SUMMARY

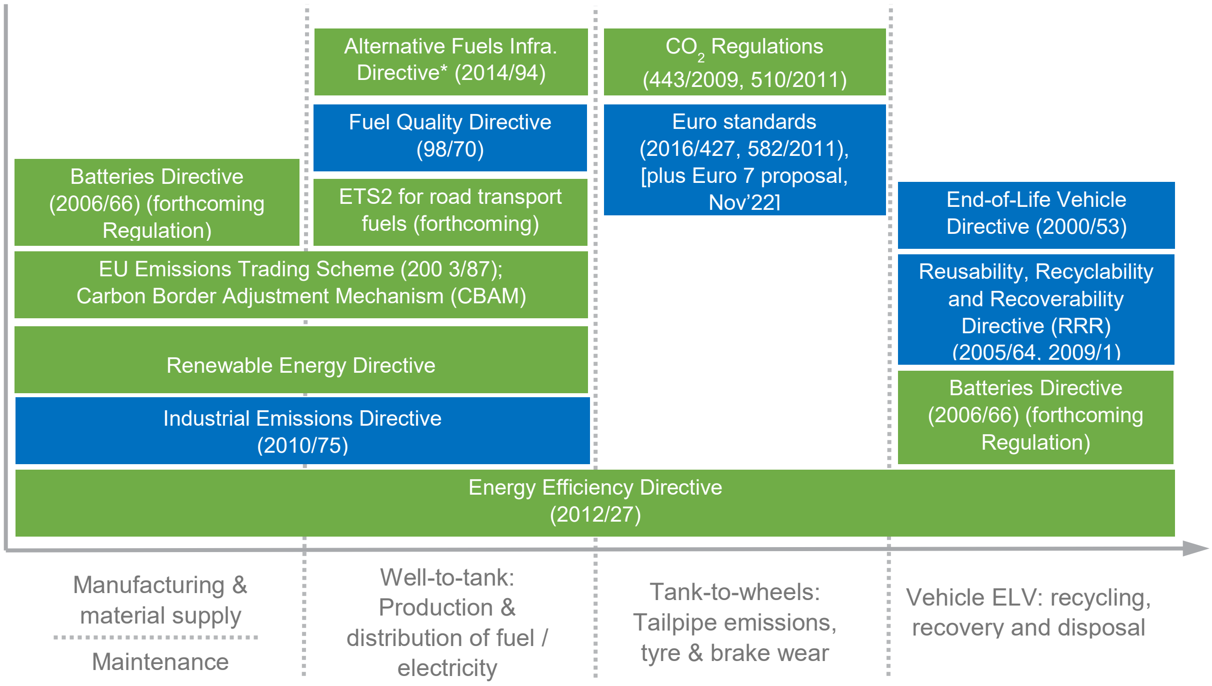
KEY FINDINGS

- The literature review indicates broad agreement that battery electric vehicles (BEVs) tend to exhibit significantly lower life cycle greenhouse gas (GHG) impacts than internal combustion engine vehicles (ICEVs), despite initially higher manufacturing emissions.
- This study's life cycle assessment (LCA) modelling indicates that a typical current BEV car already saves over ~60% kgCO2eq compared to an equivalent conventional gasoline car in average EU conditions. Significant life cycle GHG emissions reductions were also found across different situations and countries.
- Analysis of the future outlook shows that, by 2030, average BEV GHG impacts in the EU27 could be 78% lower than those of an equivalent conventional gasoline car (and reach 86% lower by 2050).
- Decisive EU policy action will be needed to maximise BEV benefits and mitigate risks, including an ambitious policy agenda around circular economy approaches for vehicle components (especially batteries) and further research in battery technology.
- Tailpipe CO2 emissions regulations provide a suitable regulatory framework. However, LCA reporting should be encouraged.
- Incentives for right-sized BEVs/batteries may be needed as BEVs consolidate their market position.

Introduction

The European Green Deal and Fit for 55 initiatives have resulted in a substantial revision of the regulatory and policy landscape at EU level on the environmental performance of road vehicles. Key policy initiatives and legislation are the Industrial Strategy, the Circular Economy Action Plan, the proposed Batteries Regulation, the revision of the End-of-Life Vehicles Directive (ELV), the EU Emissions Trading Scheme revision proposal and the revised regulation on CO_2 emissions standards for cars and vans, among others – see Figure ES1.

Figure ES1: Simplified mapping of key European legislation to vehicle life phase



Source: Ricardo (own elaboration.)
Notes: Additions/updated proposals in 2021 / Fit For 55 legislative package highlighted in green.

The take-up of BEVs is expected to be the main mechanism for achieving the CO_2 regulation for passenger cars. However, BEVs are only zero emission at their point of use, and a range of policies need to work synergistically to ensure overall reductions in environmental impacts across the full life cycle. Life cycle assessment (LCA) is a methodology that can provide a more complete analysis as it covers environmental impacts arising from production of raw materials and components, vehicle use, production and supply of fuel/energy, and vehicle end-of-life including recycling and reuse.

This study provides the TRAN Committee with an up-to-date expert assessment and comparison between the life cycle's carbon footprint of BEV and ICEV passenger cars, for the current and future perspective (based on policy and technological development). Other life cycle environmental impacts are also discussed where relevant.

Literature overview

An extensive literature review and harmonisation effort was carried out on ICEV and BEV LCAs, comprising industry and independent reports and scientific papers.

The results clearly indicated that BEVs are characterised by higher GHG impacts during the production phase, largely due to the battery packs. However, this initial disadvantage is then significantly overcompensated by lower GHG emissions during the use phase. A large variability was seen in results from the literature, which was most significantly due to the assumed use phase electricity grid mix.

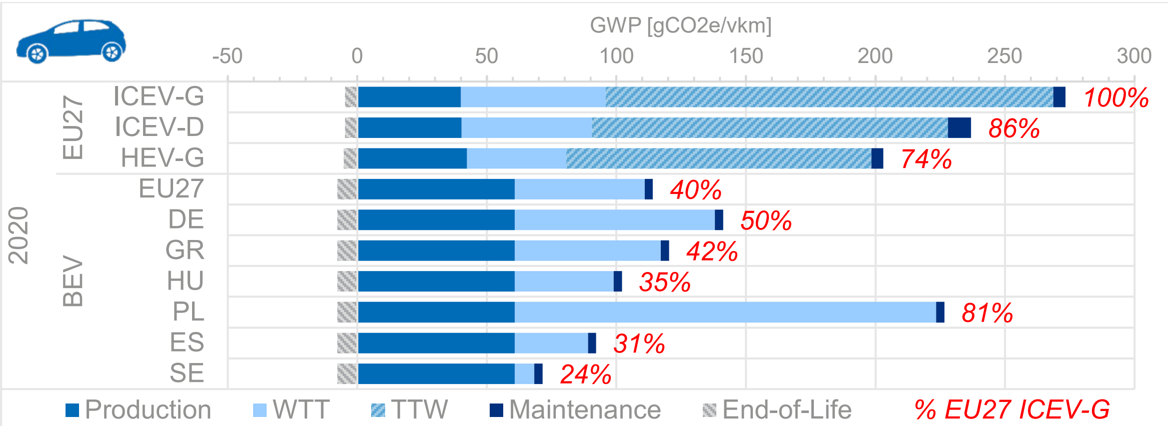
The review also highlighted research and knowledge gaps, among which notably: end-of-life impacts and mitigation strategies (including new recycling processes, and possible second life battery scenarios); supply risk and environmental and social impacts relating to the growing demand for critical raw materials; future evolutionary trends in the battery technology mix.

Current and future outlook for the comparison of ICEVs and BEVs

Ricardo selectively updated the LCA modelling of passenger vehicles, previously developed for DG CLIMA (Hill, et al., 2020), to better reflect both the current situation and the future modelling to better align this with the EU's Fit for 55 package. This analysis provided a quantitative assessment of the potential influence of a range of elements on the life cycle GHG emissions of ICEVs and BEVs.

The analysis complements the literature review and found that BEV passenger cars are expected to already reduce GHG impacts by over 60% in the EU27, compared to gasoline ICEVs (Figure ES2). The analysis also found equally significant GHG savings potentials for most of the other geographies/situations explored. Analysis of the future potential (i.e. to 2030 and beyond), factoring in technology and policy impacts, showed very significant benefits for all countries assessed, due in particular to a cleaner electricity mix (GHG impacts of BEVs up to 78% and 86% lower than ICEVs, respectively by 2030 and 2050) (Figure ES3).

Figure ES2: Regional variations in life cycle GHG impacts for a Lower Medium Car (i.e. C-segment; VW Golf or similar), 2020, EU27, selected EU countries

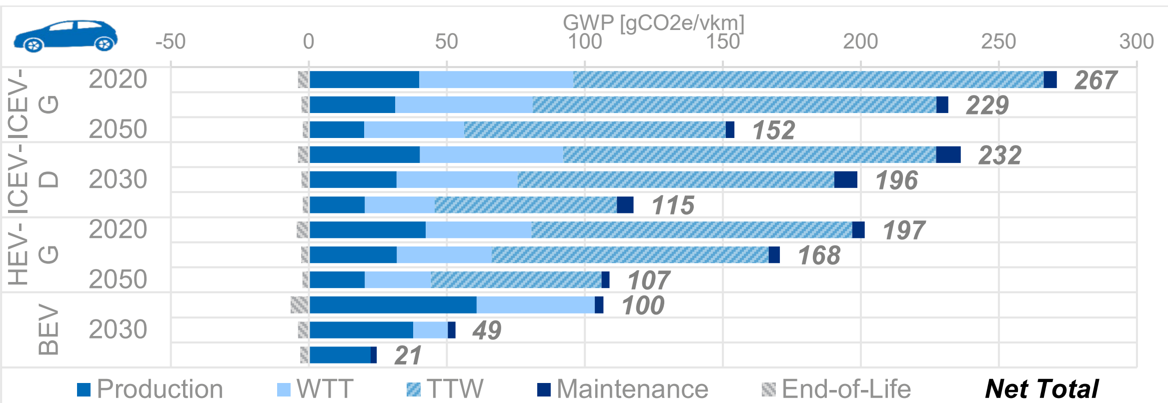


Sources: Life cycle impacts calculated by Ricardo, January 2023.
Notes: ICEV-G/D = gasoline/diesel internal combustion engine vehicle, HEV-G = gasoline hybrid electric vehicle. Production = production of raw materials, manufacturing of components and vehicle assembly; WTT = fuel/electricity production cycle; TTW = impacts due to vehicle operation emissions; Maintenance = impacts from replacement parts/consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal. GWP = Global Warming Potential. DE=Germany, GR=Greece, HU=Hungary, PL=Poland, ES=Spain, SE=Sweden.

The study also assessed sensitivities of the results to a number of other key parameters, including lifetime km, ambient temperature and electric range/battery size and improvements. These showed that the overall findings, were not significantly affected.

A comparison of alternative low carbon fuel/energy options for gasoline ICEVs and BEVs also highlighted that it is likely that large scale deployment of e-fuels or biofuels in road transport will still have higher emissions than a move to BEVs.

Figure ES3: Current and future life cycle GHG impacts for a Lower Medium Car, EU27



Sources: Ricardo LCA modelling, January 2023.

Policy recommendations

The current and expected policy framework was compared against the findings of the LCA. Results clearly show that the revised target on tailpipe CO_2 emissions, which promotes an accelerated transition to zero-emission vehicles (predominantly BEVs), is expected to lead to significant net GHG emission reductions on a life cycle basis across the EU.

Legislation on vehicle manufacturing and end-of-life, along with energy transition policies are compatible with a scenario in which BEVs offer a clear decarbonisation pathway for road passenger vehicles from the life cycle perspective, well beyond the decarbonisation potential of ICEVs (even when using sustainable fuels, such as e-fuels).

However, decisive policy action on some specific issues will be needed to maximise the benefits of BEVs and mitigate existing risks. The following policy recommendations were derived:

- Develop an ambitious policy agenda around battery recycling and circular economy concepts for critical raw materials. The combined effectiveness of the Battery Regulation and revised ELV Directive needs to be closely monitored to ensure these instruments deliver on policy goals. Particular attention should be given to enforcement, monitoring methods and targets in view of potential market and technological innovations in the next years.
- Tailpipe CO_2 emissions regulations provide a suitable regulatory framework, considering current technical limitations for a regulation on a life cycle basis and the complementary legislation to regulate upstream and end-of-life emissions. However, harmonised LCA reporting should be encouraged to improve the effectiveness and transparency of mitigation measures across life cycle stages.
- As BEVs consolidate their market position, incentives to promote right-sized BEVs/batteries may be needed, for example, in terms of energy efficiency targets for BEVs or for zero-emission vehicles more widely.
- Further EU-wide research may be needed to foster innovation in the field of battery technology, and particularly on more materially-efficient battery variants that utilise smaller amounts of critical elements per unit of energy storage.
- A wider set of policies, including policies to promote a modal shift towards sustainable travel modes and the adoption of mobility-as-a-service, will continue to be relevant to further reduce emissions on a passenger-km basis.

1. INTRODUCTION

1.1. Background context

In order to meet the Paris Agreement and European Green Deal objectives, the EU's goal is to achieve at least a 55% greenhouse gas (GHG) emissions reduction by 2030 and climate neutrality by 2050 (European Commission, 2022a) (including a 90% reduction in GHG emissions from transport in the same year). According to DG MOVE's "Statistical pocketbook 2022", road transport is responsible for the highest share of transport's GHG emissions in the EU27 (77% in 2020), and passenger cars are responsible for the largest share of these (59% in 2020), and have therefore been a particular focus for regulation (European Commission, 2022b).

The Green Deal sets out a number of pieces of legislation that would need to be reviewed earlier than planned in order to ensure that they are consistent with delivering net-zero emissions by 2050. This includes a proposal for a revision to the regulation on CO_2 emissions standardsfor cars and light commercial vehicles (LCVs), which was published in July 2021 as part of the "Fit for 55" legislative package (Council of the European Union, 2022). The revision includes raising the targets for reducing exhaust CO_2 emissions for new cars to 55% by 2030 (and to 50% for new vans) and to introduce a 100% CO_2 emissions reduction target by 2035 for new cars and vans[1].

The Commission Communication on a "Sustainable and Smart Mobility Strategy" also mentions the importance of boosting the uptake of low- and zero-emissions vehicles, as well as renewable and low-carbon fuels for transport, without further delay (European Commission, 2020). In particular, it is anticipated that the take-up of battery electric vehicles (BEVs) will be the main strategy/mechanism for achieving the CO_2 regulation's targets (with smaller contributions also from other zero-emissions vehicles). BEVs are also expected to help address other sustainability shortfalls of the transport sector, namely its contribution to air pollution and its dependence on fossil fuels.

However, BEVs are only zero emission at their point of use, and a range of policies need to work synergistically to ensure overall reductions in environmental impacts across the vehicle life cycle. Life cycle assessment (LCA)[2] is a methodology that can provide a comprehensive analysis that covers environmental impacts arising from production of the raw materials, manufacturing and use of the vehicle, production and supply of fuel/energy, and vehicle end-of-life including recycling and reuse. Therefore, LCA can provide a more holistic comparison of the impacts of BEV and internal combustion engine vehicles (ICEVs) and help identify hotspots throughout the different life cycle stages, in order to better understand opportunities to reduce them.

1.2. Aims and objectives for the study

This study provides the TRAN Committee with an up-to-date expert assessment and comparison between the life cycle's carbon footprint of BEV and ICEV passenger cars.

The study aims to reach the following objectives:

- Overview of BEV and battery technology developments.
- Comparison of BEV vs ICEV LCA by life cycle stage.

1 The Council and the European Parliament reached a provisional political agreement on stricter CO_2 emissions performance standards for new cars and vans.

2 As per the definition of ISO 14044, LCA addresses the environmental aspects and potential environmental impacts (e.g., use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave) (ISO, 2006a).

- Understanding the current and future outlook based on Fit for 55 and technological developments.
- Provision of policy recommendations.

1.3. Scope and methodology

The scope of the study focuses on key aspects, as described in Table 1-1.

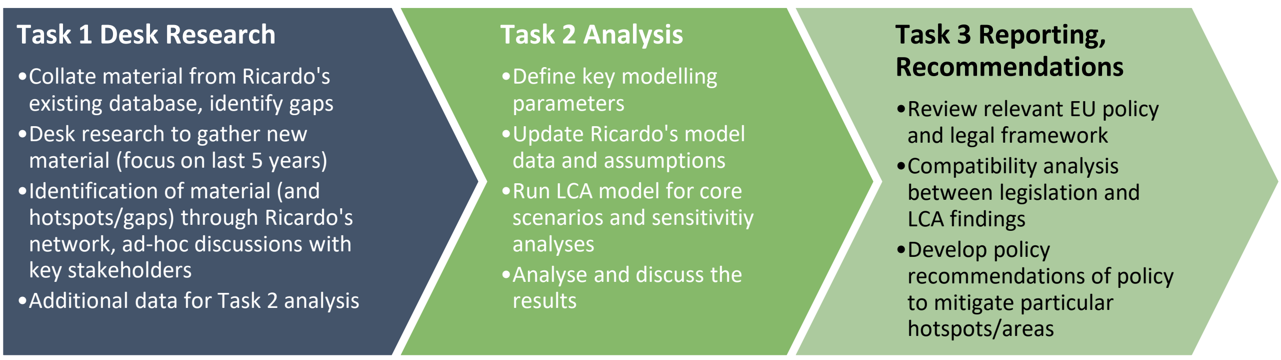
Table 1-1: Scope of the study

Scope	Summary of Coverage for the Study
Vehicles and Powertrains	Passenger vehicles only - focused on passenger cars. Conventional gasoline or diesel ICEVs, and BEV.
Geographic	Focus on the EU, with consideration of the effect of regional electricity mix (for the use phase) covering six EU countries – Germany (DE), Greece (GR), Hungary (HU), Poland (PL), Spain (ES) and Sweden (SE). Accounting for key influencing factors from the supply chain that fall outside Europe as far as feasible (e.g. particularly for critical material supply, battery manufacturing).
Temporal	Current situation (2020 data year); with future projections/estimates to at least 2030 (as influenced by the Fit for 55 legislative package), with also the 2050 outlook.
Impacts	The focus for the review and analysis will be on GHG/global warming potential and resource efficiency (e.g. energy efficiency via cumulative energy demand, etc.) consistent with the European Green Deal objectives. Other impacts are highlighted where they provide additional insights relevant to meeting the overall project objectives.

Source: Ricardo (own elaboration).

The following figure provides an overview of the core project tasks, which will be used to deliver on the aims and objectives for the project, which are discussed in more detail in the following sections.

Figure 1-1: Overview of project tasks



Source: Ricardo (own elaboration).

In **Task 1**, we perform a systematic collection and screening of a broad range of recent literature sources on LCA of ICEVs and BEVs (and on EV batteries), including: peer-reviewed scientific papers and independent reports by reputable bodies, e.g.: International Energy Agency (IEA), International Council on Clean Transportation (ICCT), etc. This review is informed by our network of contacts and ad hoc

discussions with key stakeholders to identify further literature sources to update and enhance the evidence, particularly when there are data gaps or challenges related to data collection.
The review focuses on the following key research areas:

- General vehicle LCA for EV vs ICEV.
- EV Battery LCA and technology improvement.
- Critical materials for batteries: impacts, supply risks and recycling.
- Charging infrastructure, grid integration/balancing, second life batteries.
- Alternative fuel production chains and electricity mix.
- End-of-life recycling and battery second-life.

In **Task 2**, we provide a quantitative and qualitative assessment of the potential influence of a range of future changes in the life cycles and supply chains of ICEVs and BEVs on their life cycle GHG impacts[3], beyond those elements already captured and discussed by the surveyed literature in Task 1. For this, we use a comprehensive and detailed LCA model of passenger vehicles, which was previously developed in-house by Ricardo. This allows for bespoke sensitivity analyses to address these identified future changes.

In **Task 3**, we provide policy recommendations based on findings from literature review and the quantitative and qualitative comparison of BEVs against ICEVs. These build on the following steps:

- Detailed review of the relevant policy and legal framework at EU level resulting from the Green Deal and Fit for 55 initiatives and recent revisions, considering their contribution to GHG emissions and wider economic impacts across all vehicle life cycle stages.
- A high-level assessment of the compatibility/consistency of current policy and legislative proposals with the findings of the analysis.
- Recommendations on the potential focus of policy actions to mitigate particular hotspots/areas of concern resulting from the LCA (particularly for BEVs). Recommendations build on evidence available and expert judgment.

[3] The phrase "GHG impact" is used to refer to the result of LCA calculations whereby the cumulative contributions of all GHG emissions combined towards climate change are expressed by a single indicator, in units of CO_2-equivalents.

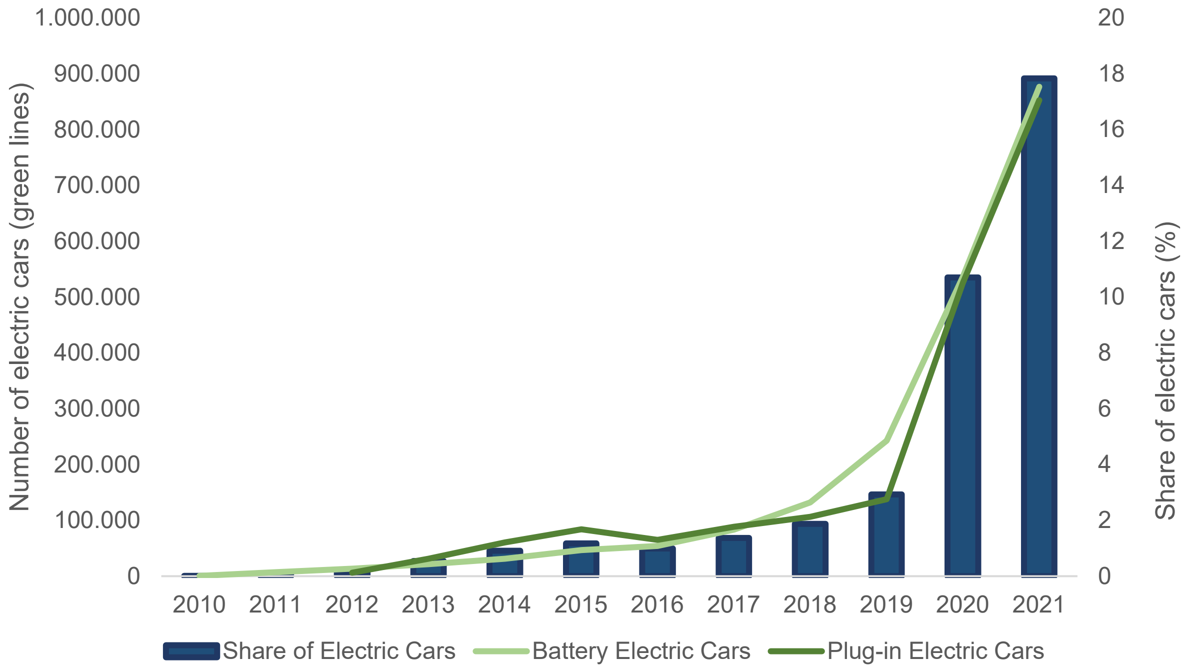
2. OVERVIEW OF BEV AND BATTERY TECHNOLOGY DEVELOPMENT

KEY FINDINGS

- Development of battery technologies in the last years has been a key factor in the increased deployment of electric vehicles (EVs) in Europe.
- Technological development has led to overall reduced mass, increased electric driving range and faster charging – influencing BEVs overall environmental performance.
- The quantities of materials used in battery manufacturing have a direct impact on the environmental implications per kWh of battery energy storage. Thus improvements in energy density will lead to lower amounts of minerals used. Lithium-Nickel-Cobalt-Aluminium Oxide (NCA) and Lithium-Nickel-Manganese-Cobalt Oxide (NMC) are the most commonly cathode technologies employed in EVs' Lithium-Ion Batteries at present, with more technologies slowly gaining shares of the market.
- EV batteries could potentially provide more extensive grid balancing and efficient use of renewable energies through either V2G (vehicle-to-grid) technologies and/or second-life application of EV batteries.

