Defossilization, Not Decarbonization:
Toward a Life Cycle-Based Standard for Automotive Greenhouse Gas Regulation

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Executive Summary

The EU regulates the climate performance of passenger cars at a single point: the tailpipe. Everything else that determines a vehicle's true climate footprint – like the carbon embedded in its steel, aluminum and battery, the fossil or renewable origin of the energy that powers it, the materials recovered at the end of its life – remains invisible to the metric that decides regulatory compliance. At the same time, the EU regulatory framework lacks precision, focusing on "decarbonization" rather than what really matters: defossilization, i.e., the reduction of fossil carbon drawn from geological storage. As a result, this White Paper argues, the regulatory framework has a structural blind spot with significant economic and political consequences: a regulation that cannot see a contribution to defossilization cannot reward it, and what regulation does not reward, industry will not finance at scale.

The consequence is a systematic misallocation of effort. A manufacturer that invests in near-zero-carbon steel, a supplier that defossilizes battery production, an energy producer that scales renewable fuels, a recycler that keeps critical raw materials in the loop – all of these elements reduce the fossil carbon a vehicle draws from long–term geological storage. None of them improves, by a single gram, the figure on which compliance with Regulation (EU) 2019/631 is assessed. The current framework thus concentrates the entire regulatory incentive on one lever, the drivetrain, while leaving the other levers of defossilization like materials and energy carriers without any regulatory value. For a Union that wants to remain a home for exactly these industries, this design choice has severe industrial-policy consequences.

The evidence confirms both the direction and the blind spot. A systematic review of 19 studies and 47 modelled scenarios finds that battery-electric vehicles reduce life cycle emissions in roughly 92% of scenarios, by 41% on average. But the range from –89% to +21% shows how strongly the outcome depends on where a vehicle is built, how carbon-intensive its production inputs are, and what energy carrier it runs on. The drivetrain is the largest single determinant; materials and energy carriers move the result substantially further, in both directions while a tailpipe-only metric captures none of this variance. It certifies two vehicles as identical whose real climate footprints may differ by a factor that matters. It does so at the very moment when the decisive competition in automotive defossilization is shifting upstream, into supply chains and energy systems.

There is another hard truth the current framework has never had to confront. Existing research points in different directions on how reliably any single lever can deliver the fleet's climate contribution on the current policy trajectory: one peer-reviewed analysis found that, at the EU's stated pace of e-mobility adoption, the passenger-car sector would deliver only around 80 million tons of the roughly 188 million tons CO_2-eq reduction needed by 2030, with combustion vehicles still making up 78% of the fleet on the road that year (Tang et al., 2023). The regulation's own compliance architecture, however, has never been built to act on that finding either way: Regulation (EU) 2019/631 assumes implicitly that electrification alone will carry the fleet's contribution to the EU's climate goals. A framework built on a single permitted lever has, by construction, no mechanism to compensate if that lever alone proves insufficient regardless of the underlying reasons that might be linked to supply chains, charging infrastructure, cost, or consumer adoption. That structural vulnerability exists regardless of how the electrification ramp-up is currently tracking; the Commission's own introduction of a multi-annual compliance mechanism for 2030–2032 (see Section 3.2), allowing a shortfall in one year to be offset by over-performance in another, is itself an acknowledgment that shortfall risk is real enough to require a buffer.

This uncomfortable conclusion is compelled by the regulation's own logic: a regulator that is serious about its climate targets cannot rely on a single lever with no fallback if that lever underperforms. It must bring the other levers into play as well. If the EU's climate goals are to be met, the alternative levers of defossilization that include low-carbon materials, renewable energy carriers and circularity must be brought into the compliance framework as a reinforcement of the same objective by every means that verifiably serves it, rather than as a retreat from the electrification path. A framework that shuts these levers out by design has no answer if the drivetrain transition alone falls short. That is a risk the EU's targets cannot absorb, and a regulatory choice this White Paper argues can no longer be defended.

Politically, the ground for correcting this is firmer than the debate suggests. A parallel review of the regulatory and political landscape finds no contestation of the defossilization objective itself, within the EU or among its member states. The Life Cycle Assessment methodology that would be required to act on the full picture is already an established EU practice, embedded, for instance, in the Ecodesign Regulation and the Carbon Border Adjustment Mechanism. Manufacturers increasingly publish model-specific life cycle studies ahead of any legal obligation. The main disagreement concerns how Life Cycle Assessment should be implemented, not whether it should be part of any regulation at all. What is now needed is an administrable regulatory architecture that turns this convergence into a workable standard and the political honesty to name the gap for what it is.

This White Paper sets out that architecture: a standard that measures what the EU actually committed to – defossilization, the reduction of fossil carbon across a vehicle's full life cycle – built on seven design principles and introduced in three phases.

The seven principles:

1. Build on existing frameworks and initiatives, such as the Battery Regulation, CRMA, CSRD/ESRS and Catena-X, instead of creating a parallel reporting regime.

2. Make Article 7a count: convert its currently voluntary life cycle-monitoring duty into mandatory, verified reporting, without yet making it compliance-determining.

3. Reward performance, not categories: replace flat credits with performance-based crediting keyed to verified carbon intensity, so a ton of avoided fossil carbon has the same regulatory value wherever in the life cycle it is avoided.

4. Close the accounting asymmetry between electricity and fuel, so both sides of the energy-carrier ledger are treated on the same basis.

5. Invest publicly in open life cycle-inventory data, preferring primary data wherever it exists, so smaller suppliers and independent verifiers are not dependent on data only the largest manufacturers can produce.

6. Protect investment predictability through a fixed, pre-announced review mechanism: a standard must not be relaxed after industry has already invested to meet it.

7. Prioritize end-of-life and recycling data, tying compliance to the circular-economy performance that current reporting frameworks develop least and that Europe's raw-material security depends on most.

The three phases: Phase 1 (2026–2029) makes life cycle reporting mandatory and verified, so a comparable dataset exists before any threshold is attached to it. Phase 2 (2029–2032) introduces performance-based crediting, beginning with the steel fast track described below and extending life cycle-parity accounting to electricity. Phase 3 (from 2032) phases in binding life cycle-based compliance thresholds; whether the tailpipe metric can eventually be retired is assessed on the basis of how effectively the life cycle standard performs in practice.

One methodological decision, however, cannot wait: the accounting rule for steel. Steel is the single largest source of embedded emissions in a conventional vehicle body, near-zero-carbon production routes are reaching industrial maturity in Europe now, and its supply chain is comparatively traceable. No other material offers a cleaner test case. This White Paper therefore recommends a steel-specific life cycle fast track: an accounting methodology developed and verified during Phase 1 and credited from the start of Phase 2, serving as the proof of concept that performance-based crediting is administrable at industrial scale. The point is as political as it is methodological. Europe's green-steel pioneers are making investment decisions today. That is why a regulatory incentive needs to be put in place while these decisions are being made, rather than a decade afterwards. If life cycle-based crediting is to be credible, it must demonstrate feasibility where the stakes are highest and the data is best. Steel is where both conditions are met first.

This pathway does not itself fix every remaining methodological choice a fair comparison requires, including system boundaries, allocation rules or standardized mileage assumptions, and it deliberately leaves questions open, including whether an absolute life cycle metric should eventually complement the standard proposed here. Resolving these is the task of an independent, consequential follow-on study proposed for 2027 onward. Without it, the pathway remains an architecture rather than an operational standard; with it, the EU gains something the tailpipe metric can never provide: a regulation that recognizes every genuine contribution to defossilization, wherever in the life cycle it is made.

This White Paper recommends a phased, principle-based and pragmatic transition towards a life cycle-based standard. This approach preserves the EU's climate ambition while broadening the regulatory framework beyond a single technological pathway.

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List of Abbreviations

BEVs	Battery Electric Vehicles
CV	Coefficient of Variation
C2C	Cradle-to-Cradle
ELVs	End-of-Life Vehicles
EoL	End-of-Life
FAME	Fatty Acid Methyl Ester
FCEVs	Fuel Cell Electric Vehicles
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEVs	Hybrid Electric Vehicles
HVO	Hydrotreated Vegetable Oil
ICEVs	Internal Combustion Engine Vehicles
ICE-CNG	Internal Combustion Engine (powered by) Compressed Natural Gas
ICE-D	Internal Combustion Engine (powered by) Diesel
ICE-G	Internal Combustion Engine (powered by) Gasoline
ILUC	Indirect Land Use Change
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LUC	Land Use Change
PCF	Product Carbon Footprint
PHEVs	Plug-In Hybrid Electric Vehicles
sLCA	Social Life Cycle Assessment
SUV	Sport Utility Vehicle
TSLCA	TransensusLCA
TTW	Tank-to-Wheel
UCO	Used Cooking Oil
VLT	Vehicle Lifetime
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
WTT	Well-to-Tank
WTW	Well-to-Wheel

1 Introduction

1.1 Background

Climate change mitigation in the transport sector, especially the reduction of the sector's greenhouse gas (GHG) emissions, is one of the most pressing challenges facing the European Union. Road transport alone accounts for approximately 15 % of EU GHG emissions, with passenger cars and light commercial vehicles representing the largest share. The EU's primary regulatory response has been Regulation (EU) 2019/631, which sets binding fleet-wide CO_2 emission performance standards for new passenger cars and light commercial vehicles. From its inception, this regulation envisioned a progressive tightening of emission-reduction requirements over time – a built-in design feature, not merely an ad hoc revision – culminating in a requirement for a 100 % reduction of CO_2 emissions for new vehicles by 2035, effectively mandating the sale of zero-emission vehicles only.

The current regulatory framework, however, is built exclusively on a tailpipe emissions metric: it measures only the CO_2 emitted from a vehicle's exhaust pipe during operation, ignoring all emissions associated with the vehicle's production, the energy used to drive it, and the eventual end-of-life treatment of the vehicle. As a growing body of scientific literature demonstrates (see Chapter 2), this exclusive focus on tailpipe CO_2 emissions in new registrations overstates the improvement in environmental performance the regulation achieves relative to the total GHG emissions of the automotive sector, and it understates the total emissions from new and existing (in-use) passenger cars and light commercial vehicles to be addressed by climate change mitigation measures. A vehicle that produces zero CO_2 tailpipe emissions may still carry a substantial carbon footprint arising from raw material extraction, battery production, and a carbon-intensive electricity supply. The current version of Regulation 2019/631 contains no incentives to lower the emission of CO_2 and other greenhouse gasses during the life cycle of those new vehicles, nor does it incentivize efforts and innovations to lower GHG emissions from the remaining lifetime of the approximately 1.47 billion vehicles already on the road worldwide, of which roughly one-fifth are operating in the EU.

To avoid a simple shifting of burdens from the use phase to other parts of the value chain, it is necessary to widen the scope of the analysis. Thinking in terms of the life cycle of products ("Life Cycle Thinking"), covering the whole value chain from raw material extraction, energy provisioning, and manufacturing to the use phase and end-of-life treatment, is an approach that tackles this problem. The methodological toolset of Life Cycle Assessment (LCA) (Hellweg and Milà i Canals, 2014) aims at offering a scientifically rigorous way to focus on the potential environmental impacts across the full life cycle of a product, which avoids biased inferences about automotive emissions that arise from focusing only on one element of a vehicle's life cycle and provides a more complete, holistic picture. In the automotive context, LCA is already frequently used to capture climate change impacts from raw material extraction and component manufacturing through vehicle use to end-of-life treatment, facilitating a differentiated and comprehensive picture of the climate change impacts of automotive mobility. Regulation (EU) 2019/631 in fact recognizes that the current regulatory approach is deficient: Article 7a mandates that the European Commission develop or adopt a methodology for reporting life cycle emissions for CO_2 (though not for the broader GHG basket) from new passenger cars. The deadline for the implementation of the Art. 7a mandate has been missed twice: in 2023 and again in 2025. Although the European Commission's December 2025 EU Automotive Package has re-opened the discussion by introducing life cycle-adjacent elements such as low-carbon steel credits and renewable-fuel credits, it falls far short of establishing a comprehensive, harmonized life cycle assessment framework. Such a framework would need to capture a vehicle's emissions on a standardized basis across the entire life cycle: from raw material extraction and vehicle manufacturing through the full use phase, to disposal, disassembly and the potential recovery of strategic raw materials at end of life.

A further, more fundamental point runs through this White Paper, specifically about CO_2, the dominant greenhouse gas across the vehicle life cycle and therefore the focus of this particular argument: not all CO_2 counted at the tailpipe is drawn from the same carbon pool (Füchsl et al., 2025; Friedlingstein et al., 2023). As discussed in greater detail below (see box, page 5) what matters for the climate system is not how many tons of CO_2 a metric records, but whether that carbon originates from fossils and thus gets newly released from permanent geological storage – the long-term carbon stock a global warming potential figure implicitly assumes is being drawn down – or biogenic and atmospheric carbon already circulating within the active carbon cycle, which does not draw down that stock regardless of the CO_2 figure recorded. This White Paper therefore focuses on defossilization – the removal of fossil carbon from a vehicle's full life cycle – as distinct from decarbonization, which counts CO_2 quantity regardless of its origin.

The methodological gap between tailpipe and life cycle accounting is not the only driver of the current debate over a revision of the EU Regulation. Concerns about competitiveness and industrial capacity in the face of heightened geopolitical risks, uneven (and in some respects disappointing progress toward the 2030 intermediate targets, see Tang et al., 2023), as well as the cost of meeting the 2035 targets have also shaped the debate. Chapter 3 discusses how these conflicting objectives have rendered climate change mitigation a much more contested issue, impeding consensus despite near-universal agreement in the EU over the urgency of slowing and, if possible, reversing climate change. This White Paper recognizes the larger economic and geopolitical context, but focuses on the methodological, life cycle-based dimension, which cuts across those other drivers of EU policy and is largely independent of how each of them is ultimately resolved.

1.2 Aim of the Study

This White Paper[1] aims to provide a scientifically rigorous and holistic analysis of regulatory measures for reducing GHG emissions across the full life cycle of vehicles, including drive technologies, energy systems, and materials. It explicitly considers the interplay of the current instruments for climate change mitigation, a Life Cycle Assessment-based approach, and other concurrent policy objectives, above all industrial competitiveness. It thus offers evidence-based input into the ongoing European policy debate over the revision of Regulation (EU) 2019/631.

This overall aim, framed throughout by the defossilization perspective set out above, is pursued through the following six objectives:

The first objective is to analyze Life Cycle Assessment (LCA) as a tool for assessing the environmental — and in particular the climate-change-related — impacts of automotive mobility.

The second objective is to summarize and critically assess the existing body of contextual knowledge on climate change impacts and their mitigation with respect to passenger cars, providing the background needed for the development of efficient and effective regulations.

The third objective is to examine the promise and limits of Life Cycle Assessment as the methodological toolset for developing and implementing measures to advance the widely agreed goal of climate change

[1] This White Paper was commissioned by the President of the Technical University of Munich (TUM), Professor Thomas F. Hofmann, through Professor Wolfgang A. Herrmann (TUM Institute for Advanced Study).

mitigation most effectively, with particular attention to the role of LCA in the upcoming revision of Regulation (EU) 2019/631.

The fourth objective is to analyze the regulatory and political context for a shift toward life-cycle-based automotive emissions regulation: the current Regulation's approach to CO_2 emissions reduction, the Commission's December 2025 proposal and alternative proposals put forth by other stakeholders, current industry practice in conducting LCAs, and the legal, political and policy incentives that drive or hinder the adoption of life-cycle approaches, including the opportunities and limits of incorporating LCA into European regulatory measures, given the contestation over climate change policy in the European Parliament and its wider political and societal environment.

The fifth objective, building on these analyses of LCA for automotive emissions and of the regulatory and political context, is to develop concrete suggestions for the further development of the Regulation. This objective follows directly from the previous ones: an LCA-based understanding of climate impacts and mitigation options is of limited value to policymakers unless it is translated into actionable regulatory proposals. By explicitly linking the methodological and empirical findings of the study to assess concrete options for amending the Regulation, this objective ensures that the analysis feeds directly into the ongoing revision process rather than remaining a purely academic exercise.

The sixth and final objective is to outline a roadmap to implementation. This objective addresses a recurring weakness in EU regulatory processes: even well-designed provisions can fail to achieve their intended effect if institutional capacities, data availability (e.g. for LCA-based reporting requirements), industry adaptation timelines, and coordination between EU and national authorities are not adequately accounted for. By setting out a realistic sequence of steps, milestones, and responsibilities for translating the suggestions developed under the fifth objective into practice, this final objective is intended to strengthen the practical relevance and policy uptake of the study's findings.

This White Paper applies identical analytical standards to all drivetrains and fuel technologies. It does not seek to determine which technology "wins"; rather, it examines the conditions under which different technologies achieve their maximum benefit for effective and efficient climate change mitigation, and the regulatory design choices that enable or impede those conditions.

This paper is envisioned as the first part of a larger, two-part project. This White Paper (1 September 2026), concludes the first part, in which we have developed the scientific and regulatory foundations, leading to the proposal for a pathway to LCA-based regulatory approach in Chapter 4. A follow-on study, envisioned from 2027 onwards, is meant to conduct an independent consequential LCA study incorporating the methodological advances identified in Part 1. We provide a sketch for that follow-on study in Section 4.4.

The scope of this White Paper is to synthesize existing LCA studies from the peer-reviewed literature and to draw conclusions about the robustness and direction of findings across studies. We did not conduct our own original Life Cycle Assessment, nor did we conduct a harmonized LCA with unified system boundaries, functional units, and allocation methods and a necessary consequential approach, which would require a dedicated research effort comparable to the TransensusLCA program. An original study in support of the further development of the regulatory framework is the central element of the planned follow-on study.

Today, the only decision the regulator asks a manufacturer to make is for or against the electric drivetrain. What this White Paper proposes instead is a framework that rewards lower GHG emissions at every phase of the life cycle for which a given manufacturer is responsible: using steel and batteries that minimize the release of fossil carbon across the full value chain from production end-of-life; supporting customers in using renewable fuels in combustion vehicles and renewable electricity in battery-electric ones; and treating high-quality recycling in Europe as part of that same corporate responsibility. Chapter 4's phased pathway offers a way to transition to a fully life cycle-based regulatory approach, rather than layering additional regulatory burdens on top of the use-phase-only tailpipe metric. The methodology and much of the data such a life cycle-based regulation needs already exist; what is needed now is a responsible sequence for putting it together in a cohesive regulatory approach, not further delay. As discussed in more detail in Section 4.1, such an approach would be unbiased in the sense of rewarding every life cycle lever — drivetrain, materials, energy carrier, and recycling — by the same measurable criteria, rather than privileging one lever by regulatory design, which is a narrower, more specific demand than the technology-neutrality principle discussed in Section 3.8, though related to it in spirit.

Chapter 4 sketches two concrete, if still preliminary, options for what that sequencing could look like in practice: a fast-track accounting rule for steel specifically, and an absolute life cycle metric as a possible longer-term alternative to the current g/km standard.

Defossilization, Not Decarbonization

This White Paper focuses on defossilization — the removal of fossil carbon from a vehicle's full lifecycle — as distinct from decarbonization, which counts CO_2 quantity regardless of its origin. The distinction matters because carbon as such is fundamentally important to life on earth; the entire field of organic chemistry may be said to be based on that insight. The notion of decarbonization has therefore prompted numerous objections in the scientific literature as overly sweeping and prone to fostering misunderstandings (Hutchings et al., 2024; Lange, 2025; Nature Editorial Board, 2026; Future Energy & Technology, 2026).

It is fossil carbon rather than carbon as such that is our primary concern from a climate change perspective, because fossil carbon behaves differently in the carbon cycle: coal, oil and gas have been locked away in geological storage for millions of years, cycling back to the surface only through slow processes like weathering and volcanism. Burning it releases, in an instant, carbon that would otherwise have stayed locked away far beyond any policy-relevant horizon. Biogenic and atmospheric carbon, by contrast, is already circulating through the fast, biologically active "green carbon cycle" (see Füchsl et al., 2025), so releasing it does not by itself draw new carbon out of long-term storage, though this does not automatically make climate-neutral either, that depends on whether what is burned is genuinely being replaced.

A systematic review of the literature shows that the term defossilization is increasingly used in some disciplines, but so far only rarely in the context of LCA- or life cycle-based regulatory approaches geared toward the automotive sector. It also, so far, is often used as a synonym for decarbonization, rending the important distinction, highlighted above, invisible.

Making defossilization the focus of a life cycle-based regulatory approach for the automotive industry asks the key question in a focused, direct way: How much carbon does a vehicle, over the course of its full life cycle draw from the slow, geological cycle into the fast one? A tailpipe-decarbonization focus falls short, and cannot answer this critical question. Chapters 2 develops the evidence base for this metric more fully; Chapter 4 offers our proposal how it could be phased into the regulatory context examined in Chapter 3.

1.3 Structure of this White Paper

Following this introductory Chapter 1, the White Paper is organized into four further substantive chapters:

Chapter 2 develops an LCA perspective on defossilizing the passenger car sector, based on a systematic review of the scientific literature on vehicle life cycle assessment. It covers the concept of vehicle LCA, an overview of findings regarding the potential for CO_2-equivalent (CO_2e) reduction across drivetrain types, a review of the methodological choices and parameter assumptions that drive variation in LCA results, and a discussion of aspects beyond defossilization including circular economy dimensions. It thus serves as a basis for the subsequent discussion both methodologically and by establishing current knowledge about GHG mitigation measures.

Chapter 3 presents an analysis of the regulatory and political context: Regulation (EU) 2019/631, the Commission's December 2025 Automotive Package, competing revision proposals, the discernible positions and current practices of the automotive industry and the positions of political parties in the European Parliament.

Chapter 4 synthesizes the findings of Chapters 2 and 3 to develop a proposal for a technically, practically and politically feasible pathway toward a life cycle-based regulatory approach. It puts forth a multi-step blueprint for integrating LCA directly into the regulatory framework for reducing GHG emissions, including through the use of low-carbon materials, the treatment of alternative fuels, and by considering fossil carbon intensity of electricity mix across the stages of a vehicle's life cycle. The chapter also addresses the governance requirements for a credible life cycle-based regulation.

The concluding Chapter 5 steps back to highlight the central contribution of the White Paper as a whole and the essential next steps for the ongoing revision of Regulation (EU) 2019/631, though without repeating the detailed agenda for the follow-up study, developed in Section 4.4.

2 LCA Perspective on Defossilizing the Passenger Car Sector

2.1 Introduction

This chapter lays out the evidence for what a life cycle perspective shows about the passenger car sector's defossilization potential, and how that picture compares to the one produced by the tailpipe approach embedded in the current EU regulation. It starts with an overview of the LCA methodology underpinning this inquiry, presents a systematic review of the literature on LCA methods and practices for passenger cars, conducted for this white paper, and synthesizes the findings across powertrains, methodological choices, and complementary defossilization levers.

Section 2.1 introduces Life Cycle Assessment as the appropriate methodological lens for assessing vehicle environmental impacts, distinguishing it from the tailpipe-based accounting that underlies current EU regulatory practice. **Section 2.2** then describes the systematic review methodology applied, including the search strategy, screening criteria, and the approach used to build the underlying evidence base of eighteen reviewed sources.

Section 2.3 presents an overview of the results, reporting total life cycle, production phase, use phase, and end of life Global Warming Potential across seven powertrain types. **Section 2.4** then turns to the methodological choices that shape these results, including LCA type, system boundary, functional unit, multifunctionality and allocation, impact assessment method, data quality, and temporal, technological, and geographical scope, while **Section 2.5** examines the parameter assumptions, such as vehicle and powertrain type, lifetime and mileage, production location, battery configuration, energy consumption, fuel blends, electricity mix, hydrogen production pathways, maintenance, and end of life treatment, that most strongly drive variation across studies.

Section 2.6 broadens the analysis beyond powertrain electrification itself, reviewing complementary defossilization levers such as green steel, metals circularity, biomaterials, closed loop plastics recovery, and biofuels and e-fuels, and assessing the extent to which each can meaningfully contribute to defossilization alongside BEV deployment. **Section 2.7** then considers important aspects beyond defossilization narrowly defined, including infrastructure readiness, supply chain risks and material sovereignty, cost and life cycle costing, and social and sustainability dimensions of the transition. Finally, **Section 2.8** draws these threads together, distilling the chapter's key takeaways and their policy implications, and closing with a discussion of what a tailpipe-based approach can and cannot deliver relative to a full LCA based alternative.

2.2 Life Cycle Assessment to Assess the Environmental Impacts of Vehicles

Life Cycle Assessment is a standardized methodology for quantifying the potential environmental impacts of a product or service across its entire life cycle. Assessing the entire life cycle of the product means to take into account the emissions from the extraction of raw materials, manufacturing and use, to the end-of-life (EoL) treatment (Hauschild et al., 2018). Its central premise is that conclusions about the overall environmental performance of a product or service should be **based on a life cycle perspective**, with the scope tailored to the specific goal and research question of the study. Individual life cycle stages may therefore be omitted when they are not relevant to the analysis, but care must be taken to ensure that excluding a stage from the analysis does not just **shift the environmental burden** from one stage to another. Excluding relevant stages may limit the conclusions and **risk shifting environmental burdens** elsewhere in the value chain. Only a full life cycle perspective ensures that **trade-offs become visible** (Hauschild et al., 2018). As the transport sector is a highly emissions-intensive sector, LCA can be used to systematically assess emissions across the life cycle of vehicles, providing policymakers, regulators, industry, and citizens with a comprehensive picture of vehicles' environmental impact and prodding the industry to reduce its environmental. Hence, LCA has become an increasingly prominent tool in the automotive sector and its inclusion into regulation is debated (see Oliveira et al., 2022 and Chapter 3).

The LCA methodology is standardized in **ISO 14040** and **ISO 14044**, which define the principles, framework, requirements, and guidelines that any compliant LCA study must follow (ISO 2006a; ISO 2006b). ISO 14040/14044 prescribe four iterative phases for an LCA (see also Hauschild et al., 2018). Beginning with the **Goal and Scope Definition** phase, the purpose and intended application of the LCA are defined. Furthermore, the methodological framework is made explicit, including the functional unit (FU), the system boundary, the impact categories considered, and the requirements for data quality. Decisions made here propagate through the rest of the study and largely determine the results and their comparability. In the **Life Cycle Inventory** (LCI) phase, data for the analysis are gathered, based on the system boundaries defined in the first phase. All relevant inputs (energy, materials, resources) and outputs (emissions to air, water, and soil; waste flows) associated with the processes are scaled to the FU. In the **Life Cycle Impact Assessment** (LCIA) phase, characterization factors are assigned to the inventory flows, allowing the analysis of their environmental consequence for specified impact categories, such as climate change (calculated via Global Warming Potential, GWP), acidification, particulate matter formation, and resource depletion. To interpret the results, significant issues are identified, the data completeness is evaluated, and sensitivity or scenario analyses can be performed. From these analyses, limitations, and recommendations can be drawn. **Interpretation** constitutes a distinct phase that, however, runs in parallel with the other three phases rather than being conducted only at the end, allowing the goal and scope to be refined as the analysis progresses.