Electric vehicles (EVs), particularly their batteries, have evolved significantly since their (re)introduction in the modern era, dating back to the GM EV1 introduced in the 1990s (Top Gear, n.d.). Modern-day electric cars are now becoming widespread and reaching mainstream status in Europe in terms of sales volumes and acceptance by the public: in 2021, and according to the European Environment Agency, 6% of new cars sold in the EU27, Iceland, Norway and the United Kingdom were BEVs (EEA, 2022) – see Figure 2-1 below. A key factor for their improvement and increased deployment has been development of battery technology – increasing gravimetric energy density (in Wh/kg) and reduction in cost per kWh – as well as improvements in manufacturing efficiency/scale.

Figure 2-1: New registrations of electric cars, EU-27



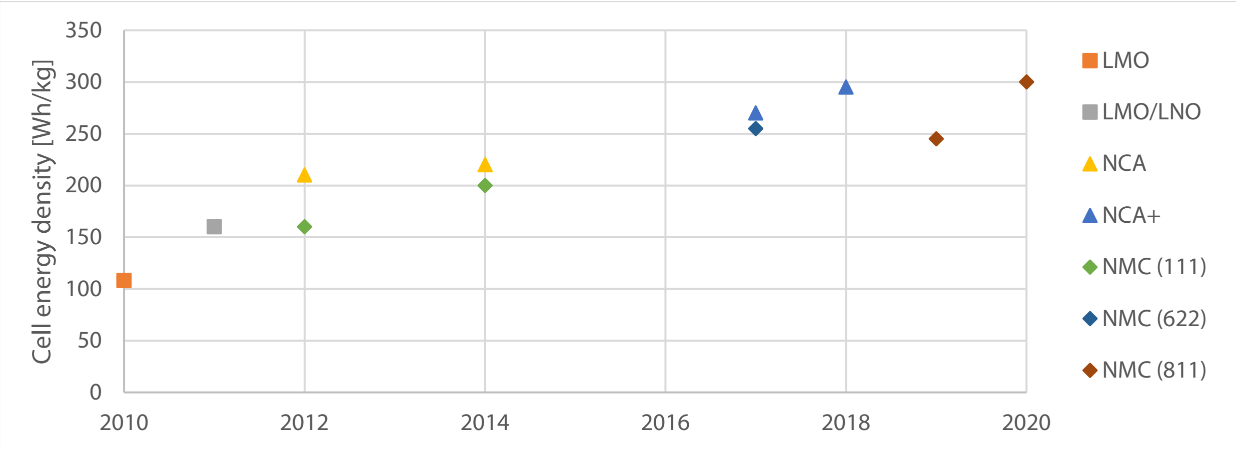
Source: (EEA, 2022), recreated by Ricardo.

The very earliest generations of modern hybrid and EVs introduced in the late 1990s and early 2000s used nickel-metal-hydride batteries but shifted to using lithium-ion batteries (LIBs) instead with the introduction of the first modern mass-produced EVs (like the Nissan Leaf and Mitsubishi i- MiEV/Peugeot iOn/Citroën C-Zero). According to Bloomberg New Energy Finance (BNEF), battery cell energy density has almost tripled since 2010, from just over 100 Wh/kg to around 300 Wh/kg (CleanTechnica, 2020) (Figure 2-2).

This technical development directly affects the production emissions of EVs, which is dominated by the manufacturing of the in-vehicle battery. 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 energy density tend to directly reduce the environmental impacts in manufacturing, per kWh of battery energy storage. Improved battery technology also impacts the operational phase (through reduced mass per unit of energy storage, longer battery lifetime/improved durability) and end-of-life aspects (recyclability, potential for second-life applications, etc.).

The main components of a LIB are the cathode, the anode, the liquid electrolyte and the separator, and the cathode in particular has a strong impact on the overall energy density.

Figure 2-2: Battery-cell energy densities have almost tripled since 2010 according to BNEF



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

LIBs are usually divided into categories according to the elements that are used for their cathodes. The most common categories that have been used in modern EVs include:

1. Lithium-Nickel-Cobalt-Aluminium Oxide (NCA)
2. Lithium-Nickel-Manganese-Cobalt Oxide (NMC)
3. Lithium-Ion-Phosphate (LFP)
4. Lithium-Manganese Oxide (LMO)

The NCA and NMC chemistry types are the most commonly employed in EVs at present (though LFP have been becoming more popular recently due to lower material costs). Both offer long life cycles (1000-2000 cycles) (IEA, 2021), but they vary in terms of gravimetric energy density, which have typically ranged between 200 and 250 Wh/kg for NCA, and between 140 and 200 Wh/kg for NMCs. However, the most recent formulations have reportedly even higher energy densities (Figure 2-2). The NMC chemistry is currently the most dominant in BEVs as well as plug-in hybrid electric vehicles (PHEVs), since its lifetime is longer than for any other solution currently in the market. NMCs also come in different formulations, depending on the specific ratios of Nickel:Manganese:Cobalt (e.g. NMC 111, etc, as shown in the figure above), with efforts underway to reduce the amount of cobalt because of cost, availability and environmental and social concerns (see Sections 3.8.1 and 3.8.2 for further discussion on this topic).

LFP batteries have previously been used more often in heavy duty vehicles (HDVs); however, this technology has seen greater use also in certain passenger car models (particularly in China) in recent years. To put this into context, a global OEM (Volkswagen) has planned to include the LFP technology in its entry-level models (IEA, 2021). The excellent thermal stability of LFP, as well as the combination of high resilience with lower costs per kWh have made them more attractive from a cost perspective, safer and simpler to use in tasks where the size and the weight are not so important. Moreover, the lack of cobalt or nickel (both critical raw materials, as discussed in Section 3.8.1) makes them a competitive option for the near future.

The LMO chemistry has seen significant use in passenger cars in previous years but is now mostly limited to electric bikes and some classes of commercial vehicles (due to mainly poorer performance/energy density compared to NMC), however it is a technology that is free of cobalt, which might be very advantageous in the future.

There have also been a range of other technical improvements to BEVs, in terms of overall reduced mass, increased electric driving range and faster charging – which also influence their overall environmental performance.

Finally, the effect of BEV charging/infrastructure on the overall electricity network is also an important consideration in relation to the overarching integration of the energy and transport sectors. In particular, there is a potential role for EV batteries to provide more extensive grid balancing and efficient use of renewable energies through either vehicle-to-grid (V2g) technologies and/or second-life application of EV batteries used to provide short-term storage. These aspects are discussed in more detail in later Section 3.8.3 of this report.

3. LITERATURE OVERVIEW: COMPARISON OF LCA IMPACTS BY LIFE CYCLE STAGE

KEY FINDINGS

- An extensive literature review and harmonisation effort was carried out on ICEV and BEV LCAs, focusing on GHG impact estimates (hundreds of data points).
- Production GHG impacts for BEVs are higher than for ICEVs (on average, +46% at present, +30% estimated over the next three decades).
- Production GHG impact estimates for future BEVs point to significant margins for reduction, mainly due to improvements in battery energy density.
- Vehicle use phase dominates overall life cycle GHG impacts (6-7 times higher than production emissions for ICEVs, ~2x higher for BEVs), resulting in overall lower emissions for BEVs than ICEVs (on average, -30% at present, -60% estimated over the next three decades, due to the ongoing decarbonisation of electricity grid mixes).
- Use phase GHG impacts of BEVs vary significantly depending on the regional grid mix.
- Life cycle GHG impacts increase with vehicle class and size (thereby favouring smaller and lighter vehicles), although this proportionality is less strong for BEVs than it is for ICEVs.
- End-of-life GHG impact estimates across the reviewed studies cannot be directly compared (nor harmonised) due to methodological inconsistencies.
- Several aspects are not yet sufficiently addressed in the passenger vehicle LCA literature, including: end-of-life impacts and mitigation strategies (including recycling and battery 2nd life); issues relating to the growing demand for critical raw materials; future evolutionary trends in battery technology mix.

3.1. Introduction to Life Cycle Assessment (LCA)

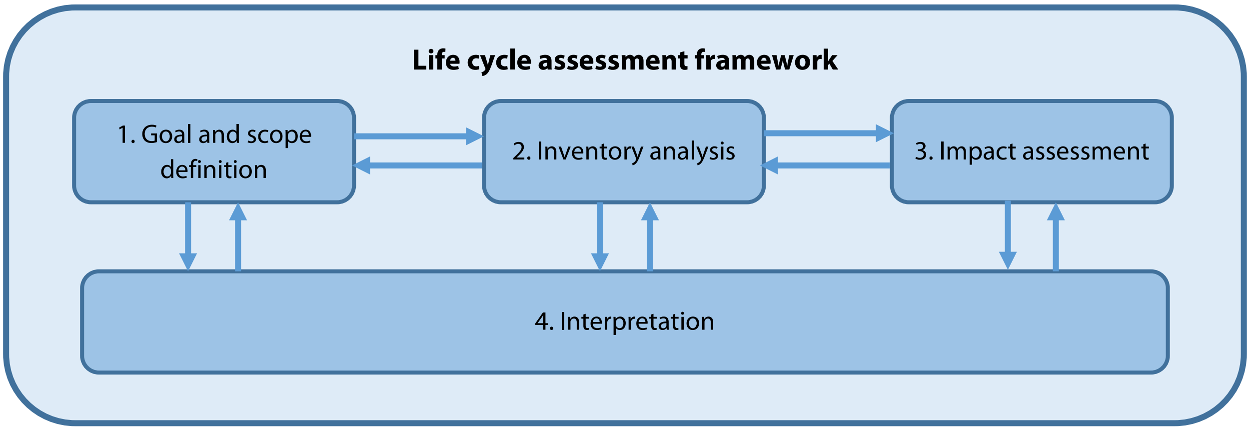
Over the past four decades, Life Cycle Assessment (LCA) has become the methodology of choice to study and assess the environmental impacts of a wide range of technical, industrial and agro-industrial processes. The first studies with a "life cycle" perspective were conducted in the 1960's and 70's (before the "LCA" term was actually coined) to try and reduce energy consumption at a time when the latter was perceived to be a major constraint for the industry; LCA was then made into a standardised procedure for the first time by the Society of Environmental Toxicology and Chemistry (SETAC) in 1993 (Consoli, et al., 1993), and subsequently, in the late 1990s, the International Office for Standardization issued a series of norms that codified its fundamental methodological structure. The latter norms were then superseded by the newer ISO 14040 and 14044 (ISO, 2006a) (ISO, 2006b), and integrated by ISO/TS 14048 (ISO, 2002) and ISO/TR 14047 (ISO, 2012), which remain valid to this day.

According to ISO 14040 and 14044, a LCA must be conducted in four stages (illustrated in Figure 3-1):

1. Goal definition and scoping
2. Life Cycle Inventory
3. Impact Assessment
4. Interpretation

The following sub-sections briefly discuss these four stages (more detail on stages 1, 2 and 3 is then provided in Annex 2).

Figure 3-1: The four stages of LCA, according to ISO 14040



Source: Ricardo (adapted from ISO 14040).

3.1.1. Goal and scope definition

Goal and scope definition is a fundamental first step when initiating an LCA.

The purpose of setting the **goal** is to clearly define purpose of an assessment. ISO standards mandate that its definition shall be consistent with the intended application of the LCA results, including considerations of whether the assessment is intended to be comparative (between alternative options), and who the intended recipients are (e.g. technical experts, policy makers or the general public).

As part of setting the goal of the study, a clear and unequivocal definition of the **functional unit (FU)** of the assessment must be provided, with reference to which all the material and energy flows shall then be scaled. The FU should be expressed in terms of a specific function that the product under assessment is intended to serve (e.g. in the case of passenger vehicles, a suitable FU would be the transportation of a passenger over a given distance).

After having defined the goal of the study, its **scope** must be defined too, thereby specifying which elements and stages of the life cycle of the system are to be included in the assessment and setting a suitably appropriate system boundary. "In setting the scope, all relevant assumptions made to develop the study must also be reported (for more details see Annex 2)".

In general terms, four key phases may be identified along the full life cycle of a product or system, namely:

1. *Raw material acquisition, refinement, and production of intermediate components, and transportation thereof to the manufacturing plant.*
2. *Product manufacturing, including all the processes directly managed by the manufacturer.*
3. *Product use and maintenance.*
4. *Product end-of-life (EoL) scenarios and associated waste treatment processes.*

A complete LCA (often referred to as a "**cradle-to-grave**" assessment) should always include all four phases; however, reduced-scope LCAs are also to be found in the literature, which only comprise the first two life cycle phases (such assessments are referred to as "**cradle-to-gate**").

For more important methodological details on the Goal and scope stage of LCA, please refer to Annex 2.

3.1.2. Life Cycle Inventory Analysis (LCI)

This stage requires a compilation of a so-called "**life cycle inventory (LCI)**" of all the input and output material and energy flows to/from nature that are associated to all the processes associated with all life cycle phases that are included in the chosen scope for the assessment.

Three main types of data sources may be used to compile the LCI, in descending order of general reliability and preference:

(1) Data obtained through direct measurements, usually provided by the manufacturer of the product being assessed.

(2) Data from previous studies available in the scientific literature, and more specifically, in up-to-date and industry-vetted LCI databases.

(3) Data inferred by means of educated estimates, or taken from proxy processes, based on previous analyses and the analyst's experience.

For more important methodological details on the LCI stage of LCA, please refer to Annex 2.

3.1.3. Life Cycle Impact Assessment (LCIA)

In this third methodological stage, the input and output flows comprising the LCI are "translated" into a number of aggregated indicators of potential environmental impacts, to facilitate the interpretation of the results (in rigorous LCA terminology, this process is called "classification and characterisation").

For example, all emissions of GHG (e.g. carbon dioxide, methane, sulphur hexafluoride, etc.) are classified as related to the Global Warming Potential impact category which measures the impact on climate change. Then, all of the inventoried individual GHG emissions are scaled ("characterised" in rigorous LCA terminology) according to their relative potential to contribute to global warming, compared to carbon dioxide (i.e. as CO_2 equivalents), and can thus be summed to generate a single final "Global Warming Potential" impact indicator.

For more important methodological details on the LCIA stage of LCA, please refer to Annex 2.

3.1.4. Interpretation

In the interpretation stage of an LCA the findings from the previous stages of inventory analysis and impact assessment are considered alongside each other in order to generate conclusions which are in line with the goal and scope. This stage should also state the limitations of the study and provide recommendations. It should be noted that this stage is often an iterative process.

There are **multiple sources of uncertainty** that are invariably associated to all LCA calculations. These are due to: intrinsic variability in key model parameters and assumptions; partial reliance on data from generic or proxy processes; possible uncertainties in supply chains; methodological uncertainties in characterisation models and – if used – in normalisation and weighting; etc. Thus, it is often recommendable that a **sensitivity analysis** be carried out as a key element of the interpretation stage.

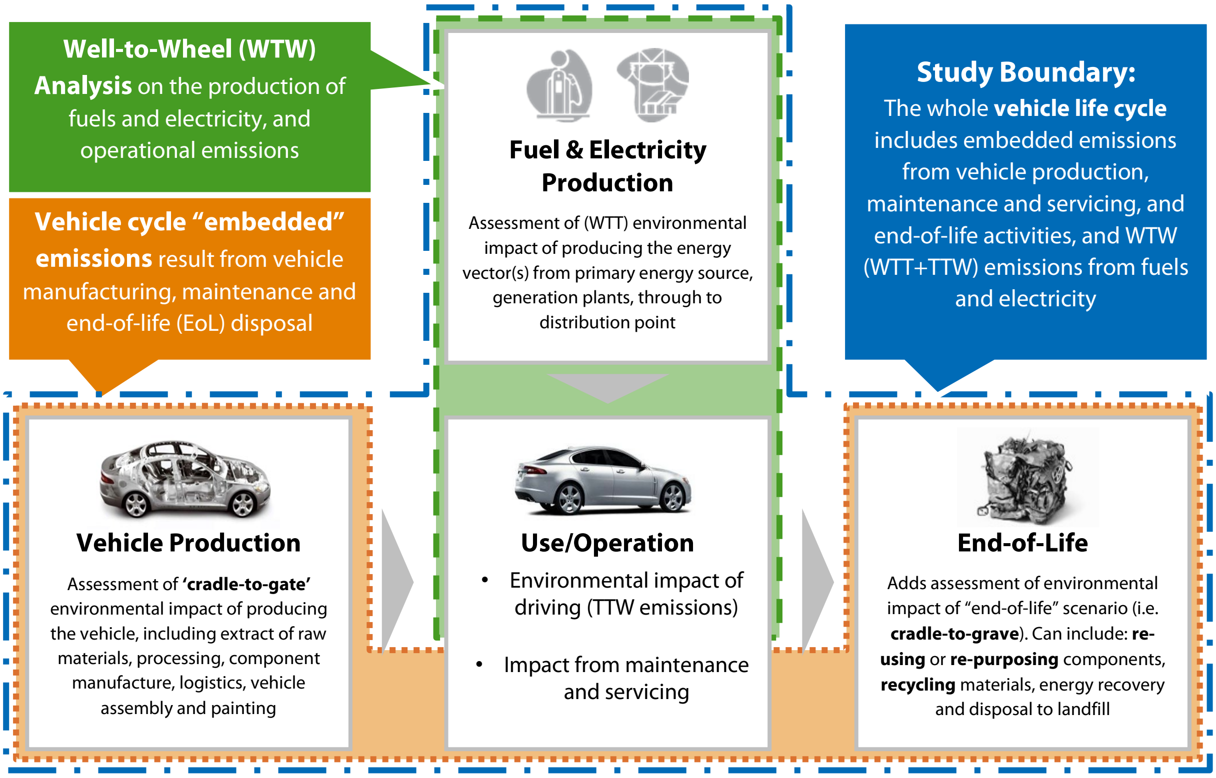
3.2. The life cycle of a passenger vehicle

3.2.1. The main life cycle stages of a vehicle

The life cycle of a modern passenger vehicle can be relatively complex, requiring the modelling of a number of integrated supply chains, such as that for the production of the xEV battery, and that for the energy carriers (i.e. fuels and/or electricity) used in the vehicle use phase, in addition to the vehicle's own supply chain. In fact, in many vehicle LCAs in the literature, the latter two supply chains are often modelled separately as nested sub-systems, as illustrated in Figure 3-2 (with a more detailed illustration provided in the Annex 2, Figure A1).

Additionally, modelling the end-of-life stage also often entails significant additional complexity, especially when the system boundary is set so as to include the subsequent recycling of the waste materials (as briefly discussed in Section 3.2.2 below).

Figure 3-2: Schematic scope of the assessment (system boundaries)



Source: Ricardo (own elaboration).
Note: Infrastructure for energy production (electricity and fuels) is also included. Electricity storage and charging/refuelling infrastructure is excluded. WTT = Well-to-Tank; TTW = Tank-to-Wheel.

3.2.2. Key modelling aspects and parameters

Three alternative **FUs** have been adopted in the LCA literature for passenger vehicles, as follows:

- **FU_1:** *"The transportation of one passenger over a distance of 1 km"*, expressed in units of [passenger×km].
- **FU_2:** *"The transportation provided by one passenger vehicle over a distance of 1 km"*, expressed in units of [vehicle×km].
- **FU_3**: *"One passenger vehicle"*, expressed in units of [vehicle].

It is noteworthy that, strictly speaking, only the first one (FU_1) rigorously refers to a clearly specified function, as required by ISO 14040, while the other two are progressively more vague. FU_2 fails to specify that the intended function is to transport passengers, and to indicate how many of them are transported; FU_3 even fails to explicitly indicate any function at all for the vehicle. As a consequence, the choice of FU affects the degree of comparability across different studies. Specifically, FU_3 is only suitable for comparing results among LCAs of similarly-sized vehicles that may be assumed to have comparable lifetime activities and usage patterns. FU_2 extends the validity of the results to vehicles with different expected lifetime activities. Finally, FU_1 allows consistent comparisons to be drawn, not only across all passenger vehicles, but also, if desired, to other means of transport whose main designated function is also the transportation of passengers (e.g. trains, buses, etc.).

From a quantitative perspective, all three FU are related, and results calculated for one of them may be expressed in terms of any of the others[4], by taking into account the following two key parameters:

- **VO** = average vehicle occupancy, expressed in units of [passenger/vehicle].
- **LA** = lifetime activity, expressed in units of [km].

Since VO and LA are always affected by intrinsic variability, it is recommendable that these key model parameters be subject to sensitivity analysis.

The LCA literature is also divided in terms of the adopted **end-of-life (EoL) allocation method**. Three main options are available in this regard, respectively referred to as:

- **"Cut-off"**: 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 Annex 2.

3.3. Literature review and harmonisation

The following sections will discuss the main findings from an extensive literature review of vehicle LCA studies that was undertaken. The sources used for this review were a combination of a large number of LCAs (scientific papers and industry and independent reports) previously identified for previous work[5], and the results of a series of systematic searches on Web of Science, using keywords such as "LCA", "ICEV" and "BEV". The latter search specifically targets the latest peer-reviewed scientific literature from 2018 onwards only.

Out of all the LCA literature thus retrieved, those studies that did not meet the following **screening criteria** were deemed not usable for comparative purposes and were therefore discarded:

- The scope must include the whole vehicle (i.e. no battery only, or fuel/electricity only studies);
- The scope must not be limited to vehicle manufacturing (i.e. no "cradle-to-gate" studies);
- The studies must transparently disaggregate the vehicle production and use phases;
- The FU must be clearly stated;
- The assumed vehicle lifetime activity (LA) and – where applicable – average vehicle occupancy (VO) parameters must be clearly stated.

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4 $FU_1 = FU_2 \times VO = FU_3 \times VO / LA$.

5 E.g. for Ricardo's recent work for JRC (2019), EC DG CLIMA (2020) and the UK DfT (2021a).

The main focus was then placed on interpreting the literature findings in terms of **life cycle GHG impact**, broken down by vehicle life cycle phase. In order to ensure the level of consistency required, the results were subjected to a harmonisation procedure, leading to a common FU and assumed vehicle lifetime activity (LA) across the whole spectrum of the studies reviewed, as follows:

- **FU:** "The transportation provided by one passenger vehicle over a distance of 1 km", expressed in units of [vehicle×km].
- **LA** = 225,000 km (a value estimated to be broadly representative for typical medium-sized passenger vehicles in Europe (Hill, et al., 2020).

Further harmonisation that takes into account local climate conditions would have been beneficial. This is because BEV battery performance may suffer in lower temperatures, which could result in higher GHG emissions, but it could not be done due to insufficient detail being available in the reviewed studies.

Also, because of irreconcilable differences in the modelling of the end-of-life, this latter phase of the vehicle life cycle was not included in the harmonisation procedure (see Section 3.6 and Annex 2), and as a result, the harmonised results are only calculated and reported here for the first three life cycle phases, i.e.: raw material sourcing + vehicle production (aggregated together), and vehicle use.

More detail on the harmonisation procedure itself is provided in Annex 2.

3.4. Summary of findings from the literature review – vehicle production (from raw materials)

In general terms, and within the same vehicle size class, the GHG emissions associated to the first two phases of the vehicle's life cycle (i.e. raw material sourcing and vehicle production) tend to be higher for BEVs than for ICEVs. This is due for the most part to the comparatively heavy and resource-intensive battery packs, which can be responsible for up to 50% of the total GHG BEV production emissions – see more details in Annex 2.

An additional factor that also tends to lead to comparatively higher production GHG emissions for BEVs vs ICEVs is the former's often greater use of advanced lightweight materials, as part of a general design strategy to limit vehicle mass and thereby further improve in-use energy consumption and, consequently, total driving range (which is still often perceived by consumers to be one of the key limitations of BEVs). This factor is especially relevant for relatively smaller electric vehicles, which feature correspondingly smaller battery packs.