An advantage of LCA is that it can be specifically tailored to the product studied, including the need to specifically tailor the LCA phases to fit the purpose. The four phases of an LCA study are defined in the ISO standards, but **the choices on how to set out the frame,** especially in the goal and scope definition, **are not standardized, allowing the practitioner to frame and set key parameters for the assessment.** As a consequence of this flexibility, performing an LCA is not a single, uniquely defined exercise, which makes comparing different LCAs challenging (Huber & Fröhling, 2024). Depending on the question being asked, for instance, the system boundary can be drawn in very different ways (Xia & Li, 2022). This can be shown when looking at an exemplary life cycle of a car:

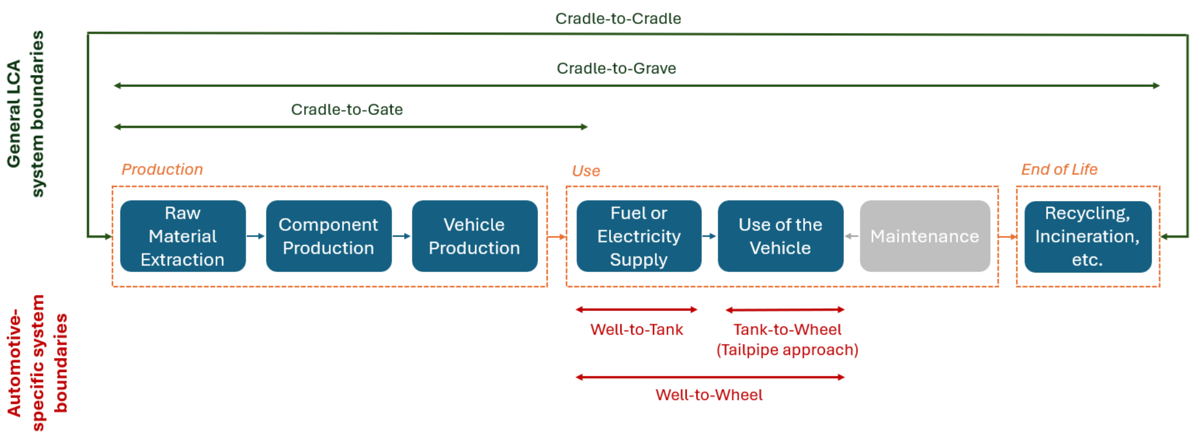

Figure 1: Exemplary Life Cycle of a Passenger Car and Different System Boundaries

Figure 1 illustrates how the different system boundaries commonly used in automotive LCA relate to the vehicle's life cycle. The life cycle itself is divided in three stages. The **production stage** comprises raw material extraction, component production, and vehicle production. The **use stage** consists of the supply of fuel or electricity, the operation of the vehicle, and its maintenance. The **EoL stage**, finally, considers recycling, incineration, and other forms of disposal.

The upper green arrows in Figure 1 mark the general LCA system boundaries. **Cradle-to-gate** stops at the factory gate and therefore covers only production emissions. **Cradle-to-grave** extends the boundary to include use and EoL and is the most common scope for comparing powertrain technologies. Based on the **Cradle-to-Cradle** (C2C) design concept (McDonough & Braungart, 2002), a C2C **assessment** closes the loop, treating EoL material flows as possible inputs to a subsequent product life cycle. In the automotive sector additional specific system boundaries are used, assessing the energy carrier rather than the vehicle as the product under study (see red arrows in Figure 1). **Well-to-Tank** (WTT) covers the fuel or electricity supply chain up to the vehicle, **Tank-to-Wheel** (TTW) covers the actual operation of the vehicle, and their combination, **Well-to-Wheel** (WTW), captures the full energy-carrier life cycle from primary resource to motion at the wheel. The vehicle's production, EoL, and upstream energy production emissions are explicitly outside the WTW boundary. TTW is the scope that the **tailpipe approach** currently embedded in the emission standard set by the EU Regulation 2019/631 follows. Other system boundaries are also sometimes used for LCAs as a function of specific goals or limited availability of reliable data for some life cycle stages, such as cradle-to-gate plus use-phase configurations, which include vehicle operation but omit EoL, or system boundaries that deliberately omit maintenance activities, are driven by the study's goal and the availability of reliable data for each life cycle stage.

2.3 Literature Review Methodology

In order to screen the broad existing LCA literature, summarize the current knowledge from LCAs regarding the aims of this study, and derive key aspects needed for a thorough assessment, we carried out an **explorative systematic review of the literature** (Figure 2). This approach was chosen to enable a broad and efficient screening of the extensive body of literature on automotive LCA, while retaining a structured and traceable selection process. Search criteria were environmental LCA of passenger cars, preferably applying a cradle-to-grave scope, conducted in a European context, and published from 2020 onwards. The main focus was placed on greenhouse gas (GHG) emissions and Global Warming Potential (GWP), reflecting the urgency of climate change, and the automotive sector's substantial contribution to it. The latter two criteria reflect the geographic and temporal focus of this White Paper. The initial database search in Elicit, Perplexity, Claude, and ChatGPT yielded 188 articles, which were reduced to 132 after sorting out duplicates. Screening of titles and abstracts against the inclusion criteria narrowed this set to **35 articles**. To ensure adequate coverage of relevant studies not captured by the initial search terms, a snowballing approach was applied, yielding **5 further sources**, so that a **total of 40 articles** were reviewed.

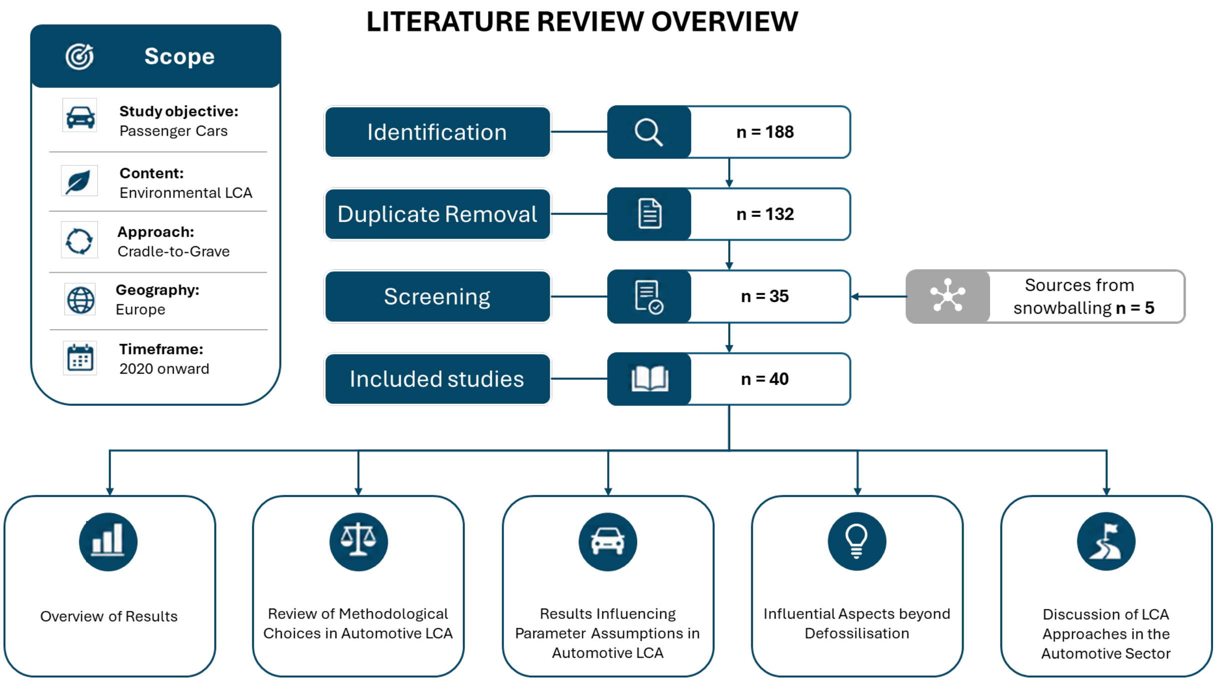

Figure 2: Structure of Explorative Literature Review

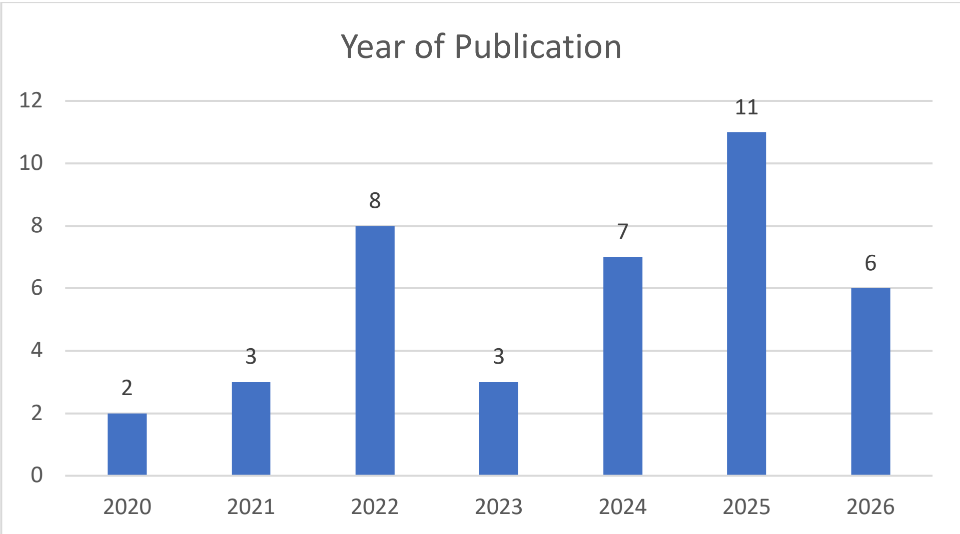

Figure 3: Number of Studies Included in the Literature Review by Year

2.3.1 Data Collection and Analysis

Once the final literature set had been established, data extraction and analysis proceeded along two complementary paths.

First, for the **quantitative analysis of the reported life cycle results**, we gathered all findings across the life cycle phases under consideration and converted the reported GHG emissions to tons of CO_2-eq (t CO_2-eq) or grams of CO_2-eq per kilometer (g CO_2-eq/km)tons to allow comparison and aggregation across studies reporting in different units. For every life cycle phase, four measures were then calculated: absolute emissions (t CO_2-eq), relative emissions (g CO_2-eq /km), contribution to total life cycle emissions (%), and performance of different powertrains relative to the gasoline-powered internal combustion engine (ICE-G) baseline under the same conditions, scenarios, or assumptions. Summary statistics, comprising the maximum, minimum, median, mean, standard deviation, coefficient of variation (CV) where the data permitted, and number of observations (n), for each life cycle phase and powertrain then form the empirical basis for the comparisons presented in Section 2.4.

Second, for the **qualitative synthesis of findings and statements**, we recorded information about the methods used, spotlight results, and major conclusions for the selected studies. This qualitative record underpins the discussion presented in Sections 2.5/2.6, and preserves the context and caveats attached to individual findings, which numerical findings alone do not capture.

2.4 Overview of Results

2.4.1 Non-Exhaustive Overview of Relevant Actors Actively Involved in Automotive LCA Discussions

Table 1: Main Actors Actively Involved in European Automotive LCA Discussions

Universities	Institutes/Organizations	Companies
Cambridge CISL	Argonne National Laboratory	BMW Group
Chalmers University of Technology	BRGM — French Geological Survey	Ecoinvent Association
Eindhoven University of Technology	European Commission Joint Research Centre	Sphera
ETH Zurich	Forschungsstelle für Energiewirtschaft/Research Institute for Energy (FfE) Munich	Volvo Car Corporation
Karlsruhe Institute of Technology	Fraunhofer	
Leiden University	Institut für Energie- und Umweltforschung Heidelberg	
Massachusetts Institute of Technology	International Council on Clean Transportation	
Norwegian University of Science and Technology	Johanneum Research	
Oxford Brookes University	Paul Scherrer Institute (PSI)	
Politecnico di Milano	Ricardo Energy & Environment	
Technical University of Berlin	Swiss Federal Laboratories for Materials Science	
Technical University of Braunschweig		
Technical University of Munich		
University of Bath		
University of Groningen		

The European vehicle-LCA landscape is shaped by a relatively small group of research, policy, industry, and data-infrastructure actors. Universities and research institutes such as Leiden CML, Chalmers, Oxford Brookes, PSI, KIT, TUM, NTNU, TU Berlin, TU Braunschweig, ifeu, Fraunhofer, FfE, BRGM, Ricardo, and the JRC provide the methodological and empirical basis for assessing the life-cycle impacts of passenger cars, batteries, charging, powertrains, raw materials, and end-of-life systems. Within this landscape, **TranSensus LCA** (TSLCA) was a key European harmonization project that brought together research organizations, policy actors, consultancies, and OEMs. **The completed project resulted in a set of commonly developed LCA guidelines for zero-emission road transport**, covering vehicles, batteries, mobility scenarios, and the full life cycle.

Several actors provide essential modeling infrastructure. PSI contributes prospective tools such as **carculator** and **premise**, while ecoinvent and Sphera/GaBi supply the background life-cycle inventory data used in many studies. Policy-facing organizations such as the ICCT and the European Commission's JRC translate LCA evidence into regulatory and market-relevant guidance, while ifeu and Fraunhofer support German and European assessments with fleet, driving, and technology data.

OEMs such as BMW and Volvo contribute an industry perspective by applying LCA to vehicles, batteries, supply chains, and product carbon footprints. These industry efforts are reflected directly in Catena-X, the automotive data ecosystem for standardized and supplier-specific Product Carbon Footprint data exchange across the value chain, launched in 2021 under BMW Group leadership with substantial German federal funding (BMWK, 2023; Köllner 2024) to foster continuous, digital information flows across original equipment manufacturers (OEMs), suppliers, dealer associations, and infrastructure providers with the goal of operational efficiency and scalability (Nagel, 2025). Catena-X's Product Carbon Footprint (PCF) Rulebook aligns with ISO 14040/14044 and ISO 14067 and adopts a harmonized, cradle-to-gate attributional accounting framework restricted to the single impact category of climate change; it prioritizes supplier-specific primary data while explicitly avoiding a centralized public database in order to protect commercially sensitive information and safeguard against accidental violations of EU competition law.[2] Since transitioning from a publicly funded research consortium into an operational industry standard in mid-2024, however, Catena-X has drawn criticism for its cost relative to its results: as of April 2025, the data exchange infrastructure, built at a cost of approximately €245 million (including some €108 million in public funding) has been used by only about one hundred companies with active applications from 35 additional ones pending (Kroker, 2024; Kerkmann, 2025; Kanning, 2023).

2.4.2 Data Description

Following the literature review, source selection process, and data analysis (see Section 2.3), the compiled data presents the GWP of different powertrains, a necessary starting point given that each powertrain has a distinct tailpipe emission profile, while current EU regulation treats powertrains equivalently on this tailpipe basis rather than according to other life cycle phases.

The dataset draws on **19 studies and sources**,[3] from which **47 distinct scenarios or settings** were extracted, reflecting the variety of conditions applied across the literature. This variation, both between and within studies, is a central driver of dispersion among results, with studies differing along the following main dimensions (the impact of each factor is discussed in more depth later in this study):

[2] Catena-X is structured to align with the foundational data sovereignty and decentralized identity principles of Gaia-X, the broader European cloud infrastructure initiative launched in 2019 to foster data/digital sovereignty.

[3] One of the included studies is a literature review, whose reported average values have been included in our results. However, as these values represent averages across multiple studies, this source is not reported in the metadata description or in the corresponding graphs.

- **LCA Type** (see Section 2.5.1): all sources conduct attributional LCA, either implicitly or explicitly, with two also incorporating some consequential modeling (see Figure 4). Half of the sources additionally include one or more prospective LCA elements, while the remainder do not (see Figure 5 and Figure 8).
- **System boundary** (see Section 2.5.2): sources differ in system boundary, with most applying cradle-to-grave, followed by cradle-to-gate combined with WTW or with the use phase; only one source targets WTW specifically (see Figure 6).
- **EoL Allocation** (see Section 2.5.4): sources differ in how they allocate the burdens of the EoL stage, applying either the avoided burden method or the cut off method (see Figure 7).
- **Vehicle type** (see Section 2.6.1): sources reference different vehicle segments (e.g. SUV, middle-segment, mini-car) using either a specific reference vehicle, a segment-weighted average or a theoretically constructed vehicle (see Figure 12).
- **Vehicle lifetime mileage** (see Section 2.6.2): assumed lifetime mileage varies significantly both between sources (from 150,000 km to 280,000 km), and among scenarios within the same source, typically reflecting sensitivity analysis. Also, annual mileage is modelled differently across studies (see Figure 10).
- **Production** (see Section 2.6.3): sources differ in the locations considered for production, particularly for BEV battery production and chemistry (e.g. China, Germany, EU-average).
- **Energy consumption patterns** (see Section 2.6.5): sources and their sensitivity analyses alternate between WLTP, WLTP-adjusted, and real-world fuel and electricity consumption (see Figure 13), as well as across driving conditions (e.g. city and highway driving).
- **Electricity modeling** (see Section 2.6.7): electricity is modelled differently both between and within sources, in terms of geographic reference (e.g. EU-average, selected Member States, Germany, best-case/worst-case location), static or dynamic modeling (see Figure 11), and future grid development scenarios (e.g. JRC-based, optimistic and pessimistic, location- or region-specific).
- **Hydrogen production pathways** (see Section 2.6.8): within the FCEV category, sources consider different hydrogen production pathways, mainly grey hydrogen (fossil fuel-based), green hydrogen (electrolysis using renewable energy), and grid-based hydrogen.

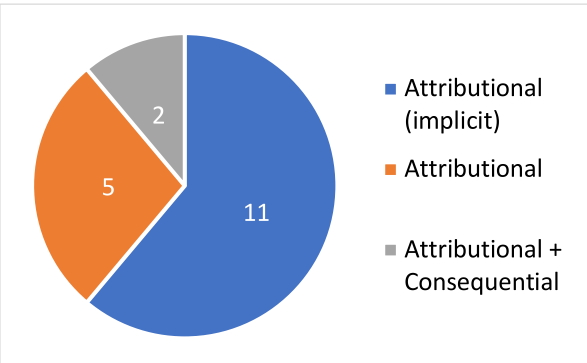

Figure 4: Overview Literature Review: LCA Type

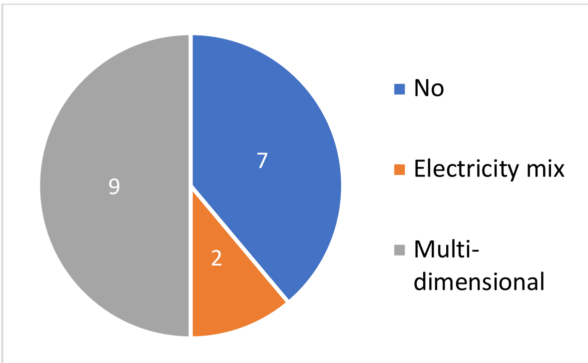

Figure 5: Overview Literature Review: Prospective LCA Type

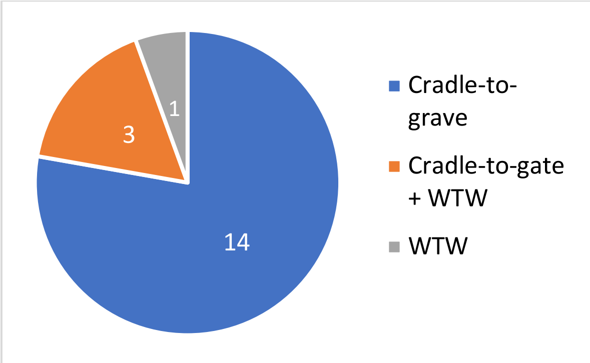

Figure 6:
Overview Literature Review: System Boundary

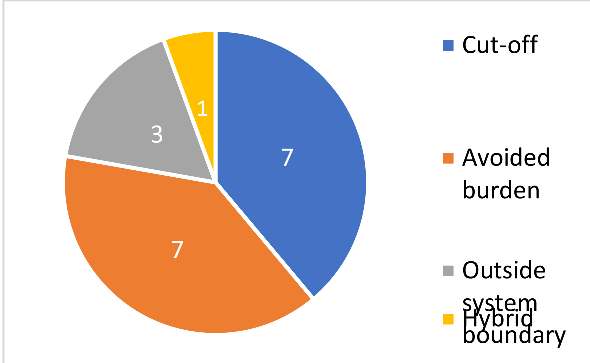

Figure 7:
Overview Literature Review: EoL Allocation Approach

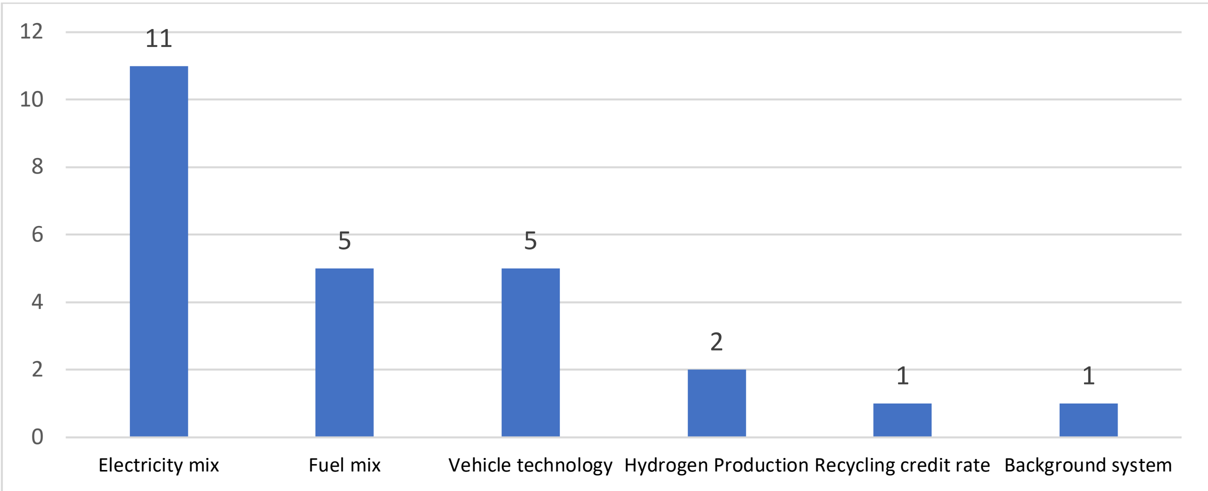

Figure 8: Overview Literature Review: Elements of Prospective LCA

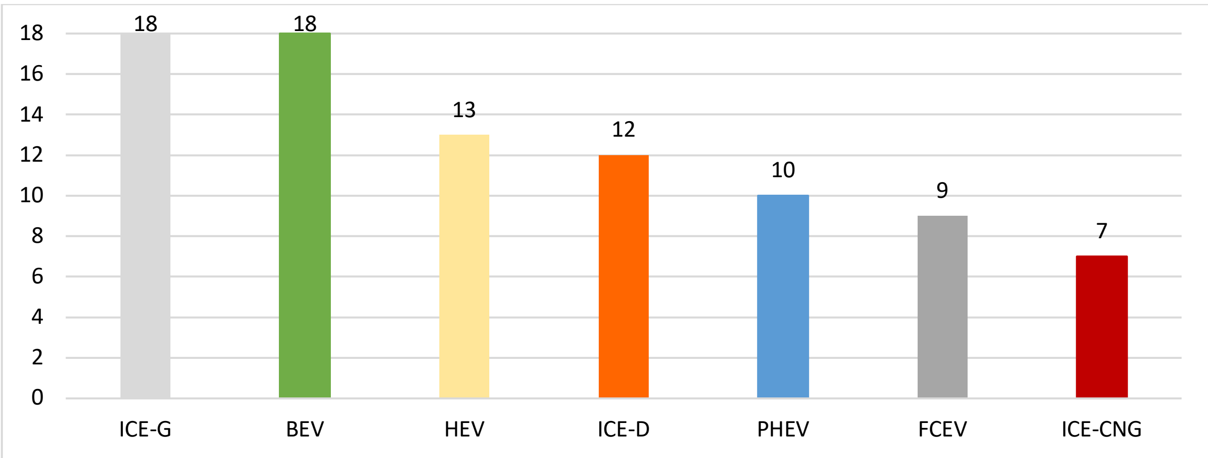

Figure 9: Overview Literature Review: Powertrain covered in Selected Study

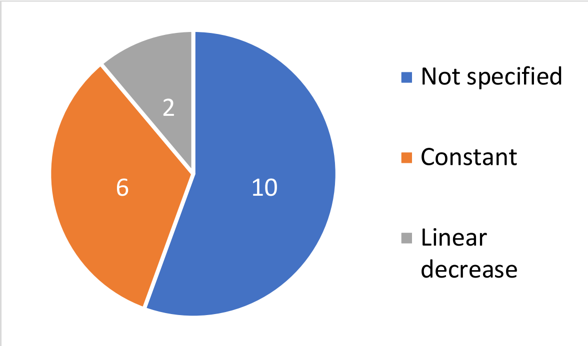

Figure 10:
Overview Literature Review: Annual Mileage

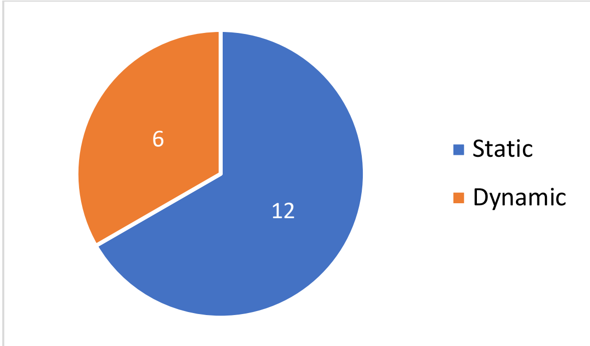

Figure 11:
Overview Literature Review: Electricity Grid Modeling

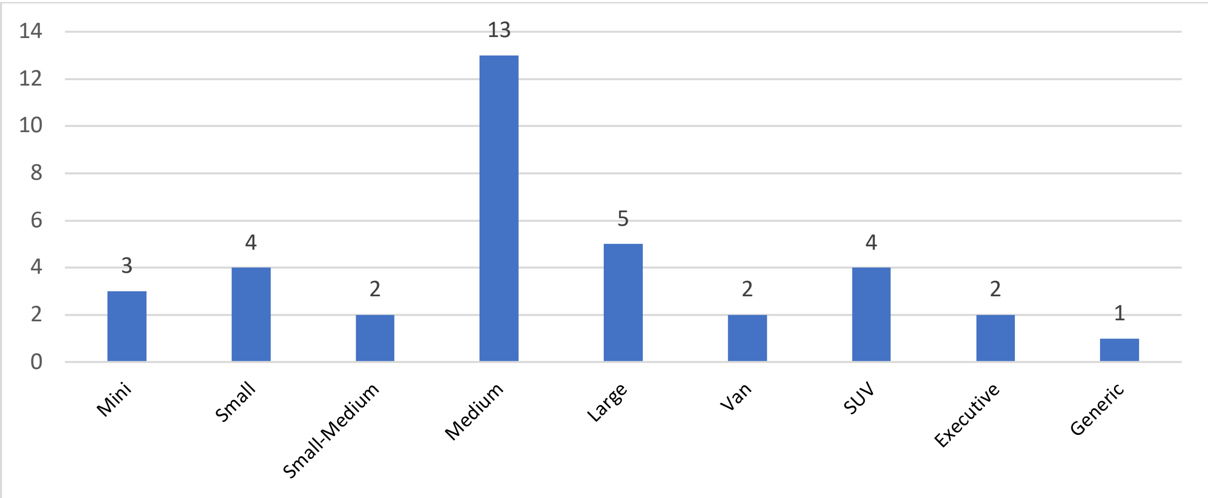

Figure 12: Overview Literature Review: Vehicle Type Considered

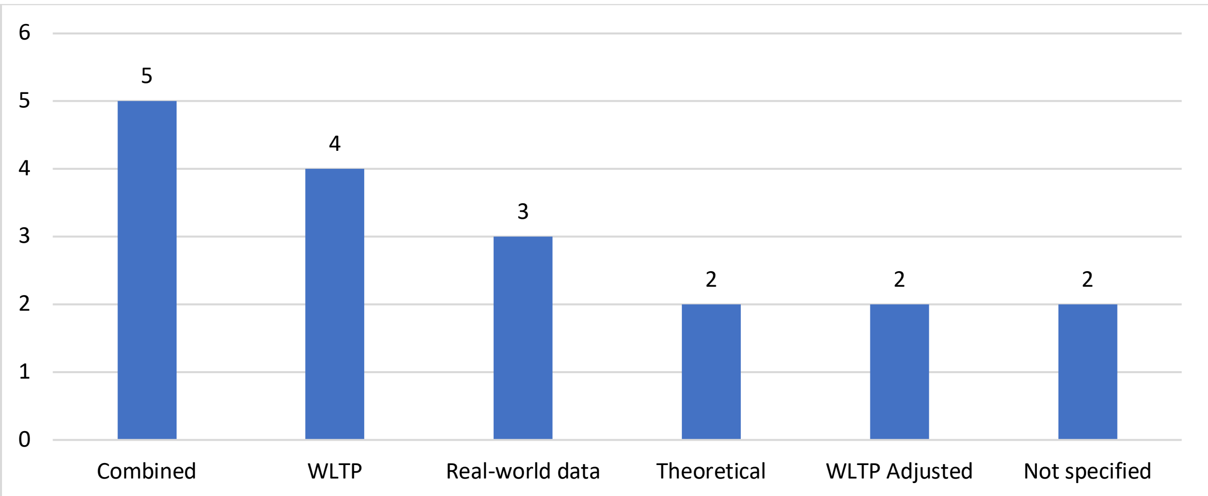

Figure 13: Overview Literature Review: Energy Consumption Modeling

2.4.3 Total Life Cycle Global Warming Potential (GWP)

Figure 14 illustrates the range of absolute GHG emissions results across the reviewed literature. In this regard, **conventional powertrains display similar life cycle GWP outcomes**. ICE-G (n = 29) and ICE-D (n = 23) report average lifetime emissions of 223 g CO_2-eq /km and 210 g CO_2-eq /km (46 and 43 t CO_2-eq), respectively, while ICE-CNG (n = 14) is marginally lower at 193 g CO_2-eq/km (41 t CO_2-eq). Dispersion is moderate across all three (CV of approximately 15-18%). HEV (n = 16) follow a similar pattern, with only a modest downward shift relative to ICE-G, averaging 185 g CO_2-eq /km (37 t CO_2-eq), with a CV of approximately 16%.

Among alternative powertrains, dispersion increases. PHEV (n = 21) report an average of 157 g CO_2-eq/km (35 t CO_2-eq), with a CV of approximately 27% and a range of 58 to 242 g CO_2-eq/km. BEV (n =60) report the lowest average lifetime emissions among all powertrains (121 g CO_2-eq/km, 25 t CO_2-eq), with a CV of 43.5% and a range of 24 to 243 g CO_2-eq/km. FCEV (n = 26) present the widest range of all powertrains reviewed, from 39 to 456 g CO_2-eq/km, with a CV of approximately 60% and an average of 160 g CO_2-eq/km (33 t CO_2-eq).

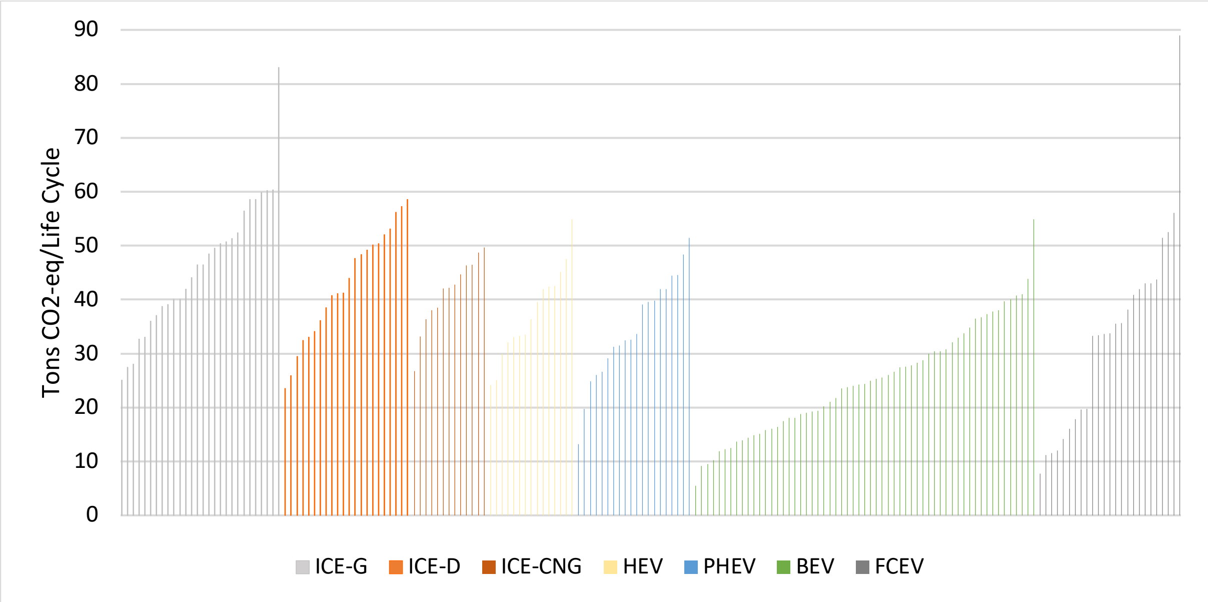

Figure 14: Total Life Cycle GWP Across the Reviewed Literature.

Because absolute GWP estimates are influenced by the parameter and methodological choices specific to each underlying study (see Section 2.5 and Section 2.6), a more robust basis for powertrain comparison involves considering, within each study, the relative GWP reduction potential of a given powertrain against an ICE-G baseline assessed under the same conditions (Figure 15).

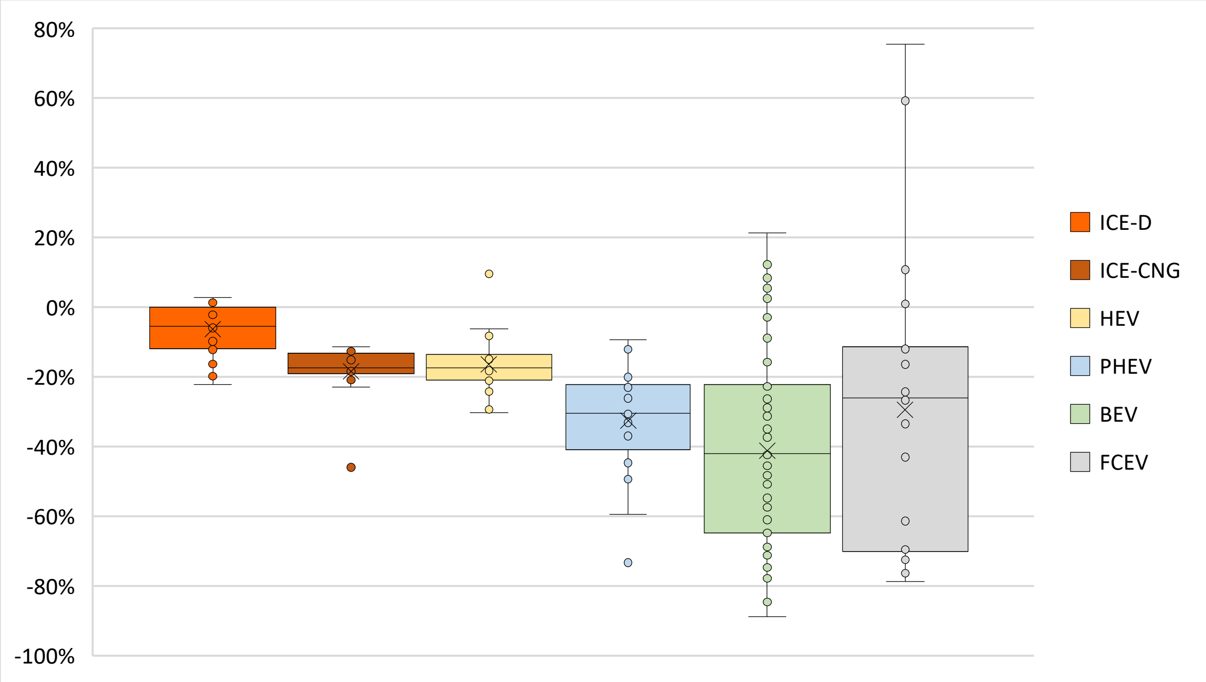

Figure 15: GWP Reduction Potential of Various Powertrains Relative to ICE-G Baseline. Box plots show the distribution of GWP reduction potential (%) reported across the reviewed literature for ICE-D, ICE-CNG, HEV, PHEV, BEV, and FCEV, each expressed relative to an ICE-G baseline assessed in the same study. Boxes denote the interquartile range (25th to 75th percentile) of reported values; the horizontal line marks the median and the cross marks the mean; whiskers extend to the most extreme values within 1.5 times the interquartile range, and individual markers beyond the whiskers represent outlying results from specific studies.

On this basis, **ICE-D performs only slightly better than ICE-G on average** (-6% GWP). Different studies result in significantly different GWP reduction potential: 9% of results report a reduction exceeding 20%, 30% fall between -10% and -20%, 26% between -2% and -9%, 13% report no difference, and 22% report higher GWP than ICE-G. **ICE-CNG** relies on a considerably smaller sample, but all results point to a GWP reduction potential, averaging -18%, with all but one falling within the -11% to -23% range. **HEVs consistently perform better than ICE-Gs**, with all but one study reporting a reduction of at least 6%, and a relative concentration of results (62.5%) between -21% and -13%.

PHEVs show increasing dispersion of results, ranging from -9% to -73% (average of -32%), and unlike for HEVs or ICE-CNGs, this dispersion is not concentrated around the mean but spread across the full range with no clear clustering. Notably, all results point to a reduction of GWP compared to ICE-Gs. **BEV results are highly dispersed**, with an average of -41% GWP against ICE-G and a range from -89% to +21%, visible in the size of the corresponding box in Figure 15. Notwithstanding the dispersion, approximately **92% of studies point to a GWP reduction potential**. In addition, results are dispersed quite regularly across quartiles: except for the fourth quartile, which contains both positive and negative values, the first three quartiles present a range of approximately 20% (±3%) between upper and lower bound.

Finally, **FCEV GWP reduction potential is highly dispersed**, ranging from -79% to +85% compared with ICE-G. Similarly to BEVs, approximately 82% of estimates indicate a reduction of GWP relative to ICE-Gs, with two results ranging +1% to +2%, one result at +11%, and two results higher than +60%. However, differently from BEVs, results among the negative values are extremely dispersed (visible in the larger box in Figure 15).

2.4.4 Production Phase Global Warming Potential

ICE powertrains powered by gasoline, diesel, or CNG exhibit similar production phase GWP, averaging approximately 35 g CO_2-eq/km, with 90% of the estimated GWP per vehicle falling between 5 and 9 t CO_2-eq. As a share of total life cycle GWP, the production phase contributes on average 14% for ICE-G, 16%

for ICE-D, and 19% for ICE-CNG, within a comparatively restricted range of11% to 25%. Comparing ICE-D and ICE-CNG against ICE-G directly, current research either assumes equal production emissions or suggests a slight increase of 5% to 10%, with the exception of one study reporting a +13% increase for ICE-D relative to ICE-G.

HEVs and PHEVs follow a broadly similar pattern, with a modest increase in production-related emissions (42 g CO_2-eq/km and 37 g CO_2-eq/km respectively). The absolute results for HEV mirror the range observed for ICE powertrains, while PHEVs remain within a narrower 8.2 to 8.9 t CO_2-eq. The production phase contributes a somewhat higher share of life cycle emissions here, ranging from 16% to 32% (on average about one quarter of life cycle emissions). This is mirrored in the comparison against ICE-Gs: with one exception for HEVs, all results report an increase in production GHG emissions relative to ICE-Gs, though the range is wide (+6% to +68%).

BEVs are the most data-rich powertrain and show consistently higher production emissions than the powertrains above, averaging 57 g CO_2-eq/km across a wide range (36 to 131 g CO_2-eq/km, or 7.8 to 26.2 t CO_2-eq in absolute terms). Battery production accounts for a substantial share of this, averaging 54% of total production impacts, though ranging widely from 20% to 86%, a spread comparable to that observed for absolute and relative CO_2-eq emissions overall. The rich data for this powertrain allows for a statistical analysis, which shows a significant negative correlation between total BEV life cycle emissions and the contribution of production to total life cycle emissions (see Figure 16), a relationship not observed for conventional powertrains. Compared with ICE-G, all but one BEV result (the exception being a production estimate based on a hypothetical 2030 scenario) report higher production-related emissions, ranging from +11% to a threefold increase, with roughly one third of results concentrated between +68% and +87%.

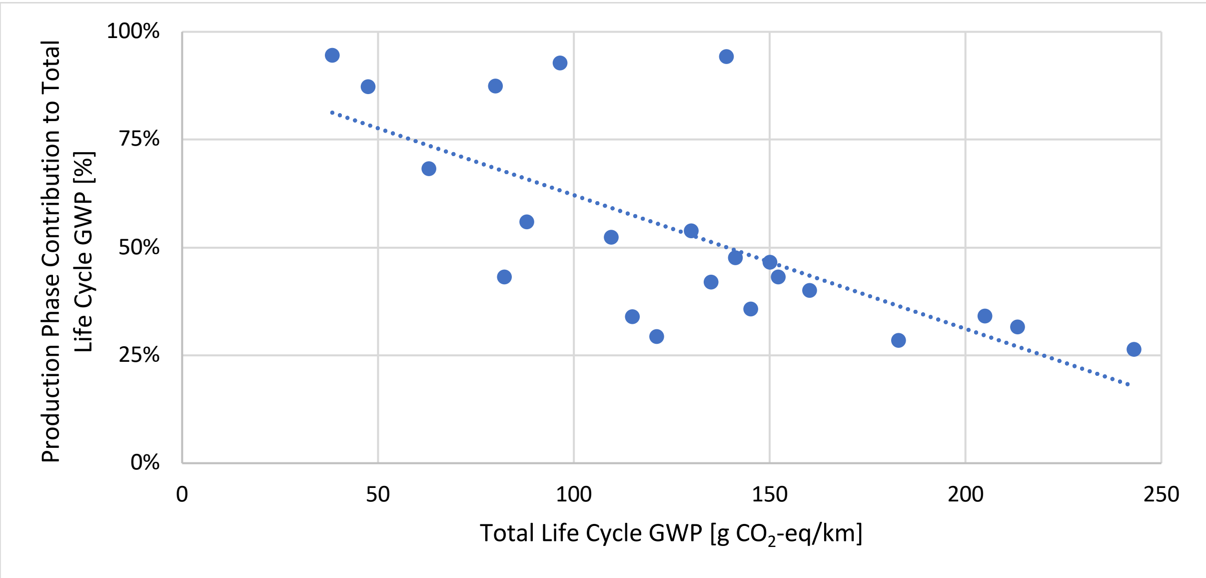

Figure 16: Correlation Between Total Life Cycle GWP and Production Phase Contribution for BEVs

FCEVs are on average more GHG-intensive during production than conventional powertrains, averaging 41 g CO_2-eq/km, with absolute results ranging from 4.5 to 13.0 t CO_2-eq. As with BEV, the contribution of production to total life cycle emissions varies considerably, from 14% to 69%, as does the contribution of the fuel cell battery component to production-related emissions specifically (14% to 60%), though this component contributes comparatively less to total production impact than the battery does for BEVs.

2.4.5 Use Phase Global Warming Potential

The use phase encompasses both WTW emissions and maintenance-related emissions.

ICE powertrains present a consistent overall WTW pattern, though absolute impact estimates vary widely across studies as a function of differing fuel consumption and mileage assumptions, ranging from 133 g CO_2-eq/km (24 t CO_2-eq) to 268 g CO_2-eq/km (53 t CO_2-eq) for ICE-G and ICE-D. **WTW emissions contribute approximately 80% to total life cycle emissions** within a fairly tight range: with the exception of two results, all fall between 71% and 89%. Within WTW, WTT contribution is likewise consistent, falling between 22% and 26% of WTW impact apart from three outliers. In terms of WTW contribution, HEVs and PHEVs show slightly lower results, averaging 75% and 68% of total life cycle emissions respectively, though the PHEV range is considerably wider (52% to 79%), a pattern mirrored in WTT contribution (average of 37%, range of 23% to 45%).

BEV emissions vary greatly on WTW emissions, ranging from 4 to 177 g CO_2-eq/km (1 to 43 t CO_2-eq). Results are distributed as follows: 31% between 4 and 16 g CO_2-eq/km, 43% between 41 and 76 g CO_2-eq/km, 11% between 87 and 104 g CO_2-eq/km, 9% between 135 and 146 g CO_2-eq/km, and 6% above 170 g CO_2-eq/km. This is mirrored in WTW contribution to total life cycle emissions, which ranges from 6% to 77% (average of 41%). **FCEVs follow a similar pattern**, though with an even wider range, from 10 g CO_2-eq/km (2 t CO_2-eq) to 331 g CO_2-eq/km (79 t CO_2-eq). WTW contribution to total life cycle emissions likewise varies widely, from 20% to 89%.

Compared with WTW, **maintenance-related emissions show a more similar pattern across powertrains**. ICE-G, ICE-D, ICE-CNG, HEV, and PHEV report almost identical or slightly differing results (within +3% to +7%), ranging from 5 to 8 g CO_2-eq/km (1.2 to 2.0 t CO_2-eq), contributing 2% to 4% to total life cycle emissions (3% on average), with the exception of a slightly higher contribution for PHEV, up to 6%.

Only BEVs and FCEVs show slightly but consistently lower maintenance-related emissions, ranging from 4 to 7 g CO_2-eq/km (1.0 to 1.7 t CO_2-eq), though the difference vis-à-vis conventional powertrains varies widely (-50% to -3% for BEVs, -20% to -8% for FCEVs). As with production emissions, the contribution of maintenance to total life cycle emissions shows a significant range for BEVs (2% to 11%) and FCEVs (2% to 10%); for both, this contribution is negatively correlated with total life cycle emissions.

2.4.6 End-of-Life Global Warming Potential

In comparison with other life cycle phases, **considerably less data is available for the EoL phase,** with only 5 of 19 sources reporting explicit EoL estimates. The available results are nonetheless worth examining. A first distinction concerns the EoL modeling approach: two studies calculate credits assigned to recycling, meaning EoL impact is negative and reduces total life cycle emissions, while three studies assign only impact-related processes to EoL, resulting in a positive EoL impact that increases total life cycle emissions.

For **ICE powertrains and HEVs, absolute results are fairly concentrated and comparable**, falling between 3.85 and 5.42 g CO_2-eq/km (0.68 to 1.39 t CO_2-eq), contributing to or decreasing total life cycle impact by approximately 2%, and varying from -5% to +8% compared with ICE-Gs. **PHEVs show slightly higher absolute impact** (average of 4.66 g CO_2-eq/km), ranging from -16% to +17% compared with ICE-Gs, while contributing slightly less to total life cycle emissions.

BEVs, by contrast, show a much wider range of both positive and negative impacts, from -8.33 to 5.77 g CO_2-eq/km (-2 to 1.27 t CO_2-eq). Contribution to total life cycle emissions is likewise more varied, ranging from a decrease of 18% to an increase of 7%. In comparison with ICE-Gs, the difference is stark: except for one value (-10%), the absolute average difference between BEV and ICE-G EoL impact is 53%. Finally, **FCEV EoL results remain more concentrated**, ranging from -4.9 to 5.35 g CO_2-eq/km, and contributing to or decreasing total life cycle emissions by approximately 3% in all cases but one. When compared with ICE-G EoL results under similar conditions, FCEVs also show higher absolute results than ICE-Gs, though less pronounced than BEVs, ranging from -14% to +39%.

2.5 Review of Methodological Choices in Automotive LCA

When conducting an LCA study, a key question is how the effects of the system under study interact with other systems. In LCA, this question is addressed through the choice between an attributional or a consequential approach.

2.5.1 LCA Type

When conducting an LCA study, a key question is how the effects of the system under study interact with other systems. In LCA, this question is addressed through the choice between an attributional or a consequential approach.

The **attributional approach** assesses the direct impacts of a product, treating the system as if it were isolated from the rest of the technosphere or economy. As a result of only assessing the focal product system, the question of where to cut off the processes arises. This issue is often addressed through **cut-off criteria** such as low contribution to physical mass or low environmental impact, thereby reducing the data-collection burden (Eltohamy et al., 2026). The **consequential approach**, by contrast, focuses on the environmental consequences of the product system and how these affect the surrounding economy and technosphere (Hauschild et al., 2018). Therefore, the attributional approach only accounts for the system under study and can provide results with more certainty, because in the consequential approach, effects on other systems need to be predicted. **Hybrid approaches** where some aspects are modelled consequential, but the rest are modelled attributional can also occur, as observed in two sources within the reviewed literature: Negri & Bieker (2025) model indirect land use change (ILUC) consequentially within an otherwise attributional framework, while VDI (2023) applies a marginal electricity mix to the use phase for the same purpose, finding that this consequential treatment raises average BEV GWP by 41% relative to an attributional average grid mix, reducing BEV's environmental advantage over conventional powertrains by 34% on average. This finding illustrates that the choice between attributional and consequential modeling is not merely a question of methodological purity, but one with material consequences for reported results.

A further layer of complexity emerges when the time horizon of the product system is taken into account. For long-lasting products such as cars, the systems in which they operate are likely to change over time, so a static assessment can fall short. This calls for an approach able to account for such future changes, known as **prospective LCA**. The prospective perspective, striving to analyze the dynamic change of the system, can be added to both LCA types.

The **most common LCA type applied in recent literature is the attributional approach**, used throughout all the reviewed sources though stated explicitly in only seven (see Figure 4), **often enriched through a prospective perspective**. Especially in the field of automotive LCA, the prospective assessment is well suited, due to the fact that vehicle operational time is usually estimated between 10 to 20 years. As this timeframe mostly targets the use phase of cars, developments in the underlying electricity mix have a significant influence on the results and should be captured through a prospective analysis (see Section 2.6.7). In this regard, all reviewed sources with a prospective element project a future electricity grid, but several extend this further to other dimensions (see Figure 8), such as vehicle technology development (e.g. enhanced battery capacity and rising PHEV utility factor) and the fuel mix (e.g. increased biofuel share in fuel blends). The EoL stage is likewise affected by whether the LCA is modelled as static or prospective (see Section 2.6.10).

2.5.2 System Boundary

The possible **system boundaries** of automotive LCA were already described in Section 2.1. The focus here is on the implications different system boundaries have on the results of a study. In the scientific literature, cradle-to-grave is the most commonly used system boundary (Da Costa et al., 2025; Eltohamy et al., 2026; Oluwalana & Grzesik, 2025; Ostojic & Traverso, 2024), although the EoL phase is often excluded (Brousek et al., 2026). Our own literature review confirms this pattern: most reviewed sources apply a cradle-to-grave boundary, three exclude the EoL phase in favor of a cradle-to-gate plus WTW boundary, and one further source targets WTW alone (see Figure 6). This divergence in system boundaries increases uncertainties because, when one life cycle phase is excluded, the results are not easily comparable.

A further discrepancy concerns the **definition of the life cycle phases** themselves. Some authors identify three basic life cycle phases (see Section 2.2 and Szumska, 2024), while others distinguish four (e.g. Jaššo et al., 2025). Comparing the contribution of individual life cycle phases across studies therefore requires agreement on what these phases should include. This need for consistency in what is included becomes even more pronounced when comparing different powertrain types, since a shared understanding of which phases are actually comparable is required. Negri and Bieker (2025), for example, include EoL within the production stage, while other studies exclude it or treat it as a separate phase, which complicates direct comparison between studies. Jaššo et al. (2025) address this issue even within studies, regarding the comparison of different powertrains. They argue that WTT emissions from electricity production for BEVs cannot be meaningfully compared to TTW emissions from fuel consumption in internal combustion engines.

These findings underline that an **agreement on system boundaries is needed**, particularly in a policy setting. The literature analysis conducted for this paper confirms that the cradle-to-grave approach is the most frequently applied, suggesting that it is a feasible basis for policy regulation. This is reinforced by the shortcomings of the tailpipe approach, which neglects entire life cycle phases and can consequently lead to misleading conclusions while risking burden shifting to other stages of the life cycle.

2.5.3 Functional Unit

The **functional unit** (FU) of an LCA is the focal unit around which all collected data are structured, and it also serves as the reference unit used to express the results of the study. Defining the FU lays the foundation for what is actually being assessed. It is therefore closely tied to the goal of the study, which could, for example, involve assessing the vehicle as a product or assessing the impacts of mobility as a service (Oluwalana & Grzesik, 2025). For assessing the environmental performance of different powertrains, it is nearly **universally agreed to use a distance-based FU**, expressed as grams of CO_2 equivalent emitted per kilometer traveled (Da Costa et al., 2025; Eltohamy et al., 2026; Ostojic & Traverso, 2024; Szumska, 2024).In fact, every source reviewed by us applies a distance-based FU, whether expressed in absolute or relative terms. Eltohamy et al. (2024), however, argue against this FU on the grounds that it does not account for whether a car transports only the driver or four passengers. An **occupancy-based FU**, however, requires further assumptions and real-world considerations to be incorporated in the model. Among the sources reviewed for this study, only Puig-Samper Naranjo et al. (2021) incorporates occupancy at all, and even this instance is occupancy-based in name only, since it assumes a single passenger throughout, effectively collapsing back into the standard distance-based FU it is meant to move beyond. Agreeing on a common FU remains a central aspect for the comparability between studies and therefore requires standardization.

2.5.4 Multifunctionality and Allocation Methods

A prominent problem in LCA in general but automotive LCA in particular is **multifunctionality.** It occurs when a process delivers multiple outputs that are not directly used as an intermediate flow within the focal product system. In automotive LCA it es relevant e.g. where material recovery at EoL is commonly assumed. The ISO standard provides a **hierarchy of solutions**, suggesting that the system should first be subdivided or expanded to avoid multifunctionality (Hauschild et al., 2018). In practice, however, this is often not possible, which creates the need to solve the multifunctionality problem mathematically through allocation. However, the choice of how emissions are allocated in particular has a significant impact on the results (Eltohamy et al., 2026; Schrijvers et al., 2016).

At the **EoL stage in automotive LCA** several different approaches can be applied to allocate emissions. These include the following:

- **The cut-off approach**, in which the impacts from EoL are either excluded entirely or fully assigned to the focal product system, meaning no credits are given for recycling, and circularity is not incentivized (allocation ratio 100 to 0).
- **The avoided burden approach**, which assigns credits to the focal product system on the basis that recycled material substitutes materials that would otherwise be newly produced (allocation ratio 0 to 100).
- **The 50:50 approach**, in which emissions are split evenly, reflecting that the material was used within the focal product system but will also be used again in a subsequent one.
- **The Circular Footprint Formula**, developed for the EU Product Environmental Footprint framework, which distributes the environmental burdens and credits of recycling or recovery between the supplier and the user of the recycled content (Zampori et al., 2019).

The **choice between these methods is far from trivial.** Switching the allocation method, for example from avoided burden to the Circular Footprint Formula, can change results by up to 33% for the EoL stage (Accardo et al., 2023). Our own results provide clear evidence of this impact: depending on the allocation method applied, the EoL stage can either function as a crediting phase, reducing total life cycle GWP through avoided burdens, or as a contributing phase, adding a positive GWP of its own. Furthermore, more specifically, the allocation method chosen directly affects which materials appear favorable, depending on the EoL opportunities they offer. These effects become even more relevant when comparing BEVs and ICEVs, since batteries contain critical and valuable materials, making the methodological choice of how to treat them at end of life particularly significant (Section 2.6.10). While it cannot be established with certainty that one allocation method is superior to all others (Eltohamy et al., 2024), it is clear that the allocation approach must remain consistent within a given study. Otherwise, results risk being skewed in favor of one alternative over another. Transparency about the chosen approach is therefore essential, and steps toward harmonization should be encouraged (Ostojic & Traverso, 2024).

2.5.5 Life Cycle Impact Assessment Method and Impact Categories

Scientific approaches known as **LCIA methods** have been established for evaluating the environmental impact of LCA studies. Many such methods exist, differing in geographical scope, in the impact categories they cover, and in how up to date they are. Among the most commonly used are ReCiPe2016, CML, and IPCC2021. These methods encompass a range of impact categories such as Global Warming Potential (GWP), Acidification, and Human Toxicity. Because the reviewed studies most often focus on Greenhouse Gas (GHG) emissions, some rely simply on GHG characterization factors rather than applying a full LCIA method (Da Costa et al., 2025; Oluwalana & Grzesik, 2025; Ostojic & Traverso, 2024). Although this emphasis on GWP dominates in research, media, and policy targets, a **broader set of impact categories** must be considered to achieve a holistic assessment of the environmental impacts and to avoid shifting burdens between categories. Only such breadth can reveal the full picture of environmental emissions associated with the studied product system.