It is also worth briefly mentioning here that, aside from GHG emissions, the use in BEVs of greater quantities of a range of critical elements is important (e.g. including Lithium, Cobalt, Nickel, Manganese, and Copper). Such materials are used in the battery packs and electric powertrains used in BEVs, and also tend to confer to the production of these vehicles comparatively higher environmental impacts in other impact categories, relative to ICEVs. Among such additional impact categories, abiotic resource depletion and human and ecological toxicity are often of particular significance. These points are discussed in more detail in Section 5.2.2.

The large role played by the battery pack in determining the production impacts of passenger vehicles highlights the key importance of the assumptions made on the battery size and type. As discussed in Section 2, three main types of lithium-ion battery (LIB) technologies are currently used in passenger BEVs (LFP, NMC and NCA), and these all vary significantly in terms of gravimetric energy density (Wh/kg) and production impacts (kgCO_2-eq/kg), with obvious consequences on the production impacts of the vehicles that utilise them.

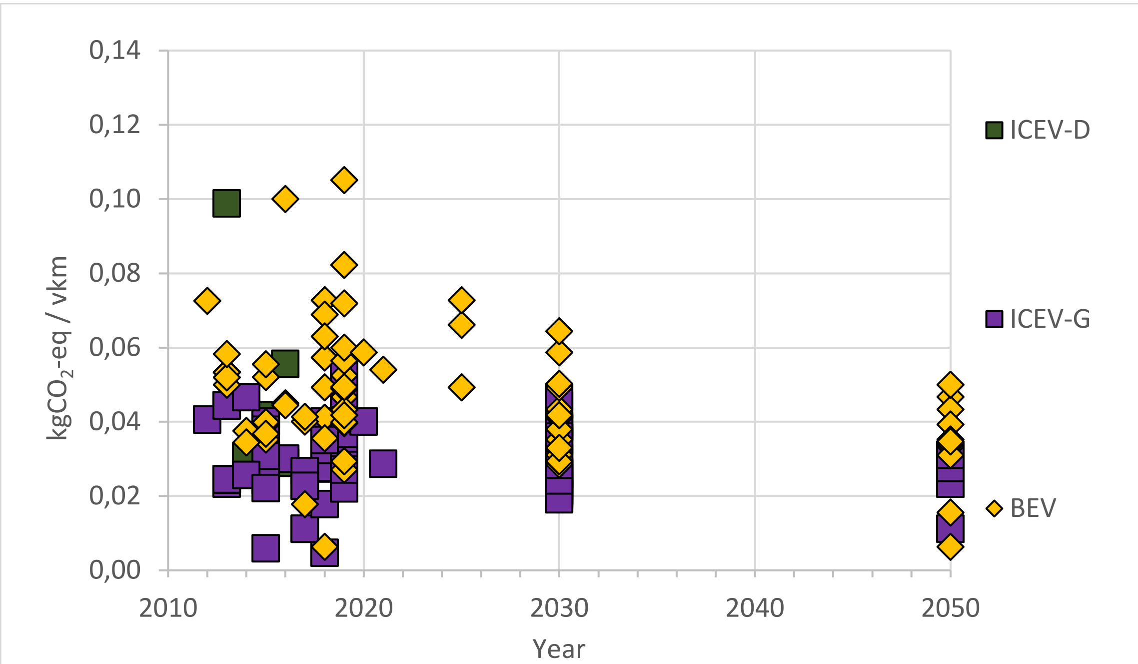
Another factor that may significantly affect the vehicle production impacts is the location of the manufacturing plants (both for the vehicle itself, and for the battery, when the two locations are distinct). This is due to the comparatively large role played by the electricity inputs to manufacturing, and the large variability in grid mix composition across different countries. The reviewed studies spanned a range of different production locations from Europe, North America and Asia.

Figure 3-3 illustrates the harmonised literature findings in terms of vehicle production GHG emissions, where the data points are positioned along a horizontal axis indicating the reference year. For years up to 2021, this corresponds to the actual vintage of the LCI data used for the calculations, whereas for all years in the future (up to 2050), this provides an indication of the time horizon used for the assumed scenario predictions.

The main indications emerging from these findings are as follows:

- All data points for vehicle production impact estimates are fairly tightly clustered within a comparatively narrow range, when considered relative to the much wider range exhibited by use phase emissions (see Section 3.5);
- BEV production emissions tend to populate the higher end of the range (on average, reported BEV production emissions are 46% higher than those for ICEVs, when including all data points; the average difference is however reduced to +30% if the comparison is made between current ICEVs and projected future BEVs, indicating significant margins for improvement in BEV manufacturing);
- Results vary with vehicle class and size in a generally linear way, although this linearity is disrupted when significantly different battery chemistries/manufacturing are assumed;
- Impact estimates for future BEVs point to significant margins for reduction, which is mainly due to assumed improvement in battery energy density.

Figure 3-3: Harmonised ICEV vs BEV GHG impact results (vehicle production)



Source: Ricardo (own elaboration).
Notes: ICEV-D = Diesel internal combustion engine vehicle; ICEV-G = gasoline internal combustion engine vehicle; BEV = battery electric vehicle.

The reviewed vehicle LCA literature was found to be lacking in terms of consideration of further aspects that may influence the current and, especially, the future production impacts of passenger vehicles.

In particular, none of the reviewed vehicle LCA studies (besides Ricardo's previous analyses for the European Commission's (EC) DG CLIMA and the United Kingdom's Department for Transport (UK DfT)) attempted to estimate the future changes in vehicle production impacts which may be brought about by a shift to new battery chemistries such as all-solid-state lithium batteries (ASSB) or even sodium-ion batteries (NIB). This point is discussed in more detail in Section 3.8.2.

The reviewed LCA literature also failed to address future projections in terms of the decarbonisation of material supply chains, beyond the simple shift to lower-carbon electricity grid mixes. In particular, the steel industry has shown potential for significant decarbonisation by shifting production from the conventional blast furnace/basic oxygen furnace (BF/BOF) process using coke as the chemical reducing agent, to an electric arc furnace (EAF) process fed by directly-reduced iron (DRI) produced using "green" hydrogen as the reducing agent (Vogl, Åhman, & Nilsson, 2018; Hybrit, 2022). Given the prevalence of steel as a key input material to the manufacturing of passenger vehicles, such a move towards low-carbon steel production could significantly reduce the production of GHG emissions of both ICEVs and BEVs in the future.

The reviewed literature also did not consider the use of a significantly increased share of renewable energy in vehicle manufacturing (even by way of sensitivity analysis), other than that already included in the local grid mix. Yet, this is a definite possibility that is being considered by several Original Equipment Managers (OEMs), through the use of "bundled" renewable energy certificates (RECs) which are backed by power purchase agreements (PPAs) that ensure the necessary additionality condition (i.e. that the renewable electricity used in vehicle manufacturing is generated in addition to the amount of renewables that is already present in the pre-existing regional grid mix).

A majority of the reviewed studies assumed NMC batteries for BEVs, but not all were sufficiently transparent in terms of the specific cathode composition (e.g. NMC-622, NMC-811, etc.) and, consequently, the assumed energy density. Some of the studies focusing on Asia (and specifically China) assumed LFP batteries instead, as these are comparatively more prevalent in those markets.

3.5. Summary of findings from the literature review – vehicle use

In clear contrast with the previous findings on the vehicle production phase, and once again within the same vehicle size class, the GHG impacts associated to the use phase of the vehicle tend to be lower for BEVs than for ICEVs. This is essentially due to a combination of two main factors:

(i) the intrinsically much higher energy conversion efficiency (from energy delivered to the power train to kinetic energy at the wheel) of the electric power train[6]; and

(ii) the often lower carbon intensity per unit of energy delivered to the power train of electricity vs the fossil fuels (e.g. gasoline and diesel) commonly employed in ICEVs.

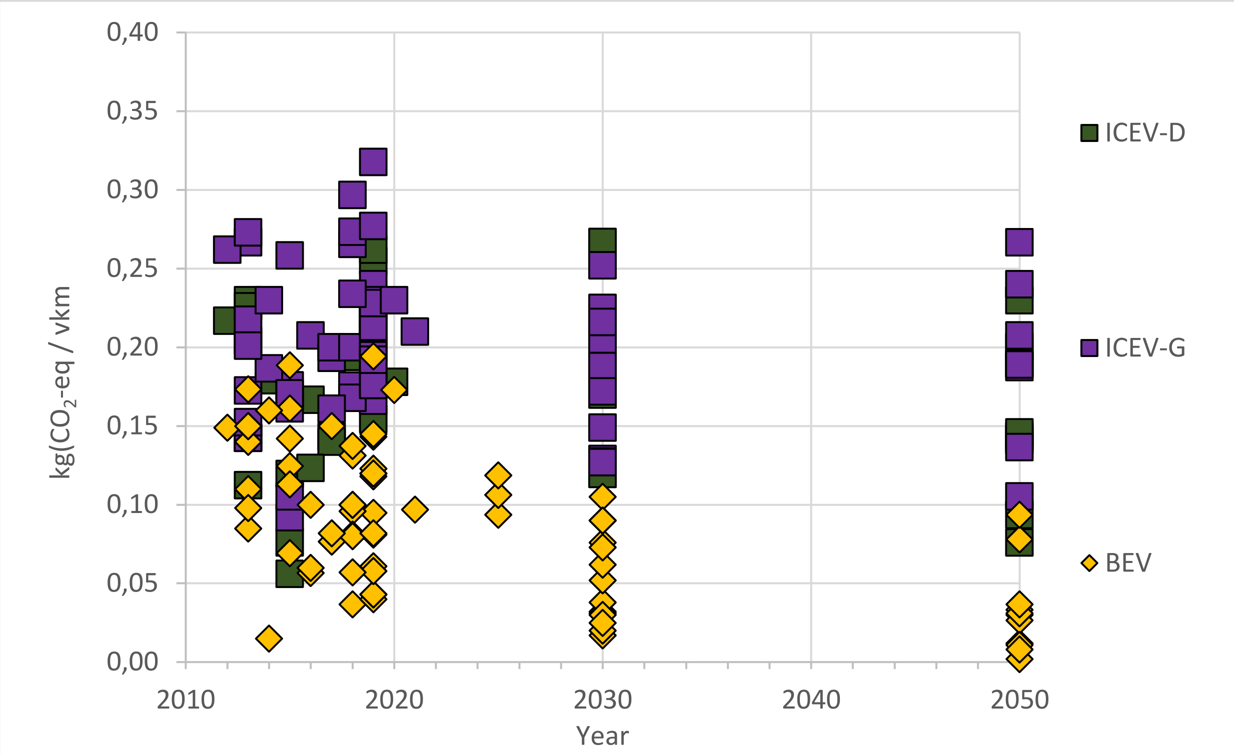
However, the latter factor is highly variable, depending on the specific electricity grid mix that is assumed to be used to recharge the BEV batteries during the vehicle use phase – see more details of illustrative studies in Annex 2.

Figure 3-4 illustrates all of the harmonised literature findings in terms of vehicle use GHG emissions, where the data points are positioned along a horizontal axis indicating the reference year. Once again,

[6] Due to thermodynamic limitations that are physically impossible to circumvent, the efficiency of internal combustion engines (ICEs) operated at normal ambient temperatures can never be higher than approximately 30%; such limitations do not apply to electric motors, which are often >90% efficient.

for years up to 2021, this corresponds to the actual vintage of the LCI data used for the calculations, whereas for all years in the future (up to 2050), this provides an indication of the time horizon used for the assumed scenario predictions.

Figure 3-4: Harmonised ICEV vs BEV GHG impact results (vehicle use)



Source: Ricardo (own elaboration).

Notes: ICEV-D = Diesel internal combustion engine vehicle; ICEV-P = gasoline internal combustion engine vehicle; BEV = battery electric vehicle. Note different vertical scale vs Figure 3-3.

The main indications emerging from these findings are as follows:

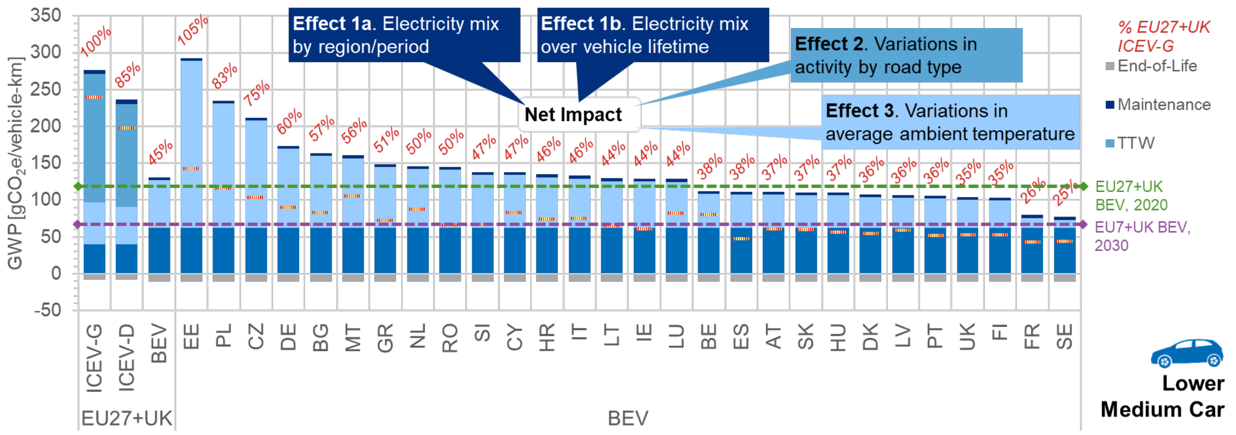
- The data points for vehicle use phase impact estimates span a much wider range than those for the production emissions (see Section 3.4).
- In absolute terms, use phase GHG impacts are higher than production emissions for all vehicle types; however, a significant difference is observed between ICEVs (use phase GHG impacts 6-7 times higher than production GHG impacts) and BEVs (use phase GHG impacts only 1.8 times higher than production GHG impacts, when including all data points).
- BEV use phase GHG impacts tend to populate the lower end of the range (on average, reported BEV use phase GHG impacts are 54% lower than those from ICEVs, when including all data points).
- Results vary with vehicle class and size, although this proportionality is less strong for BEVs than it is for ICEVs.
- Impact estimates for future BEVs point to significant margins for reduction, which is mainly due to assumed improvement in electricity grid mix decarbonisation (on average, reported use phase GHG impacts for future BEVs are 73% lower than for current ICEVs, and only 1.2 times higher than production GHG impacts for the same vehicles).

It is however noteworthy that all the reviewed LCAs (except Ricardo's LCAs for EC DG CLIMA and UK DfT, the results of which are however not included in Figure 3-4) modelled the electricity grid mix in a simplified and "static" way. I.e. the calculations were performed while assuming that the grid mix composition will remain the same for the whole duration of the service life of the vehicle. However, the reality is that in most countries efforts are underway to decarbonise electricity generation. Therefore, the "static" assumption mentioned above is likely to lead to erroneous, and pessimistic, life cycle GHG impact estimates for BEVs. Some of the reviewed studies then also report results calculated assuming one or more alternative "static" grid mix compositions, which are intended to be representative of specific years in the future (and the resulting data points are also reported in Figure 3-4).

However, as also discussed elsewhere in the scientific literature (Hoekstra, 2019), a different approach would arguably be more appropriate and conducive to more realistic results, namely one that assumes a "dynamic" grid mix composition that is allowed to change over time throughout the expected service life of the vehicle.

The latter is exactly the methodological approach that was used in Ricardo's previous study for EC DG CLIMA (Hill, et al., 2020), and the results from this study (Figure 3-5) clearly illustrate the dependency of the vehicle use phase GHG impact on the composition of the grid mix for the region/country where the vehicle itself is assumed to be driven. As predictable, lower GHG impacts correspond to countries where the grid mix is already significantly decarbonised (e.g. Sweden, France), and/or where there is an aggressive decarbonisation in place (e.g. UK, Portugal, etc.). Conversely, for those countries where the grid mix is still heavily reliant on fossil fuels, and specifically coal (e.g. Poland and the Czech Republic), the net advantage of switching from ICEVs to BEVs is significantly reduced.

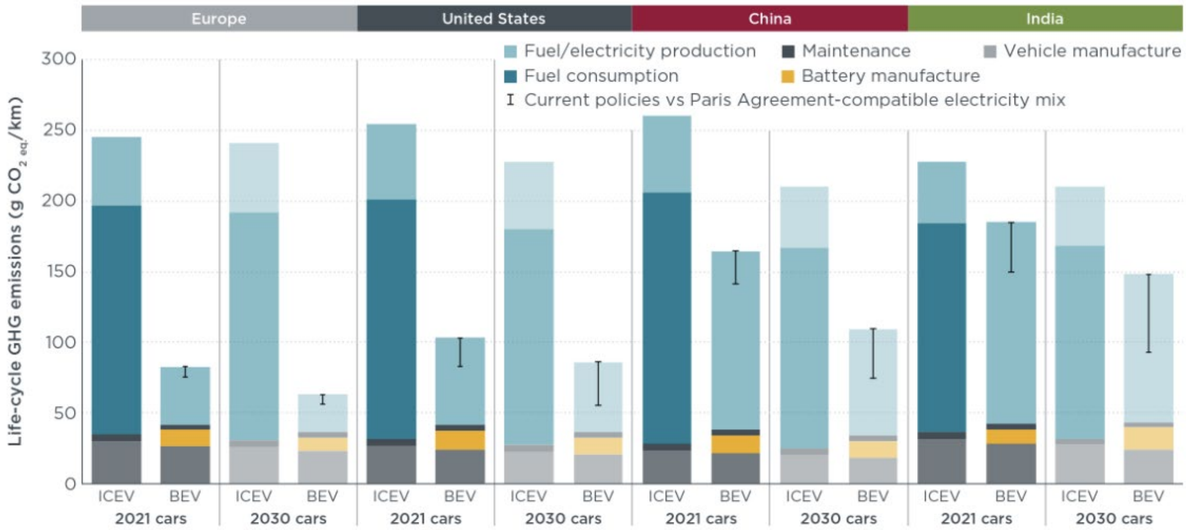
Figure 3-5: Effect of electricity grid mix and other regional effects on use phase GHG impacts of passenger vehicles, with country-specific results for BEVs, across all the member countries of the EU, plus the UK



Source: Ricardo modified from (Hill, et al., 2020)

A similar range of variation in the use phase GHG impact of BEVs vehicles across different regions (beyond Europe) was also reported in the 2021 White Paper (Figure 3-6) published by ICCT (ICCT, 2021b). Once again, the main responsible factor that underpins the observed changes is the assumed grid mix composition: the error bars indicate the difference between the development of the electricity mix according to stated policies (the higher values) and what is required to align with the Paris Agreement.

Figure 3-6: Effect of regional electricity grid mix on use phase GHG impacts of passenger vehicles, with region-specific results for BEVs operated in Europe, the USA, China and India



Source: (ICCT, 2021a).

3.6. Summary of findings from the literature review – vehicle end-of-life

As already mentioned in Section 3.3, the reviewed literature was inconsistent in the way the end-of-life of the vehicles was addressed (or in some cases even failed to address this altogether). In particular, some of the studies adopted the "cut-off" approach (see Section 3.2.2 and Annex 2) and thus only estimated the impacts and emissions associated to vehicle dismantling and to the landfilling and incineration of the materials that cannot be recovered, while excluding from the system boundary all the subsequent material sorting and recycling processes. Other studies, instead, adopted the "avoided burden" approach, and included in the calculations both the impacts of recycling and the associated emissions credits due to the primary (i.e. virgin) materials that were assumed to be displaced by the recycled materials themselves (the latter calculations typically result in a net negative impact budget for the end-of-life phase as a whole).

Given the wide range of assumptions and methodological differences, it is therefore not possible to draw clear overarching messages from the literature, as pertains to the vehicle end-of-life phase.

Also, the reviewed vehicle LCA literature was found to be lacking in terms of consideration of further aspects that may influence the current and, especially, the future end-of-life impacts of passenger vehicles. In particular:

- None of the reviewed studies explicitly addressed the ongoing changes and improvements in end-of-life recovery and recycling of battery elements, and the potentially large effects that these trends could have, not only on end-of-life (EoL) impacts, but also on battery manufacturing in the future. Some of these aspects are elaborated on in Section 3.8.2.
- None of the reviewed studies considered the possible reduction of life cycle impacts for BEVs due to the possible re-purposing of EoL batteries for a second-life use (e.g. in grid storage applications). For some discussion of the implications of these strategies, once again, see Section 3.8.2.

3.7. Summary of findings from the literature review – overall life cycle

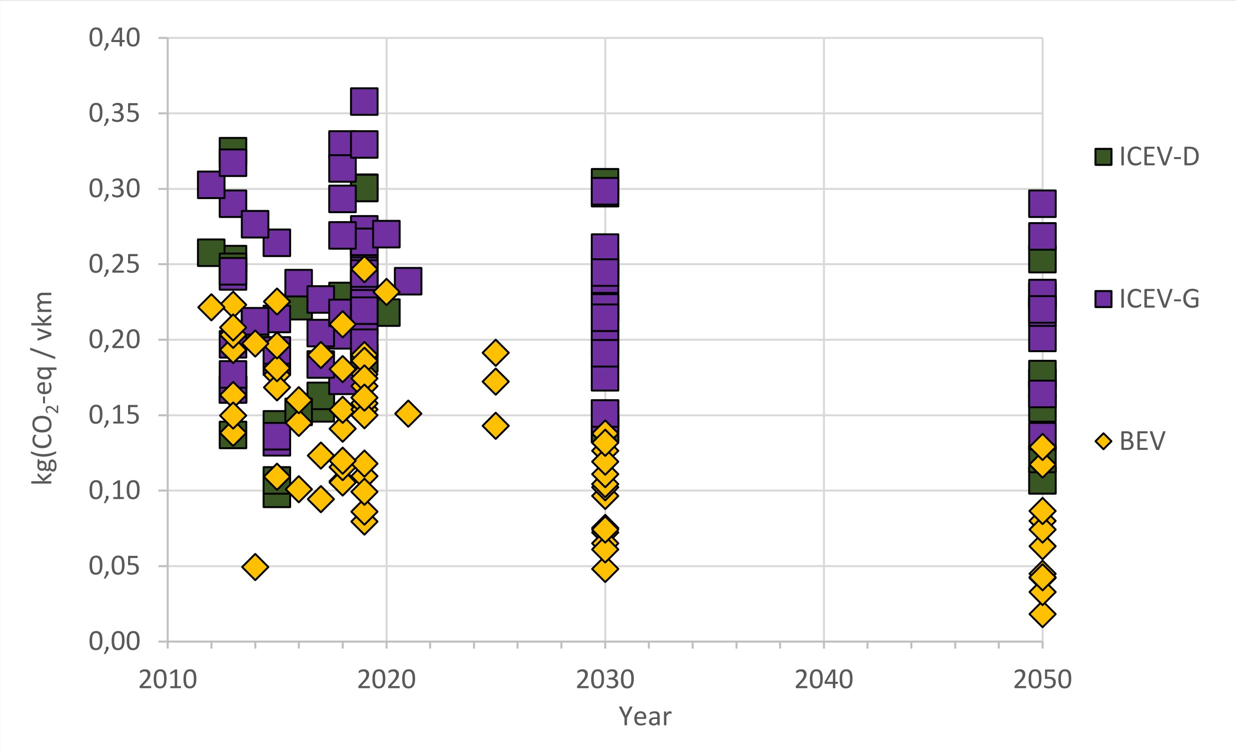
The overall harmonised life cycle GHG emission results for passenger vehicles (including vehicle production and use) from all the reviewed literature are reported in Figure 3-7, where, once again, the data points are positioned along a horizontal axis indicating the reference year. The main indications that emerge from these results tend to mirror those already seen when discussing the use phase in isolation (Section 3.5), which is not surprising, given the dominance of the use phase emissions relative to the other life cycle phases. In particular, the following general observations can be made:

- ICEVs (both gasoline and diesel) populate the higher end of the life cycle emissions range, despite their lower initial up-front emissions during the production phase.
- ICEVs are also characterised by a very limited scope for future emissions reductions, which is due to the fact that the conversion efficiency of ICEs is already approaching the hard limit imposed by thermodynamics[7].
- On average, current BEVs already exhibit life cycle GHG impacts that are statistically significantly lower than those from ICEVs (average: 0.13 *vs* 0.22 kg(CO_2-eq)/Vkm; data range: 0.05-0.25 *vs* 0.10-0.36 kg(CO_2-eq)/Vkm).
- BEV emissions estimates for the future (up to 2050) point to further significant reductions, which is due to the on-going decarbonisation of the electricity grid mix in most countries.