When assessing BEVs in particular, performance on GWP is better than that of ICEs (see Section 2.4.3). A more comprehensive analysis, however, also reveals **disadvantages of BEVs in other categories** such as human toxicity, metal depletion, and water use. The total energy demand from BEVs likewise deserves attention (Jungmeier et al., 2024). Considering more impact categories yields a fuller picture, but this raises the question of how to deal with the trade-offs it reveals, since no drivetrain performs better in all impact categories. To overcome this barrier additional steps such as **normalization** and **weighting** are required. The ISO standard 14040 (ISO, 2006a) recommends these steps as well, though only as optional. Even in the harmonization approach from TSLCA, they do not provide a standardized approach for normalization and weighting (Jose et al., 2026). Overall, to strengthen the comparability of studies, LCA scholars and practitioners need to define a common LCIA method, standardize the impact categories used, and agree on weighting factors to be able to assess the relative importance of results across impact categories.

2.5.6 Primary vs. Secondary Data

LCA distinguishes between **primary** and **secondary data.** Primary data are producer-specific data for each specific product and its components, based on actual use under specified conditions (use cases). Such data are the ideal input for modeling the **foreground**, that is, the specific product system under study, because they describe the real processes at hand. In practice, however, **primary data are scarce** (Eltohamy et al., 2024) or at least considered confidential information, so they are typically replaced with secondary data, i.e. published values from scientific articles and industry reports, which typically report generic industry averages. Automotive LCAs illustrate this tension clearly, as manufacturer-specific data would considerably strengthen the analysis, yet obtaining such data from industry remains challenging, so most published studies rely on secondary sources, a pattern confirmed by our own review: all eighteen sources rely on secondary data, though five explicitly incorporate primary data modeling for specific processes. Secondary data are more readily available and form the backbone of LCA databases, of which Ecoinvent is by far the most widely used (Liu et al., 2024; Oluwalana & Grzesik, 2025). GREET, LCA for Experts, and various regional databases are also employed across the scientific community (Da Costa et al., 2025). A key advantage of these databases is that they supply a full background system, meaning that predefined process datasets can either be used directly or adapted to the setting under study. Even so, **the choice of database is not neutral**, since different databases can change the results, and LCA accuracy can be improved substantially when high-quality primary data are introduced where they matter most. What is therefore needed is a shared understanding, particularly in the automotive context, of which process steps must be based on primary, product-specific data to be considered reliable (Eltohamy et al., 2024), together with a common convention on which background database to use.

2.5.7 Temporal, Technological and Geographic Scope

These dimensions must be clearly defined within the goal and scope phase, as they determine the extent to which the assessment reflects the real conditions of the product system under review. **Greater representativeness requires closer alignment with the relevant time period, production technologies, and geographical context**. However, as outlined in Section 2.5.6, LCA studies frequently rely on secondary data, which may not fully capture the specific characteristics of the product system being assessed (Oluwalana & Grzesik, 2025). This is particularly relevant for battery production, where **rapid innovation** can render older datasets insufficient for representing current industry conditions. Similar technological changes include shifts in battery chemistry and evolving manufacturing practices. Geographical representativeness is also essential, as production conditions, energy systems, and vehicle operation can vary substantially across locations (see Sections 2.6.3 and 2.6.7). For example, the performance of BEVs may decline in colder environments, meaning that the location of vehicle use can materially influence assessment outcomes (Raugei, 2022). This implies that assessment rules should require current and geographically representative data, with transparent justification whenever secondary or generic datasets are used and with a clear and coherent link with the scope of the study.

2.6 Result Influencing Parameter Assumptions in Automotive LCA

In addition to methodological choices, LCA outcomes are shaped by **parameter (or inventory) assumptions**: decisions about the values assigned to inputs within the chosen methodology, affecting numerical results rather than model structure. The following sections examine these assumptions in detail, complementing the discussion of methodological choices as a second driver of variation in LCA findings.

2.6.1 Vehicle and Powertrain Type

Sitting between parameter and methodological assumptions, a first decisive parameter in any LCA study is the **vehicle type** under study. While all vehicles share the same basic function of transporting passengers, they are **highly heterogeneous** in space, features, materials, weight, longevity, and power. This heterogeneity translates into substantial differences in impact in GHG emissions, which can be up to 52% higher for a large, heavy luxury vehicle than for a small, light-weight vehicle (Ellingsen et al., 2016). Notably, while all passenger vehicles are categorized as M1 (and thus covered by Regulation EU 2019/631), a market segment classification (e.g. Sport Utility Vehicle, mini car) is commonly applied in LCA practice. This **segmentation**, however, is **not governed by any settled standards** and the classification remains inconsistent, underscoring the need for a reproducible framework to translate physical vehicle attributes into comparable analytical categories. This inconsistency is directly reflected in our results, where the studies we reviewed use different terminology for broadly equivalent segments, such as "medium segment", "medium size", "compact class", and "C segment". Coverage also varies considerably, spanning mini cars through to vans and SUVs, though the medium segment dominates, appearing in more than 75% of the reviewed studies, six of which cover more than one vehicle type.

Beyond vehicle type, the **central object of comparison in automotive LCA is most commonly the powertrain**: the set of components that generate and deliver power to the road surface, including the engine and its auxiliary systems. Passenger vehicles can be classified into the following five categories based on powertrain configuration.

- **Internal Combustion Engine Vehicles** (ICEVs) rely exclusively on the combustion of a liquid or gaseous fuel (gasoline, diesel, compressed natural gas, biodiesel, e-fuels or fuel blends) for propulsion, with no onboard electric drive system.
- **Hybrid Electric Vehicles** (HEVs) combine an internal combustion engine with a battery and electric motor that recovers braking energy and assists propulsion but cannot be charged externally.
- **Plug-In Hybrid Electric Vehicles** (PHEVs) extend this configuration with a larger battery chargeable from the grid, enabling a limited all electric range before the combustion engine engages.
- **Battery Electric Vehicles** (BEVs) are powered exclusively by a battery pack and electric motor, with no combustion engine on board.
- **Fuel Cell Electric Vehicles** (FCEVs) generate electricity onboard through the electrochemical reaction of hydrogen and oxygen in a fuel cell, powering an electric motor without combustion.

In automotive LCA, reflecting the growing importance of mobility electrification, the most frequently examined powertrain pairing is **BEVs compared to ICEVs as a baseline**, followed by HEVs and PHEVs. FCEVs are increasingly studied as a potential alternative to BEVs. This ordering broadly matches our own review: ICE-Gs and BEVs form the most consistently investigated pairing, followed by BEVs, ICE-Ds and PHEVs, while FCEVs and ICE-CNGs are explored in only around half of the reviewed sources. Scope also varies by source: seven sources compare three powertrains, typically ICE-Gs, BEVs, and one further type, while only three extend the comparison across all seven powertrain variants considered in this paper.

For both vehicle type and powertrain type, a first major choice for practitioners is defining the **reference vehicle and technology**. Two approaches are available, partly determined by the goal of the study (comparison of a specific vehicle vs comparison of a fleet): the **use of averages**, weighted either by sales or by production (e.g. Negri & Bieker, 2025), or the **use of a specific vehicle as reference** (e.g. Brousek et al., 2026). A closer look at our own reviewed sources refines this picture further by adding a third approach: a **theoretical vehicle** constructed to embody typical characteristics. While averages and theoretical vehicles are widely applied to obtain generalizable results, specific vehicle reference is particularly relevant for emerging technologies, where only a small number of models exist (currently, for example, the only FCEVs commercially available in Europe are the Toyota Mirai and the Hyundai NEXO).

Overall, the **choice of vehicle type and powertrain comparison can substantially influence LCA results**. However, although individual results may diverge significantly, patterns across study averages remain largely consistent despite this variation (Das et al., 2023). Nonetheless, it is important to clearly define the goal, scope, and functional unit of each LCA (see Section 2.2 and 2.5.3): comparing the environmental impact from a mini car against an SUV raises the underlying question of whether the two vehicles perform the same function.

2.6.2 Vehicle Lifetime and Mileage

Once vehicle and powertrain types are defined, the definition of **vehicle lifetime** (VLT) and mileage represents a crucial parameter choice and a central determinant of LCA outcomes. VLT refers to the total number of years a vehicle remains in operation, from production and sale to its last kilometer and end of life. **LCA literature does not converge on a single VLT value**: TSLCA suggests 15 years, UNECE applies 20 years, and the tool developed by Jungmeier et al. (2024) allows a maximum lifetime of 16 years. Our own literature review reflects this same lack of convergence: around one in four of studies we reviewed does not specify a VLT value at all, while the others span a range from 10 to 20 years. A comparable divergence appears also in empirical data across EU Member States, where the average age of EoL Vehicles (ELV) ranges from 19.0 years in Germany (Umweltbundesamt, 2025) to 24.7 years in Portugal (Agência Portuguesa do Ambiente, 2026). Beyond being a location specific parameter, standardizing VLT is further complicated by its intrinsic uncertainty, since it necessarily represents an estimate about the future. The importance of VLT becomes even more evident when considering its effect on modeling operation-related emissions over times, which depend on the evolving electricity grid mix and fuel blend, as well as on the year in which the vehicle’s EoL occurs. Different assumed time horizons can therefore generate significant indirect impact through these coupled parameters.

The importance of VLT becomes even more evident when considering its effect on modeling operation-related emissions over time, which depend on the evolving electricity grid mix and fuel blend, as well as on the year in which the vehicle's end of life occurs. Different assumed time horizons can therefore generate significant indirect impact through these coupled parameters.

Closely linked to VLT, mileage represents both the total distance traveled over a vehicle's lifetime and the annual distance traveled within a single year. As with VLT, and compounded further by the vehicle heterogeneity discussed in Section 2.6.1, **no standard mileage value commands consensus**: the literature reports a range from 150,000 to 257,600 km (Da Costa et al., 2025), while guidelines diverge as well, with TSLCA specifying 200,000 km and UNECE leaving the parameter unspecified. Since the FU adopted throughout the reviewed literature is distance-based (see Section 2.5.3), total mileage must be specified for any such assessment: however, our own review confirms a wide range, from 150,000 to 280,000 km, partly depending on vehicle type. In combination with VLT, the **modeling of annual mileage** can vary substantially, whether assumed constant, linearly decreasing, or non-linearly decreasing over the VLT. A declining profile is increasingly supported by empirical evidence (Viri & Mäkinen, 2025): ageing vehicles see more frequent breakdowns and declining efficiency, raising costs and discouraging long trips, while often shifting into a secondary, low-mileage role within households with access to another, newer vehicle, which then takes over most annual use. This variation is borne out in our own review as well: ten sources leave annual mileage unspecified, six assume it to be constant, and only two apply a linearly decreasing profile. Notably, none apply the non-linearly decreasing profile recommended by TSLCA, despite its status as the primary EU harmonization reference for this parameter.

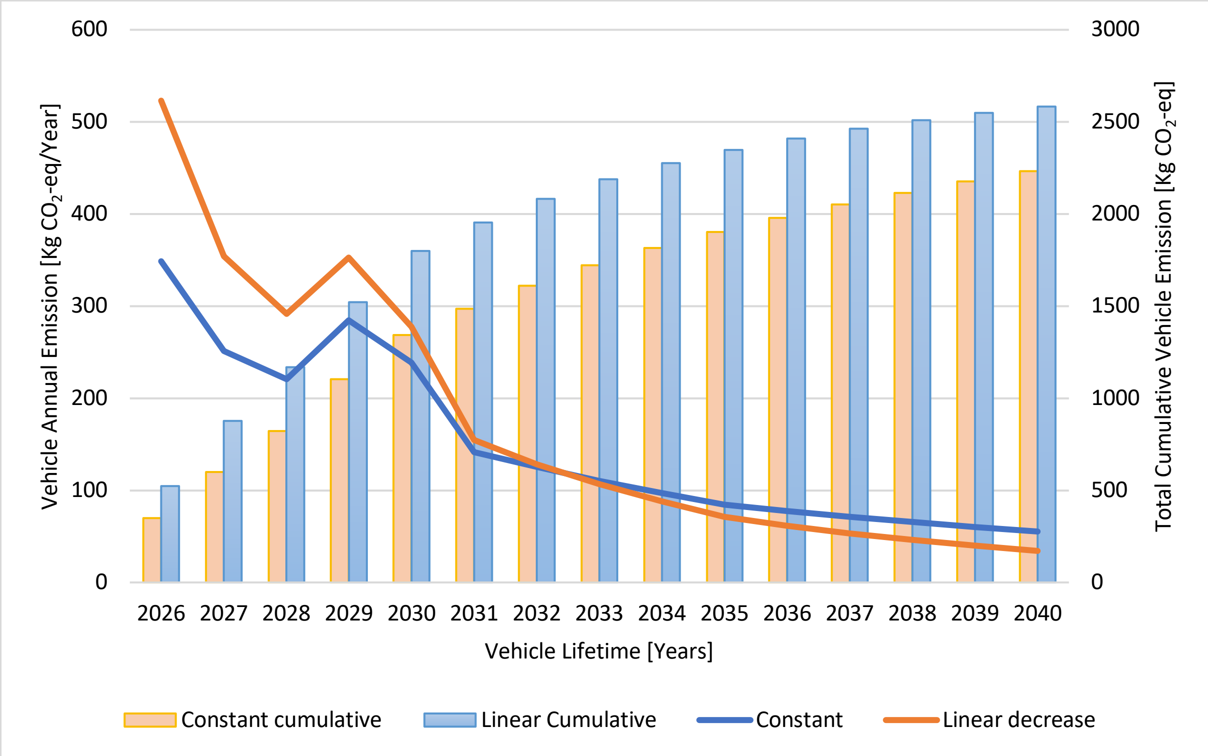

Figure 17: Comparison of Well-to-Wheel CO_2-eq Emissions for BEVs with Constant and Linear Decrease in Annual Mileage. Source: own elaboration based on Christensen & Petrenko (2017); Joint Research Centre (2024); Negri & Bieker (2025).

Figure 17 illustrates the effect of this modeling choice on WTT GWP emissions for the same hypothetical BEV, comparing constant versus linearly decreasing annual mileage while holding all other parameters constant, including the annual carbon intensity of the electricity grid (decreasing according to the JRC POTEnCIA scenario), total mileage, VLT, and BEV efficiency (0.15 kWh/km). The comparison shows that, *ceteris paribus*, assuming a decreasing annual mileage profile yields approximately 16% higher WTT emissions than assuming constant annual mileage. This arises from the coupling of each year's total kilometers with that year's specific grid carbon intensity: under the decreasing profile, more kilometers are driven early on, when the grid is more carbon intensive, and this front-loaded effect is not offset by the lower mileage driven later, once the grid has decarbonized.

Given the dominance of the distance-based FU, these **parameters emerge as major determinants of LCA results** (Cox et al., 2020), directly shaping the per kilometer impact amortization for BEVs. Eltohamy et al. (2026), for instance, find that increasing BEV mileage by 50,000 km relative to the reference value lowers GWP by 10-20%, while decreasing it by the same amount increases GWP by 20-30%. Mileage is therefore a decisive factor in powertrain comparison, with a considerably larger effect of decreasing total mileage on production dominated life cycles such as BEV (+22% for BEVs versus +4% for ICEVs in Negri & Bieker, 2025). Taken together, these findings indicate that assumptions on mileage remain in need of standardization.

2.6.3 Vehicle Production

Although not typically identified as a primary source of uncertainty in LCA results, the modeling of vehicle **production** (excluding the battery, addressed separately below) remains a significant input to overall outcomes. In this stage, the extraction, processing, and manufacturing of raw materials become paramount. As Eltohamy et al. (2024) indicate, in practice, to model the production stage there are three approaches: **full modeling** of the specific extraction process, the **use of generic LCI data** drawn from databases or literature, or a **hybrid approach** combining primary and secondary data to reflect more location specific conditions (see Section 2.5.6). These approaches carry different implications for how much location and route specific extraction processes matter, since impacts can vary substantially depending on location and production practices. For structural parts, for instance, Chinese and Indian steel and aluminum carry substantially higher embodied GHG emissions than European or hydro powered production, and switching sourcing regions can materially change a vehicle's cradle-to-gate footprint (Winjobi et al., 2022). Data granularity likewise varies considerably across studies, ranging from aggregated figures to a detailed material by material breakdown, to which energy and auxiliary substances must be added (Ricardo et al., 2020). A comparable component level contribution analysis of vehicle carbon footprint is provided by Hirz & Nguyen (2022), illustrating the practical trade-off between the granularity such disaggregation offers and the data availability it requires.

Overall, while data specificity and granularity are important, a degree of realism is warranted: given the sheer volume of materials, components, and suppliers behind a single vehicle, reliance in large part on aggregated and generic data is often the more feasible path for practitioners.

2.6.4 Electric Vehicles' Battery

Within the production phase, a major element affecting LCA results is the production and specification of the **battery for BEVs**.

Battery production exerts significant influence on both GHG emissions and primary energy demand (Jungmeier et al., 2024), and is the main source of disparity in GHG emissions between BEVs and conventional vehicles in cradle-to-gate assessments, driven by raw material extraction and energy intensive manufacturing (Vieira et al., 2025). Despite broad agreement in the literature on the importance of this driver, the resulting impact estimates vary widely, ranging from less than 40 kg CO_2-eq/kWh to more than 200 kg CO_2-eq/kWh (Jaššo et al., 2025). These variations are determined by three main factors. First, **battery chemistry**, dominated by Lithium-Ion batteries (Da Costa et al., 2025), plays a central role, and the choice of cathode material also exerts significant influence, since its composition determines raw material demand. Second, **material sourcing** represents a major factor, as raw materials sourced from different locations through different processes can significantly affect results (Schenker & Pfister, 2025). Third, and partly related to sourcing, the **location, scale, and timing of production** are also major determinants of battery production impact, operating mainly through the local electricity mix, a critical factor given the energy intensity of the process. Negri & Bieker (2025), for instance, estimate a difference of up to 54% in GHG emissions between the best-case scenario (an LFP battery produced in Europe) and the worst-case scenario (an NMC622 battery produced in China). Battery production therefore occupies a foreground position in LCI modeling.

Beyond the production phase, **other battery configuration choices determine impact further downstream**. Among these, **battery capacity** is paramount, as it strongly influences VLT (see Section 2.6.2). Two challenges follow from this. First, standardized test cycles for batteries are still lacking (Eltohamy et al., 2024). Second, battery capacity can be modelled as either constant or deteriorating over time, for both BEVs and PHEVs, with most of the literature assuming constant capacity for simplicity. However, while real world degradation appears markedly better than early conservative assumptions, battery capacity still declines over time (Geotab, 2026). For this reason, batteries are more appropriately compared on the basis of total energy delivered over their service life rather than nominal storage capacity. **Battery lifetime** is similarly a crucial element in determining this component's impact. This matters because of the potential need for **battery replacement**, which depends on a range of factors including battery chemistry, temperature, power, and driving conditions (Oluwalana & Grzesik, 2025). The literature assumes both no replacement and replacement (e.g. Kawamoto et al., 2019), with this assumption frequently tested in sensitivity analysis.

Overall, **battery specifications are clearly a central element in determining BEV impact**, given the energy intensity of production, raw material extraction, and the role of capacity and lifetime. Notwithstanding this, future trends appear promising on several fronts. BEV production emissions are expected to become only marginally higher than those of conventional vehicles (Linder et al., 2023), and some estimates indicate the eventual possibility of carbon free battery production (Märtz et al., 2022). **Battery capacity has also been increasing steadily**, with realistic scenarios projecting increases of 62% in capacity and 37% in energy density by 2050 (Isilti & Tate, 2026). While promising for BEVs, these prospective trends also introduce additional uncertainty into LCA, particularly in the interpretation of results rather than in LCI construction itself, which can still be grounded in existing technologies. Conclusions drawn on the impact of current battery production may therefore be misleading if they do not account for these prospective improvements.

2.6.5 Fuel and Energy Consumption During Vehicle Operation (Use Phase)

Moving from production to the use phase, a major factor affecting both absolute results and relative powertrain performance is the **energy consumption** assigned to each powertrain and vehicle type. Different powertrains draw on different energy carriers, measured in different units (see Section 2.6.1): ICEVs and HEVs consume fuel (L/100 km), BEVs consume electricity (kWh/100 km), FCEVs consume hydrogen (kg/100 km), and PHEVs draw on both (L/100 km plus kWh/100 km). Different vehicle types naturally require **different consumption patterns**, producing wide variability in reported energy consumption across the literature (Da Costa et al., 2025).

The most decisive factor identified in the literature, however, is the persistent **discrepancy between Worldwide Harmonized Light Vehicles Test Procedures (WLTP) and real-world energy consumption**. WLTP were developed to harmonize *ex ante* vehicle consumption testing and serve as the standardized laboratory test used to measure fuel consumption, GHG emissions, and electric range for light vehicles. Despite this harmonizing intent, WLTP figures systematically fall short of representing real world vehicle consumption. The European Commission (2024) estimates a gap of around 24% in GHG emissions between WLTP and real-world values, with an 18% gap in fuel consumption specifically. Liu et al. (2024) estimate an even larger divergence, in the range of 30 to 40%. A sensitivity analysis by Negri & Bieker (2025) illustrates how this choice affects different powertrains unevenly: use phase-dominated life cycles (ICE and HEV) benefit more from using WLTP than production phase-dominated life cycles (BEV). PHEVs emerge as particularly sensitive to this adjustment, losing up to 50% of their life cycle impact when WLTP values are used directly rather than adjusted ones. This sensitivity is corroborated by other studies (e.g. Onat & Kucukvar, 2022), which find that differences in the assumed **PHEV utility factor** (i.e. the share of driving distance covered in electric mode), can produce up to a 50% difference in energy consumption for this powertrain. For this reason, most academic studies use adjusted WLTP values or real-world data rather than relying on WLTP figures directly, a pattern our own review only partly bears out: four of the eighteen reviewed sources rely on WLTP figures directly, three use real world data throughout, and five apply a combination, most often pairing real world data for ICEs with adjusted figures for BEVs and FCEVs.

Beyond this core discrepancy, other factors also shape vehicle energy consumption during operation. **Charging losses** are a significant component of BEV electricity consumption, whereas fuel losses for conventional vehicles are comparatively negligible (Jaššo et al., 2025). **Driving style** and **driving conditions** are likewise considered crucial determinants of actual in use emissions (Rimpas et al., 2025), alongside their effect on maintenance needs (see Section 2.6.9). Urban versus highway driving, and aggressive versus moderate driving style, further complicate the picture, leading some authors to call for future research on modeling and integrating human driving behavior into LCA frameworks (Da Costa et al., 2025).

This dimension, however, appears particularly difficult to reconcile with the broader goal of standardization and harmonization.

Notwithstanding these additional complexities, estimating appropriate and representative energy consumption across vehicle types and powertrains remains a major source of uncertainty in automotive LCA. Given how unevenly this uncertainty affects different powertrains, it warrants sustained attention from practitioners seeking to harmonize and refine consumption calculations toward closer alignment with real world fuel and energy use.

2.6.6 Fuel Blends and Alternative Fuels

Alongside energy consumption, the **composition of the fuel blend** is a decisive parameter for any ICE based powertrain (ICE, HEV, and the combustion share of PHEV), since it materially shapes how these conventional powertrains compare environmentally against newer alternatives. Contemporary ICEVs in Europe typically run on **fossil gasoline and diesel with modest biofuel blending**: gasoline blended with up to 5% (E5) or 10% (E10) bioethanol by volume, and diesel blended with up to 7% (B7) FAME biodiesel. Most automotive LCA studies model fuels using these standard blends, or a fossil baseline with an assumed bio share, rather than a fully parameterized fuel mix. The sensitivity of results to this assumption appears more limited than might be expected: Negri & Bieker (2025) find that excluding indirect land use change (ILUC) effects entirely does not significantly lower overall impact, since the biofuel share in current and projected blends remains small.

Biofuels and **e-fuels** represent the two main pathways for reducing the fossil share of ICE-based powertrains without changing the drivetrain itself, though both raise significant challenges for LCA (Sarathy et al., 2022). The assessment of **biofuels**, liquid or gaseous fuels produced from biomass is dominated by **land use change**, both direct and indirect (LUC and ILUC), which can dominate GHG results and remains highly uncertain, alongside feedstock choice and co-product allocation (Fokaides et al., 2023). This produces a genuine duality: advanced or waste-based biofuels can deliver substantial WTT GHG reductions when land use change is negligible, whereas first generation crop-based biofuels with significant land use change can match or exceed fossil fuel GHG intensity. A further choice to be made to assess biofuels is how to treat biogenic carbon. A common assumption in biofuel LCAs is that CO_2 released during combustion is fully offset by feedstock uptake, making the process "carbon neutral" (Matuštík & Kočí, 2022). This, however, is a simplification that ignores the timing of carbon uptake and release, which becomes especially relevant when considering that different biomass types have different rotation periods. Methods to address this issue, such as dynamic LCA, GWPbio, or the 1/+1 method, can be applied (Füchsl et al., 2025).

E-fuels, or synthetic fuels, combine electrolytic hydrogen with CO_2 from air, biogenic, or industrial sources into fuels that are compatible with existing ICE infrastructure (Uchida et al., 2025), such as existing fuel stations, fuel transport vehicles, and, notably, engine systems. Their environmental specifically climate performance is dominated by a single variable, the electricity used for electrolysis: on a coal heavy or average grid, e-fuels can perform worse than the fossil fuels they replace, whereas when the electricity mostly comes from, a fully e-fuel powered ICEs could theoretically perform better than BEVs and FCEVs powered by renewables (Negri & Bieker, 2025). This **strong dependence on electricity carbon intensity** is confirmed by Bouter et al. (2026), whose results illustrate that it is the energy source, not the energy carrier type, that ultimately determines environmental advantage (see also Figure 18). Using the 2023 EU average electricity mix, e-methane and e-diesel produced 42% and 80% higher WTW GHG emissions than their fossil counterparts, while coal-based electricity increased emissions by 421% and 567%, respectively. By contrast, production based on solar PV, nuclear power, or wind reduced emissions by approximately 73% to 95%, showing that e-fuels can achieve a substantial WTW advantage over fossil fuels when produced from renewable electricity, even as the same fuels remain more GHG intensive than fossil fuels under today's actual EU grid mix. Direct electricity use for BEVs, however, outperforms both e-fuels and hydrogen across every one of the seven electricity sourcing scenarios considered**,** reinforcing that even under favorable conditions, e-fuels do not close the gap to direct electrification. In this regard, even under near zero carbon electricity, the multi-step conversion chain is inherently inefficient, so matching BEV level performance at fleet scale would require several times more renewable capacity than direct electrification.

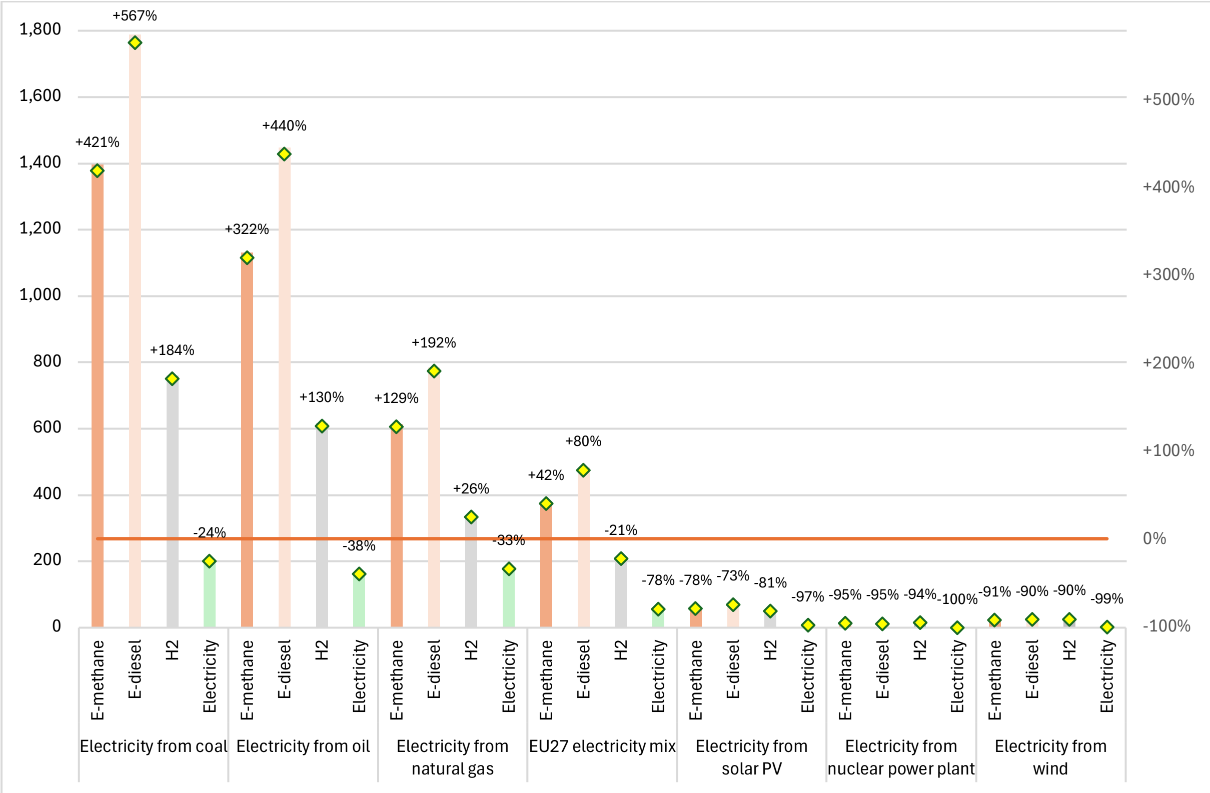

Figure 18: WTW GWP of selected e-fuels (e-methane and e-diesel), hydrogen (H2), and direct electricity use, calculated across seven electricity sourcing scenarios (coal, oil, natural gas, EU27 average electricity mix, solar PV, nuclear and wind). Diamond markers and percentages show the GWP reduction potential relative to the fossil-fuel baseline of 268 g CO_2-eq/km (indicated by the horizontal line). Source: own elaboration based on Bouter et al. (2026).

As it is likely to develop further in the future, LCA studies also need to account for **fuel composition development**. The EU projects the continued use of E10 and B7 as the fuel blend baseline, with gradually increasing shares of advanced biofuels concentrated in sectors where direct electrification is harder to achieve, such as heavy duty, aviation, and maritime transport, rather than in passenger cars. E-fuel volumes in road transport are projected to remain limited but growing, concentrated in residual ICE fleets. Despite these promising trends, the literature broadly agrees that these **alternative fuels will remain confined to hard to electrify sectors** rather than becoming a valid alternative for the passenger car fleet. This finding applies to averaged comparisons within the existing vehicle fleet; it does not address a dedicated new-vehicle category running exclusively on renewable fuels — referred to elsewhere in this White Paper as VEEF (Vehicles Exclusively Using Eligible Fuels, see §3.3) — a distinction that matters for the regulatory options discussed in Chapter 4 (see also the KIT/DBFZ study discussed in §4.3 for a more differentiated, policy-focused assessment). It is also worth noting that this literature is structured around comparing vehicles by drivetrain — a framing shaped in part by the political debate it was conducted within — rather than around identifying the management decisions, from development through procurement to recycling, that this White Paper's regulatory framework aims to reward. This distinction matters: findings bounded to averaged fleet-wide comparisons cannot by themselves make recommendations for a regulatory framework whose purpose is to make currently irrelevant options relevant to manufacturers.

2.6.7 Electricity Mix

The **electricity mix**, its future **development**, and the associated GHG intensity of that mix (hereafter **electricity grid carbon intensity**, measured in kg CO_2-eq/kWh) are the most frequently examined parameters in automotive LCA comparisons across powertrains. Beyond determining part of the emissions associated with the production phase of any vehicle, this parameter is particularly decisive for BEVs and PHEVs, whose environmental performance, and therefore their standing relative to other powertrains, depends heavily on the values selected for it (Jungmeier et al., 2024). Reflecting the weight this parameter carries for BEV outcomes specifically, Un (2026) calculates a "**breakeven electricity carbon intensity**" of approximately 600 g CO_2-eq/kWh: this is the grid carbon intensity threshold above which BEVs cease to outperform conventional powertrains. Notably, as shown in Figure 19, all EU27 Member States are already below this threshold and all but Poland and Cyprus report a grid carbon intensity below 500 g CO_2-eq/kWh well under the breakeven value while the EU average sits at just 183 g CO_2-eq/kWh less than a third of the breakeven point. In other regions of the world, such as India and China, however, studies report that the preferability turns against BEVs.

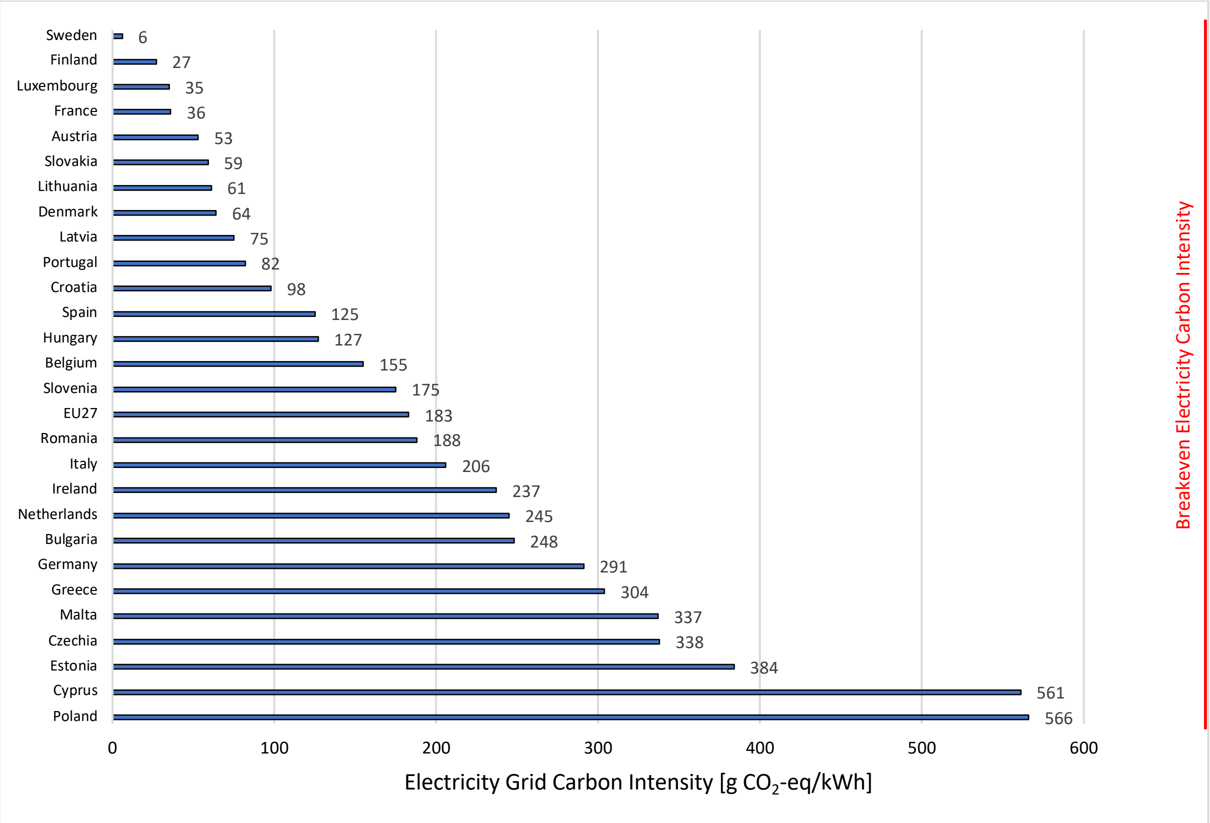

Figure 19: Electricity Grid Carbon Intensity of EU27 Member States in 2024 (source: EEA, 2025). The red line marks the breakeven electricity carbon intensity of 600 g CO_2-eq/kWh calculated by Un (2026)

While modeling the electricity mix is central to assessing the potential benefit of a shift to electrified mobility, **it remains methodologically challenging and there is no consensus on how to do so**. First, electricity mixes vary considerably across locations, even within Europe, producing markedly different results depending on where the assessment is anchored. In Poland, for instance, BEV performance is much weaker than in Sweden, approaching the GWP of conventional powertrains. The electricity mix can further be modelled either **location-based**, using the average grid mix where consumption occurs, or **market-based**, using a supplier specific mix tied to contracts and certificates. However, the literature overwhelmingly favors the former. A further modeling choice concerns whether the **infrastructure for electricity distribution** is included in the assessment. Bekel & Pauliuk (2019), for example, estimate that fuel supply infrastructure alone, excluding electricity generation itself, contributes around 3.7% of total GWP for BEVs in the German context, a contribution that is limited but not negligible.

A further crucial component of electricity mix modeling concerns **temporal resolution**. Even within a single year, daily and hourly variation in the energy mix affects grid carbon intensity, a challenge that is largely neglected in the literature and possibly negligible in practice, though this has not been systematically tested. This intra year granularity question is dwarfed, however, by a much larger temporal modeling choice: whether to treat the grid's carbon intensity as **static or dynamic** across the VLT. Our own review confirms that this larger choice, rather than intra year granularity, is where practice actually diverges: roughly two thirds of the reviewed sources model the grid statically, applying a single carbon intensity value across the entire use phase, while the remaining third model it dynamically, based on scenario projections. While adopting a dynamic perspective is generally recognized as essential to accurately capture the impact of operations under changing grid conditions, some guidelines, such as the Product Environmental Footprint, permit static modeling as well, whether for simplicity or to avoid the risk of cherry picking favorable or unfavorable projections. In the vehicle context, the consequences of choosing a static grid carbon intensity can be substantial, and depend on the reference location, since a lower current static carbon intensity implies a smaller impact on results. Eltohamy et al. (2026) estimate only a 10% difference in climate impact from this choice, whereas Negri & Bieker (2025) find that using a current EU average grid intensity would increase BEV impact by almost 60%, though BEVs would still outperform ICEVs on a life cycle basis under that scenario. Intrinsic to grid development modeling is uncertainty about future grid mix composition, which necessitates the use of multiple scenarios. Both TSLCA and UNECE agree on the need to model electricity dynamically, and on the need to rely on institutional, policy-based scenarios.

Although reaching agreement on a common scenario remains challenging, since different practitioners rely on different scenarios, there is widespread agreement in the European context that the grid will progressively decarbonize: historical figures indicate a 62% drop in GHG intensity by 2024 relative to 1990 and most scenarios therefore agree on the direction of further grid decarbonization (see Figure 20), though agreement on direction does not extend to agreement on its magnitude.

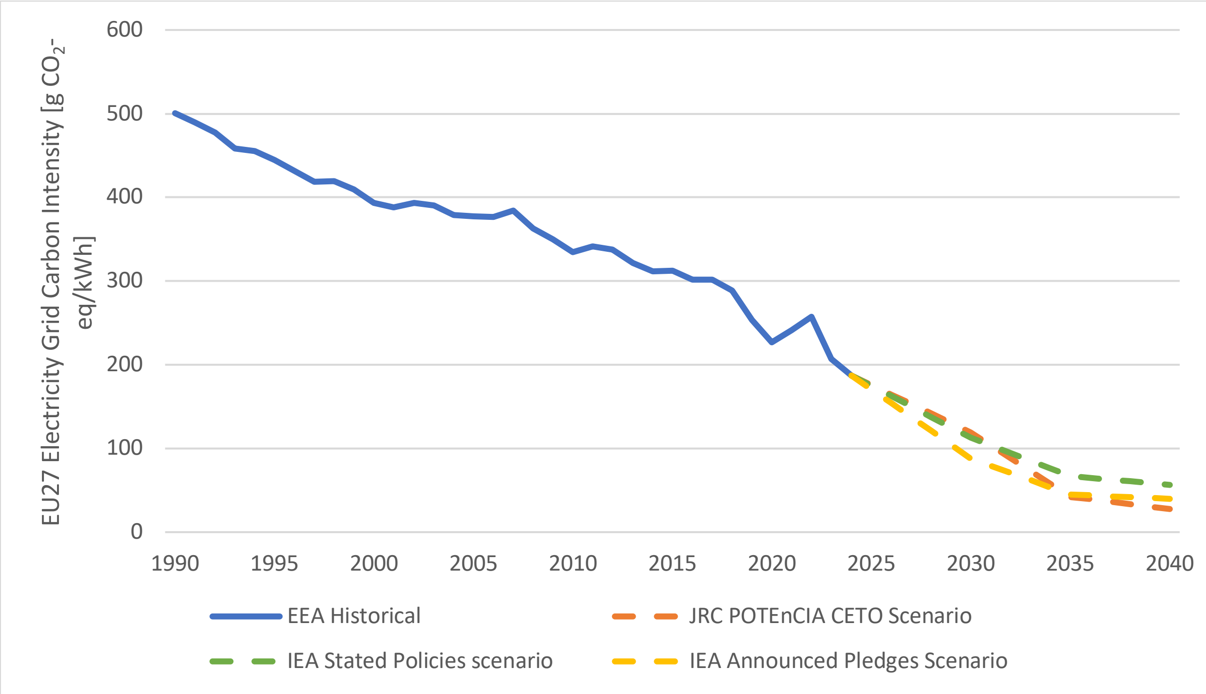

Figure 20: Historical (1990-2024) and Projected (2025-2040) Electricity Grid Carbon Intensity in EU27. Source: own elaboration based on EEA (2025); IEA (2024); JRC (2024).

2.6.8 Hydrogen Production Pathways

Much as electricity mix determines the use phase impact and the relative environmental advantage of BEVs, the **hydrogen production pathway** is what determines the impact of FCEVs, since the vehicle itself emits only water at the tailpipe. Hydrogen production pathways are conventionally taxonomized by feedstock and process using a color-coded shorthand (De Blasio, 2024), but two poles matter most for FCEV LCA. **Grey hydrogen**, produced via unabated steam methane reforming of natural gas or coal gasification, dominates current supply and carries a heavy footprint (11 kg CO_2-eq/kg H2). **Green hydrogen**, produced via electrolysis powered by renewable electricity, carries near zero direct emissions, with upstream impact then depending mainly on the electricity mix and electrolyzer manufacturing (2.02 kg CO_2-eq/kg H2). A closely related variant, **grid mix electrolysis**, uses the same equipment as green hydrogen but draws on the average grid rather than dedicated renewables, and behaves worse than grey hydrogen (17.2 kg CO_2-eq/kg H2), illustrating that electrolysis alone guarantees nothing about climate performance (Maniscalco et al., 2024). Despite growing policy attention, low emissions hydrogen still accounts for under 1% of global supply, with the vast majority remaining fossil based (IEA, 2025). Each pathway therefore carries a fundamentally different impact profile, making the production route a defining parameter for FCEV LCA results.

Reflecting this, Burchart & Przytuła (2025) identify the hydrogen production pathway as the **single most influential factor determining FCEV life cycle GWP**. The resulting variability in reported figures is substantial, mirroring the pattern observed in the Result Section. Negri & Bieker (2025) find that FCEV use phase emissions can fall below those of BEVs under the green hydrogen route, whereas under the grey hydrogen route, results are more comparable to those of a HEV. This carries two related consequences for assessing FCEV performance. First, it is the pathway, rather than the powertrain type itself, that ultimately determines relative performance. Second, relying solely on TTW, or tailpipe, emissions for FCEVs would be misleading, since this approach would systematically categorize FCEVs as outperforming conventional powertrains, regardless of how the hydrogen was actually produced.

2.6.9 Maintenance

Alongside the environmental impact arising from the energy used to power the vehicle (WTT), **maintenance** emerges as another significant factor influencing LCA results at the use stage. Indirect emissions arise from maintenance through the production, consumption, and installation of additional materials and components. These include the replacement of fluids (oil, coolant, brake fluid), filters (air, fuel, cabin), and specific components (tires, brakes, belts, sensors). Several challenges complicate the definition of an appropriate and representative maintenance pattern. **Vehicle and component heterogeneity** means each vehicle type carries its own specifications and maintenance needs. A **lack of component level data** compounds this, since most LCA studies analyze aggregated material data rather than component-specific data (see Section 2.6.3). Maintenance is also **usage pattern dependent**, as maintenance intervals, much like energy consumption, are strongly influenced by driving style and conditions.

Given these challenges, it is unsurprising that many studies either neglect this life cycle phase or treat it as negligible (Eltohamy et al., 2024). Our own review confirms how widespread this omission is: nine of the reviewed sources exclude maintenance entirely. Whether this is truly justified is questionable, however: Negri & Bieker (2025) estimate that maintenance can account for between 2% (gasoline ICEVs) and 8% (FCEVs powered by green hydrogen) of total life cycle GWP. There is broad agreement in the literature that **conventional powertrains require more maintenance than BEV and FCEV** (Biemann et al., 2024; Rimpas et al., 2025), a pattern largely confirmed by our own results (see Section 2.4.5), although the magnitude of this difference varies considerably, from 3% (Jungmeier et al., 2024) to 50% (Vieira et al., 2025) between BEVs and ICE-Gs. In summary, while often overlooked, maintenance is a meaningful part of the vehicle life cycle, and further standardization of its treatment appears to be a significant element in the broader effort to harmonize LCA results.

2.6.10 End-of-Life Pathways

EoL represents the final stage of the vehicle life cycle: the point at which a vehicle is retired from active use and subsequently **dismantled, recycled, or otherwise disposed of.** How this is done has a significant impact on total life cycle emissions. In the EU, this process is currently governed by the ELV Directive (2000/53/EC), which envisions that vehicles are deregistered, collected by an authorized treatment facility, depolluted (fluids, batteries, and other hazardous parts removed), dismantled for reusable parts, and then shredded so that metals can be separated and recycled, while the resulting automotive shredder residue (ASR) is further processed for material and energy recovery, with only a residual share sent to landfill or incineration for final disposal. Despite high metal recovery rates, current EoL pathways only marginally recover plastics and complex components, and a substantial share of vehicles disappears from the formal system through export or unrecorded disposal, further complicating the picture. Despite these structural gaps, EoL remains a crucial part of the vehicle life cycle: Eltohamy et al. (2024), for example, investigate the effect of varying recycling efficiency across powertrains and find that enhanced recycling efficiency yields a 5 to 10% reduction in total life cycle GWP for BEVs, making it a secondary but non-negligible driver of comparative environmental performance.

Among vehicle components, **batteries in BEVs** carry particular importance at EoL. Practitioners commonly assume a 20% capacity criterion, disposing of batteries once they fall below 80% of their original state of health, though this threshold is criticized as outdated by some, since the criterion was based on the more limited battery ranges of earlier vehicle generations (Zhu et al., 2021). **Several EoL pathways** for batteries are currently in use or under development, including incineration, landfilling, and recycling via hydrometallurgical (chemical) or pyrometallurgical (thermal) routes, each having a distinct environmental profile (Brückner et al., 2020; Kallitsis et al., 2022). **Circular solutions** are increasingly explored to improve: battery EoL practices, including reuse in second-hand markets as stationary energy storage (Patel et al., 2024), restoration through replacement of the most worn modules, though this remains largely impractical with current battery designs (Slattery et al., 2024), and remanufacturing using recycled materials, which studies estimate can reduce GWP by more than 50% relative to production from virgin materials (Ahmadzadeh et al., 2025; Tang et al., 2023), warranting further research into a cradle-to-cradle approach (Oluwalana & Grzesik, 2025). Overall, and often subject to intense scrutiny (e.g. Hill et al., 2023), appropriate EoL treatment for batteries is essential, since recycling helps prevent environmental and social harm, secures raw materials, and enables potential recovery for a second life (Un, 2026).

More generally, EoL phase modeling remains comparatively underdeveloped in LCA studies and requires further methodological attention. Among the challenges is the need to adopt a **prospective LCA approach** (see Section 2.5.1) to project future ELV pathways, given the intensity of current research in this field, the accompanying pace of technological advancement, and the resulting uncertainty over future outcomes. Approaches to EoL modeling and emissions accounting also vary widely across the literature (see Section 2.5.4), further complicating comparability. For this reason, many LCA studies either neglect EoL entirely, model it using contemporary EoL processes as a static proxy or rely solely on database estimates and secondary data (Jaššo et al., 2025). Given the importance of this life cycle phase, and its impact across several indicators, particularly for emerging powertrain types, greater focus is needed to harmonize EoL modeling and provide an accurate, robust assessment of its contribution to overall results.

2.7 Complementary Defossilization Pathways Beyond Battery Electric Vehicles

The previous results have clearly shown the climate advantage of BEVs, driven mostly by operation-phase emissions. However, against the EU's stated target of reducing mobility-sector GHG emissions by 37.5%, the passenger car sector's transition towards e-mobility, at the EU's current pace of adoption, can only deliver around 80 million tons of the roughly 188 million tons CO_2-eq reduction needed by 2030 (Tang et al., 2023). This shortfall, combined with the potential shortcomings of a full transition to BEVs, such as infrastructure and grid capacity constraints, means that other factors contributing to defossilization deserve consideration. **The following levers, while no substitutes for electrification, target different points in the vehicle life cycle and can therefore offer complementarily contributions to more sustainable mobility**.

First, **material choice in manufacturing and related material circularity strategies remain a significant element of the passenger car decarbonization pathway**, extending decarbonization efforts from powertrain efficiency to the still underexplored level of embodied emissions. This assumes even greater relevance given that, as shown in the results, the share of the production phase in total life cycle emissions increases as total life cycle emissions decrease. Hence, particularly for BEVs, where a rising renewable share in the electricity grid is expected to progressively lower use phase carbon intensity, material choice becomes an increasingly central driver of a vehicle's overall environmental impact. The following are some of the main developments in this regard.

Green steel targets the production phase specifically, addressing raw material extraction and component manufacturing. Although steel represents a comparatively modest 2% to 7% of a vehicle's total life cycle emissions depending on vehicle type (Hill et al., 2024), it accounts for a large share of the manufacturing phase emissions itself, giving its decarbonization direct relevance for embedded emissions. The core lever is a shift away from the traditional blast furnace and basic oxygen furnace route, which relies on coking coal, toward hydrogen based direct reduced iron (H2 DRI) combined with electric arc furnace steelmaking. Switching to fossil fuel free steel production of this kind can eliminate more than 95% of the GHG emissions associated with steel production for passenger vehicles, translating into a reduction of up to 27% in total vehicle manufacturing emissions (Bui et al., 2024). This positions green steel as one of the more direct levers available to reduce production phase emissions, independent of powertrain type, though its rollout remains constrained by the substantial increase in renewable electricity and hydrogen volumes the process requires and by a persistent cost premium relative to conventional steel.

Beyond primary steel decarbonization, material circularity in metals and components offers a complementary production phase lever, centered on high quality metals recycling, remanufacturing, and lightweight design. Recycled steel and aluminum already deliver substantial savings: scrap steel avoids around 1.49 tons of iron ore and half a ton of coal per ton steel produced, while secondary aluminum uses roughly 95% less energy than primary production, yielding significant cradle to gate CO_2 savings for vehicle bodies and structures (Bobba et al., 2020; ICCT, 2025). Remanufacturing engines, gearboxes, and other modules typically cuts life cycle energy demand by 60% to 70% relative to manufacturing new units and can lower GWP by around two thirds for the components involved, directly reducing production phase emissions of the vehicles that incorporate them (Zheng et al., 2019). Material efficiency strategies, such as fabrication loss reduction, design for disassembly, and lightweighting through optimized grades and joining, further lower the absolute mass of primary material required (Aguilar Esteva et al., 2021).

Biomaterials target a different segment of the production phase, substituting fossil-based plastics and composites with plant-derived fibers and resins in vehicle components. Recent LCA studies show that natural and coir fiber-reinforced polypropylene parts can lower cumulative energy demand and GHG emissions by roughly 24% to 40% compared with equivalent glass fiber composites (Wasti et al., 2024), while broader reviews find 20% to 50% lower carbon footprints for flax, hemp, and similar fibers relative to glass (Skosana et al., 2025). Industrial practice, however, remains concentrated in interior panels and niche components, with fully bio-based prepregs and lignin rich resins still framed as emerging technical options rather than established mass market pathways. Because composite parts represent a limited share of vehicle mass, scaling these substitutions is likely to deliver limited reductions in total life cycle GHG per vehicle, concentrated in the production phase, with current realizable contributions remaining below what is theoretically achievable at scale.

Secondary materials extend this logic to a life cycle stage where recovery has so far lagged furthest behind: the EoL treatment of automotive plastics. Current EoL pathways recover metals at high rates but only marginally recover plastics and complex components, with automotive shredder residue predominantly directed toward thermal utilization as refuse derived fuel rather than mechanical recycling, a substantial gap given that plastics constitute between 14% and 18% of the material composition of passenger cars in the EU (Reichert et al., 2026). Under a closed loop approach, plastic recovered from ELV could be reused in new vehicle production: Reichert et al. (2026) estimate a closed loop recycled content rate of 3.1% to 4.8% achievable by 2035, corresponding to a 29.5% GHG reduction relative to the incineration route currently applied to sorted shredder residue. This lever therefore targets the EoL phase in the first instance but also feeds into the production phase of future vehicles through recycled content, tying into the allocation discussion of dividing emissions across successive life cycles. The magnitude of this contribution should nonetheless be read with caution: a closed loop rate in the low single digits by 2035 is modest compared to the potential identified for green steel above.

A second major area of discussion when considering decarbonization pathways for the passenger car sector is the adoption of biofuels and e-fuels in the use phase. According to Toedter et al. (2026), the transformation of the transport sector cannot be achieved through powertrain electrification alone, making it essential to exploit the CO_2 saving potential of liquid fuels that integrate into existing supply infrastructure without technical modification. The same research group finds that European domestic feedstocks could cover between 38% and 55% of total EU road transport fuel demand with renewable alternatives by 2030, rising to between 67% and 107% by 2040 under a scenario following the RED III, where the total fuel need reduces drastically compared to 2030 (Toedter et al., 2026). Besides biofuels, e-fuels could hypothetically help reduce GHG emissions. However, their climate performance depends almost entirely on the availability of very low carbon electricity. Only e-fuel production based on renewable electricity or nuclear power allows e-fuels to outperform fossil fuels and other powertrain alternatives (Bouter et al., 2026). The study by Gimbert (2022) shows that, under an ideal scenario in which pure e-fuel is produced entirely with electricity from renewable sources, a petrol car could achieve around 20% lower life cycle GHG emissions than a BEV charged with the average EU electricity mix. This positions biofuels and e-fuels as an option for the legacy ICE fleet, particularly given the long VLT, rather than a competing pathway to BEVs. However, the potential implementation has some shortcomings. First, availability is dependent on abundant renewable electricity for e-fuel production via electrolysis, competing directly with the electricity demand of BEV charging. It is worth mentioning that a BEV uses about 5 times less electricity per kilometer than an ICEV running on e-fuel (Ueckerdt et al., 2021). Second, given this dependency, renewable electricity is more effectively used through direct electrification than routed through the multi-step, lossy conversion chain required for e-fuel synthesis (Fritz et al., 2021), meaning the more decisive contribution of these fuels may lie in sectors that are harder to electrify, such as aviation and maritime transport, rather than in passenger cars. Third, the conversion efficiency of both pathways remains comparatively low relative to direct electrification, reinforcing that biofuels and e-fuels function as a bridging technology for the existing fleet rather than a long-term substitute for BEVs.