It is however worth mentioning that some of the literature also addressed other types of environmental impacts, beyond GHG emissions impacts, which were not included in this harmonisation, but which could potentially raise some concerns in terms of the broader comparative environmental performance of ICEVs vs BEVs. Among these, the two most prominent types of impact are both related to the increased demand for critical raw materials (CRMs) for the electric power trains (vs the conventional ICEs), and more specifically for battery metals such as lithium, cobalt, and nickel. In fact, beyond representing potential bottlenecks to the widespread adoption of BEVs due to sheer availability constraints, the supply chains of these CRMs are often responsible for non-negligible impacts in terms of ecological and human toxicity, as well as related social impacts. Some of these issues are discussed here in some detail in Section 3.8.1.

[7] The maximum theoretical efficiency of an ICE is given by the so-called "Carnot limit" = 1 – (TH / TC), where TH = combustion temperature, and TC = ambient temperature, in K (= Kelvin, the Standard International (SI) unit of absolute thermodynamic temperature).

Figure 3-7: Harmonised ICEV vs BEV GHG impact results (vehicle production + use)



Source: Ricardo (own elaboration).
Notes: ICEV-D = Diesel internal combustion engine vehicle; ICEV-P = gasoline internal combustion engine vehicle; BEV = battery electric vehicle. Note different vertical scale vs Figure 3-3.

3.8. Aspects not sufficiently addressed by the existing LCA literature

3.8.1. Critical raw materials (CRMs) for EV batteries: impacts and supply risks

The rapidly growing demand for CRMs for the production of EV batteries raises concerns on the sustainability of their supply chains, in terms of: scarcity/potential global availability bottlenecks; geopolitical pressures due to geographical concentration of deposits and/or processing capacity; and the environmental and social impacts of mining and refining activities.

Specifically, over the course of the next few decades, the elements lithium, cobalt and nickel are of particular concern. Overall, there are concerns about potential future bottlenecks in the supply chains of these elements that could hamper the continued large-scale deployment of BEVs to eventually replace ICEVs globally.

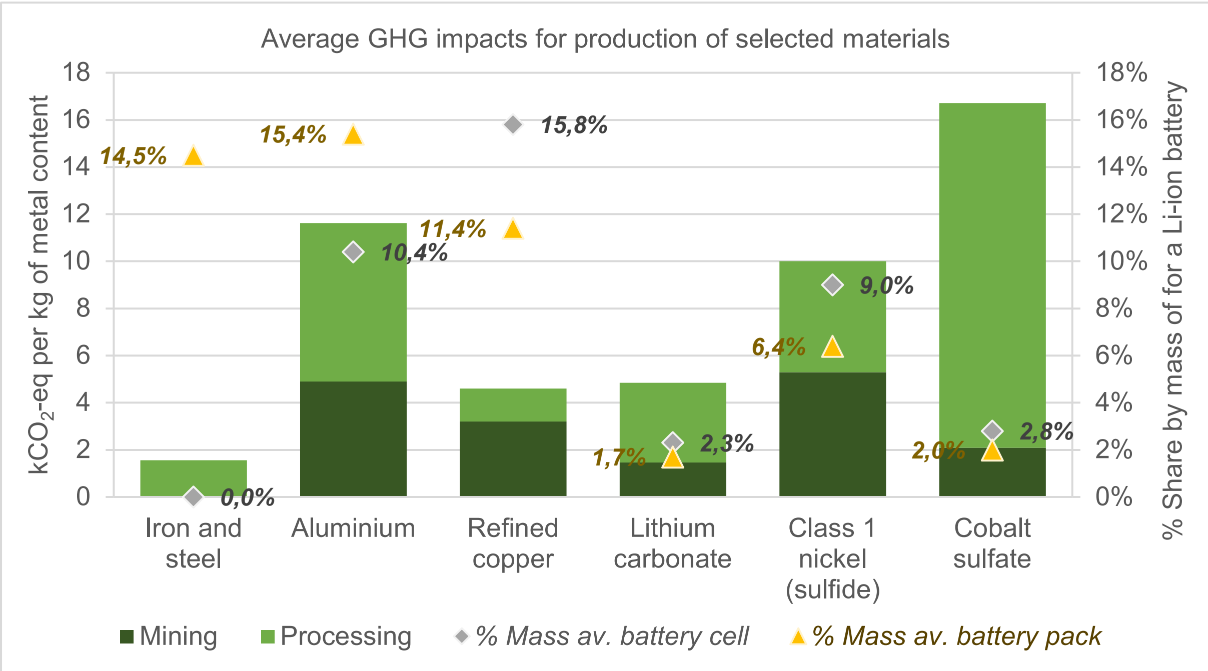
Additionally, quantitative prospective estimates of the expected global trends in GHG impacts from lithium, cobalt and nickel extraction and processing are lacking. However, given that LIB cathode production represents a sizeable share of the overall carbon emissions from BEV manufacturing, the ongoing exponential rise in demand for these metals (to satisfy the needs of the growing BEV fleet) has been identified as a possible concern, in that it could partly offset the benefit of the reduced demand for fossil fuels over the vehicles' use phase.

The average GHG impacts of the current prevalent supply chains for these three key battery elements are reported here below in Figure 3-8, expressed as kg CO_2-eq per kg metal content for the respective salts as they are input to battery manufacturing (i.e. respectively these are most commonly: $LiCO_3$, $NiSO_4$ and $CoSO_4$). To provide a frame of reference, the average GHG impact of primary steel, aluminium and copper is also included in the same figure. The figure also provides the corresponding mass shares of these materials for a typical BEV battery cell and battery pack (assuming ~2020 market mix of chemistries).

Possible alternative, and lower-carbon intensity, sources for some of these metals have been identified, such as e.g. geothermal sources of lithium in the UK (Cornish Lithium, 2022), and the possibility to extract lithium from clay deposits (USGS, 2018). However, none of these new sources of lithium have so far shown potential to significantly displace, or even supplement, its two conventional sources on the global scale (see Section 3.8.1.a). According to (IEA, 2021), the main alternative future sources for growth in supply could result in increased GHG impacts (Figure 3-9).

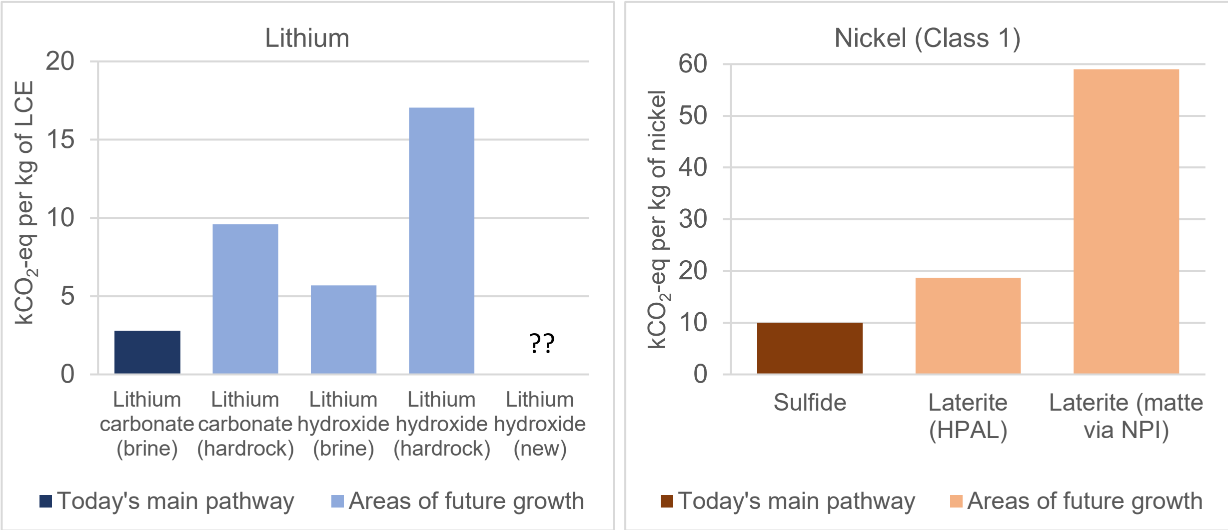
Additionally, lithium, nickel and cobalt may potentially be sourced from deep sea mining, also potentially with lower associated GHG impact. For instance, deep sea mining in the Clarion-Clipperton Zone (a geological submarine fracture zone of the Pacific Ocean, with a length of around 7000 km) has been estimated to contain up to 5 times the cobalt reserves on land, while causing lower carbon emissions per mass of metal extracted (Levin, Amon, & Lily, 2020; Paulikas, Katona, Ilves, & Ali, 2020). However, the potentially large adverse effects of deep-sea mining on marine biota are a serious concern which has not yet been sufficiently assessed.

Figure 3-8: Shares by mass of selected material used in lithium-ion batteries, and GHG impacts per kg metal content of corresponding battery manufacturing precursor materials



Source: Charts partially reproduced by Ricardo using data from (IEA, 2021) *for material GHG impacts. Data extracted from Ricardo's vehicle LCA model for the average % share of Lithium Ion (Li-ion) battery mass.*

Figure 3-9: GHG impacts for key battery materials by resource type and processing route



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

Overall, most supply risk and GHG impact mitigation assessments for all battery metals tend to point to their increased end-of-life recycling as a cornerstone strategy to be pursued (see Section 3.8.2.b).

Also, increased metal utilisation efficiency is variously identified as a key target. This can be accomplished through a combination of, in the first instance, the development of more materially-efficient battery variants that utilise smaller amounts of critical elements per unit of storage provided (see Section 3.8.2.a), and then, more holistically, through a global shift to more efficient shared mobility schemes such as Transport-as-a-Service (TaaS) to gradually replace the conventional personal vehicle ownership model (Greim, Solomon, & Breyer, 2020; Junne, Wuiff, Breyer, & Naegler, 2020; Jones, Elliott, & Nguyen-Tien, 2020; Klimenko, Ratner, & Tereshin, 2021; Kamran, Raugei, & Hutchinson, 2021).

The following sub-sections provide more details from a review of the scientific literature on the supply chain risks and associated GHG mitigation strategies for each of these three individual battery elements.

3.8.1.a. Lithium

Lithium is currently sourced from two types of crustal deposits: igneous rocks (mainly spodumene, with large deposits in China and Australia), and lithium carbonate brines from freshwater bodies, especially in Chile, Bolivia and Argentina.

Literature studies have projected that global lithium demand for BEVs may exceed the yearly available reserve by 2050, and even approach or exceed the total resource level by 2100 (Junne, Wuiff, Breyer, & Naegler, 2020; Hache, Seck, Marine, Clement, & Samuel , 2019; De Koning, et al., 2018; Tokimatsu, et al., 2018).

At present, the global lithium recycling rate is very low at around 3%, due to a combination of lack of economic incentives and prevalence of pyrometallurgical lithium-ion battery (LIB) recycling practices (see Section 3.8.2). In the coming decades, the roll-out of more widespread hydrometallurgical recycling and improved economies of scale, thanks to much larger quantities of EoL EV LIBs, may help address the supply shortage risk, while at the same time reducing the GHG impact per unit of storage capacity provided. It has been estimated that lithium recycling should reach at least 30% by 2050 to avoid the otherwise projected lithium shortage (Klimenko, Ratner, & Tereshin, 2021; Watari, Nansai, & Nakajima, 2020).

The more ambitious supply mitigation strategies then point to the development and improvement of radically new, lithium-free battery chemistries (see Section 3.8.2.a).

3.8.1.b. Cobalt

Cobalt is primarily a by-product of the extraction of copper (and secondarily, nickel), and, due to its low native concentration in the ore, it has been estimated that 40% to 60% of the cobalt content in the ore is lost during the concentration step (Petavratzi, Gunn, & Kresse, 2019). Cobalt extraction is also highly geographically concentrated, with over 70% currently coming from deposits in the Democratic Republic of Congo (DRC) (British Geological Survey, 2022). Long-standing political instability in the DRC is a significant reason for concern in terms of ensuring a dependable supply of this critical metal to the global LIB industry. Also, widespread artisanal mining in the DRC suffers from lack of regulation and safety standards, and it has been shown to entail a worrying level of child labour (World Economic Forum, 2016) (Mancini, Eslava, Traverso, & Mathieux, 2021).

Globally, over 60% of total cobalt production capacity is expected to be absorbed by the EV sector by 2050 (Seck, Hache, & Barnet, 2022), and it has been calculated that, without implementing mitigation strategies, the future demand for cobalt would clearly exceed the currently estimated reserve before 2050 (Klimenko, Ratner, & Tereshin, 2021; Watari, Nansai, & Nakajima, 2020; Seck, Hache, & Barnet, 2022).

At present, despite the economic incentive represented by cobalt's high market value, the global cobalt recycling rate is still relatively low at approximately 30%. Klimenko et al. (2021) calculated that, assuming extrapolated trends in global EV deployment and expectations for technological development in low-cobalt and cobalt-free battery options, improving the EoL recycling rate to 50% by 2050 would suffice to limit global cobalt demand to approximately 25% of the prospective reserve by 2050, and to 55% thereof by the end of the century.

In the longer term, achieving a rapid reduction in cobalt content per unit of LIB storage capacity appears to be the most promising strategy (Li, Lee, & Manthiram, 2020), up to its complete displacement in favour of completely cobalt-free chemistries (see Section 3.8.2.a).

Given the comparatively high carbon intensity of cobalt supply, the latter strategies may also be expected to result in reduced GHG impacts from BEV manufacturing as a whole.

3.8.1.c. Nickel

Indonesia is now the largest producer of nickel (37% of the total global production), followed by the Philippines (13%) (USGS, 2022). Other countries like China, Korea, Australia, and Indonesia, however, hold very prevalent roles in the global nickel supply chain network (Tian, et al., 2021).

Currently, the global recycling rate for nickel is approximately 60%; however, over 95% of nickel is not recovered in pure enough form to be re-used in battery manufacturing (Henckens & Worrell, 2020).

The demand for nickel for EV batteries is projected to increase significantly, due to a combination of EV market trends and substitution of cobalt with nickel in various cathode formulations (e.g. lower-cobalt but higher-Nickel NMCs, and also potentially, NMAs). Additionally, nickel has many structural applications (primarily, it is used in steel alloys), and therefore the growing demand for this metal in many other sectors beyond that of EVs must be carefully considered when attempting to make long-term projections on its supply and demand at the global level (Henckens & Worrell, 2020).

Guohua et al. (Yuan, Elshkaki, & Xiao, 2021) estimated the expected combined future trends in nickel demand in China and found that, without recycling, China alone could require up to 80% of the global nickel reserve by 2050. The same authors then also estimated that the achievement of significantly improved recycling practices and recovery rates for nickel could instead limit the net demand for virgin nickel to between 20% and 55% of the global reserve by the same year.

3.8.1.d. Other critical raw materials for electric vehicles

Other CRMs that are potential causes for concern in terms of limiting the large-scale deployment of EVs are rare earth elements (REEs). REEs, especially neodymium and dysprosium used in neodymium-iron-boron (NdFeB) permanent magnets, are critical for mainly offshore wind turbine generators, but their ability to provide high magnetic flux density also makes them suitable for use in vehicle applications which call for lightweight and compact magnets.

Currently, there is no economic extraction outside of the south of China of heavy rare earth elements (HREE) such as dysprosium and terbium, this is mainly due to the very low content of HREE in ores, i.e. less than 1% outside of Southern China (USGS, 2022). Light rare earth elements (LREE), on the other hand, like neodymium and praseodymium, are extracted more globally. In terms of environmental and social implications, there have been serious concerns related to the extraction and refining of REEs, mainly due to the co-presence of radioactive elements and due to the chemicals used in the leaching process, which result in radioactive waste and other toxic pollutants leaking into the wastewater, waste gas and land during the extraction and refining process (Bonfante, et al., 2021).

However, some automotive companies have already started to reduce the use of permanent magnets in EVs by using induction motors or round-wound design based on copper, which points to a likely reduction in dependence on REEs for the future (De Koning, et al., 2018).

3.8.2. EV batteries: future technology roadmaps and end-of-life recycling

3.8.2.a. Evolutionary trends in the EV battery sector

i. Battery technology mix trends

The market mix of different battery chemistries, beyond the currently employed LIB options, has been estimated that it will be dominated by the NCA and NMC cathode mixes by 2030 (IEA, 2021), however future advancements will slowly phase these out and bring new technologies into play such as all-solid-state batteries (ASSBs) and sodium-ion batteries (NIBs) in 2050. ASSBs, including those with a metallic lithium anode, have the key advantage of doing away with the liquid (and flammable) electrolyte and electrodes, and they are often considered a key player for the future of energy storage, as they are an efficient solution to safety concerns of the electric transport sector (Kotobuki, Munakata, & Kanamura, 2013). NIBs, although showing lower gravimetric energy densities than LIBs, are characterised by a good cycle life (Sarkar, Rashid, & Hasanuzzaman, 2022) and do not require critical raw materials (such as lithium, nickel and cobalt) making them "greener" and more sustainable than other chemistries (Tarascon, 2020).

In terms of future EV battery technology mixes, the IEA has estimated through different scenarios (IEA, 2021) that by 2040 the most dominant mixes in the market would be these of ASSBs batteries and the NMC 811. Moreover, in Ricardo's own recent report to the EC (Hill, et al., 2020), it was estimated that NIBs could also gain a fair share of the market alongside the other two technologies by 2040. These advancements essentially indicate that future demand for cobalt and other CRMs could be limited down to levels that would not exceed global reserves by 2050, and further reduce their carbon-intensive mining procedures.

It is worth noting that there may also be a trade-off to be made between some of the alternative/newer battery chemistries and existing nickel/cobalt-based chemistries (i.e. NMC and NCA). The adoption of cobalt-free LFP-based chemistries and NIBs may help to reduce concerns over critical resources/supply constraints and reduce costs (and have a potentially longer battery life cycle). However, these options typically have lower energy density (so require more materials per kWh capacity) than current NMC/NCA chemistries, which may offset some of the gains elsewhere in terms of energy density and GHG impact (discussed also in the next section).

ii. Battery energy density trends

As of 2020, the highest reported gravimetric energy density for a Li-ion cell at near-commercial level was 304 Wh/kg, which is based on a silicon/graphite anode, paired with NMC811 cathode (The Faraday Institution, 2020). Regarding development of higher energy densities in other technologies, a 400 Wh/kg cell with nickel-rich cathode, a $LiCoMnO_4$ cathode battery providing 720 Wh/kg and a laboratory scale ASSB cell with 400-500 Wh/kg have all been manufactured in the last couple of years (Sion Power, 2022; The Faraday Institution, 2020; Solid Power, 2022). In this context, and considering plans from the EU and Asia to produce NCA, NMC and ASSB batteries over 400 Wh/kg by 2030 (Amici, et al., 2022), it is reasonable to expect that other technologies and mixes may start overtaking conventional LIB chemistries in future years in terms of energy density (The Faraday Institution, 2020). In addition to the trends on increased cell energy density, significant battery packaging improvements are also being made – e.g. the cell-to-pack (CTP) designs proposed by CATL and BYD (Battery Design, 2022), and alternative structural battery designs being developed by others such as Tesla (Teslarati, 2022).

iii. Price and materials trends

The average cost of LIBs has declined in the last 10 years by 90% in total, and it has been forecasted to further drop at 100 $/kWh by the mid-2020s (Frith, 2021). This future drop is however dependent on maintaining steady supply with the same drop-in costs, on mineral scarcity as well as on a shift to new technologies. For instance, progress in ASSBs research and development has further created incentives, that will result in further reducing costs and scaling up production (IEA, 2021). The NIBs industry has been focusing on anode materials that can increase the cell energy density (leading to less material mass and lower GHG impacts per kWh) and also help contain cost (Karuppasamy, et al., 2020). Nonetheless, mineral prices will still play a huge part in determining battery costs, as in 2021, 50-70% of total battery costs accounted for the raw materials used in the battery manufacturing (Argonne National Laboratory, 2020). Therefore, it is of major importance that technologies making use of less scarce materials be further developed, as the trend of cost decline that was observed during the last decade is not certain to continue without further development of innovative technologies.

iv. Battery manufacturing location trends and renewable electricity

The European Commission, as well as European manufacturers and researchers, are aware that the biggest producers of EV batteries are located in Asia, and have established clear goals to decrease this gap between the two regions. A 7-25% manufacturing share of EV batteries is planned to be located in Europe by 2028 (European Commission, 2019) while the targeted EU battery manufacturing capacity is set to reach 200-290 GWh/year by 2025 (Eddy, Pfeiffer, & Staaij, 2019). Facilities in Europe have been well evolving in the last few years, as factories are planning to reach capacities in the range of 100 GWh/year to 300 GWh/year in the upcoming decade (Tesla, 2022; Automotive Cells Co., 2022; Northvolt, 2022; FREYR, 2022). Irrespectively of the targets set, this effort by European stakeholders needs to be realised in a sustainable and environmentally friendly way. To achieve this, the electricity mix that is used in battery manufacturing needs to be produced with technologies harnessing renewable energy.

3.8.2.b. End-of-life battery recycling and second life

i. Recycling processes of EoL Batteries

Recycling is one of the most sustainable solutions when a battery reaches its End-of-Life (EoL) and can no longer be re-used in an EV. Critical raw materials (CRM) that have the potential to be re-used in new battery units, can be retrieved from EoL batteries and thus close a potentially significant gap between future supply and demand for these materials. There are currently three major recycling procedures for waste Li-ion batteries: pyrometallurgical, hydrometallurgical, and direct physical recycling.

Pyrometallurgical recycling adopts a well-established existing technology that is currently used in raw mineral ore smelting, and as such it can be seen as an immediate solution for battery recycling. However, its energy demand is very high, and therefore it is only viable as long as existing facilities can be leveraged; also, it does not allow recovering lithium, or any of the lighter elements (including the graphite anode) (Trower, Raugei, & Hill, 2022). A range of hydrometallurgical recycling processes are still being developed and optimised, and overall they show promise in enabling high recovery rates for all battery elements, as well as requiring far less energy per unit of EoL battery treated. Then, if water demand and wastewater generation are minimised, their overall environmental footprint will be further reduced (Zhou, Yang, Du, Gong, & Luo, 2020). Finally, direct physical recycling aims to recover the whole cathode and anode components for re-use, thereby potentially greatly reducing recycling losses and further improving circularity. However, this latter recycling approach requires the continued adoption of the exact same chemistry in new batteries, which represents a severe practical limitation to its real-world applicability.

ii. LCAs of EoL battery recycling

Research has shown that only a small proportion of studies have included battery recycling in their scope (Aichberger & Jungmeier, 2020), and even these offer results with limited accuracy due to the built-in assumptions. However, studies have tried to quantify the recycling benefits in terms of reduced GHG impacts attributed to recycling (Aichberger & Jungmeier, 2020), while others have highlighted that battery recycling can deliver even greater environmental benefits with less energy used (Dai, Kelly, Gaines, & Wang, 2019). Aichberger and Jungmeier (2020) calculated that the median recycling benefit in terms of reduced GHG impact thanks to recycling is about 20kgCO_2e/kWh, as the recycled materials substitute the primary materials, including the additional energy required to recycle the batteries. Naturally there is potential for further improvement of LCAs of EoL battery recycling, as recycling methods that are still under development are lacking in terms of LCA coverage (Aichberger & Jungmeier, 2020) and environmental impacts that are not easily identified can be analysed in future studies.

iii. Second-life batteries as a storage solution

Another use for EoL batteries, besides recycling their CRMs, is to be utilised as stationary energy storage. This could prove to be a sustainable solution in the future, as the levels of manufacturing of new grid-storage batteries could be reduced (Kamran, Raugei, & Hutchinson, 2021). Second life batteries could be used to offer reverse energy capacity, smart grid load dispatch and storage of renewable energy surges (Shahjalal, et al., 2022). The added flexibility that is generated by these uses has led to expectations that second life batteries may be 30% to 70% less expensive than newly manufactured packs in 2025 (Engel, Hertzke, & Siccardo, 2019). From an LCA point of view, given that the cost of batteries makes up the majority of the cost of an EV, especially if the second-life use of the battery lasts a long time, the improved residual value of new EV batteries by accounting for their second-life usage might be transferred to new EVs and create significant savings.

Nonetheless, challenges exist in the implementation of the above solutions, as widespread introduction of second-life batteries could reduce the much-needed flexibility that conventional dispatchable power-plants offer (Kamran, Raugei, & Hutchinson, 2021). Moreover, as remanufacturing prices are predicted to reduce at a slower rate than new battery manufacturing costs, the anticipated 30–70% cost advantage over newly built batteries could shrink to 25% by 2040 (Engel, Hertzke, & Siccardo, 2019) while rates of CRM recoveries would be delayed due to the prolonged stay of EoL batteries in the market (Xu, et al., 2020).

3.8.3. Infrastructure: grid integration and balancing and the role of vehicle-to-grid

The expected increase in EV ownership will require more energy generation and transmission through the grid to charge the batteries. Although the increased demand for electricity to charge EV batteries puts pressure on the grid system, the EV batteries themselves also represent an opportunity to enhance grid flexibility and provide ancillary support to the additional demand. A new, maturing technology, referred to as Vehicle-to-grid (V2G), allows EV battery packs to act as a decentralised storage system to absorb and later return energy to the electricity grid when the EVs are not in use. As variable renewable energies (VREs) like solar and wind are intermittent and non-dispatchable, EV batteries can thus store energy for later use with V2G technology, thereby reducing the need for large, dedicated storage facilities (Colmenar-Santos, Muñoz-Gómez, Rosales-Asensio, & López-Rey, 2019). With the expected increase in EV ownership in the future and technological improvement in on-board energy storage system capacity in EVs, V2G could be part of the solution to meet the fluctuating energy demand profile, while ensuring grid stability and reduced carbon emissions as the proportion of VREs usage increase.

Besides V2G, there are other strategies that are currently available for managing grid load, from grid and local distribution levels to EV users, to prevent overloading and downtime, including:

- Delay charging
- Load balancing
- Variable charging speed
- Distributed solar integration

These grid load management strategies can work in coordination across levels and stakeholders. For example, a study found that delayed charging with the addition of load balancing is sufficient to prevent damaging the existing distribution transformer system in some regions without need to upgrade the infrastructure (Muñoz, Razeghi, Zhang, & Jabbari, 2016). Delayed charging pushes back charging time when electricity demand from the grid is high, while load balancing reduces the input to the EV charger to avoid grid overload. For vehicles that do not support V2G or have little plug-in time due to their usage - like delivery vehicles and taxis - decreasing their charging speed during peak grid demand can prevent overload in energy infrastructure and to meet consumer demand.

Additionally, an increasing number of EV chargers offer solar integration functionality to allow end-users to charge their EV with energy generated from their solar panels, resulting in reduced grid energy demand and reduced non-renewable energy consumption. However, there are growing concerns from grid operators about ramping up electricity demand around late afternoon to compensate for the loss of solar generation just when the typical peak energy demand begins. The so-called "duck curve" pattern describes the typical load reduction and surges associated with decentralised solar energy systems, and similar patterns are observable in multiple regions worldwide (Sioshansi, 2016). With growing world demand for EVs, V2G has a unique advantage in smoothening the duck curve as the EV storage system can capture solar energy when it is available and consume it during peak demand hours, thereby leading to an overall increase in renewable energy deployment in the grid mix. In the long run, V2G has the potential to play a significant part in the full renewable energy transition. A study estimated that solar integration and V2G can mitigate the adverse effects of increased EV ownership to the grid, compared to uncoordinated EV charging (Fakhrooeian & Pitz, 2022).

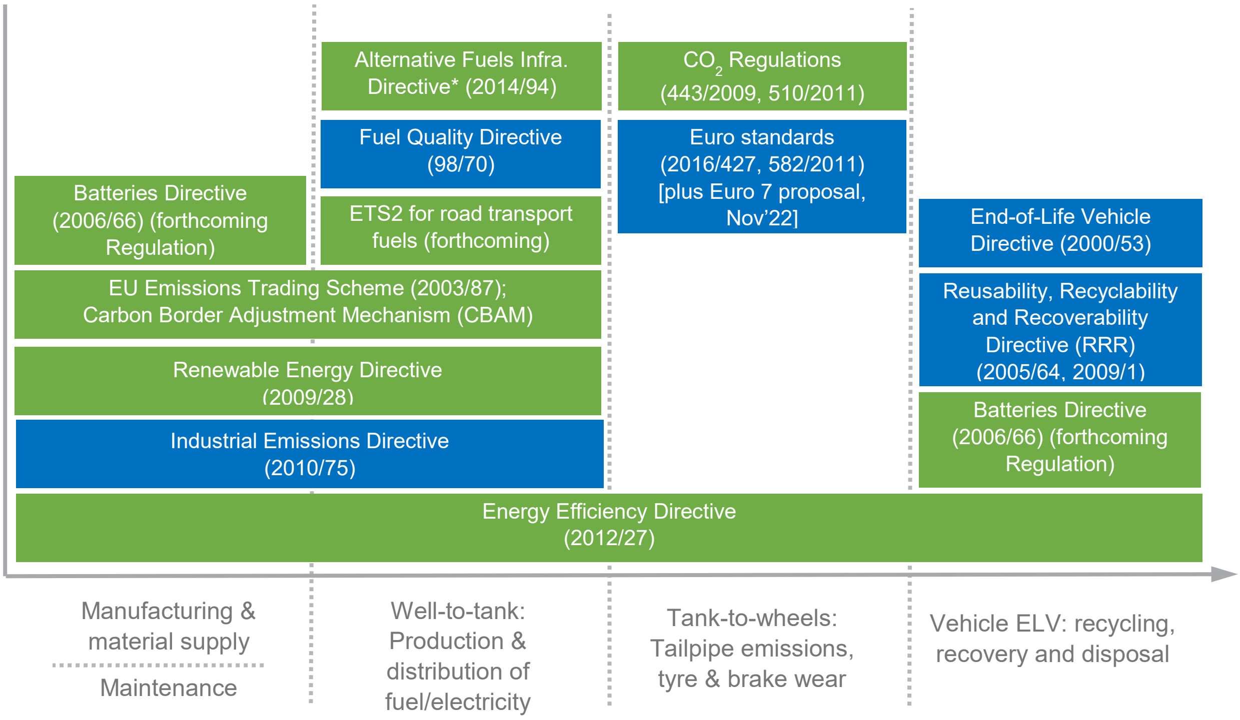
4. OVERVIEW OF RELEVANT EU LEGISLATION AND POLICY INITIATIVES

KEY FINDINGS

- A wide range of EU policies affect different vehicle life cycle stages, the large majority of which have been proposed or revised recently as part of the Fit for 55 package or separately to contribute to the objectives of the Green Deal.
- At the production and end-of-life stages, a number of policies emerging from the Circular Economy Action Plan, and particularly the Sustainable Battery Regulation and the revised End-of-Life Vehicle Directive, are expected to further reduce GHG emissions and other impacts associated with vehicle and battery production.
- The revision of the EU Emissions Trading Scheme, including the Carbon Border Adjustment Mechanism and the revised Renewable Energy Directive, impose more ambitious GHG emissions reduction targets at manufacturing and energy supply (i.e. well-to-tank) stages. The proposed ETS2 for road transport is expected to lower GHG emissions from fuels used in the existing ICEV fleet.
- At the use stage, the revised regulation on CO_2 standards for cars and vans provides an accelerated transition to zero-emission vehicles, expected to be predominantly BEVs, while the proposed Euro 7 standard may reduce air pollution impacts from both ICEVs and BEVs.

A range of policies need to work synergistically to ensure overall reductions in environmental impacts across the vehicle life cycle (see Figure 4-1).

Figure 4-1: Simplified mapping of key European legislation to vehicle life phase



Source: Ricardo (own elaboration).
Notes: Additions/updated proposals in 2021 / Fit for 55 legislative package highlighted in green.

At the **manufacturing and material supply stage**, the overarching Industrial Strategy [COM(2020) 350 final] follows the vision of the European Green Deal and aims to achieve sustainable growth and climate neutrality, covering manufacturing processes and key materials. One of the fundamentals of the Industrial Strategy is the adoption of the Circular Economy Action Plan [COM(2020) 98 final], which introduces a common methodology and principles for a "sustainable products" policy to support the circular design and sets minimum requirements to prevent environmentally harmful products from being placed on the EU market.

The Circular Economy Action Plan and Industrial Strategy are associated with a range of specific sectoral strategies focusing on key materials to create more sustainable and circular products, most of which are relevant to the automotive supply chain, including the Chemicals Strategy for Sustainability [COM(2020) 667 final], EU Strategy for Plastics in the Circular Economy [COM(2018) 28 final], EU Strategy for Clean Steel and the EU Textiles Strategy [COM/2022/141 final]. A circular economy design and management of vehicle components is expected to deliver a consistent mitigation potential across all life cycle impact categories at the production stage. In particular, circular economy concepts may mitigate resource depletion risks associated with critical raw materials used in vehicle batteries and electronic components.

In addition, the Circular Economy Action Plan foresees a review of key legislation, including Industrial Emissions Directive [2010/75/EC]; End-of-Life Vehicles Directive [2000/53/EC] and Batteries Directive [2006/66/EC], among others.

The Industrial Emissions Directive [2010/75/EC] sets requirements on pollutant emissions for large industrial installations, which covers material extraction and vehicle manufacturing activities, as well as fuel and electricity generation. The revision proposal [COM/2022/156 final/3] aims to bring it into line with the EU's zero pollution ambition, energy, climate and circular economy policy goals. This policy development is expected to mitigate non-GHG impacts from vehicle production across all powertrains and energy generation such as particulate matter formation and human toxicity potential.

The proposed Sustainable Batteries Regulation [COM/2020/798 final][8], which will repeal Directive 2006/66/EC, will establish requirements for sustainability, safety, and labelling of batteries as well as requirements for end-of-life management (described below). A carbon footprint declaration and label will be obligatory for EV batteries and other battery applications. From 2027, carbon footprint performance classes will be introduced with maximum threshold values. Requirements on recycled content, performance and durability will also be introduced gradually from 2024 onwards. In addition, the new regulation introduces due diligence obligations for rechargeable xEV batteries, among others, covering critical raw materials used in batteries (i.e. cobalt, natural graphite, lithium, nickel, and their chemical compounds). The carbon footprint declaration, with the future introduction of maximum thresholds, along with due diligence obligations and further requirements on battery production, are likely to contribute to reducing GHG impact and other impacts associated with battery production and materials extraction for BEVs.

The Due Diligence Initiative [COM/2022/71 final] will require review of operations, products and services in relation to environmental and social concerns. This will apply to companies' own operations and the operations of their subsidiaries and their entire value chains. Large EU and non-EU companies will have to adopt a plan to ensure that their business model and strategy are compatible with a transition to a sustainable economy, as well as with limiting global warming to 1.5°C in line with the

[8] In December 2022, Parliament and Council reached a provisional agreement to overhaul EU rules on batteries.

Paris Agreement. This initiative has the potential to foster decisive action from large EU and non-EU vehicle manufacturers on decarbonisation of their own operations and their supply chain.

The EU Emissions Trading Scheme (EU ETS), the Carbon Border Adjustment Mechanism (CBAM) and the Renewable Energy Directive affect **both the manufacturing and energy supply (i.e. well-to-tank) stages**.

The EU ETS [2003/87/EC] sets a cap-and-trade scheme, which works by capping overall GHG emissions of all participants in the system with a limited number of allowances that can be traded. The EU ETS covers the power sector[9], energy-intensive industrial plants[10] and the aviation sector[11]. The EU ETS revision proposal [COM/2021/551 final] is proposing to reduce the emissions from the EU ETS sectors (including the extension to the maritime sector) by 61% by 2030, compared to 2005 levels, in line with the overall 55% GHG reduction target by 2030 (on 1990 levels). This increased ambition is expected to accelerate the decarbonisation of electricity generation in the EU and further reduce the GHG impact of BEVs at the well-to-tank stage. Considering that key materials for the automotive industry (e.g. steel and iron and glass) are also included in the EU ETS, this increased ambition will also contribute to lowering GHG impact at the production stage across all vehicle powertrains.

The EU ETS revision proposal [COM/2021/551 final] also establishes a separate self-standing emissions trading system for fuel distribution for road transport and buildings (ETS2) in which fuel distributors are the regulated entities. As per the provisional agreement reached by Council and the European Parliament, the system will start in 2027 (Council of the European Union, 2022b). For road transport, fuel distribution for both commercial and private vehicles will be included in the scope. This new scheme for road transport fuels is expected to contribute to lowering GHG impact from fuels used in the existing ICEV fleet.

To minimise carbon leakage (i.e. companies based in the EU moving carbon-intensive production abroad to take advantage of lax standards, or EU products being replaced by more carbon-intensive imports), the EU ETS revision proposal includes a Carbon Border Adjustment Mechanism (CBAM)[12]. Under the CBAM, EU importers will buy carbon certificates corresponding to the carbon price that would have been paid, had the goods been produced under the EU's carbon pricing rules. The CBAM will be phased in gradually, in parallel to a phasing out of the free allowances under the EU ETS, which is the current mechanism to prevent carbon leakage in some sectors.

The Renewable Energy Directive [2018/2001/EC] sets binding renewable energy targets and comprises measures for the different sectors to make it happen. The Fit for 55 revision [COM/2021/557 final] includes the following targets by 2030: 40% of energy from renewable sources, transport GHG intensity reduced by 13%, 2.5% of renewable hydrogen and synthetic fuels and 2.2% of advanced biofuels. Together with the Fuel Quality Directive [2009/30/EC] it also regulates the 'sustainability criteria' of biofuels.

At the use stage, the most critical regulation is the CO_2 Emissions Standards for Cars and Vans Regulation [2019/631/EC], which sets EU fleet-wide CO_2 emissions targets and includes a mechanism to incentivise the uptake of zero- and low-emission vehicles. The EC proposal [COM(2021) 556 final], as well as the provisional agreement of the Council and the European Parliament, requires average

9 Power stations and other combustion plants with ≥20MW thermal rated input (except hazardous or municipal waste installations).

10 Oil refineries, coke ovens, iron and steel, cement clinker, glass, lime, bricks, ceramics, pulp, paper and board, aluminium, petrochemicals, ammonia, nitric, adipic and glyoxylic acid production, CO_2 capture, transport in pipelines and geological storage of CO_2.

11 Intra-EEA flights only.

12 CBAM will initially cover a number of specific products in some of the most carbon-intensive sectors: iron and steel, cement, fertilisers, aluminium, electricity and hydrogen, as well as some precursors and a limited number of downstream products. Indirect emissions would also be included in the regulation in a well-circumscribed manner (Council of the European Union, 2022c).

emissions of cars to reduce by 55% from 2030 (50% for vans) and by 100% from 2035 compared to 2021 levels. This means that all new vehicles registered as of 2035 will be zero-emission in terms of the tailpipe CO_2 emissions. This provides an accelerated transition to zero-emission vehicles, expected to be predominantly BEVs.

The provisional agreement on CO_2 standards for cars and vans also includes wording on CO_2 neutral fuels whereby the Commission will make a proposal for registering vehicles running exclusively on CO_2-neutral fuels after 2035. In addition, the text requires the Commission to develop a common EU methodology, by 2025[13], for assessing the full life cycle of CO_2 emissions of cars and vans placed on the EU market, as well as for the fuels and energy consumed by these vehicles. Based on this methodology, manufacturers may, on a voluntary basis, report to the Commission on the life cycle emissions of the new vehicles they place on the market. This intends to provide consistent data reporting of the full life cycle CO_2 emissions.

To complement CO_2 emissions targets with sufficient deployment of charging infrastructure, the Fit for 55 package also included the proposed Alternative Fuels Infrastructure Regulation [COM/2021/559 final], which would repeal the previous Directive 2014/94/EU. For publicly available electric charging infrastructure for cars and vans, the draft regulation sets out mandatory national fleet-based targets (e.g. for every BEV a total power output of at least 1 kW should be provided). It also sets out distance-based targets on the TEN-T core and comprehensive network (e.g. maximum distance between publicly accessible recharging pools for cars should be 60 km by 2026).

In November 2022, the Commission proposed a new emission standard for road vehicles: Euro 7 [COM(2022) 586 final]. The new rules will further reduce air pollution limits from new motor vehicles sold in the EU and expand the scope to non-exhaust emissions, starting with brakes' emissions from cars and vans along with new battery durability requirements. In this sense, the new Euro 7 standards are expected to contribute not only to reducing air pollution emissions from ICEV, but also to abating emissions of ultrafine particles from brakes also present in BEVs and to improving battery durability.

The Energy Efficiency Directive [2012/27/EC] sets targets for reduction in energy use across all energy products. Under the Fit for 55 revision [COM/2021/558 final], a more ambitious binding annual target for reducing energy use at EU level will be set at 9% reduction in energy consumption by 2030.

At the end-of-life stage, the End-of-Life Vehicles Directive [2000/53/EC] sets targets for reuse/recycling (85%) and reuse and recovery (95%) of components from end-of-life vehicles. This piece of legislation is being revised with the aim to address the new technologies, materials and challenges that have emerged since its adoption, including new methods for the reduction of waste generation, promotion of more circular business models and new processes to extend the lifetime of vehicles. This is complemented by the Reusability, Recyclability and Recoverability (RRR) Directive [Directive 2005/64/EC], which requires manufacturers to design vehicles so that minimum thresholds of vehicle's parts and materials may ultimately be reused, recycled and recovered.

The proposed Sustainable Batteries Regulation [COM/2020/798 final] mentioned above also introduces requirements to ensure that batteries are readily removable and replaceable, which will facilitate the repurposing of batteries from EVs for a second life (e.g. as stationary energy storage systems, or integration into electricity grids). The proposal also sets increasingly stricter targets on collection rates, recycling efficiencies and recovery of materials, particularly for valuable materials such as copper, cobalt, lithium, nickel and lead. Specific IT tools, such as the battery passport, will be introduced to

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[13] Under the current regulation [2019/631/EC], the Commission shall no later than 2023 evaluate the possibility of developing such a methodology.

increase transparency of the battery market and the traceability of large batteries throughout their life cycle.

The (revised) End-of-Life Directive along with the proposed Sustainable Batteries Regulation are expected to promote innovation and new business models in end-of-life reuse, recovery and recycling of battery elements and other vehicle components and reduce end-of-life GHG impacts or generate net positive effects.

5. COMPARISON OF LIFE CYCLE IMPACTS OF BEVS VS ICEVS: CURRENT AND FUTURE OUTLOOK

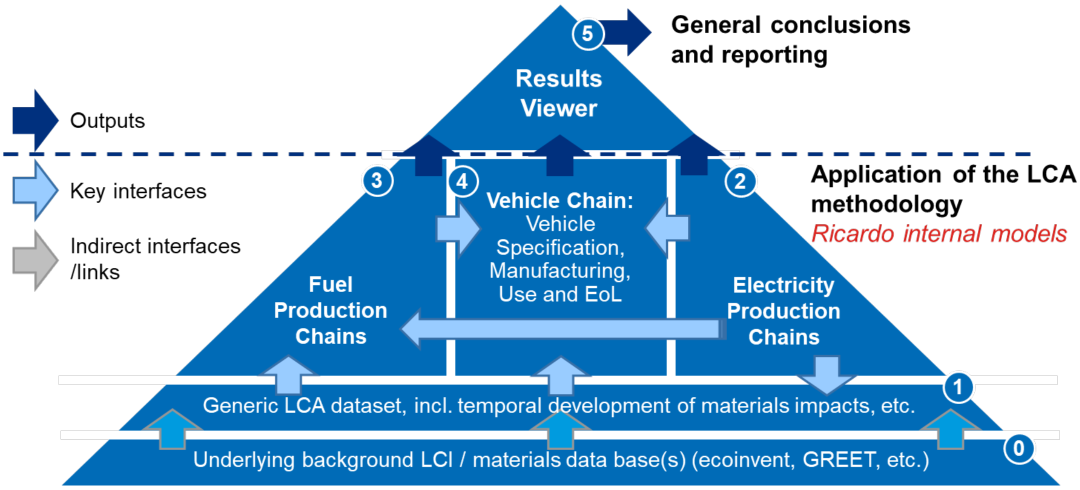
KEY FINDINGS

- Significant life cycle GHG emissions reductions have been found for battery electric cars compared to conventional gasoline and diesel vehicles operating in average EU conditions, as well as across different situations across different countries.
- A typical battery electric car in the current situation is already estimated to save over ~60% GHG impacts compared to an equivalent conventional gasoline car.
- For BEVs, production impacts are around 50% higher than gasoline cars in 2020 (mainly due to the batteries) and make up 58% of total estimated life cycle GHG impacts. By 2050, production emissions for BEVs may only be slightly higher than conventional vehicles.
- Analysis of the future outlook (e.g. accounting for the effects of technology and European policy proposals and long-term objectives) shows that the GHG benefits of BEVs are expected to further increase. By 2030, average GHG reductions in the EU27 could reach ~78% reduction compared to an equivalent conventional gasoline car. A combination of improved battery technology and a further decarbonised electricity grid are the key drivers for this. By 2050, these savings could further increase to 86%.
- BEVs also provide significant improvements for a range of other environmental impact categories. Reduction in direct air pollutant emissions (by up to 100% for most) is particularly important to reduce human health impacts in urban environments.
- Net end-of-life (EoL) impacts are estimated to reduce the overall GHG impact from the vehicle life cycle by around 7% for BEVs, due to credits from material recycling and energy recovery. Improvements in the future recycling and recovery of critical materials (and electronic components) were shown to help maximise BEVs benefits in the future, increasing these net EoL credits to over 12% of the total life cycle impacts by 2050.

5.1. Overview of the analysis of current and future outlook

One of the key objectives of this project is to provide an assessment of the current and prospective future comparison of ICEV vs BEV passenger cars (i.e. based on Fit for 55 /policy and technical developments). To meet this objective, we have selectively updated the comprehensive and detailed LCA modelling of passenger vehicles, previously developed in-house by Ricardo for the European Commission (Hill, et al., 2020). An overview of Ricardo's modelling framework is provided in Figure 5-1 below, with a further summary of some of the key updates to the modelling provided in Annex 3 of this report. This has been used to provide a mainly quantitative assessment of the potential influence of a range of future changes in the life cycles and supply chains of ICEVs and BEVs on their life cycle GHG impact and Cumulative Energy Demand (CED), beyond those elements already captured and discussed by the surveyed literature (in Chapter 3). The rest of this chapter provides a summary and discussion of the results of this analysis.

Figure 5-1: Outline of Ricardo's vehicle LCA modelling framework, used in this project



Source: Ricardo (own elaboration).