Within the biofuel category, a further technological distinction differentiates Fatty Acid Methyl Ester (FAME) and Hydrotreated Vegetable Oil (HVO) 100% in ways that matter for the legacy-fleet pathway. FAME, the conventional biodiesel produced by transesterification of vegetable oils or animal fats, still contains oxygen and unsaturated double bonds, this makes it prone to oxidation and cold-weather gelling (Hunicz et al., 2021). Therefore, the EN 590 diesel specification caps its blend share at 7% (B7) in conventional pump diesel and constrains the absolute emission reduction achievable through this route. HVO, by contrast, is produced by hydrotreating rather than transesterification. The feedstock oils are reacted with hydrogen to yield a paraffinic hydrocarbon chemically similar enough to fossil diesel that it can be used at any blend ratio without engine modification, including neat as HVO100 (Almeida et al., 2026). Calculated on a well-to-wheel basis under the RED III methodology, the GHG savings achievable through HVO depend strongly on feedstock and processing energy, where a stand-alone facility running exclusively on used cooking oil (UCO) can reach savings of up to around 93% relative to fossil diesel (Kourkoumpas et al., 2024). Enriching the perspective of possible HVO production routes and their associated emissions, HVO produced from UCO with green hydrogen has been shown to reduce global warming potential by roughly 80% (Ajeeb et al., 2025). However, as indicated in the study from Toedter et al. (2026), the share of UCO in Europe is only about 1% from the total possibly available feedstock energy potential. Therefore, the ability to widely spread HVO production and the use of HVO100 remains questionable. FAME's reduction, by contrast, is structurally bounded by the 7% blend limit, so even a low-carbon FAME molecule translates into only a small per-liter reduction at the pump. For the legacy ICE fleet pathway discussed above, HVO100 therefore offers a considerably larger emission-reduction lever per litre of fuel substituted than FAME. Feedstock availability nonetheless remains a shared constraint across both routes. RED III explicitly caps the contribution of food- and feed-crop-derived feedstocks and of UCO precisely because sustainable biomass is finite (Kourkoumpas et al., 2024) tying the technology comparison back to the land-use change discussion above.

Taken together, **these levers can meaningfully contribute to future efforts to defossilize passenger vehicles, though each remains complementary to, rather than a substitute for, powertrain electrification**, and each is bounded in a different way. From an LCA perspective, the overall conclusion is that BEV deployment remains the principal pathway for reducing GHG emissions from passenger cars, complemented by production phase decarbonization, closed loop recovery, and renewable fuels for the residual share electrification cannot reach in time.

2.8 Influential Aspects beyond Defossilization

The findings so far largely focused on GHG emissions and GWP, the main aspects to achieve defossilization of the passenger car sector. While this issue is central to mitigating climate change, it does not fully capture the wider conditions that determine whether alternative vehicle technologies can be deployed at scale and assessed meaningfully. Infrastructure availability, user behavior, supply chain resilience, cost structures, social impacts, and the integration of sustainability indicators all influence the real-world performance and techno-economic and societal viability of vehicle technologies.

2.8.1 Infrastructure

Infrastructure is one of the most important enabling conditions for the adoption of alternative vehicle technologies. For battery electric vehicles, **insufficient charging infrastructure** remains a major barrier to a complete transition, as limited availability, uneven spatial distribution, and concerns about reliability reduce consumer confidence and practical usability (Bitencourt et al., 2023; Da Costa et al., 2025). At the same time, increasing BEV demand towards 2050 may place significant **pressure on electricity grids**. Without flexibility strategies, grid capacity may become insufficient to accommodate growing charging demand (Märtz et al., 2022). Vehicle to grid systems could reduce this pressure by allowing BEVs to function as distributed storage units (Wohlschlager et al., 2024), although this requires compatible infrastructure, market incentives, and user participation. Infrastructure constraints also affect FCEVs, for which **hydrogen refueling networks** remain very limited and associated technology costs are high (Burchart & Przytuła, 2025). Even where sales shares increase, the long-term diffusion of FCEVs will depend strongly on the development of hydrogen production, distribution, storage, and refueling systems. Comparable infrastructure requirements apply to biofuels and e-fuels. Although these fuels can partly use existing vehicle and distribution infrastructure, achieving a substantial impact would require the construction of large-scale production facilities. For e-fuels in particular, the technologies required to capture CO_2 for e-fuel production remain at an early stage of development, which further limits their large-scale deployment (Fritz et al., 2021).

2.8.2 Supply Chain Risks and Material Sovereignty

The shift towards electrified mobility changes the material basis of the automotive sector. While defossilization reduces dependence on fossil fuels during vehicle operation, it increases **strategic dependence on minerals and metals** required for batteries, electric motors, power electronics, and hydrogen technologies. Raw material sovereignty, therefore, becomes a central policy concern. It refers to the ability of an economy or region to secure reliable, responsible, and affordable access to critical materials while reducing excessive dependency on concentrated or vulnerable supply chain (see Büthe et al., 2026). This issue is particularly relevant for the European Union, where vehicle electrification is closely linked to industrial competitiveness, energy security, and geopolitical resilience.

Cobalt production in the Democratic Republic of the Congo illustrates the risks associated with concentrated supply chains. Cobalt is a key material for several battery chemistries, and its supply chain has been associated with social, environmental, and governance concerns (Jaššo et al., 2025). These risks include geographical concentration, exposure to political instability, mining related environmental burdens, and concerns regarding labor conditions. Such dependencies may create vulnerabilities for manufacturers and policymakers, particularly if demand increases faster than responsible supply capacity. The same applies for other materials as well, including aluminum, silver, copper, neodymium, dysprosium and lithium (Løvik et al., 2021). Policies targeting electrification must address material availability, recycling capacity and responsible sourcing standards. A critical materials assessment can provide a strategic assessment of those aspects and can contribute to evolving a bigger picture capturing sustainability.

2.8.3 Costs and Life Cycle Costing

Life Cycle Costing (LCC) assesses the costs associated with a vehicle over its lifetime, including production, operation, maintenance and, where included, EoL costs. While ICEVs may still have lower manufacturing costs due to mature production systems, their use-phase is costly (Liu et al., 2024). Over time, fuel and spare part costs can add more than 10% to the end value of ICEVs (Eltohamy et al., 2024). BEVs, by contrast, often involve higher upfront costs, mainly because of the battery, but can become more competitive over the vehicle lifetime due to lower energy and maintenance costs. This competitiveness has improved in recent years as battery prices have declined, with studies showing increasing economic attractiveness in countries such as Denmark and Spain (Da Costa et al., 2025). Since purchase costs remain an important barrier to consumer acceptance, policy incentives can support further BEV adoption (Rimpas et al., 2025).

FCEVs remain less economically attractive because of high vehicle costs, hydrogen prices and limited refueling infrastructure (Burchart & Przytuła, 2025). Although hydrogen may be cheaper to produce than some synthetic fuels such as butanol or polyoxymethylene dimethyl ether (Liu et al., 2024; Schemme et al., 2020), this does not necessarily imply lower total ownership costs for FCEVs.

2.8.4 Social Life Cycle Assessment

Social Life Cycle Assessment (sLCA) expands vehicle evaluation beyond environmental and economic indicators by examining **social risks and impacts across the life cycle**. Relevant aspects may include labor conditions, health and safety, human rights, community impacts, governance, and consumer related issues. These indicators are particularly important for vehicle technologies that rely on globally distributed supply chains and critical raw materials. A key challenge is that social indicators may be qualitative, semi-quantitative, or quantitative, and data availability is even more scarce than in environmental LCA. Reference scale assessment provides an ordinal evaluation of social performance or risk, whereas impact pathway assessment seeks to model consequential social impacts (UNEP, 2020). Both approaches can provide valuable insights, but they differ in data requirements, interpretability, and methodological robustness. For passenger cars, sLCA is therefore relevant when comparing powertrains with different material requirements, production locations, and supply-chain structures. This can help identify potential social trade-offs that are otherwise not be visible. However, among the assessment methods of the three sustainability pillars, it is the least harmonized one (Ostojic and Traverso, 2024).

2.8.5 Life Cycle Sustainability Assessment

Considering the climate targets in the EU, the environmental assessment method provides the best-suited assessment approach to quantify the environmental performance of vehicles. However, other aspects beyond defossilization also need consideration in order to get a more concrete picture. As described in the section above, these factors could be, for example, the infrastructure, supply chain risks for critical materials, life cycle costs, or social impacts. An approach for a combined assessment method including all three sustainability pillars is Life Cycle Sustainability Assessment (LCSA). It aims to **integrate environmental, economic, and social dimensions into a broader assessment framework**. In the case of vehicle assessment aimed at comparing different powertrains, a technology with low operational emissions may still face challenges related to material supply, social risks, infrastructure costs, or affordability. However, Ostojic & Traverso (2024) identify several methodological barriers. Studies may use similar functional units but different system boundaries across the environmental, economic, and social pillars. This creates a need for stronger alignment across the assessments.

The results from LCA can support the decision pathway for a climate sensitive mobility transformation. But in the end this transformation cannot work without consumer acceptance, infrastructure readiness, cost effectiveness and the social risks associated with it. Furthermore, due to the dependency of the EU on critical raw materials from outside its borders, responsible sourcing needs to be established and geopolitical risks considered. These aspects need to be considered together in order to assess whether vehicle technologies are not only low-carbon, but also economically viable, socially responsible, and resilient in the long term.

2.9 Key Takeaways

This section highlights the key takeaways from our analysis of the promise and limitations of an LCA approach to automotive sector GHG emissions, particularly against the EU's current tailpipe approach. Policy implications will be discussed in greater detail in Chapter 4 after the analysis of the regulatory and political context in Chapter 3.

The first key takeaway is that **automotive LCA results are significantly shaped by choices and assumptions operating at different levels:** some are purely methodological (e.g. multifunctionality), some depend on data availability (vehicle type, production location, primary vs. secondary data), and others are hybrid choices (e.g. vehicle lifetime, mileage, and future scenario selection). This flexibility is what allows LCA to serve a wide range of purposes, adapting to different goals, questions, and audiences rather than forcing every LCA study into a single rigid template. However, while no single choice is inherently wrong if transparently communicated and properly justified, the variation resulting from this lack of standardization significantly threatens comparability. In a regulatory setting demanding full scale LCA, leaving such choices to individual practitioners would be problematic, risking outcomes shaped by desired conclusions rather than scientific principles. **Harmonization and standardization of methodological and parameter assumptions (specifically for automotive sector LCAs) therefore emerge as preconditions for any LCA-based regulation.**

In this regard, **the scientific community, often together with industry, has long called for developing shared standards and guidelines**. ISO 14040/14044 provides the general reference standard underpinning LCA but remains too general to address the specific challenges of automotive LCA. More recently, and most notably, the TransensusLCA project brought together academic and industry experts to produce a consolidated set of guidelines for automotive LCA, and UNECE has pursued a similar process at global rather than European level. Industry initiatives such as Catena-X have also moved toward standardization, though limited to carbon footprint calculation rather than full LCA. What all these guidelines share, however, is a voluntary, non-binding character: their existence suggests real potential for agreement, but a **shift toward mandatory regulatory guidelines appears far more difficult, given the sheer volume of assumptions that would need to be settled**.

Second, **BEVs consistently exhibit better climate performance than conventional powertrains across the reviewed studies, though with wide variation in magnitude, driven largely by the electricity mix**. BEV's higher production emissions are systematically offset by lower operation phase emissions, though the point at which this advantage materializes differs between studies: such reported breakeven distances over the vehicle lifetime range from as low as 6,000 km in the best cases to 60,000 km; in extreme scenarios, there is no breakeven at all. The main driver of this variation is how the electricity mix is modelled. Given the projected future increase in the renewable share of the electricity mix, both at European level and within individual Member States, this dynamic strengthens rather than weakens the case for electrification on a forward-looking basis, and underscores why static grid assumptions systematically understate BEV performance. Because uncertainty in electricity mix modeling translates directly into uncertainty about the performance of future transport systems, **a shared understanding of the future grid, including a common view on the pace of decarbonization, is a necessary basis for policy development in this area**.

Third, **FCEVs' environmental performance depends largely on the assumed hydrogen production pathway, which also directs attention to future infrastructure development**. The hydrogen production route drives an order of magnitude swing in FCEV emissions, from below BEV levels under green hydrogen to closer to HEV performance under grey. As with BEVs, a tailpipe approach would always categorize FCEVs as favorable over conventional alternatives, since they emit only water at the tailpipe, underscoring the advantage of LCA in delivering a clearer picture of actual climate performance by accounting for upstream emissions as well. Low emissions hydrogen, moreover, still accounts for under 1% of global supply, alongside high production and consumption costs. These findings underscore both how a tailpipe approach delivers an incomplete picture of any technology's real benefits, and the **need to include infrastructure and capacity development considerations when evaluating the feasibility of various solutions to passenger car decarbonization**.

Fourth, **focusing on GWP alone presents BEVs, and FCEVs powered by green hydrogen, as the superior powertrains, but considering additional impact categories reveals a more diverse and less one-sided picture**. As discussed, BEVs outperform ICEVs on GWP but can perform worse on impact categories such as human toxicity, metal depletion, and water use, driven largely by battery raw material extraction. Combined with the broader aspects reviewed in Section 2.8, such as infrastructure readiness, raw material sovereignty, cost, and social risk, this suggests that no single assessment method can, on its own, support a complete judgement of which powertrain is preferable. For policy development, this means LCA is a well-suited tool for identifying more climate friendly vehicles, but the **broader consequences of a rapid shift to vehicle electrification warrant equally serious consideration**.

Fifth, **complementary levers beyond powertrain electrification, such as low carbon materials, circularity, and alternative fuels, can meaningfully reduce embodied and residual emissions**. Green steel and metals circularity target embodied emissions directly, though bounded by vehicle steel content and by renewable electricity and hydrogen supply constraints; biomaterials and closed loop plastics recovery add further, more modest gains. Biofuels and e-fuels can meaningfully reduce residual combustion fleet impact but are bound by feedstock and electricity availability, positioning them as most relevant for hard-to-electrify sectors rather than as a competing pathway for passenger cars. Therefore, defossilization strategy should be paired with complementary material, circularity, and sectoral fuel allocation policies rather than treated as sufficient on its own. For policy development, this suggests that **a strategy focused on powertrain electrification alone would leave a substantial share of embodied and residual emissions unaddressed.**

Fifth, **the literature relies almost exclusively on attributional LCA, leaving other LCA related methodologies underexplored**. As briefly illustrated in Section 2.8.5, LCSA could offer a more complete picture of the trade-offs and benefits inherent to the mobility sustainability transition for passenger cars, though the lower degree of methodological maturity, particularly for sLCA, together with the difficulty of agreeing on inherently subjective weighting methods for combining the three pillars, means significant work remains before this approach could be applied at scale. Consequential LCA may also emerge as a more appropriate tool for understanding the systemic impact of the sector under study, since it models the response of the broader system in both environmental and market terms, closely related to which is the study of rebound effects, meaning the direct, indirect, and economy wide behavioral responses that can partially offset a technology's efficiency gains. Both methods, however, remain subject to numerous assumptions of their own, exposing them to the same underlying problem as attributional LCA. Overall, while the academic sector seems destined to keep pushing the research frontier through **LCSA, consequential LCA, and rebound effect studies**, and while such approaches may well deliver a more complete picture, their **complexity and high degree of uncertainty appear to limit their potential as regulatory policy tools**.

3 Regulatory and Political Context

Current analyses and debates in the EU over defossilization of the automotive industry and the role of LCA-based approaches to achieving this goal, to which the EU has committed itself as a crucial component of climate change mitigation, take place in the context of European and national rules and regulations, as well as current practices in the industry. This section provides an overview of this context.

Section 3.1 summarizes the approach to CO_2 emissions reduction, especially the specific requirements for passenger cars, in the current version of EU Regulation 2019/631 (including any amendments and revisions adopted as of July 2026). It shows that a more holistic LCA approach, even though called for in §7a of the Regulation, is largely absent from the current version of Regulation 2019/631. Indeed, to some extent the Regulation prevents an LCA approach by its narrow focus on tailpipe emissions, which excludes from consideration all CO_2 emissions prior to the use phase of the vehicle (raw materials mining and refining or reuse/recycling, as well as during the production of the vehicle and its components) as well as after the "end of life" of the vehicle – key elements of a holistic LCA, as discussed in section 2.

Section 3.2 then summarizes the key changes proposed by the EU Commission as part of its December 2025 Automotive Package, specifically its Proposal for Amending Regulation 2019/631 as regards CO_2 emission performance standards, and discusses to what extent the proposal by the Commission shifts the requirements for CO_2 emissions in the Regulation towards an LCA approach. As discussed in section 3.3, various other stakeholders have made for public debate and/or have submitted to the EU Commission and Parliament alternative proposals that would go further than the Commission's proposal in revising the Regulation – or explicitly push back against certain revisions. We focus here on proposals that would go further in moving towards an LCA-based regulation or reject such a shift. Section 3.4 summarizes the position(s) of the automotive industry regarding the proposed revisions to Regulation 2019/631, especially concerning the overall climate change mitigation goals, the CO_2 emission reduction requirements and a comprehensive LCA approach.

As shown in Section 3.5, even though Regulation 2019/631 currently does not require the automotive industry to conduct CO_2 emission-focused LCAs, many companies in the industry actually have adopted LCA-based approaches for some or even all of their current models or their supply chains. Section 3.6 then examines to what extent the LCA practices in the automotive sector may be a function of obligations or incentives to adopt more of a life cycle perspective or even conduct full-blown LCAs arising from other laws, regulations or public policies governing the automotive sector in the European Union.

In section 3.7, we then zoom out to consider more generally the opportunities and limits of incorporating LCA approaches into regulatory measures in the EU, especially regulations governing the automotive sector. Finally, section 3.8 briefly considers the political feasibility and constraints, given the consensus on the goal of climate change mitigation and on the need for CO_2 emission reductions but also existing conflicts over the means to best achieve them and how to strike the right balance vis-à-vis other objectives, which has turned LCAs into a contentious issue.

3.1 Regulation 2019/631 and Its Approach to CO_2 Emissions Reduction

Regulation (EU) 2019/631 establishes CO_2 emission performance standards for new passenger cars (category M1) and light commercial vehicles (category N1) registered within the European Union. As an EU Regulation rather than a Directive, it is directly applicable in all Member States under Article 288 TFEU; it does not require transposition into national law, and it creates binding obligations for manufacturers as soon as it enters into force (Rotondo 2013). All automobile manufacturers placing vehicles on the EU market must therefore comply with its terms, and Member States rely on decentralized national administrative agencies to operationalize and enforce these obligations.

The Regulation sets EU-wide fleet targets rather than targets for individual vehicles or firms. Compliance is assessed at the level of "manufacturers," a term that under Article 3 of the Regulation includes a parent company together with all of its "connected undertakings." So, for compliance purposes, the CO_2 emission reduction obligations apply, for instance, to the Volkswagen Group in the aggregate rather than to each individual brand of the group (comprising VW, Audi, Porsche, Škoda and SEAT/Cupra).[4] Each manufacturer's specific annual emissions target is derived from the EU-wide fleet target and adjusted for the average mass of the vehicles it registers, so that heavier vehicles are assigned somewhat higher permissible emissions than lighter ones (Suarez Corujo et al. 2023). Manufacturers may also pool their fleets under Article 6 of the Regulation, allowing an over-complying manufacturer and an under-complying one to be treated as a single entity for compliance purposes – a mechanism used, for example, by the Mercedes-Benz Group in combination with Volvo Cars and Polestar (Sachs and Koester 2021). Non-compliance triggers an excess-emissions premium of €95 per gram of CO_2 per kilometer of target exceedance, multiplied by the number of vehicles registered.

Substantively, Regulation 2019/631 originally set EU-wide targets of 95 g CO_2/km for new passenger cars and 145 g CO_2/km for new light commercial vehicles. As revised by Regulation (EU) 2023/851 in the context of the EU's "Fit for 55" package (Erbach 2023), the Regulation as currently in force requires a 55% reduction in fleet-wide average emissions for passenger cars by 2030 (relative to 2021 levels), and a 100% reduction by 2035 – effectively prohibiting the sale of new vehicles with internal combustion engines not running exclusively on eligible carbon-neutral fuels (Hernández 2026).

Throughout, compliance is measured exclusively on the basis of tailpipe (use-phase) CO_2 emissions, as determined under the standardized Worldwide harmonized Light vehicles Test Procedure (WLTP). This tailpipe-only architecture is the central feature that distinguishes the current Regulation from a holistic LCA approach: emissions generated during the extraction and processing of raw materials, the manufacturing of vehicles and their components (including, critically, battery production), and the treatment of vehicles at the end of their life are not covered by Regulations 2019/631. Even the use phase is only partly covered: A battery-electric vehicle counts as a "zero-emission" vehicle under the Regulation regardless of the amount of fossilized carbon emitted when producing the electricity to charge it (while a combustion-engine vehicle's emissions are assessed solely on the basis of fuel combusted during use).

The one explicit acknowledgment of life cycle-thinking in the current Regulation is found in Article 7a (introduced via Regulation 2023/851 and building on Recital 50 of the original 2019/631 text), which requires the European Commission to monitor and report on the life-cycle CO_2 emissions and energy consumption of passenger cars and light commercial vehicles and to develop a common EU methodology for assessing and consistently reporting such emissions. Crucially, however, this monitoring obligation, addressed to the Commission, is only intended to inform future policy development, and it does not translate into a reporting obligation for manufacturers. Since 1 June 2026, manufacturers may submit life-cycle emissions data on a voluntary basis, based on the methodology for assessing life-cycle CO_2 emissions across the production, use, and end-of-life phases published by the Commission at the end of 2025, but there is no public indication that any manufacturer has yet to do so. In sum, the current version of Regulation 2019/631 contains no more than a nod toward life cycle assessment.

3.2 The December 2025 Commission Proposal for a Revision of Regulation 2019/631

On 16 December 2025, the European Commission published its proposal to revise Regulation 2019/631, framed as balancing progress towards climate-neutrality against concerns about the competitiveness and

[4] Similarly, the Stellantis Group (Peugeot, Citroën, Opel, Fiat, Jeep and Alfa Romeo) forms one "fleet," as does the BMW Group (BMW, MINI and Rolls-Royce).

resilience of the European automotive industry and the preservation of a strong European production base (European Commission 2025a). It contains five principal elements:

- Multiannual compliance mechanism for the 2030–2032 period
- Recognition of alternative defossilization pathways; credits after 2035
- Less stringent required reduction of emissions 2035, conditional on credits
- Extra incentives for small electric vehicles
- Change in vehicle labelling requirements

The Commission proposes extending the multiannual compliance mechanism, already in place for 2025–2027, so manufacturers' compliance with the 2030 targets will be assessed based on the average over the three years 2030–2032, allowing a shortfall in one year to be offset by over-performance in another. Second, the proposal introduces credits for sustainable renewable fuels (including RFNBOs, advanced biofuels and biogas) and for the use of low-carbon "green" steel in vehicle production. Third, manufacturers can use those credits to offset up to 10% of their otherwise required 100% fleet-average reduction of CO_2 emissions after 2035, thus effectively turning the required reduction from a complete elimination of tailpipe emissions into a 90% reduction (compared to the 2021 baseline) if a manufacturer has earned the necessary credits.[5] Fourth, the proposal introduces "super credits" for small electric vehicles manufactured in the EU, under which each qualifying vehicle would count as 1.3 vehicles when calculating a manufacturer’s fleet-average emissions.[6] Finally, the proposal incorporates harmonized digitally accessible vehicle-labelling requirements – previously separately goverened by the Fuel Economy Labelling Directive (1999/94/EC) and now also covering zero-emission vehicles, vans, and second-hand vehicles – directly into Regulation 2019/631.

According to the Commission, this package preserves the EU's commitment to climate change mitigation while providing manufacturers with greater flexibility and technological openness (European Commission 2025a; 2025b). Independent assessments have been considerably more critical. The International Council on Clean Transportation (ICCT) argues that the proposed flexibilities – lowering the 2035 target from 100% to 90%, combined with the new fuel and steel credits – constitutes a fundamental shift that risks weakening the effectiveness of the existing standards, increasing cumulative CO_2 emissions, creating investment uncertainty, and slowing the uptake of zero-emission vehicles (Dornoff et al. 2025; see also Mathieu & Gimbert 2026).

Assessed specifically against the benchmark of a holistic LCA approach, the proposal contains, at best, marginal advances. The low-carbon steel credit is the clearest LCA-adjacent element, reflecting a cradle-to-gate perspective on a portion of a vehicle's production-phase emissions; the enhanced vehicle-labelling provisions could in principle create a pathway for communicating life cycle information to consumers in the future. However, the core compliance mechanism remains centered on tailpipe emissions at the use-phase stage; raw-material extraction, battery and other parts manufacturing, production emissions, recycling performance, and end-of-life treatment remain outside the calculations for which the Regulation contains requirements and a compliance mechanism. The super-credit mechanism for small electric vehicles rewards a vehicle category rather than any verified life cycle outcome, since eligibility is not tied to measured environmental performance. And the renewable-fuel and low-carbon-steel credits constitute narrowly bounded exceptions rather than elements of a general life cycle accounting

[5] For small commercial vehicles (vans) the Commission additionally proposes to lower the 2030 target from a 50% to a 40% reduction relative to 2021 (European Commission 2025a, 10).
[6] The criteria for what counts as "made in the EU" are left to be defined later through a delegated act, i.e., subsequent rule-making by the Commission.

framework applicable across all powertrain technologies. In sum, the December 2025 proposal incorporates select life cycle elements at the margins of an architecture that remains fundamentally tailpipe-based, consistent with the observation of Beylot et al. (2025) that the mobility sector still lacks a harmonized, comparable life cycle assessment framework.

3.3 Alternative Proposals for Revisions

The European Commission's December 2025 proposal did not emerge in a vacuum: its accompanying *Impact Assessment* documents a range of alternative proposals that stakeholders had put forward before the Commission finalized its proposal, which incorporated some of those inputs (in modified form) and set aside others (European Commission 2025c).

Several stakeholders explicitly called for a more thoroughgoing shift toward life cycle-based regulation. The Automotive Industry Association of the Czech Republic (AutoSAP), for instance, proposed a gradual introduction of an LCA-based approach with legislative reviews scheduled for 2029 and 2033, while HORSE Powertrain and the European Biogas Association advocated well-to-wheel accounting frameworks that would move regulation beyond tailpipe emissions. The Commission's proposal did not adopt a comprehensive LCA framework, opting instead for an incremental introduction of selected life cycle elements. A related but more circumscribed proposal, the Carbon Correction Mechanism (CCM), would have adjusted manufacturers' targets according to the market deployment of eligible low-carbon fuels; the Commission ultimately rejected this option, citing concerns about data lags, unpredictability of fuel availability, and the risk of encouraging a less energy-efficient fleet (European Commission 2025c).

Two proposals for recognizing alternative powertrains were, by contrast, incorporated into the Commission's preferred package, albeit in constrained form. The Vehicles Exclusively Using Eligible Fuels (VEEF) concept, strongly supported by synthetic- and bio-fuel producers, would treat vehicles running solely on certified renewable fuels as equivalent to zero-emission vehicles; the Commission adopted this option subject to quantitative limits and eligibility conditions. The reason a separate fuel-credit mechanism is needed at all is worth stating plainly, since it is otherwise easy to read the proposals below as an additional consideration layered on top of the existing standard rather than as a correction to a gap in it. Compliance under Regulation (EU) 2019/631 is determined by the WLTP-type approval test specified under Regulation (EC) 715/2007, which measures tailpipe CO_2 output under standardized conditions and does not distinguish the origin of the fuel actually used. Renewable content blended into pump fuel under RED III's own mandates earns no recognition when that measure is applied: a vehicle running on blended fuel is credited exactly as if it had run on unblended fossil fuel. The fuel-credit and renewable-fuel-vehicle mechanisms exist specifically to correct that gap.

Similar to the VEEF proposal, a proposal to recognize "advanced" off-vehicle-charging hybrid electric vehicles (OVC-HEVs, including plug-in hybrids and range-extender EVs with long electric ranges) as zero-emission vehicles after 2035 was incorporated in a limited, capped form.

Manufacturers and industry associations – including Stellantis, the French *Plateforme de la Filière Automobile* (PFA), and AutoSAP – had also pushed for a more expansive super-credit system for small battery-electric vehicles than the 1.3-multiplier ultimately adopted by the Commission. Proposals to earmark revenue from fees imposed for exceeding emissions targets toward, in particular, the EU Innovation Fund, instead of the EU's general budget, was rejected (European Commission 2025c).