5.2. Current state of play/performance comparison

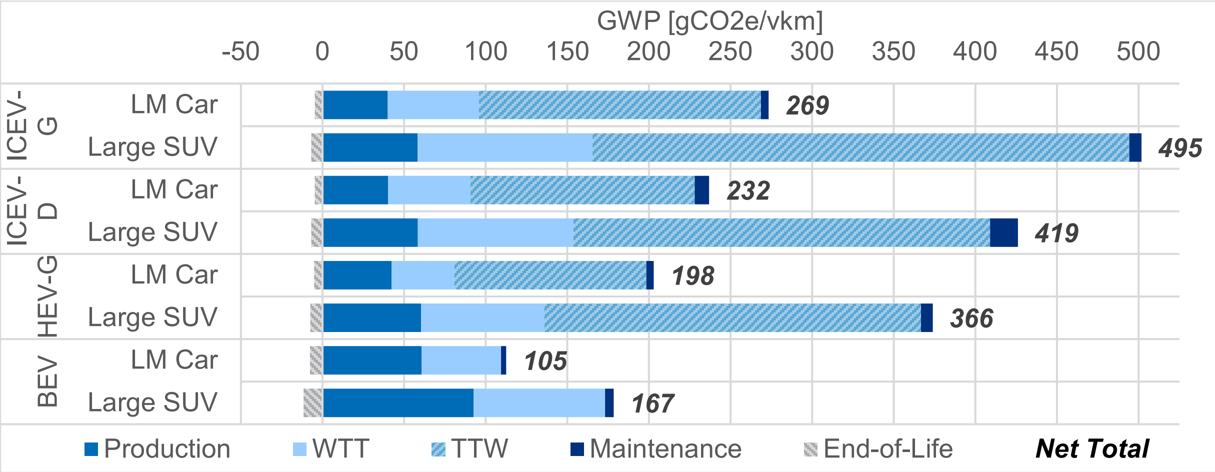
5.2.1. Current life cycle GHG and CED impacts

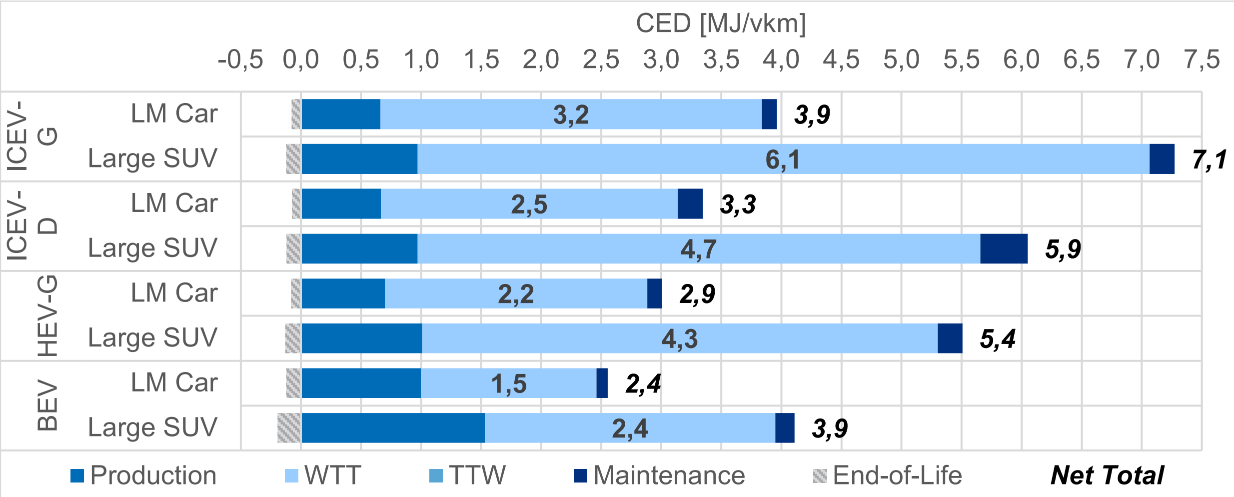
For the current performance comparison, LCA modelling is based on the current policy scenario assumptions (i.e. aligned to the updated EC REF2020 scenario (European Commission, 2021a)). Figure 5-2 provides a summary of the main results for the life cycle GHG impacts for typical passenger cars operating in the EU. Results are presented for the Lower Medium Car (i.e. VW Golf size or similar) and Large SUV (i.e. Volvo XC90 or similar) segments. This provides a comparison of the estimated current (~2020) performance for conventional ICEVs, HEVs and BEVs powertrain types. Some high-level results are also shown in the figure for the cumulative energy demand (CED) LCA indicator – which provides a good indication on the overall efficiency of the use of primary energy (important in the context of limited renewable energy sources). Based on the modelled lifetime energy/recharging requirements and battery life cycle, no traction battery replacements were required for passenger cars in typical use, consistent with the expectations of manufacturers and the assessment of Ricardo's internal EV and battery technology experts (Ricardo et al., 2020).

The results for GHG impacts (in kgCO_2eq for the GWP– global warming potential) clearly show the significant benefits of BEVs in comparison to conventional gasoline and diesel ICEVs and hybrids. Already in 2020, a new BEV is expected to reduce GHG impacts by over 60% compared to a conventional gasoline vehicle, when operating in real-world conditions over 15 years (and with a typical 225,000 km lifetime for Lower Medium Cars, 270,000 km for large SUVs). This is an even greater saving than previously found in our analysis for DG CLIMA (Ricardo et al., 2020) (i.e. a 55% reduction for BEVs), mainly due to a more up to date (and cleaner) electricity mix for 2020 (and also for the updated European Commission modelling projections to 2030), compared to the previous work. The reduction in impacts for the CED indicator are also substantial, but slightly less than for GWP.

As can be seen in the charts, the trends in results for Lower Medium Cars and Large SUVs are broadly similar, with slightly higher reductions for Large SUV BEVs when comparing with similar powertrains (although the majority of these vehicles tend to be diesel). Therefore, the rest of the analysis in this report chapter will focus on the Lower Medium Car segment.

Figure 5-2: Breakdown of the current GWP and cumulative energy consumption impacts for a Lower Medium Car and Large SUV, 2020, EU27





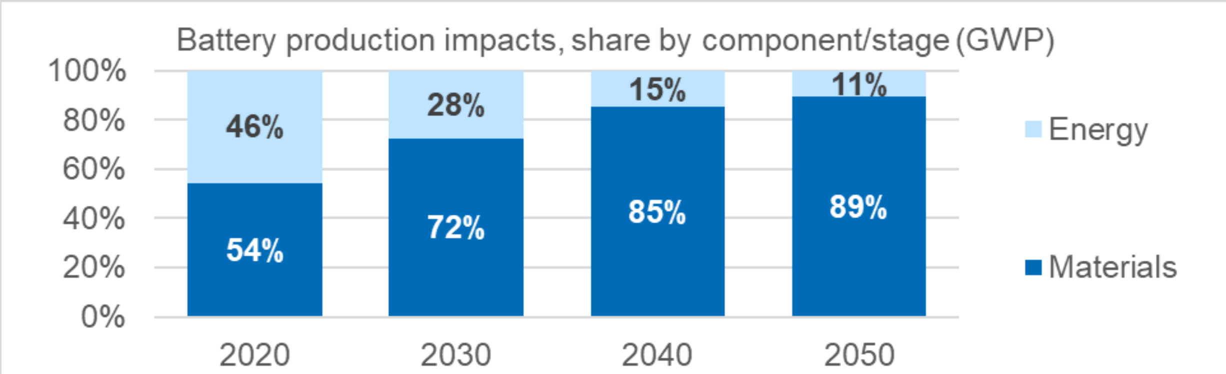
Sources: Ricardo LCA modelling, January 2023.
Notes: GWP = Global Warming Potential; CED = Cumulative Energy Demand.
***Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the 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. **Net Total** = the sum of the positive and negative (e.g. end-of-life credit) impact components included in the bar chart.*

In the following subsections there is a further discussion on the analysis by life cycle stage, and some key sensitivities analysed to explore the influence of key parameters.

5.2.1.a. Impacts from the vehicle and battery production phase

The majority (over 80%) of the GHG impacts from the manufacturing of the components common for all vehicle types (i.e. the 'Glider') is due to the use of steel, aluminium and plastics (see Figure 5-4). As discussed earlier, in Chapter 3.4, the manufacturing of BEVs results in significantly higher emissions than conventional gasoline and diesel vehicles due to battery production. For the current situation, these production impacts (due mainly to materials and energy consumption) are around 50% higher for BEVs (and over half the total life cycle impact of a BEV), with the battery accounting for around a third of the total production impact. However, improvement in the technical performance of these batteries has seen extremely rapid in recent years and further improvements are anticipated in the future (which is analysed and discussed further in Section 5.3). Increases in the scale of xEV battery manufacturing has also led to efficiencies and reduced overall impacts. GHG impacts from energy consumption currently accounts for almost half of battery manufacturing emissions (Figure 5-3). However, a shift to more European-centric supply and manufacturing chains for EV batteries, is reducing such manufacturing impacts (where materials production and the electricity supply is less GHG intensive). Many vehicle manufacturers are now also specifying the use of renewable electricity in their battery supply contracts, which will further reduce impacts.

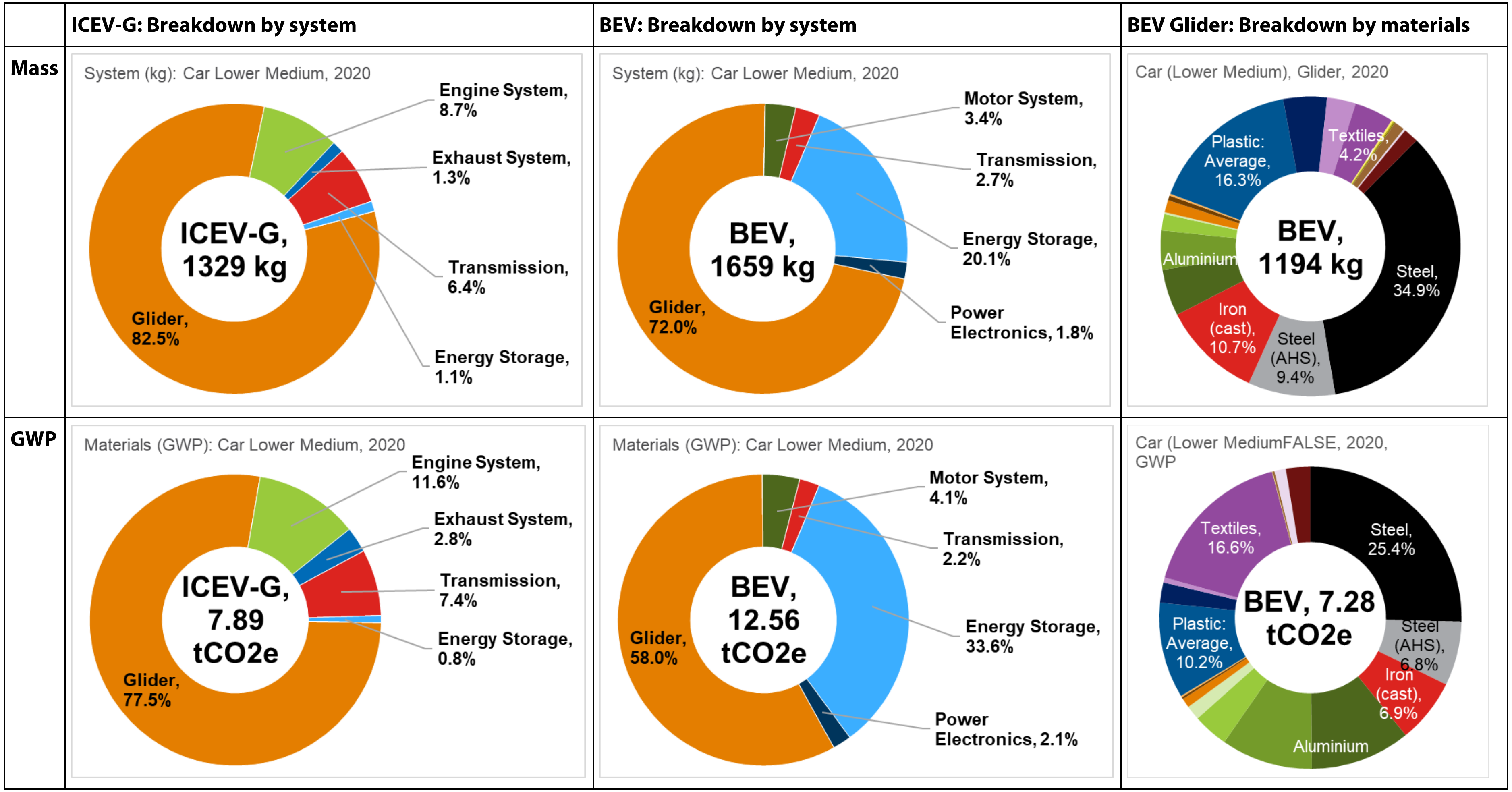
Figure 5-3: Breakdown of GHG impacts for BEV battery production, EU27 supply mix



Source: Ricardo modelling, January 2023.

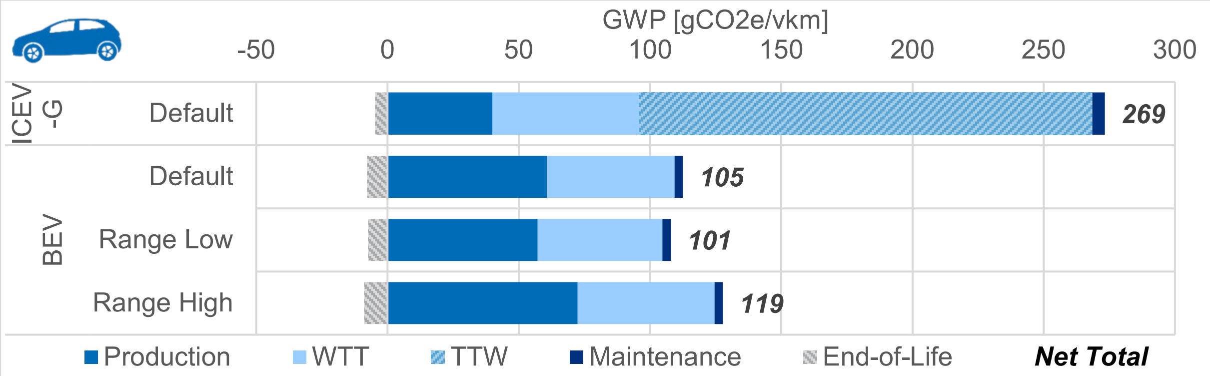
The size of the battery is a key determinant of the overall life cycle GHG impacts of a BEV, and there are models available on the market with a wide variety of different battery size and range options. Therefore, a sensitivity analysis has been performed on the influence of this on the overall comparison. Figure 5-5 below provides a summary of the results for life cycle GHG impacts for the default range/battery size, and for low and high alternatives, which are also representative of those available on the market currently for Lower Medium Cars. The results show a variation in the GHG reduction of BEVs compared to a conventional gasoline vehicle (i.e. ICEV-G) of 56%-62%. This variation is mostly due to differences in manufacturing impacts (with smaller effects due to the influence on vehicle mass changes on energy consumption for different battery sizes). The assumed end-of-life battery recycling also offsets some of the changes in net GHG impacts.

Figure 5-4: Breakdown of vehicle mass and material GHG impacts by system for a Lower Medium Car, 2020, EU27



Sources: Ricardo LCA modelling, January 2023.
Notes: AHS = Advanced High-Strength (steel); Glider = all other components that are not powertrain-specific (i.e. mainly the vehicle body, chassis, interior, wheels, etc.).

Figure 5-5: Sensitivity on the influence of electric range/battery size on GHG impacts, Lower Medium Car, 2020, EU27



Sources: Ricardo modelling, January 2023.
Notes: Default electric range for a BEV in 2020 is assumed to be 320 km with a 50 kWh battery. Low range is assumed to be 260 km (with a 40 kWh battery), and high range is 520 km (with an 81 kWh battery).

5.2.1.b. Impacts from the vehicle use phase and regional variations

Besides the lifetime activity, a key determinant of the life cycle impacts from the vehicle use phase are the operating conditions (e.g. driving on different road types, ambient temperature, etc.) and particularly the electricity mix/source used to power BEVs. These parameters can all vary significantly across Europe, and so the potential effects of these variations have been explored using Ricardo's model. The following six EU countries (see Table 5-1) were selected to provide a range of different situations. Their selection was based on a consideration of geographic location (also affecting ambient temperature), size, electricity grid mix and shares of driving on urban/non-urban roads (as BEVs operate particularly efficiently in urban conditions).

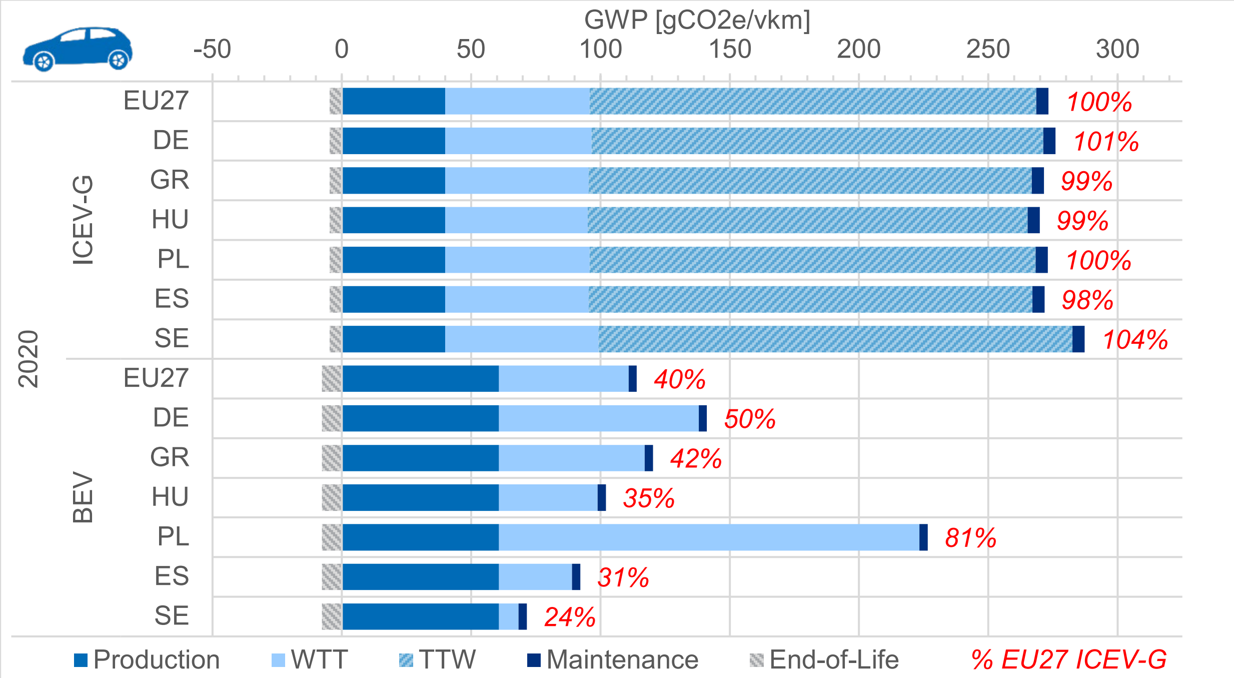
Table 5-1: Key parameters for different EU27 countries

2020	Germany	Greece	Hungary	Poland	Spain	Sweden	EU27
EU Region	North/West	South	East	North/East	South/West	North	**Av.**
#Cars *	~48 million	~5 million	~4 million	~25 million	~25 million	~5 million	**~246 million**
gCO_2/kWh **	314	454	215	710	177	8	**229**
Urban Km ***	26.7%	35.0%	14.8%	21.5%	27.7%	32.5%	**28.0%**

Sources: * (ACEA, 2022b); ** (EEA, 2022); *** *Based on EC modelling data from* (Ricardo et al., 2020).

The following Figure 5-6 shows the variation in the results for conventional gasoline cars (ICEV-G) and for BEVs for the six different countries, compared to the EU27 average in 2020. The small variations in results for ICEV-G is due mainly to different driving shares by road type, and to a lesser extent by accounting for differences in average ambient temperature (also discussed further later). There are much more pronounced variations for BEVs, mostly driven by the country's electricity mix (and its projected change over the vehicle lifetime). However, in all cases, the life cycle GHG impacts for BEVs are lower than for conventional gasoline cars.

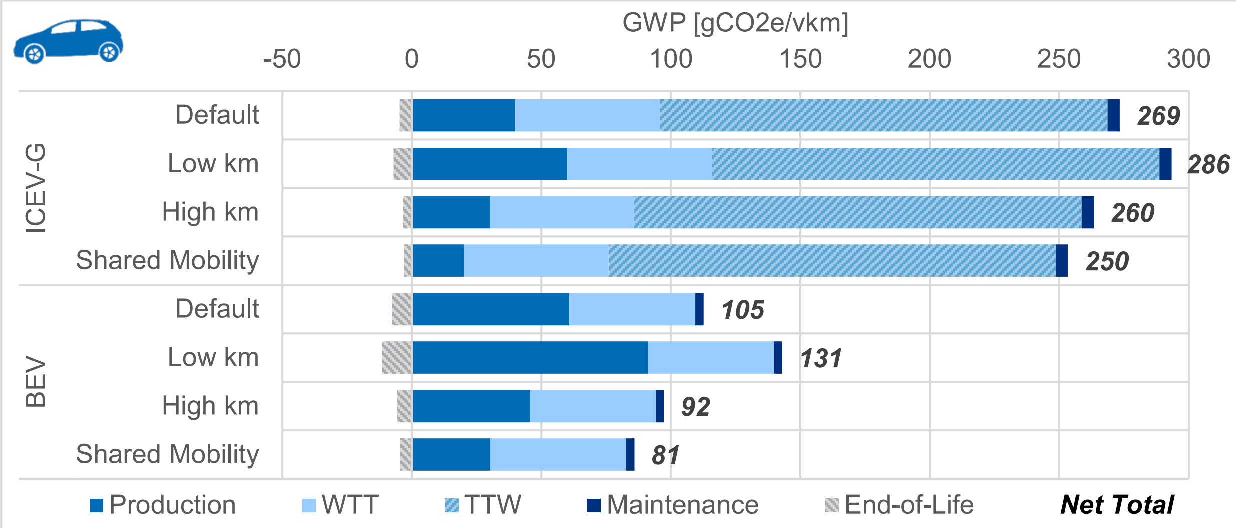
Figure 5-6: Regional variations in life cycle GHG impacts for Lower Medium Cars, 2020, EU27, selected EU countries



Sources: Ricardo modelling, January 2023.
Notes: The variation in use phase impacts is influenced by variations in the share of driving on different road types, differences in average ambient temperature and the change in energy mix (also over the vehicle lifetime).

As indicated, one of the most important factors affecting both the absolute life cycle impacts and the comparative impacts of ICEVs and BEVs is the overall lifetime activity. Since the impacts in the use phase for BEVs are lowest, higher lifetime km improve the relative comparisons with ICEVs (and lower km reduce the benefits). The following Figure 5-7 provides an illustration of the significance of lifetime km to the comparison through three alternative usage conditions. These include low km (150,000 km, often used in the LCA literature), high km (300,000 km) and shared mobility (i.e. very high – 450,000 km, double the default assumption). The sensitivity shows a relatively modest variation of life cycle GHG impacts reduction for BEV between 54% to 68% versus a gasoline ICEV operating in similar conditions.

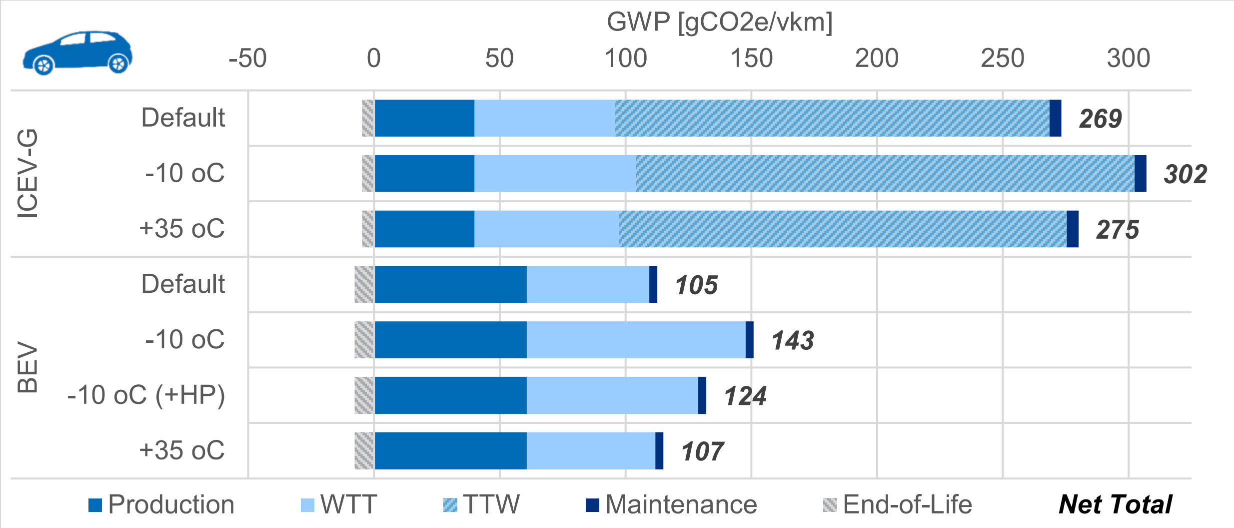
Figure 5-7: Sensitivity on the influence of lifetime vehicle activity on GHG impacts, Lower Medium Car, 2020, EU27



Sources: Ricardo modelling, January 2023.
Notes: The default lifetime activity for a Lower Medium Car is assumed to be 225,000 km; sensitivities for low/high lifetime activity assessed were for 150,000 km and 300,000 km; in addition, a very high 'shared mobility' scenario assumed double the default lifetime activity at 450,000 km.

A final sensitivity relevant to the use phase was also run, involving the exploration of the effect of (average) ambient temperature - based on previous analysis/settings from (Ricardo et al., 2020). The energy consumption and consequential operating range is significantly affected by colder weather (and to a lesser extent hotter conditions) due to a combination of passenger cabin heating and impacts on the powertrain/battery efficiency. However, the efficiency of conventional vehicles is also affected to a lesser degree, and since these have much higher impacts from operation, the absolute effects are fairly similar – as can be seen in Figure 5-8 below. It should be noted that the results shown in this sensitivity can be considered extreme ranges, since none of the EU27 countries experience average annual temperature conditions with this variation. The results show that in the 35 °C case, the relative GHG impact reduction for BEVs is almost exactly the same (at ~61% reduction), but for the -10 °C case (without an efficient heat pump) the benefits are reduced to ~53% compared to the conventional gasoline vehicle.

Figure 5-8: Sensitivity on the influence of ambient temperature on GHG impacts, Lower Medium Car, 2020, EU27



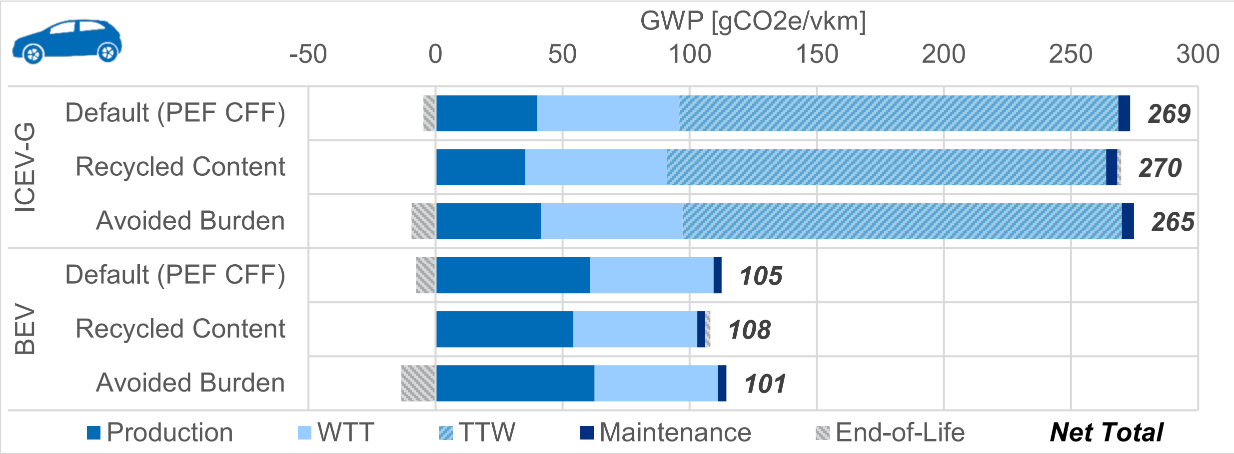
Sources: Ricardo modelling, January 2023.
Notes: Ambient temperature sensitivities assume 100% operation over the lifetime of the vehicle at the indicated ambient temperature, to provide extreme upper/lower bounds. HP = a heat pump system used in some EVs to provide more efficient cabin heating and battery thermal management.

5.2.1.c. Impacts from the vehicle end-of-life phase

Depending on the end-of-life (EoL) method applied, impacts from the final EoL phase can be positive (e.g. cut-off/recycle content method) or negative (e.g. PEF CFF – as applied here, or avoided burden) where net credits (i.e. shown as negative emissions in the results presented here) are applied/relevant for materials and energy recovery. The European legislation (e.g. EC End-of-Life Vehicle (ELV) Directive) and national implementations ensure high levels of recycling of vehicles and recovery of materials (typically over 80% for steel and aluminium). However, automotive battery recycling and recovery rates/efficiency is relatively low/immature currently, mainly due to the currently low volumes of EVs reaching this phase. However, as mentioned in Chapter 3, there is rapid development and investment in this area and the proposed Battery Regulation (European Commission, 2020) sets improved future requirements on battery recycling and recovery rates, which will yield significant benefits to the overall life cycle impacts from the EoL phase of new vehicles put on the market today. Further benefits are also expected (and calculated in our modelling) as a result of potential second-life applications for BEV batteries.

It is important to note that the EoL method applied also affects the treatment of recycled/secondary material used in the production stage. Since the EoL method can significantly influence the presentation and magnitude of the impacts assessed for the production and EoL phases, the effects are also further illustrated in a sensitivity on this, shown in Figure 5-9. It can be seen that the method adopted has a bigger effect on the results for BEVs versus ICEVs.

Figure 5-9: Sensitivity on the influence of the end-of-life (EoL) allocation methodology on net life cycle GHG impacts, Lower Medium Car, 2020, EU27



Sources: Ricardo modelling, January 2023.

5.2.2. Other environmental impacts

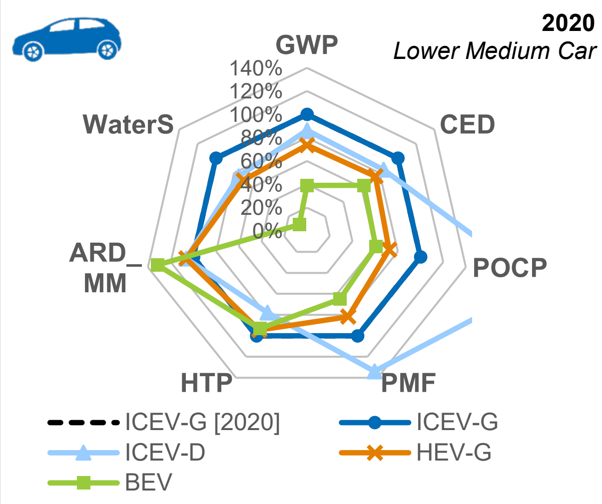
In addition to impacts due to life cycle GHG emissions and energy consumption, it is also important to consider the other environmental and health impacts of a vehicles life cycle. This provides for a more holistic assessment and helps understand where there might be different hotspots/trade-offs. Figure 5-10 provides a high-level comparison of the performance of BEVs compared to ICEVs and HEVs for a range of seven key criteria for both Lower Medium Cars and large SUVs (see Annex 3 Table A2 for further information on these impact categories).

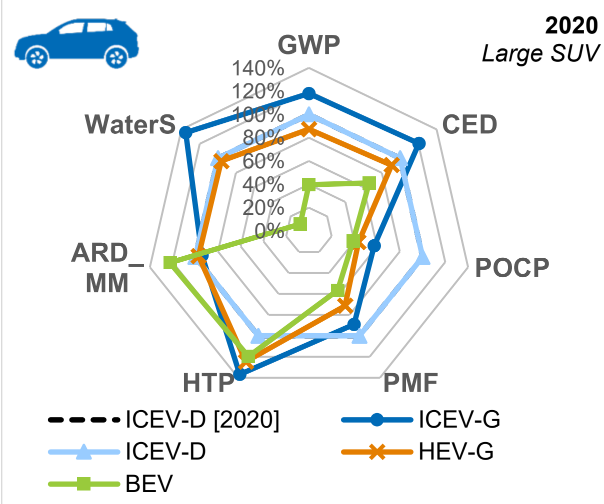
Whilst BEVs do not have exhaust emissions, there are still non-exhaust particulate emissions (from tyre and brake wear) and emissions associated with the vehicle manufacturing and electricity production. The non-exhaust emissions of BEVs are assumed to be similar to other vehicle types as there are currently no robust datasets available on their emissions versus conventional vehicles. Tyre wear emissions from BEVs are likely to be higher due to their higher weight, but brake wear emissions are likely to be lower due to regenerative braking (Ricardo, 2021a). The recent Euro 7 proposal of the Commission also aims to address tyre and brake wear emissions in the future (European Commission, 2022a).

Overall, the results show that BEVs perform better (in most cases significantly) than the ICEV and HEV powertrains across all the impact criteria (and also individual air quality pollutants), except for abiotic resource depletion – minerals & metals ('ARD_MM' in this report). This LCA indicator attempts to capture material scarcity impacts across a wide range of substances. However, the impacts are completely dominated by the use of copper and electronic components. Critical materials used (in relatively very small quantities, by mass) in batteries and electric motors (notably lithium, cobalt, nickel and rare earth metals – discussed in earlier Section 3.8.1) do not appear to significantly influence the results. This makes this indicator less useful to assess known concerns about the supply, and these materials are very important to consider at a wider system/fleet level, where effective recycling is important to recover them for reuse.

In terms of impacts on human health, exposure is particularly important for the actual health impacts resulting from air quality pollutants (which is also not captured in LCA), and most of the emissions from BEVs occur in life cycle phases (i.e. manufacturing, electricity generation) that are largely outside of heavily populated areas (unlike for direct exhaust emissions from vehicles with combustion engines).

Figure 5-10: Summary of relative impacts for Lower Medium Car and Large SUV for selected metrics, 2020, EU27





Sources: Ricardo modelling, January 2023.
Notes: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100% for Lower Medium Cars and relative to a 2020 conventional diesel ICEV = 100% for large SUVs.
GWP = Global Warming Potential, CED = Cumulative Energy Demand, POCP = Photochemical Ozone Creation Potential, PMF = Particulate Matter Formation, HTP = Human Toxicity Potential, ARD_MM = Abiotic Resource Depletion, minerals and metals, WaterS = Water Scarcity; further information see Annex 3 Table A2.

5.3. Factors affecting the future outlook and other uncertainties

There is a significant number of factors that will affect how the performance of conventional ICEVs and BEVs will change in the future in terms of GHG emission impacts, as well as in other areas. This section of the report provides a summary of the main factors identified that will influence the future potential and comparison, and a summary of where future effects have been quantifiable in our LCA modelling for the future 2030 (and 2050) periods.

5.3.1. Policy and legislative drivers for future change

The first area that will affect the future life cycle GHG performance of passenger cars are policy and legislative drivers for change relevant to new vehicles sold in the EU. Table 5-2 below provides a summary of the areas Ricardo has identified as most relevant for the LCA of passenger cars, and particularly for BEVs. A further discussion of some of these policies is also provided in later Section 1.1.

Table 5-2: Key LCA areas and influencing factors affected by recent EU policy

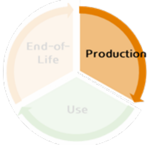
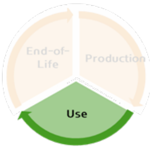
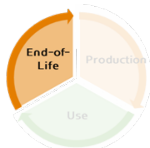
Area	Key influencing factors affected by recent EU policy
Electricity mix	Changes to current and projected electricity generation/supply mix driven by the Renewable Energy Directive, EU ETS (cap), etc.
Fuel mix projections	Proposed revisions to the Renewable Energy Directive will affect the share of substitution of fossil fuels with low carbon alternatives and the nature of these.
Raw materials	Influence of the EU ETS, Batteries Regulation and proposed Carbon Border Adjustment Mechanism (CBAM) on future improvements for future decarbonisation of steel, aluminium and plastics, battery materials, etc. In addition, corporate sustainability and carbon reduction targets are driving demand for recycled materials, and other decarbonised materials (e.g. 'fossil-free steel').
Vehicle specification and performance (i.e. energy efficiency)	Proposed revisions to the CO_2 regulations; technological improvement to conventional vehicles, xEV powertrains and particularly batteries are driving efficiency/ CO_2 emission improvements. The Euro 7 proposal is likely to improve comparison of BEV with ICEV for air pollutant impacts, but also introduce durability requirements (and battery passport) for BEVs.
Infrastructure considerations	The widespread availability and accessibility of public charging infrastructure (as provided for under the Alternative Fuels Infrastructure Directive (AFID), now to be replaced with a Regulation; in 2019-2021 Ricardo performed both the evaluation and the impact assessment for the current AFID and its revision) is likely to reduce the need for larger EV batteries/take-up of longer-range vehicle options. A range of policy drivers, costs and technological developments are driving/influencing uptake of smart-charging, V2G, battery-supported charging, etc.
Battery specification and manufacturing	Technological development of batteries, such as battery energy density/chemistry projections, battery sizes, carbon footprint and the share of manufacturing by geography/location will also be influenced by the proposed Batteries Regulation.
End-of-life aspects	Future proposals on battery recycling, recovery rates and material recycled content as part of the Sustainable Battery Regulation will help provide certainty for the development of efficient collection and recycling in Europe. There are also strong separate drivers for OEMs to become more vertically integrated and retain control of critical materials. Improved provisions for reuse and repurposing (i.e. second life) of batteries will facilitate future applications.

Sources: Ricardo analysis.

5.3.2. Market and technical drivers for future change

In addition to policy and legislative drivers, there are also market drivers of changes and technical developments/improvements that will affect the future performance and comparison. The following Table 5-3 provides a summary of the key influencing factors for future comparisons that Ricardo has been able to quantify (at least to some degree) in our LCA models. The table also provides an indication of whether these factors are affected by policy and/or technical improvements. Key factors that we are not able to quantify in our modelling at all include the potential effects of V2G (discussed in earlier Section 3.8.3) and potential changes to the sourcing and manufacturing (i.e. through new or improved processes) of a wide range of materials, as well as the consequence of economy-wide/global effects of climate change related policies/actions.

Table 5-3: Key factors affecting BEV vs ICEVs' future performance

Phase	Key Factors for Future Comparison	Expected Effect	
		Policy	Tech.
Production 	Reduced production impacts across all powertrain types due to:		
	• **General (all powertrains):**		
	○ Decarbonisation of electricity used in manufacturing (vehicles, batteries, etc.)	✓	
	▪ Includes also a shift/localisation in battery manufacturing	(✓)	
	○ Moderate decarbonisation of materials (e.g. based on electricity mix, potential process efficiency/changes)	✓	✓
	○ Mass reduction due to:	(✓)	(✓)
	(a) improved components (reduces footprint),		✓
	(b) shift to lightweight materials (increases footprint)	(✓)	
	• **Additional for BEVs:**		
	○ Improved vehicle/powertrain efficiency reduces requirement for energy storage capacity (all xEVs)		✓
	○ Improved battery density (Wh/kg)/performance, production efficiency; offset of this by increased range & battery size (kWh)		✓
Use 	• **General (all powertrains):**		
	○ Reduced vehicle energy consumption through a range of technological improvements (to meet EU CO_2 targets)	✓	
	▪ Includes various mass-reduction measures	(✓)	
	• **For ICEVs:**		
	○ Increased use of lower carbon liquid and gaseous fuels	✓	✓
	• **Additional for BEVs:**		
	○ Decarbonisation of electricity used in operation (over the vehicle lifetime)	✓	
	○ Improvements in electric motor efficiency		✓
	○ Net component mass reduction (especially battery) improving energy consumption		✓
	○ No xEV battery replacement needed		✓
	○ Battery density (Wh/kg) improvement slightly offset by increased range & battery size (kWh)		✓
End-of-Life 	• **General (all powertrains):**		
	○ Lower credits per kg of recycled materials, due to displacement of more decarbonised virgin material production (via elec. mix)	✓	
	○ Lower vehicle mass (due to light weighting) so fewer materials to recycle (reduces credits)	(✓)	✓
	○ Decarbonisation of electricity used in recycling processes	✓	
	○ Higher recycling recovery rates (particularly battery materials)	✓	✓

Phase	Key Factors for Future Comparison	Expected Effect	
	o Higher share of lightweight materials (increases credits from recycling these)	(✓)	
	o Lower credits for energy recovery (decarbonised elec. grid)	✓	
	• **BEVs:** Potential extra credits for second life use of xEV batteries	(✓)	✓

Sources: Ricardo modelling, January 2023.
Notes: ✓ = direct effect, (✓) indirect effect.

5.4. Future outlook and sensitivities

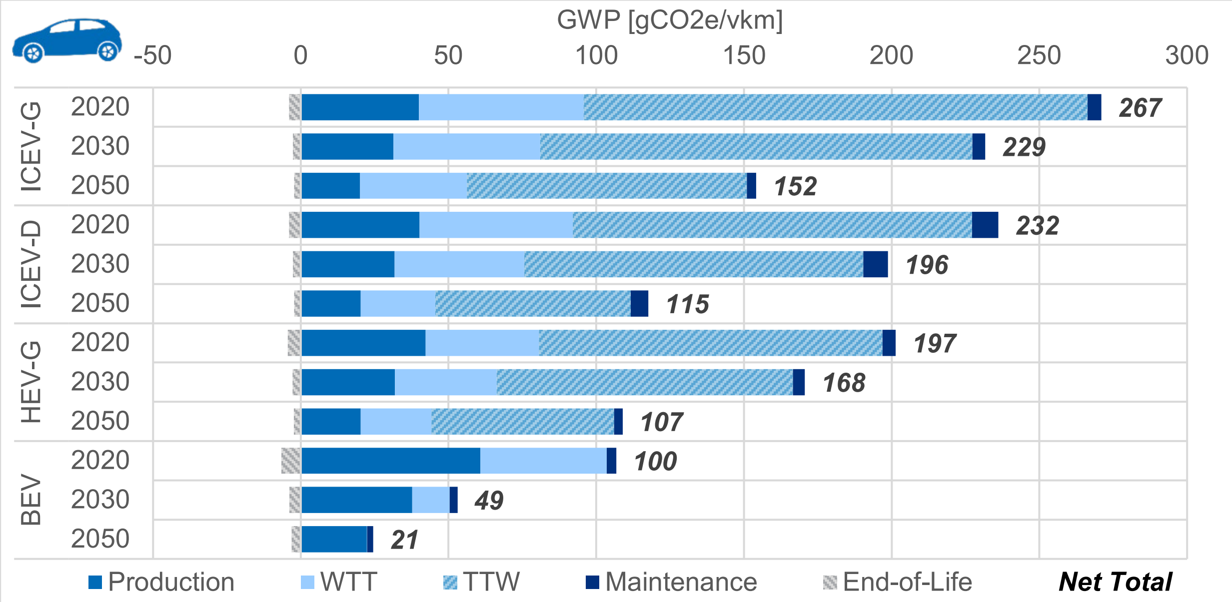
This section of the report provides a summary of the LCA results of our analysis for the 2030 (and 2050) period, where future effects were quantifiable (as outlined in the previous section). Where feasible, we have made updates to our LCA modelling to account directly (or indirectly) for the anticipated impacts of the Fit for 55 (FF55) proposals, and other recent EU policy and anticipated technical or market developments in the 2030-2050 time-horizon (e.g. employed to help meet the EU's net-zero objective for 2050).

5.4.1. Results on the potential future outlook for GWP and CED impacts

The following Figure 5-11 provides a summary of the results of the analysis of the future outlook, factoring in relevant changes influenced by Fit for 55 and the longer-term net-zero objectives. Updated results for 2020 are also presented, reflecting accounting for the effects of future proposals and actions on the vehicle's life cycle (e.g. greater electricity grid decarbonisation and low carbon fuel deployment, increased battery collection and recycling rates, etc.). This already leads to some smaller reductions in the net life cycle GHG impacts for all vehicle types compared to the results presented in earlier Section 5.2.

The GHG impact are projected to decrease in future years from ICEVs and BEVs, due to a combination of technical improvements to vehicle efficiency and xEV batteries, and also decarbonisation of fuel and electricity supplies. The increased use of decarbonised electricity and adoption of low GHG steel and aluminium technologies is anticipated to help reduce production impacts for all passenger cars. However, the performance of vehicles with combustion engines does not improve to the same degree as for BEVs. European Commission modelling projections (e.g. from the Fit for 55 proposals) (European Commission, 2021a) show a modest increase in deployment/substitution of biofuels (or other low carbon fuels) into public refuelling stations/supply, while these fuels are assumed to be increasingly used to reduce emissions in sectors where zero tailpipe emission technologies are less likely to be available (e.g. aviation). The results of the analysis show that the average EU27 reduction in life cycle GHG impacts for BEVs vs gasoline ICEVs could increase to 78% by 2030 and to 86% by 2050. In 2050, the EU's electricity grid is modelled to be almost net-zero on average (see Annex 3 for further information on this), so BEV impacts are almost entirely resulting from vehicle production, maintenance and EoL activity.

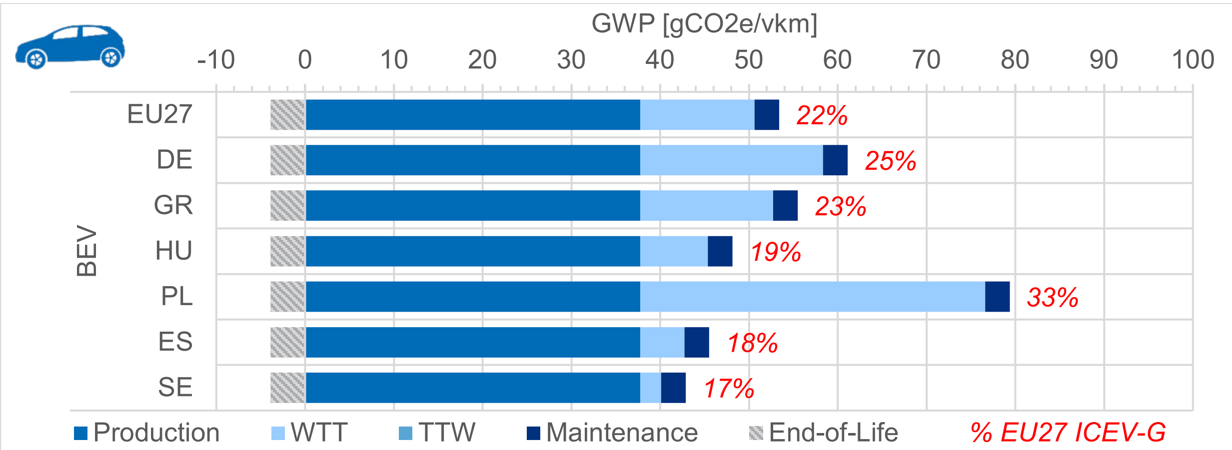
Figure 5-11: Breakdown of the future outlook for life cycle GHG impacts for a Lower Medium Car, 2020 / 2030 / 2050, EU27



Sources: Ricardo LCA modelling, January 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.

Since the EU electricity grid is projected to significantly decarbonise by 2030 (based on the Commissions Fit for 55 package modelling scenarios), the regional variation in the performance of BEVs versus ICEVs reduces very significantly in comparison to the 2020 current policy scenario (Section 5.2). This is illustrated in Figure 5-12 below, where the minimum reduction in life cycle GHG impact for a new medium BEV passenger car is 67% compared to a conventional gasoline ICEV in 2030 (compared to only 19% in 2020) for Poland.

Figure 5-12: Regional variations in life cycle GHG impacts for Lower Medium Cars, 2030, EU27, selected EU countries



Sources: Ricardo modelling, January 2023.
Notes: The variation in use phase impacts is influenced by variations in the share of driving on different road types, differences in average ambient temperature and the change in energy mix (also over the vehicle lifetime).