Following publication of the proposal, stakeholder responses diverged sharply along an industry-versus-environmental-organization fault line, echoing the divide already visible in the pre-proposal debate over alternatives. The eFuel Alliance argued that a tailpipe-only framework effectively predetermines battery-electric vehicles as the only viable technology and called for moving toward a genuinely life cycle-based approach – while also proposing narrower amendments such as removing the proposed 3% cap on fuel credits and allowing such credits to apply immediately rather than only from 2035 (eFuel Alliance 2026). ACEA and CLEPA focused on regulatory predictability, enabling conditions (charging infrastructure, affordable electricity, raw-material security) and giving manufacturers the freedom to meet any given target in whatever ways they might find most cost-effective (ACEA 2026; CLEPA 2026). Environmental organizations and independent research institutes mostly took the opposite view: the ICCT argued that the proposed amendments already constitute a significant retreat from the existing regulatory trajectory, while also questioning whether the proposed fuel and steel credit mechanisms risk double-counting emissions reductions already captured elsewhere in EU climate legislation, particularly the EU Emissions Trading System (Dornoff et al. 2025).

Taken together, these alternative proposals reveal that a significant share of stakeholders – across the spectrum from renewable-fuel producers to environmental advocates – favored moving Regulation 2019/631 further toward a life cycle basis than the Commission's proposal ultimately did, even as they disagreed sharply about the direction such a shift should take and about whether the current proposal already goes too far or not far enough in weakening near-term ambition.

3.4 The Position(s) of the Automotive Industry

The European automotive industry's position on the summer 2026 revision of Regulation 2019/631 can be examined at three levels: the European trade association level, the German national level, and the level of individual manufacturers.

At the European level, ACEA – representing seventeen major European car, van, truck and bus manufacturers – regularly affirms full support for the EU's climate-neutrality objectives while arguing that the current regulatory framework is disconnected from market realities and must become more flexible (ACEA n.d.b). Concretely, ACEA calls for extending the compliance-averaging period to 2028–2032, for converting the Commission's conditional 90% 2035 target into an unconditional one accompanied by a workable and immediately available compensation mechanism for the remaining 10%, and for preserving "technology neutrality" together with the reintroduction of a review clause before 2035 (ACEA n.d.c; n.d.d). CLEPA, representing more than 3,000 automotive suppliers across the EU, has articulated closely aligned demands jointly with ACEA, emphasizing that supplier competitiveness depends on regulatory flexibility for technologies such as plug-in hybrids and range extenders (CLEPA 2026).

The German Association of the Automotive Industry (VDA), whose approximately 620 members include BMW, Mercedes-Benz and Volkswagen alongside numerous suppliers, affirms a comparable commitment to the Paris Agreement while pointing to some €320 billion in planned R&D investment and €220 billion in capital expenditure through 2030 (VDA 2026). The VDA's demands – including an emphasis on "Technologieoffenheit" (technology openness) – closely mirror ACEA's, reflecting the overlapping membership and the prominent position of German OEMs in the European debate.

Beneath this seeming consensus at the association level, individual manufacturers diverge – in ways that correlate closely with their compliance situation. According to the Mathieu et al. (2025a) analysis of the first half of 2025, Volvo Cars, BMW, Stellantis and Renault were comfortably over-compliant, while the Volkswagen Group was expected to be just-so on track for compliance, and the Mercedes-Benz Group was unable to meet its target independently, relying instead on a pooling arrangement with the over-compliant Volvo Cars and Polestar. This compliance picture helps explain the pattern of public advocacy: Mercedes-Benz, described by Matthieu et al. (2025b) as "the loudest opponent of the EU targets" among individual manufacturers, has pressed hardest for regulatory relief, and Stellantis's CEO has called for a ten-year delay of the internal combustion engine phase-out (see also Guillaume et al. 2025). Notably, the over-compliant BMW Group nonetheless published a dedicated October 2025 policy paper calling for a reorientation of the regulatory framework toward full life cycle carbon accounting after 2030 – making BMW the only major OEM to explicitly advocate an LCA-based regulatory approach in a dedicated position paper (BMW Group 2025). The flexibility-oriented position of the association is also contested by prominent voices from the industry: Audi's CEO has publicly criticized the renewed combustion-engine debate as "counterproductive,"[7] and Volvo Cars – whose pro-electrification stance is consistent with the strategic orientation of its parent company, Geely – signed an open letter opposing any weakening of the 2035 target; Volvo had earlier withdrawn from ACEA over a similar disagreement (Spiegel 2025; Carey 2022).

On the specific question of whether LCA should become a binding regulatory instrument under Regulation 2019/631, the dominant industry position – articulated at the global level by OICA, at the European level by ACEA, and at the individual-OEM level, e.g., by Volkswagen – is that LCA remains valuable as a voluntary management tool but is not yet suitable as a basis for regulatory target-setting. OICA points to the sheer complexity of automotive supply chains (three to seven tiers spanning multiple regions) and to the latitude that ISO 14040/14044 leaves for methodological choices, both of which undermine comparability across manufacturers (OICA 2022). ACEA similarly holds that LCA should remain voluntary and adds that EU law already governs each life-cycle phase: manufacturers are regulated under the fleet regulation, fuel suppliers under the Renewable Energy Directive and the Emissions Trading System, and recyclers under the Battery Regulation and End-of-Life Vehicles Directive. A further LCA regulatory layer would be redundant (ACEA 2021, 2025). Volkswagen's position paper adds that it sees several methodological prerequisites as not yet being in place, especially data availability and reliability across global supply chains, and a harmonized secondary database (Volkswagen n.d.).

CLEPA stands out as a partial exception among industry associations: its policy priorities report for 2024–2029 with a few caveats but explicitly calls for the CO_2 regulation reviews for cars and trucks to be based on LCA, on the grounds that a tailpipe-only focus fails to capture vehicles' full environmental impact (CLEPA 2024). Overall, industry actors' voluntary internal use of LCA – most major OEMs already publish some form of life cycle results, as discussed in section 3.5 – coexists with broad reluctance to see LCA become a binding compliance standard, not because they question whether LCA has analytical value, but out of concern about whether it is ready to serve as a legally binding regulatory instrument.

3.5 The Practices of the Automotive Industry

Although Regulation 2019/631 does not require manufacturers to conduct full, stand-alone, CO_2-focused life cycle assessments, a combination of regulatory and market pressures has led much of the automotive industry to already adopt life cycle-oriented practices. Three EU legal instruments are especially important drivers, even though none of them mandates a standalone LCA outright. The **Corporate Sustainability Reporting Directive (CSRD)** requires companies of essentially all sizes to report annually on their sustainability impacts across their own operations and their value and supply chains, explicitly including Scope 3 emissions, which in practice necessitates life cycle-oriented data collection even though the Directive does not name LCA as such (Directive (EU) 2022/2464). The **Ecodesign for Sustainable Products Regulation (ESPR)** excludes passenger vehicles as such (since they are covered by sector-specific legislation) but applies to vehicle components such as tires that are not otherwise regulated. And the **EU**

[7] Although the regulatory compliance of Audi is ultimately assessed as part of the Volkswagen Group to which it belongs, due to the EU's focus on vehicle "fleets" (see section 3.1), it is a distinct brand with its own management and often distinct approaches to public relations, marketing, etc. Its publicly separate position on sustainability, including CO_2 emissions, LCA, etc. demonstrates that these issues are not just a matter of legal/regulatory compliance but also of the public image and marketing strategy, which due to heterogeneity in tastes typically does not occur at the level of entire fleets.

Battery Regulation requires a carbon-footprint declaration for each battery model at each manufacturing plant, based on life cycle methodology.[8]

Against this backdrop, actual industry practice displays considerable variation and methodological fragmentation, alongside striking differences in transparency. Some manufacturers – notably BMW, Audi and Mercedes-Benz – publish detailed, model-specific carbon-footprint or "vehicle footprint" reports drawing on a formal LCA methodology. Others, such as Porsche, mention life cycle principles only briefly in broader sustainability disclosures without publishing model-specific results, while Stellantis discloses that it conducts LCAs internally across most of its fleet without publishing the underlying results, and Škoda references life cycle principles as part of a broader environmental strategy without model-specific reports. Volvo stands out for regularly publishing updated, dedicated LCA reports for individual models as part of a deliberate sustainability-branding strategy.

Despite this heterogeneity, a closer look reveals underlying convergence among German and other EU manufacturers on several technical dimensions: virtually all rely on the ISO 14040/14044 standards as their methodological foundation (even though third-party verification is distributed across competing certification bodies such as the various TÜV organizations); most rely on the CML-2001 impact-calculation methodology developed at Leiden University; many rely on the same commercial software platform, Sphera (formerly GaBi); and all rely on the WLTP framework to model use-phase consumer driving behavior.[9] German manufacturers further converge in reporting use-phase emissions under two standardized scenarios – a standard European electricity mix and a hypothetical 100% renewable scenario – which, while not fully realistic under either assumption, at least enhances comparability across manufacturers' disclosures (cf. Alshadafan 2020). Notwithstanding this convergence on methodological building blocks, the underlying raw data remain largely unpublished even by the most transparent manufacturers, so that the exact analytical steps behind published results remain opaque, constraining both comparability across firms and the broader credibility of voluntary industry LCA disclosure.

The underlying motivations for the adoption of life cycle approaches appear to be similarly varied but ultimately mutually reinforcing. Reputational and brand-credibility considerations are central: because supply-chain (Scope 3) emissions are estimated to be, on average, roughly eleven times higher than a vehicle manufacturer's own direct (Scope 1) emissions and account for more than 70% of a manufacturer's total footprint, product-level life cycle assessment has become effectively indispensable for establishing credible Scope 3 targets. Third-party sustainability disclosure frameworks – the Global Reporting Initiative, the Global Compact, the Carbon Disclosure Project (CDP), and the Science Based Targets initiative (SBTi) – further pressure manufacturers toward cradle-to-grave assessment, and ratings frameworks such as EcoVadis treat a verified LCA as a mechanism for substantiating higher sustainability scores. A newer avenue, Environmental Product Declarations (EPDs), currently remains largely confined to heavy commercial vehicles, though a dedicated Product Category Rule for passenger cars, finalized in 2024, provides the methodological foundation for full-vehicle EPDs, should manufacturers choose to take up the option at scale. In sum, while the EU's regulatory landscape does not (yet) obligate a standalone automotive LCA, it is pushing the industry toward more of a life cycle approach through a web of indirect data-reporting incentives and obligations, even as methodological fragmentation – which industry-led

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[8] The Regulation only requires a partial LCA (see section 2.2), in that the vehicle's driving/use phase is excluded, on the grounds that downstream driving emissions are not under the manufacturer's control, which somewhat paradoxically complicates the execution of a genuinely holistic, full-vehicle LCA (Regulation (EU) 2023/1542, Annex II).

[9] Measurement standards reflect both market and non-market interests of the stakeholders who get to have a say at the rule-making stage (Büthe 2012), suggesting a need for a political analysis of the process of setting standards, which, however, is beyond the scope of this study.

initiatives like Catena-X (see Section 2.4.1) have so far only partly resolved – continues to limit comparability across firms.

3.6 LCA Obligations and Incentives in other Laws, Regulations and EU Policies Governing the Automotive Sector

Beyond Regulation 2019/631, a wide and increasingly dense web of EU legal and policy instruments shapes – and in some cases directly mandates – the use of life cycle methodologies in the automotive sector, including EU Regulations, which are directly applicable and immediately binding on firms, and EU Directives, which bind only Member States and require "transposition" through member state legislation before they create firm-level obligations (Article 288 TFEU).[10] Beyond these legislative acts, the EU also adopts recommendations and non-binding policy instruments, such as the European Green Deal, which lack binding force but frequently shape the contents of subsequent binding legislation (Rotondo 2013; Pasqua 2026).

Among directly binding Regulations, three stand out for imposing genuine LCA-related obligations on the automotive sector. The EU Battery Regulation (2023/1542; see also Section 3.5) imposes the most extensive obligations: manufacturers must produce a carbon-footprint declaration, based on life cycle methodology, for each battery model at each manufacturing plant. They also must implement a mandatory digital battery passport (phased in through February 2027) alongside extended producer-responsibility obligations for end-of-life battery management – though, as noted in section 3.5, the Regulation explicitly excludes the vehicle's use phase from the battery's carbon-footprint calculation. The Critical Raw Materials Act (2024/1252) does not impose LCA obligations directly but requires environmental-footprint calculations, based on relevant international LCA standards, for the extraction, concentration and refining stages of critical raw materials used heavily in EV batteries and various electronics components of cars.[11] The Ecodesign for Sustainable Products Regulation (2024/1781; see also Section 3.5) excludes complete vehicles, but applies to vehicle component parts not otherwise regulated, such as tires, and for those components requires digital product passports covering material composition and environmental footprint.

In addition, other regulations create what might be called indirect or *de facto* (though not *de jure*) LCA obligations. The EU Taxonomy Regulation (2020/852), for instance, effectively requires life cycle evidence to demonstrate that an economic activity makes a "substantial contribution" to an environmental objective without causing significant harm (the "Do No Significant Harm" test) – a test that, in the automotive context, can require manufacturers to show, through LCA, that climate-mitigation gains do not undermine circular-economy objectives.

Among Directives – which, again, create firm-level obligations only via national transposition – several point clearly toward a life cycle orientation. The Corporate Sustainability Due Diligence Directive (2024/1760) calls for companies to exercise due diligence across their "chain of activities," from raw-material extraction through end-of-life, which necessitates life cycle thinking even though the Directive does not itself mandate a formal LCA. The Corporate Sustainability Reporting Directive (2022/2464), discussed in section 3.5, requires sustainability reporting across a company's entire value chain, again without explicitly naming LCA as the required methodology. The proposed (not yet adopted) Green Claims Directive would, exceptionally, impose LCA obligations directly, requiring companies making life cycle-

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[10] The process of transposition allows member states to significantly delay implementation, as illustrated by the Corporate Sustainability Due Diligence Directive's transposition deadline, originally set for 26 July 2026, extended to 26 July 2028 after no Member State had transposed it.

[11] In a further echo of the Battery Regulation's approach, the CRM Act explicitly excludes the use phase and end-of-life from the required footprint calculation on the grounds that these fall outside the responsible operator's direct control.

based environmental claims about a product to substantiate those claims on the basis of the product's full life cycle. And the End-of-Life Vehicles Directive (2000/53/EC), while not itself mandating an LCA, requires manufacturers to design vehicles for circularity and to use minimum shares of recycled content – obligations that in practice are difficult to satisfy without relying on life cycle methodologies to demonstrate compliance.

Finally, Recommendations and policies – including the European Green Deal, the 2025 Automotive Package itself, and the Commission's Recommendation on the Use of Environmental Footprint Methods (which established the Product and Organization Environmental Footprint, PEF/OEF, methodologies) – do not themselves impose obligations but frequently become binding indirectly once referenced by subsequent Regulations: the ESPR and Battery Regulation, for instance, both require the use of PEF/OEF-consistent methodologies, converting an otherwise voluntary recommendation into an effectively mandatory obligation within their scope.

Taken as a whole, this overview of the larger context shows that manufacturers already operate under a fragmented but expanding set of obligations – some directly binding, some pending transposition, some merely persuasive – that collectively push the industry toward more comprehensive life cycle accounting. A comprehensive LCA mandate focused on vehicle emissions thus would hardly be a radical departure.

3.7 Opportunities and Limits of Incorporating LCAs into Regulatory Measures

To gain a thorough understanding of the current state of scientific knowledge concerning LCA's promise as a regulatory tool and the principal obstacles that have limited its uptake, we conducted an abbreviated systematic review of the literature on how, and how well, life cycle assessment can be incorporated into binding regulatory measures, with a specific and rapidly growing literature devoted to the automotive sector (see Appendix for the methodological details of the reviews, which started by identifying 144 sources through searches in several bibliographic databases, cumulating in an in-depth review of 29 articles).

LCA's central conceptual promise for regulation is the prevention of "problem-shifting:" because it covers the entire life cycle of a product, it can reveal whether a policy intervention that reduces environmental impact at one stage merely displaces that impact to another stage – geographically, temporally, etc. (Sala et al. 2021). This promise is not new: the U.S. Environmental Protection Agency commissioned the first public LCA study in 1974, but as Jegen (2024) documents, uptake in binding regulation was slow and has remained incomplete over the ensuing decades, notwithstanding many refinements in LCA methodology and practice. A number of existing instruments nonetheless demonstrate that binding, life cycle-based regulation is achievable: the EU's Renewable Energy Directive requires life cycle GHG calculations for biofuels. The U.S. Renewable Fuel Standard, implemented through the GREET modeling tool, mandates life cycle accounting for transportation fuels. California's Low Carbon Fuel Standard is widely regarded as a best-practice model, setting binding life cycle carbon-intensity targets and operating a credit-trading market that lets any fuel pathway compete on verified life cycle performance rather than technology identity. And in the realm of transport emissions specifically, the EU's FuelEU Maritime Regulation and the International Civil Aviation Organization's CORSIA scheme both establish binding well-to-wake or life cycle-based emissions targets, demonstrating that sector-wide LCA-based regulation is achievable even in complex, multi-stakeholder international settings (Klass and Heiring 2017; Conway 2022; Ingwersen et al. 2025).

The automotive-specific literature nonetheless finds that binding life cycle-based vehicle regulations remain essentially absent, with existing frameworks continuing to rely on tank-to-wheel (tailpipe) accounting despite a well-documented "burden-shifting" problem: measures that reduce use-phase emissions, especially electrification, may increase production-phase or end-of-life emissions (see also Jiao et al. 2025). As discussed in greater detail in chapter 2, production-phase emissions for battery-electric vehicles are substantial. In addition, as discussed in chapter 2.5.7, real use-phase emissions depend heavily on the carbon intensity of the electricity grid (see also Andersson and Börjesson 2021; Koroma and Alwosheel 2026).

Three clusters of obstacles to LCA-based regulation emerge consistently from this literature. First, methodological obstacles center on the latitude the ISO standards 14040 and 14044 leave for choices of system boundary, functional unit, allocation method, and impact-assessment methodology (see chapter 2). Such latitude may be very appropriate for research but problematic where consistent regulatory implementation, comparability, and legal defensibility matter. These challenges are compounded by the unresolved debate over whether attributional or consequential LCA is more suitable for policy analysis (Sala et al. 2016; Pryshlakivsky and Searcy 2021; see also chapter 2.4.1. of this study).

Second, data obstacles concern both the sheer cost of comprehensive data collection (historically 70-80% of an LCA study's cost) and the confidentiality with which manufacturers, particularly of batteries, treat production data, contributing to wide variation in published estimates (Berkhout and Howes 1997; Hawkins et al. 2012; Setyoko, Nurcahyo, and Sumaedi 2023).

Third, governance and political-economy obstacles are perhaps the least appreciated but arguably most consequential: Jegen (2024) identifies four interacting sources of difficulty – the value judgments embedded in any choice of impact category or weighting scheme; the dominant role of industry in LCA standard-setting bodies such as ISO TC207/SC5, which creates risks of regulatory capture or delay/stalling (see also Alshadafan 2020); limited state capacity, with LCA expertise typically concentrated in specialized agencies disconnected from operational ministries; and the straightforward political opposition that LCA-based regulation, like carbon pricing, tends to generate among the industries and supply chains on which it would impose costs. A further governance asymmetry – the EU's life cycle-inspired treatment of biofuels under the Renewable Energy Directive alongside its continued tailpipe-only, zero-emission treatment of electric vehicles – has been characterized as an inconsistency in system boundaries that systematically favors electrification over renewable fuels regardless of comparative life cycle performance (Andersson and Börjesson 2021).

The literature nonetheless converges on a set of best-practice regulatory design principles capable of addressing many, though not all, of these obstacles. These include:

- standardizing methodology through automotive-specific product category rules verified through the existing type-approval process, on the logic – drawn from the precedent of simplified recyclability calculations under ISO 22628 – that policy robustness matters more than academic precision (Lehmann, Berger, and Finkbeiner 2018);
- public investment in open-access life-cycle-inventory databases, following examples such as Germany's ProBas database or the U.S. National Renewable Energy Laboratory's Life Cycle Inventory Database, to reduce dependence on proprietary data (Sonnemann and Margni 2015; Jegen 2024);
- conditionality mechanisms that link regulatory incentives to verified, real-world life cycle performance thresholds – for instance electricity-grid carbon-intensity triggers for EV subsidy eligibility – rather than to fixed technology assumptions, as exemplified by California's LCFS (Xue et al., 2023; Koroma and Alwosheel, 2026);
- mainstreaming life cycle considerations into existing legal instruments, such as public-procurement rules under the EU's Clean Vehicles Directive, rather than requiring wholesale regulatory redesign (Jegen 2024);

- building iterative, adaptive review mechanisms into any life cycle-based framework so that methodology and data requirements can evolve as measurement science and market conditions mature (Walser et al., 2017; Alrabiah and Drew, 2022).

Taken together, this literature suggests that the technical and institutional building blocks for a more genuinely life cycle-based EU vehicle-emissions regulation largely already exist, even as methodological heterogeneity, data limitations, and political-economy resistance continue to constitute formidable and interacting obstacles to their full deployment.

3.8 Support and Opposition to Changes in CO_2 Emission and LCA Provisions in the Revision of Regulation 2019/631 in the European Parliament

Whether and to what extent Regulation 2019/631 moves toward an LCA approach ultimately depends on political majorities in the European Parliament, where climate-related policies are often contested despite widespread support for the EU's climate objectives in principle, consistently favor balancing those objectives against industrial competitiveness (Gheuens 2025).

This divide was already sharply visible in the negotiation of Regulation 2023/851, which introduced the 100% 2035 CO_2-reduction target and the associated de facto ban on new internal-combustion-engine vehicles. The Greens/European Free Alliance (EFA), the Progressive Alliance of Socialists and Democrats (S&D) and Renew Europe strongly supported that outcome, while the European People's Party (EPP) – whose rapporteur Jens Gieseke warned the measure would harm competitiveness and cost jobs – and the European Conservatives and Reformists (ECR) strongly opposed it. The measure passed the Parliament by only a narrow margin (340 in favor, 279 against, 21 abstentions), and the German government nearly blocked its final Council adoption in March 2023 over the treatment of e-fuels. The December 2025 Commission proposal for revising Regulation 2019/631 – with its 90% (rather than 100%) 2035 target, its retention of a role for combustion-engine vehicles running on eligible fuels, and its emphasis on flexibility – diverges from the preferences of the Greens/EFA, S&D and Renew Europe and instead more closely tracks the long-standing position of the EPP and ECR that climate objectives should be balanced against the need to maintain industrial competitiveness.

Nonetheless, the Commission's proposal by no means has assured support: Center-right party groups have pushed for changes beyond what the Commission's proposal already contains. The EPP as the currently largest political group in the Parliament (188 MEPs, ahead of S&D's 136 and the ECR's 78), under the banner of "technology neutrality" is pushing for all drivetrain technologies' contributions to decarbonization should equally count toward compliance. It has also proposed creating an entirely new zero-emission vehicle category for vehicles running exclusively on renewable fuels, extending the compliance-averaging period from three to five years, and further expanding the super-credit system for small vehicles. The ECR has voiced closely aligned opposition to the combustion-engine phase-out. At the same time, on the left, the Greens/EFA formally announced in May 2025 that they would vote against the Commission's 2025 amendments as "unjustified and harmful," while the S&D has called for the Parliament to hold the line at the original 2023/851 targets and to maintain 2035 as the last year of new combustion-engine vehicle production.

On the specific question of whether an LCA methodology should be incorporated into Regulation 2019/631, political alignments are even less predictable, as it does not map cleanly onto the standard left–right climate-ambition axis. Both the EPP and the Greens/EFA have expressed support for incorporating LCA methodology, but for different reasons and with different implications for bindingness: the EPP frames a comprehensive cradle-to-disposal environmental-impact methodology as advancing technology neutrality (since it would let renewable-fuel and hybrid pathways demonstrate their comparative merits on a full-life cycle basis, rather than being disadvantaged by a tailpipe-only metric that favors electrification by construction), while continuing to insist that any such methodology should be applied on a voluntary basis. The Greens/EFA, by contrast, support LCA methodology because it would capture battery production, critical raw materials, energy supply, recycling and end-of-life impacts that a tailpipe-only framework ignores – and they favor mandatory, rather than merely voluntary, application. These differences reflects a legal process already underway: Recital 50 of the original 2019/631 (and Recital 33 of the amending Regulation 2023/851) required the Commission to assess the feasibility of a common EU methodology for life cycle CO_2 emissions reporting, a mandate the Commission fulfilled by publishing a proposed methodology (covering the production, use, and end-of-life phases) by the end of 2025, with manufacturers required only to report life cycle data voluntarily from June 2026 onward – and, as of this writing, with no public indication that any manufacturer has yet done so.

The overall picture that emerges is one in which broad, cross-party agreement on the ultimate goals of climate-change mitigation and CO_2 emissions reduction – which prevailed with comparatively little contestation prior to the COVID-19 pandemic and Russia's invasion of Ukraine – has given way to political and distributional conflict over the pace and means of achieving those goals. This shift is exemplified by the fact that previously uncontroversial technical terms such as "technology neutrality" have themselves become politically charged. Within that broader conflict, the question of whether (and if so, when and how) LCA-based reporting requirements should become mandatory rather than voluntary under the revised Regulation 2019/631 has become a bone of contention: Notwithstanding cross-party agreement about LCA's analytical value in principal, there is sharp disagreement about its regulatory status, the resolution of which, like the revision of Regulation 2019/631 more generally, appears likely, if at all, to be adopted only with a bare parliamentary majority.

Systematic Review Methods Appendix, Chapter 3

For the analysis summarized in Section 3.7, a systematic review of the literature was conducted in May and June 2026 (see also the Literature Review Flow Diagram in Figure 21). The review was designed as a brief systematic review of the literature intended to establish what the scientific community currently knows about the opportunities and limits of incorporating Life Cycle Assessment (LCA) into regulatory measures, with particular attention to the automotive sector. While limited in scope due to project time constraints, the review followed core principles of systematic review methodology (Snyder 2019; Xiao and Watson 2019), including predefined search terms, explicit inclusion and exclusion criteria, and a structured screening process.

The literature search was conducted primarily through Google Scholar. Full-text versions of identified articles and chapters were subsequently obtained from bibliographic databases, such as JSTOR, publisher platforms, such as SpringerLink and Elsevier ScienceDirect and from various e-book collections and interlibrary loan. European Commission reports and policy documents, identified through Google Scholar searches, were accessed online, mostly via the official websites of the publishing institutions.

Searches were conducted in Google Scholar, with results displayed using Google Scholar's default relevance-ranking. The search strategy focused on identifying literature addressing the relationship between Life Cycle Assessment (LCA), environmental governance, public policy, sustainability regulation, climate policy, and life cycle-based approaches to regulation. Particular attention was given to literature concerning the automotive sector, transport regulation, electric vehicles, battery governance, life cycle emissions, and transport defossilization.

The following search terms and search strings served as the basis for the literature search. Related terms were frequently combined, modified, and refined during the search process to broaden or narrow the scope of results as needed:

- "Life Cycle Assessment" AND regulation
- "Life Cycle Assessment" AND policy
- "Life Cycle Assessment" AND governance
- "Lifecycle-based regulation"
- "Lifecycle governance"
- "Environmental governance"
- "Lifecycle thinking" AND policy
- "Policy implementation" AND LCA
- "Life Cycle Assessment" AND automotive sector
- "Life Cycle Assessment" AND vehicle regulation
- "Lifecycle emissions" AND automobiles
- "Battery lifecycle" AND EU regulation
- "Circular economy" AND lifecycle management

During the search process, related terms were combined using Boolean operators (e.g., AND) and search strings were iteratively refined when initial results proved either too broad or insufficiently relevant to the research questions. Additional searches using variations of the listed terms were conducted to ensure adequate coverage of the literature.