5.4.2. Exploration of sensitivities and uncertainties for future performance

The overall GHG impacts from all phases of the vehicle life cycle are projected to be lower (and most significantly for BEVs) for the 2030-2050 time-horizon. As a result, the variations in the life cycle GHG performance of BEVs in terms of the previously explored lifetime km, electric range and ambient temperature effects are of a lower magnitude (though similar effects) for 2030-2050.

However, in conducting the sensitivity analysis there are further uncertainties introduced for the LCA modelling, with the two most significant being (i) the rate of improvement in battery energy density (which correlates highly with GHG impacts per kWh of storage), and (ii) the future low carbon fuel mix. Therefore, analysis of alternative scenarios has also been explored for these, which are presented in the following Figure 5-13.

For the first of these sensitivities, a 'worst' and 'best' case scenario has been explored where the effects of high or low improvements in battery energy density are compounded with low or high electric range assumptions (i.e. which directly affects battery size). However, the resulting variation in overall life cycle GHG impacts for BEVs is relatively small, between 76% and 79% reduction for the worst and best case scenario compared to a gasoline ICEV operating in average EU27 conditions.

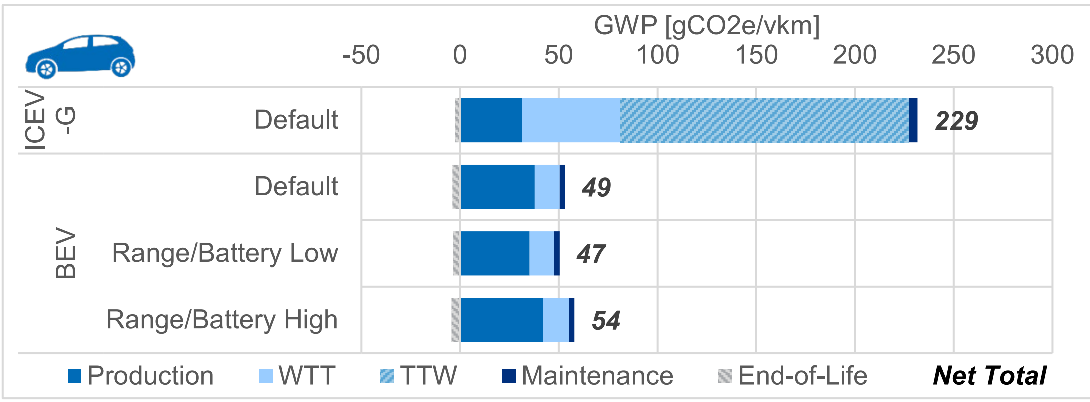
The second sensitivity analysis - presented in Figure 5-13 – examined the influence of alternative low carbon fuel options for conventional gasoline ICEVs and BEVs:

- In the case of BEVs, the main difference resides in the use of 100% renewable energy sources (in the e-fuels/renewable electricity (RE) option in the figure) compared to the use of average electricity grid mix.
- For ICEVs, different fuel blends are assumed (more details are provided in Annex 3).

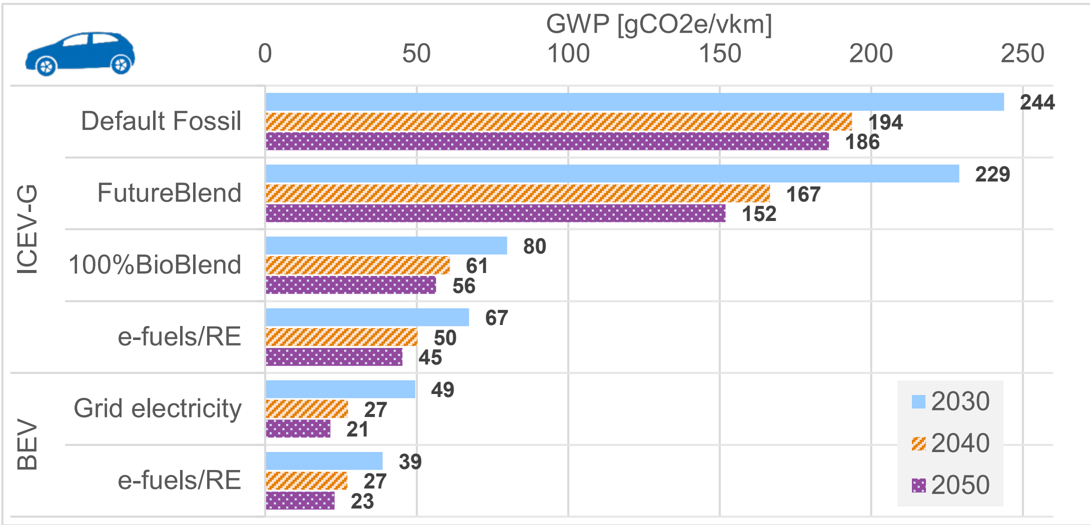
For this sensitivity it was also important to consider not only GHG impacts, but also overall life cycle energy consumption (via the CED – LCA indicator).

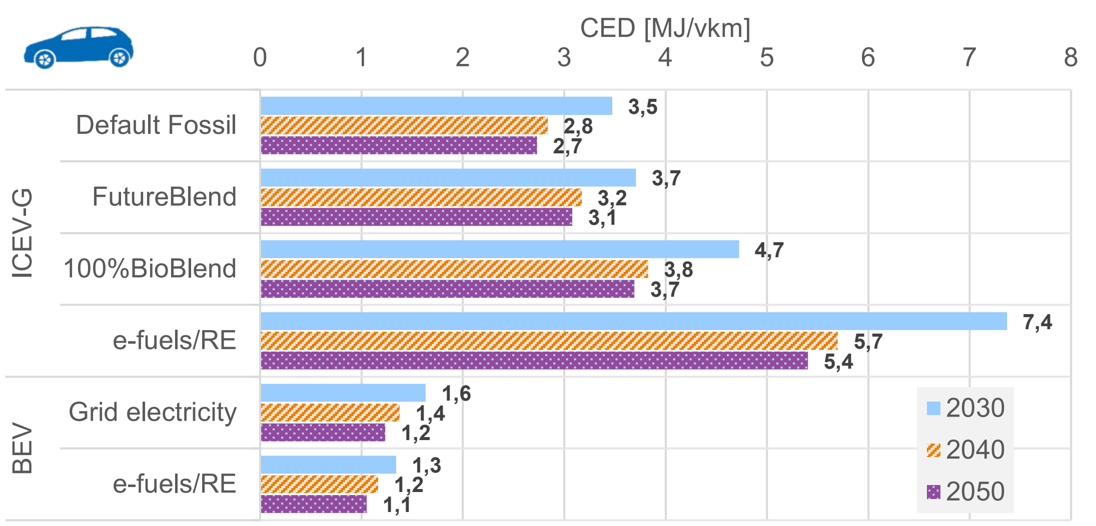
Figure 5-13: Sensitivity analysis on the influence of range/battery parameters and energy mix on GHG and energy consumption impacts, Lower Medium Car, 2030-2050, EU27

Battery /Range (2030)



Energy Mix (2030-2050)





Sources: Ricardo modelling, January 2023.

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).

The scenarios for biofuels was developed by Ricardo and should not be seen as a projection of actual biofuel mix, but as an illustrative scenario. They do not reflect existing or proposed EU low carbon fuel policy and neither scenario seem likely for the deployment of these fuels in road transport. The assumptions behind these sensitivity tests have been defined mainly to highlight that it is likely that large scale deployment of e-fuels or biofuels in road transport will still have higher emissions than a move to BEVs/zero-emission vehicles.

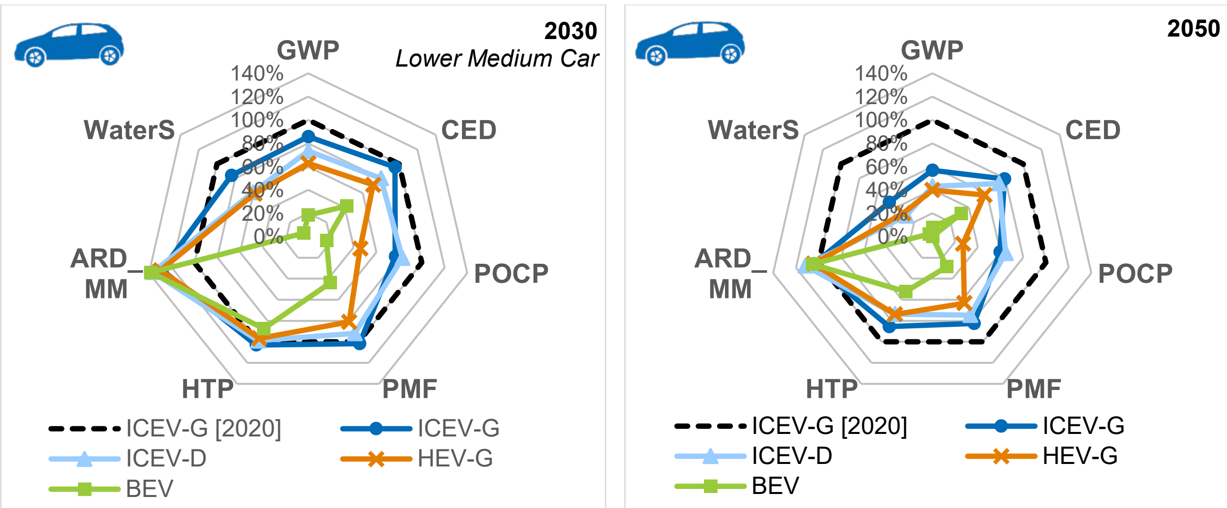
As expected, the analysis shows that the GHG impacts are reduced to a minimum when renewable electricity is used: either directly for the BEV and in the form of e-fuels for the ICEV. In addition, the GHG impacts of the BEV in the best case are always lower than the ICEV-equivalent. The use, in ICEV, of a blend comprising 100% biofuel (i.e. not including any e-fuels) also results in significant reductions in GHG impact. Given the future expectations for decarbonisation of electricity, the overall GHG impacts from the BEV become even lower and the net benefits of the BEV (in terms of these lower impacts) increase compared to the ICEV.

In terms of resource use, BEVs have some challenges in terms of certain scarce mineral resources. However, the use of e-fuels in ICEVs would require many times greater use of primary renewable electricity sources compared to BEVs. There are also limits on the potential for provision of sustainably sourced biomass for a wide range of applications, including those in the transport and wider energy sector.

5.4.3. Future outlook for other environmental impacts

The following Figure 5-14 provides a high-level comparison of the performance of BEVs compared to ICEVs and HEVs for a range of seven key criteria for the 2030 and 2050 time periods. Overall, the performance of BEVs relative to other powertrains improves further across all seven metrics compared to the current/2020 situation (Figure 5-10). Significant improvements are also seen for ICEVs due to improved energy efficiency, fuel mix, and also anticipated effects of the Euro 7 proposals in reducing real-world emissions of key air quality pollutants. This is particularly the case for diesel cars, where reductions in NOx emissions improve both the POCP and PMF indicators. The increase in impacts for the ARD minerals & metals indicator for ICEV and HEV powertrains between 2020 and 2030 is due to a greater use/share of (cast) aluminium in the glider (i.e. non-powertrain components). This has been assumed to contribute to vehicle mass reduction (to further improve vehicle energy consumption), driven by the more stringent CO_2 targets for passenger cars proposed as part of the Fit for 55 package. For BEVs, there is a reduction in this metric for the powertrain-specific elements mainly due to improvements in battery energy density resulting in less material use (and also increased battery recycling efficiency/material recovery rates). This is offset by the change in the glider (i.e. as mentioned for ICEV and HEV), resulting in more similar results across all powertrains compared to the 2020 situation. In the longer term, it is assumed that some of the aluminium is displaced through the greater use of polymer composite materials (such as carbon fibre) for even greater mass reduction.

Figure 5-14: Summary of relative impacts for Lower Medium Cars for selected metrics, 2030 and 2050, EU27



Sources: Ricardo modelling, January 2023.
Notes: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100%. GWP = Global Warming Potential, CED = Cumulative Energy Demand, POCP = Photochemical Ozone Creation Potential, PMF = Particulate Matter Formation, HTP = Human Toxicity Potential, ARD_MM = Abiotic Resource Depletion, minerals and metals, WaterS = Water Scarcity; further information see Annex 3 Table A2.

5.5. Limitations and uncertainties

The first thing to note is that LCA is inherently imprecise/uncertain: uncertainty affects both input data and computational steps subject to methodological choices. When considering the future outlook, this of course further increases the level of uncertainty, and expert judgment on future changes in key data/assumptions has been applied in cases where more direct/quantified and robust projections were not available. In common with LCA studies overall, the results presented in this report should be viewed as having uncertainties associated with them, and **results should not be taken as absolute values/comparisons.** In addition, the analysis is provided for generic vehicle types (which is beneficial for the objective of this study), and the validity of the results for specific single vehicle models will be strongly influenced by their specific design, specifications and performance. For some of the most important assumptions and parameters affecting the overall results, a sensitivity analysis has been performed to help illustrate how they affect the relative performance of different vehicle types, and therefore how much some of the results might be expected to vary depending on the specific situation.

A comprehensive assessment of the key limitations and uncertainties for the data and methodology employed was provided in our previous vehicle LCA report for DG CLIMA (Ricardo et al., 2020), upon which the analysis for this study has been built. Most of these are still valid for this study, though there have been a range of further improvements made across a range of areas, which are briefly summarised in Annex 3 of this report.

Whilst Ricardo's modelling has captured in a quantitative way (at least to a degree) a very wide range of elements and how these might change in the future, there are a number of areas where quantification of impacts was not possible. Key aspects, some with particular relevance also for BEVs, include the following (and have therefore also been discussed in Section 3.8):

- *Decarbonisation of sourced materials:* Whilst the analysis accounts for the decarbonisation of electricity on material sourcing in a generic way, we have only been able to account for improved process efficiency and newer low carbon processes for a selection of key materials (i.e. steel, aluminium and plastic), and only in a limited way.
- *Demand for critical minerals:* It has not been possible to estimate or quantify the effects of increased demand for critical raw materials (particularly for batteries) and how changes in these sources and processing might affect their GHG or other impacts.
- *Other effects of economy-wide decarbonisation*: the actions taken to improve energy efficiency and reduce GHG impact to meet medium and long-term emission targets are widespread and wide-ranging. In particular, there may be significant net impacts resulting from efforts to decarbonise the economy on the extraction, processing and transport of raw materials and components (and in vehicle manufacturing). However, these effects are only partially captured in our projections for future impacts for the production (and end-of-life) phase.
- *The effects of V2G/interactions of EVs with the energy system*: as discussed earlier in Section 3.8.3, there is a potential role for BEVs/their batteries to provide grid services, which may help to offset the impacts of their batteries, but this cannot yet be quantified.

6. POLICY RECOMMENDATIONS

KEY FINDINGS

- The revised target on tailpipe CO_2 emissions, which promotes an accelerated transition to ZEVs (predominantly BEVs) in the 2030-2035 horizon, is expected to lead to net GHG impact reductions on a life cycle basis.
- The current and expected policy framework regarding vehicle manufacturing and end-of-life requirements, along with policies to decarbonise electricity generation, are compatible with a scenario in which BEVs offer a clear decarbonisation pathway for road passenger vehicles from the life cycle perspective.
- Decisive policy action on some specific issues will be needed to maximise the benefits of BEVs and mitigate existing risks. It is essential to develop an ambitious policy agenda around circular economy approaches for vehicle components at EU level, particularly for xEV batteries recycling, recovering and reusing.
- Tailpipe CO_2 emissions regulation provides a suitable regulatory framework, considering current technical limitations for a regulation on a life cycle basis and complementary legislation to regulate upstream and end-of-life emissions. However, harmonised LCA reporting should be encouraged to improve the effectiveness and transparency of mitigation measures across life cycle stages.
- Incentives to promote right-sized BEVs/batteries may be needed as BEVs consolidate their market position. These could be introduced in terms of energy efficiency targets for BEVs or zero-emission vehicles more widely.
- There is a need for further EU-wide research to foster innovation in the field of battery technology and particularly on more materially-efficient battery variants that utilise smaller amounts of critical elements per unit of storage provided.
- A wider set of policies, including policies to promote a modal shift towards sustainable travel modes and the adoption of mobility-as-a-service, will continue to be relevant to further reduce emissions on a passenger-km basis.

6.1. Compatibility of policy framework with LCA findings

Results from the outlook in Section 5 clearly show that the revised target on tailpipe CO_2 emissions, which promotes an accelerated transition to zero-emission vehicles (predominantly BEVs), in the 2030-2035 horizon, is expected to lead to significant net GHG impact reductions on a life cycle basis. Whilst BEV production impacts are higher, this is more than offset by in-use impacts, and the difference in production emissions is also anticipated to significantly reduce by 2030 and beyond.

GHG impacts of BEV vary between Member States, primarily due to differences in the carbon intensity of the electricity generation, and, to a smaller extent, in urban/rural/motorway road driving shares and climatic conditions. Nonetheless, net GHG emissions reductions on a life cycle basis of BEV (compared to ICEV) hold across Member States, including countries with a more carbon intense grid. This justifies an EU-wide policy to accelerate the transition to BEVs.

Besides GHG impacts, the analysis shows that BEVs consistently perform better than ICEV across most environmental impact categories on a life cycle basis[14]. This means that the transition to BEVs is

[14] The only higher impact for BEVs relates to abiotic resource depletion, minerals and metals, which is generally due to the use of particular materials (particularly copper and electronic components).

expected to be fully compatible with the European Green Deal ambition of climate neutrality, zero pollution and circular economy.

The higher GHG impact associated to the first two phases of the vehicle's life cycle (i.e. raw material sourcing and vehicle production) of BEVs compared to ICEVs is due for the most part to the comparatively heavy and resource-intensive battery packs, which can be responsible for up to 50% of the total GHG BEV production emissions. In addition, the rapidly growing demand for CRMs for the production of EV batteries raises concerns on the sustainability of their supply chains, in terms of resource depletion effects; geopolitical pressures due to geographical concentration of deposits and/or processing capacity; and the environmental and social impacts of mining and refining activities.

In this sense, the Sustainable Battery Regulation goes in the right direction with the gradual introduction of carbon footprint thresholds for batteries, recycling and recovery targets for raw materials, battery replacement requirements to facilitate second-use and specific tools such as the battery passport to improve end-of-life traceability. The regulation is expected to foster investment in battery recycling markets and promote the use of less carbon intense material sources. However, potential enforceability issues should be closely monitored considering that, as matters stand, only a small fraction of battery production capacity, and even less material extraction and processing, is located in the EU. In addition, the suitability of proposed monitoring methods and targets (e.g. carbon footprint thresholds) in place should be reviewed in light of potentially disruptive market and technology developments.

GHG impacts of BEVs heavily depend on electricity generation mixes (as a proxy to carbon-intensity of electricity supplied to transport end users). The decarbonisation pathway for the power sector provided by the EU ETS, in combination with the energy efficiency and renewable energy directives, is clearly compatible with a further reduction of BEVs GHG impact on a life cycle basis across the EU, with GHG emission reductions of around 78% compared to conventional gasoline cars by 2030.

Overall, the current and expected policy framework regarding vehicle manufacturing and end-of-life requirements, along with energy transition policies, are compatible with a scenario in which BEV offer a clear decarbonisation pathway for road passenger vehicles from the life cycle perspective, well beyond the decarbonisation potential of ICEV (even when using sustainable fuels, such as e-fuels). However, decisive policy action on some specific issues (particularly around recycling and reusing of batteries and electronic components) will be needed to maximise the benefits of BEVs and mitigate existing risks (e.g. supply of CRM).

6.2. Recommendations

As a results of the findings and conclusions of the analysis, the following policy recommendations are derived:

- A consistent approach to **reporting on GHG impacts from car manufacturers on a life cycle perspective** (i.e. based on common EU or international methodology), as foreseen in the current legislation from 2025, would provide key data to identify further GHG hotspots and improve the effectiveness of mitigation measures across life cycle stages. Additional benefits may also emerge from its use in reporting and communicating comparable environmental performance of vehicles to investors and customers. As such, more widespread LCA reporting should be encouraged and mandatory reporting could be considered in the future.
- The current **tailpipe CO_2 emissions regulation** represent a more suitable policy framework, compared to a regulation on a life cycle basis, considering the following aspects:

  - There is currently no harmonised EU or international methodology or testing method to move the regulation to the life cycle approach[15]. Also, the complexity of monitoring and enforcing an LCA-based metric for regulatory purposes is likely to entail high administrative costs and potential enforceability issues.
  - Major life cycle stages of a vehicle's climate impact, such as fuel supply or electricity production, are the responsibility of many economic actors, other than carmakers (e.g. carmakers cannot control whether cars use advanced and synthetic fuels). Hence, the policy framework needs to target many players with a range of policies working synergistically.
  - The existing and forthcoming policy framework following the Green Deal and its Fit for 55 package (e.g. Circular Economy Action Plan, revised EU ETS, Sustainable Battery Regulation and revised ELV Directive) are expected to provide a solid baseline for reducing upstream and end-of-life GHG impact.

- Although the GHG benefits of BEV compared to ICEV hold across all vehicle sizes, the environmental performance of BEV decreases with potential 'upsizing' to large/SUV cars (or models with much higher electric range). Larger and heavier vehicles require bigger battery packs for similar autonomy ranges. For similarly sized models with different size battery packs, the additional utility of a higher range should be offset against the higher emissions. In this sense, **incentives to promote right-sized BEVs and batteries** may be needed as BEVs consolidate their market position. These could be introduced in terms of energy efficiency targets for BEVs or zero-emission vehicles more widely,[16] via a future revision of the regulation on CO_2 emissions standards for cars and vans or via separate legislation.
- It is essential to develop an ambitious policy agenda around **battery recycling and circular economy concepts for CRM** at EU level. The effectiveness of the Sustainable Battery Regulation, in combination with the revised ELV Directive, needs to be closely monitored in the next years to ensure these instruments deliver on policy goals. Particular attention should be given to enforcement, monitoring methods and targets in view of potential market and technological innovations in the next years.
- There is a need for further EU-wide research to foster **innovation in the field of battery technology** and particularly on more materially-efficient battery variants that utilise smaller amounts of critical elements per unit of storage provided, such as cobalt-free lithium-ion battery chemistries (e.g. LFP) and sodium-ion batteries. However, because these technologies can typically have lower energy density than current lithium-ion NMC/NCA chemistries, the net effect on GHG impact needs to be considered as well.
- A **wider set of policies** will continue to be relevant to meet Europe-wide sustainable transport objectives, even as the uptake of new technologies drives a decrease in GHG impact on a vehicle-km basis. For instance, these include policies to promote a modal shift towards sustainable travel modes and the adoption of mobility-as-a-service, which can further reduce emissions on a passenger-km basis.

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[15] The development of such a methodology is the objective of (a) the TranSensus LCA project under Horizon Europe Programme, (b) a newly set up UNECE IWG (informal working group) on automotive life cycle assessment (A-LCA), which aims to develop globally harmonised guidelines for vehicle carbon footprint/LCA. Both initiatives are scheduled to complete in 2025.

[16] If energy efficiency targets apply to zero-emission vehicles in general, powertrain-specific targets may be required because energy efficiency of zero-emission powertrains (e.g. battery-electric vs fuel cell electric) is fundamentally different.

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This study provides an up-to-date expert assessment and comparison between the life cycle's carbon footprint of battery electric and internal combustion engine passenger cars. It presents evidence from the literature and from life cycle assessment modelling and concludes with policy recommendations. The analysis includes sensitivities, regional variations for six Member States, and also the effects of technical and legislative development on the potential outlook up to 2050.

PE 733.112
IP/B/TRAN/IC/2023-047

Print ISBN 978-92-848-0241-8 | doi:10.2861/067390 | QA- QA-04-23-172-EN-C
PDF ISBN 978-92-848-0240-1 | doi:10.2861/43673 | QA- QA-04-23-172-EN-N