Search results were reviewed in order of Google Scholar's relevance ranking. The search strings listed above were not used exclusively as separate searches. Rather, they served as a pool of search terms that were combined, modified, and refined throughout the search process. Across all searches combined, approximately the first fifteen pages of relevance-ranked Google Scholar results were screened based on titles and abstracts. This process yielded 144 potentially relevant studies, with relevance initially determined by Salome Varamishvili (Research Intern at the IR Chair/Research Group) based on titles and abstracts. Screening was discontinued after approximately fifteen pages because subsequent results increasingly consisted of studies focused exclusively on technical engineering applications of LCA (see exclusion criteria, below) and yielded few additional sources meeting the inclusion criteria.

No publication-year restrictions were imposed. Foundational studies and recent publications emerged through the same relevance-ranked search process. The search therefore captured both early contributions to life cycle thinking and contemporary discussions of life cycle-based regulation.

Inclusion Criteria – Sources were included if they:

- focused on Life Cycle Assessment (LCA), Life Cycle Management (LCM), life cycle governance, or life cycle-based environmental management;
- addressed environmental governance, public policy, sustainability regulation, climate policy, or regulatory decision-making;
- examined life cycle-based approaches in the automobile, transport, battery, energy, circular economy, or related sectors;
- discussed life cycle emissions, transport defossilization, battery governance, sustainability regulation, or environmental impact assessment;
- provided methodological, theoretical, empirical, or policy-relevant insights regarding the incorporation of LCA into regulatory frameworks; and
- were peer-reviewed journal articles, academic books, book chapters, doctoral dissertations, or credible institutional reports.

Exclusion Criteria – Sources were excluded if they:

- focused exclusively on technical engineering aspects without addressing regulatory, governance, or policy implications;
- discussed sustainability issues without adopting a life cycle perspective;
- lacked sufficient methodological transparency, such that the study did not clearly explain its data sources, methods, or analytical procedures;

- focused primarily on technological optimization or engineering performance without broader policy implications; or
- examined highly specific technical cases without any discussion of broader regulatory implications or debates.

Screening and Selection Procedure: Potentially relevant studies identified through the search process were screened in three stages.

First, titles of the 144 potentially relevant studies were reviewed. 82 studies were excluded at this stage, primarily because they focused exclusively on technical engineering applications of LCA without discussing governance, regulation, or public policy implications. This left 62 studies for abstract review.

Second, abstracts were reviewed to assess their relevance to the research questions. Twenty-two studies were excluded at this stage, leaving 40 studies for full-text review.

Third, full texts were reviewed to determine their substantive contribution to understanding the opportunities and limits of incorporating LCA into regulatory measures, particularly in the automotive sector. Eleven studies were excluded during full-text review, resulting in a final sample of 29 sources. All these 29 sources are included in the list of References in the full report underlying Section 3.7.

The final sample consists of peer-reviewed journal articles, academic books, book chapters, doctoral dissertations, and institutional reports addressing the use of Life Cycle Assessment in environmental governance, public policy, sustainability regulation, and automotive-sector regulation.

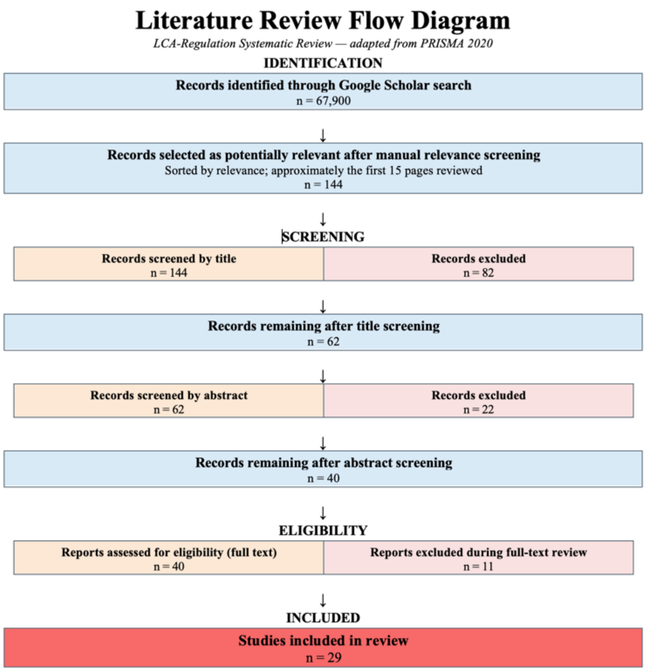

Figure 21: Methodology of Systematic Review of the Literature on LCA-Based Regulations: Flow Diagram

4 A Blueprint for Nuanced, More Comprehensive Defossilization of the Automotive Sector

This study set out to provide evidence-based input into the revision of Regulation (EU) 2019/631, focused on life cycle-wide defossilization outcomes rather than on any particular technology. This chapter asks what the evidence assembled in Chapters 2 and 3 mean for the revision of that Regulation, and what a workable path toward defossilization-focused life cycle-based regulatory approach would look like.

Two things follow directly from the evidence. First, the drivetrain alone does not determine outcomes and should not be considered in isolation. A vehicle's climate impact is set jointly by its drivetrain, its materials and its energy carrier, so that a regulatory approach that only considers the drivetrain while holding the other two fixed will fall short. Second, the missing piece is not evidence nor even political will, as shown by Chapters 2 and 3. What is missing is an accepted, workable way to act on them. This chapter therefore does not ask which drivetrain wins but sets out a pathway towards a more comprehensive, life cycle-based regulatory approach.

4.1 What the Evidence Means for a Non-Discriminatory Standard

What is missing is not capability, not scope in principle, and not even, in the abstract, agreement on direction. What is missing is a scientifically sound, workable, and non-discriminatory regulatory approach that turns an already broad consensus on principles into a concrete requirement and incentives, treating every route and contributing factor to lower fossil-carbon use on an equal footing, including the drivetrain, materials, and the energy carrier it relies upon. The point of doing so is not comparison for its own sake. It is to make sure the sector's contribution to climate mitigation is as large as it can actually be, rather than as large as a single, easily gamed metric makes it look. An approach that lets existing and future technologies compete on equal, fairly measured terms is also most likely to achieve whichever combination of vehicle, material and energy-carrier choices delivers the best achievable outcome, because it does not rule out any pathway to defossilization before the evidence is in.

4.1.1 Why Tailpipe Accounting Misses the Point

Our review of 19 LCA studies, comparing life cycle emissions of vehicles with various different drivetrains (see Chapter 2) showed: battery-electric vehicles (BEVs) have, on average, the lowest life cycle GHG emissions, with an average life cycle GWP 41% lower than conventional gasoline-powered internal combustion engine (ICE) vehicles. This overall finding, that BEVs reduce life cycle-assessed emissions, is robust across a range of conditions and to various changes modeling assumptions; it holds for approximately 92% of the cases considered in these LCA studies.

At the same time, LCA-based estimates of GHG emissions when comparing BEVs to ICEs range from −89% to +21% overall, with the minimum driving distance required for the lower use-phase emissions of BEVs to make up for their higher production emissions ranges from approximately 6,000 to 60,000 km, with environmental performance highly dependent on the extent to which the electricity used to charge the batteries is generated from sustainable source.

A tailpipe-only metric, which ignores emissions from vehicle production emissions, upstream electricity production, maintenance, and end-of-life handling of the vehicle, **cannot distinguish a BEVs near the low end of the range of life cycle emissions from one near the high end**. It also cannot see where in the accounting boundary an emission has simply been moved rather than avoided. Chapter 2 finds that BEV production emissions can run up to 68% higher than ICE production emissions, an effect more than offset by lower use-phase emissions across the large majority of scenarios reviewed, consistent with the net reduction reported above, so this production-phase figure should not be read in isolation from that total picture.

Separately, Chapter 2 finds that the climate benefit of e-fuels and e-diesel, relative to their fossil counterparts, depends heavily on how the electricity used to produce them is generated: made with renewable electricity, e-fuels substantially outperform fossil fuels; made with today's actual EU electricity mix, the same fuels are more emissions-intensive than the fossil fuels they are meant to replace. This finding, too, is an artifact of only considering what happens at the tailpipe: the underlying emissions have not changed, only whether the metric we use can "see" them. Further emission-reduction measures are also not considered, and are therefore not rewarded, by such accounting, such as the use of low-carbon ("green") steel or recycled ("secondary") materials, recovered through circular economy methods that can, for an increasing range of raw materials, deliver materials of equal quality with vastly lower emissions than "virgin" raw materials production from mining.

The overarching commitment to climate change mitigation, in the EU and among its member states, is not in question. However, this paper argues that achieving that overarching goal requires a commitment to defossilization rather than just decarbonization. As demonstrated by the deficiencies of the tailpipe-only approach of the current version of Regulation 2019/631 (as implemented), decarbonization targets can, in principle, be met by shifting emissions; a defossilization target cannot, because **defossilization asks how much carbon is being drawn out of long-term fossil storage over the course of the vehicle's entire life cycle**. It thus constitutes a more precise and stronger version of the same underlying commitment, not a competing one.

For biofuels, the calculation of total defossilization effects is complicated further by land-use change: the assessment of biofuels, liquid or gaseous fuels produced from biomass, is dominated by land-use change, both direct and indirect (LUC and ILUC), which can dominate the resulting GHG accounting and remains highly uncertain, alongside feedstock choice and co-product allocation (Fokaides et al., 2023). Synthetic e-fuels can in principle be GHG-neutral, but only when their production draws on renewable, low-carbon electricity; even then, their round-trip energy efficiency ($\eta \approx 0.14$) is far below that of direct battery-electric use ($\eta \approx 0.75$), an issue discussed further in Section 4.1.4. Here too, the defossilization metric asks the key question in a more focused manner: How much carbon is drawn from the slow, geological cycle into the fast, biologically active one? A tailpipe metric cannot answer that question.

4.1.2 The Drivetrain, Materials and Energy Carrier Move Together

Chapter 2 shows that the drivetrain is the primary source of variation: the choice of internal combustion, battery-electric, fuel-cell or plug-in-hybrid powertrain affects total life cycle emissions in several ways and more than any other single choice.

A second important parameter is the (fossil) carbon intensity of the electricity or fuel used to power it. A high-carbon electricity mix has a comparable effect on BEVs, FCEVs, PHEVs and e-fuel-powered ICEVs alike; conventional diesel and gasoline vehicles, and to a lesser extent biofuel-powered ones, are comparatively more insulated from this, because their upstream carbon intensity varies less between markets. For BEVs specifically, life cycle performance loses its advantage over conventional powertrains above roughly 600 g CO_2e/kWh grid intensity; on the data reviewed for Chapter 2, every EU member state's current electricity mix is already below that threshold; in some other regions and countries, switching to BEVs currently still risks worsening the overall life cycle GHG emissions. Over time, the advantage of BEVs for achieving defossilization is likely to increase, given projected improvements in the efficiency and the declining costs of sustainable energy production (e.g., Kerschbaum et al., 2025; Lazard, 2025), which should allow all countries to reduce the fossil carbon intensity of their electricity mix. Realizing these gains for climate change mitigation, however, depends upon actually increasing electricity production from solar, wind, hydro, and other sustainable sources of energy *at least in proportion to* the projected massive increases in electricity demand for transportation (e.g., IEA, 2026) – an ambition on which many countries still fall short, despite large increases in clean energy capacity (IRENA, 2025).

Materials are a further lever, distinct from the drivetrain and energy-carrier choices above, though not weighted equally with them from an LCA perspective: emission reductions available through the choice of materials are real though generally more modest in scale. Steel illustrates this: it typically accounts for anywhere between 2% and 7% of a vehicle's total life cycle emissions, depending on vehicle type, though a considerably larger share of the manufacturing phase specifically, which gives its decarbonization direct relevance for embedded emissions (see Hill et al., 2024). Switching to fossil-fuel-free steel production can eliminate more than 95% of the GHG emissions associated with steel production, translating into a reduction of up to a 27% in total vehicle manufacturing-phase emissions (Bui et al., 2024), as recognized in the proposal for an emission "credit" in the 2025 Automotive Package. Secondary (recycled) aluminum needs 95% less energy than primary production.

Plastics and polymer composites are a further, less-studied lever: Recycled plastics can also help mitigate climate-relevant emissions, particularly when design-for-sustainability and design-for-disassembly approaches are applied to reduce material variety, facilitate disassembly, or support separating different plastics at the EoL stage (e.g., Rios et al., 2015; Abuzied et al., 2020; Lander et al., 2023), meriting more attention as vehicles increasingly substitute lightweight plastics for metal components. Battery-material recycling and second-life use lower the footprint specifically of electrified drivetrains. A regulatory design that credits manufacturers specifically for verified high-quality recycling outcomes under their End-of-Life Vehicle responsibility — rather than only reporting fleet-average end-of-life data – would give this principle direct force: the revised End-of-Life Vehicles Regulation (COM(2023)451, political agreement reached December 2025) already sets minimum recyclability (85% by mass) and recoverability (95% by mass) thresholds and a requirement that at least 15% of mandatory recycled-plastic content come specifically from end-of-life vehicles. Tying CO_2-emission credits to verified compliance with these already-binding thresholds, rather than creating a parallel metric, is key issue to be addressed in the follow-on study proposed in Chapter 1. Recycling and end-of-life recovery therefore matter twice over: they lower a vehicle's own life cycle footprint, and – by keeping materials accessible for other value chains beyond the automotive sector – they extend emission reductions past what automotive-specific accounting alone can capture. None of these materials levers are visible to a tailpipe-only metric, and none of them require settling the choice of drivetrain first.

None of this makes the drivetrain less important. Because it sets a vehicle's total energy demand during the production phase as well as the operation/use phase, and because it interacts with the materials and energy-carrier findings above rather than sitting apart from them (a heavier battery changes material demand, and a combustion engine's fuel choice changes upstream energy demand, the drivetrain remains the single most far-reaching lever in this picture. A very recent study reinforces this point directly: For the U.S. vehicle fleet, Campbell and Geyer (2026) find that retiring a still-functional ICE vehicle and replacing it with a BEV would yield net climate benefits under most conditions (92% of modelled scenarios), due primarily to the efficiency gap between electric and combustion drivetrains. It underscores that the drivetrain is a necessary lever for mitigating climate change in the automotive sector – but not on its own a sufficient one, as the materials and energy-carrier choices are independently significant contributors to a vehicle’s actual footprint. In short, vehicle, material and energy-carrier choices all move the outcome together. A regulatory approach that only considers how to incentivize changes in the drivetrain while holding the other two fixed is not asking the right question, and the answers it produces will not describe a vehicle's full climate performance.

A related point is worth emphasizing: The results of applying any measurement standard often depend greatly on the assumptions built into the use cases incorporated into such a metric. Chapter 2 documents a massive performance gap for plug-in hybrids: WLTP type-approval assumes roughly an electric-mode driving share of about 84%, whereas real-world data suggests it is closer to 27%, resulting in a very different LCA performance. That finding is not a verdict on plug-in hybrids as a technology, but demonstrates the use case-dependence of measurement validity and the reliability of test procedures across different use patterns (see also Alshadafan 2020; Büthe 2012).

4.1.3 A Non-Discriminatory Standard Uses Specific Data, Not Averages

In addition to the need to consider emissions across all life cycle phases, which is why we advocate an LCA approach, understanding, measuring, and reducing total GHG emissions also requires considering where and how vehicles, batteries, and components are actually made. Two vehicles can have entirely different total footprints depending on whether their steel came from a hydrogen-reduction plant or a conventional blast furnace, whether their battery cells were produced on a grid dominated by coal or by hydropower, and how far the vehicle and its components traveled to reach the point of sale. This is not just a question of technology, nor even geography as such, but pf jurisdiction, i.e., the legal and regulatory context, as well as the societal demand for, or opposition to, and the political economy of, climate change mitigation policies (see Beiser-McGrath and Bernauer 2024; Gaikwad et al., 2022; Hutchings et al., 2019; Soubelet et al., 2024).

The importance of specific data, moreover, is not unique to tailpipe accounting: an LCA relying on generic, average input data can suffer the same weakness. Because automotive supply chains are global, a metric that works with global average values is not incentivizing supply chains and companies with ambitious targets, but favors those lagging behind. A life cycle approach with specific data is not simply more scientifically complete and accurate. It is the only approach that can meaningfully compare the greenhouse gas emissions (which have global warming effects at the atmospheric level wherever around the globe the emissions occur) from vehicles that are produced with global supply chains (which describes essentially the whole modern automotive industry, including manufacturers based in Bavaria).

4.1.4 Regulatory and Political Analysis Leads to the Same Conclusion as the Technical-Environmental Analysis

There is, within the EU and among its member states, widespread agreement about the need for an energy and transport systems transformation. Similarly, the commitment to decarbonization or better yet, as we have argued above, defossilization, is nearly universally shared. Rather, stakeholders differ over how best to reach these goals, given a spectrum of needs and constraints. As shown in Chapter 3, political contestation over some aspects of implementation has been ongoing for several years, leaving EU policymakers divided, and has prompted political contestation over some previously uncontroversial issues and even particular terms. The politicization has had spillover effects for discussion over the extent to which the EU should adopt LCA as a regulatory requirement. As is often observed in analyses of evidence-based or "evidence-informed" (Bowers and Testa, 2019) public policy: The adoption of LCA as a regulatory requirement is contentious in practice despite being recognized as scientifically clearly superior.

Regulation (EU) 2019/631 is, even assuming adoption of the December 2025 Automotive Package, a tailpipe-only instrument. The Automotive Package adds a small number of life cycle-adjacent elements (Article 7a life cycle monitoring, low-carbon steel credits, and renewable-fuel credits, needed because the WLTP-type approval test used for compliance does not distinguish blended from unblended fuel (see Section 3.3.)). But these elements apply to, at most, 10% of a manufacturer's compliance obligation and do not add up to a life cycle-based regulatory approach. A fuller life cycle-based approach was on the table before the Commission's proposal (Auto SAP (the Czech automotive industry association), Horse (the ICE-powertrain joint venture of Renault and Geely) and the European Biogas Association all argued for it), but it was not adopted. That was a choice, not an oversight.

At the same time, political parties are not actually as divided as it might appear, and there is ample room for compromise. The EPP has moved from general demands for technology-neutrality (in principle sensible but in the context of recent years politically toxic, as discussed in Chapter 3) to concrete legislative proposals built on, and in principle supporting, life cycle thinking. Greens/EFA and S&D continue to support LCA integration into EU legislation. The centrist EU party groups diverge primarily in ambition and on some of the details: Greens/EFA and S&D seek make LCA mandatory as a way to accelerate what we have called defossilization. By contrast, the EPP has framed its proposals for voluntary adoption of (more of) an LCA approach as means to preserve – not to slow down but also not to accelerate – the existing 2035 targets while widening the range of technologies through which the targets can be reached. Thus, EPP rapporteur Massimiliano Salini's May 2026 draft report proposes to create a new vehicle category that treats e-fuel and biofuel vehicles as zero-emission (in the terminology used elsewhere in the Brussels debate, vehicles exclusively using renewable fuels, VEEF) and to raises the fuel-credit cap from 3% to 10% (Salini, 2026). In other words, members of the EU Parliament are split over voluntary versus mandatory adoption, and over what should count as "zero-emission," not over whether life cycle thinking belongs in the regulation at all.

Industry is also split, though practice is already ahead of the regulation. ACEA, VDA and Volkswagen argue LCA should stay voluntary, citing supply-chain complexity and the lack of a harmonized methodology. BMW and CLEPA argue the opposite. Irrespective of that disagreement, a growing number of manufacturers (see Section 3.5 for examples) already publish model-specific carbon-footprint studies using ISO 14040/14044 as a common basis, and others publish such studies for individual models albeit without doing so across their entire fleet. The industry-led Catena-X initiative is in place to facilitate the exchange of standardized product-carbon-footprint data across parts of the supply chain. Though its use in practice is still limited, it can in principle be scaled up to European level quite easily.

Put together, Chapters 2 and 3 converge from two independent directions. On capability, the methodology (ISO 14040/14044) and a common data architecture (Catena-X product carbon footprints, the LCA standards used across major OEMs) as well as processes and an infrastructure for gathering and analyzing data across the life cycle already exist; none of this needs to be built from scratch. On scope, both chapters underscore the importance of considering materials, production, energy carriers and end-of-life treatment together – and not to consider the drivetrain in isolation but in combination with energy-carriers used across both production and operation. This is not just the consistent conclusion of rigorous scientific studies of LCA methods and models — the roughly five-fold efficiency gap between direct battery-electric use ($\eta \approx 0.75$) and e-fuel pathways ($\eta \approx 0.14$) alone moves results more than any other single parameter reviewed in Chapter 2 — it is also widely recognized by policymakers and industry practitioners. Almost all the political party groups in the European Parliament that have taken an explicit position on the issue (notable EPP, ECR, Greens/EFA and S&D) all support integrating life cycle assessment into vehicle regulation in some form, several manufacturers already publish model-specific life cycle studies, and CLEPA explicitly calls for LCA-based regulation. An LCA-based regulatory approach to automotive GHG emissions at the EU level is not a fringe position, nor is it facing principled opposition.

Quite to the contrary, our analyses suggest: It would be environmentally, economically *and politically* self-defeating for the EU and its member states to continue to pursue a regulatory strategy that provides only a very partial and thus biased understanding. It gives the appearance of improvements in automotive GHG emissions by focusing exclusively on the use phase of the cars sold and operating in the EU, at the risk of pushing more of the manufacturing of the vehicles sold in the EU market to non-EU countries where production-phase GHG emissions are substantially higher (possibly to the point of undoing any gains from the use phase), but beyond the control of tailpipe-only EU regulatory measures. In light of these considerations, adopting an LCA approach may in fact be an emerging consensus, which would simultaneously boost sustainability and strengthen the EU, but with which the regulatory architecture has not yet caught up.

4.2 A Pathway to an Unbiased, Comprehensive Regulatory Approach

Section 4.1 established why a tailpipe-only metric cannot see what a life cycle-based one can. This section sets out what a life cycle-based approach could look like in practice: the goal it should serve (4.2.1), the data basis it would need (4.2.2), seven principles that should guide its design (4.2.3), and a phased roadmap for introducing it (4.2.4).

4.2.1 The Goal

The goal is a standard that is scientifically sound yet workable in practice, unbiased and captures (and incentivizes reductions in) GHG emissions across the entire life cycle of the vehicles covered by Regulation 2019/631. These qualities of what we are advocating are not rank-ordered but simultaneously required: A standard that is scientifically ideal but overly complex or dependent upon unrealistic assumptions will not be adopted. A standard that can be readily implemented but is not scientifically sound will not be credible. Every element of the blueprint below is built to satisfy all of the four qualities, not to trade one off against the others.

4.2.2 Transparent Assumptions and the Need for a Common Basis

Comparing pathways fairly requires holding a set of methodological choices and data constant across them: system boundary, allocation method, electricity-mix scenario, vehicle lifetime and mileage, and end-of-life pathway, among others. The literature synthesis and analysis presented in the paper demonstrates the consequences these choices have, but cannot settle every one of them. Section 4.2.3 below lays out principles for how to get to an LCA-based regulatory approach, independently of how each individual assumption is ultimately resolved. Details will need to be settled in subsequent work, sketched at the end of this section.

4.2.3 Seven Principles for the Pathway

1. Build on existing regulatory frameworks and initiatives. A future life cycle-based regulatory approach should, as much as possible, build on and incorporate laws, regulations, and validated standards already in place rather than creating a parallel methodology from scratch: the Battery Regulation's carbon-footprint declaration and passport, the CRMA's environmental-footprint declarations, CSRD/ESRS Scope 3 reporting, the work of the TransensusLCA initiative, and the Catena-X Product Carbon Footprint Rulebook between them already cover large parts of the materials and reporting framework a life cycle standard would need. What remains is to close the gaps between these instruments and harmonize them, given that, for instance, none of them currently link vehicle-level compliance under Regulation 2019/631 to the material- and component-level data they already collect. This also answers the administrative-burden objection before it is raised: the reporting obligations already exist and are already being met under other instruments; what is missing is consistency and interoperability between them, not a new compliance regime. LCA-based regulation is also not a novel instrument for the EU: the Ecodesign for Sustainable Products Regulation (EU 2024/1781), which replaced the 2009 Ecodesign Directive, already requires a full life cycle approach for a wide range of product groups, though it explicitly excludes vehicles from its scope. This White Paper's focus, in contrast to Ecodesign's broader remit, is deliberately narrower: pros and cons of an LCA approach specifically for the automotive sector and specifically for CO_2 emissions, not the wider set of goals, such as material circularity or extended product lifespan, for which variations of LCA are used in other EU policy areas and which are not necessarily aligned with climate mitigation

specifically. LCA as a regulatory tool is therefore both familiar to, and compatible with, EU policymaking; what would be new is applying it to cars for climate purposes, not applying it at all.

2. Convert Article 7a's monitoring duty into the bridge to bindingness. The currently voluntary life cycle data submission under Article 7a should become mandatory for all manufacturers placing vehicles on the EU market, verified through the existing type-approval process rather than a new parallel audit regime, but should not yet be compliance-determining in its own right. This builds an audited, comparable dataset across the whole fleet before any binding threshold is attached to it, directly addressing industry's objection, documented in Chapter 3, that current data and methodology are not yet consistent enough to bear regulatory weight.

3. Replace flat credits with performance-based crediting, keyed to verified carbon intensity rather than category membership. The current flat 1.3× small-EV super-credit and flat 10% steel/fuel cap apply the same benefit regardless of how carbon-intensive the underlying production actually was. A performance-based design keeps the same policy tool, with credits for lower-carbon production, while linking the size of the credit to the verified, actual fossilized carbon footprint established by each manufacturer's Article 7a reporting. The point is not measurement for its own sake: a credit tied to verified performance is what gives manufacturers incentives to pursue their own abatement measures, or to agree specific reduction commitments with their suppliers, rather than a reason simply to report a number. And where such incentivized innovations allow even greater defossilization more efficiently, they are likely to diffuse through market competition or through institutionalized standard-setting. Such bottom-up harmonization has pitfalls, but tends to be far more efficient (and faster) than common standards negotiated between governments (Büthe and Mattli 2011).

4. Close the electricity/fuel accounting asymmetry. The current framework treats grid electricity as a fixed input to BEV life cycle performance (implicitly presuming zero emissions, while in reality the emissions from the upstream production of the electricity are highly variable). At the same time, it credits improvements in fuels explicitly (while capping those credits at a low level). Both sides of the energy-carrier ledger should be treated in maximally comparable ways, which should be readily feasible once grid-intensity data exists.

5. Invest publicly in open life-cycle-inventory data. Smaller suppliers, independent researchers and regulators themselves currently have no independent way to verify the primary data larger manufacturers submit. An open-access secondary-data layer, comparable in structure to the (now no longer curated) European ELCD database, Germany's ProBas, or the US NREL LCI database (USLCI), should be co-funded publicly, using the CirculaTUM project (which includes circular-economy research initiative on automotive materials) itself and comparable university-based initiatives as a template. This complements industry initiatives such as Catena-X rather than competing with them: Catena-X is a valuable project, but it reflects the manufacturers and suppliers who have adopted it, not the whole industry; it remains the right mechanism for supplier-specific primary data exchange among its participants, while a public secondary-data layer serves independent verification. Wherever robust, product-specific primary data already exists, the standard should prefer it explicitly over secondary averages; the *Expertenkreis Transformation der Automobilwirtschaft*'s Carbon Accounting report (2024) makes the same case for the automotive supply chain specifically, and secondary data should remain a fallback for the parts of the chain where primary data is not yet available, not a permanent substitute for it.

6. Preserve investment predictability through a fixed, pre-announced review mechanism rather than ad hoc renegotiation. A standard that can be relaxed after manufacturers have already invested to meet it penalizes exactly those who moved early. A review clause, understood from the outset as a mechanism for tightening the standard as data quality improves rather than as an opening to weaken

it – in line with best practice in technical standard-setting worldwide – gives manufacturers the planning certainty a credible standard needs. Correcting genuine technical errors is different from relaxing a target once adopted, and the pathway below treats them differently.

7. Prioritize end-of-life and recycling data, the least developed part of current reporting frameworks, tying it to the recycling provisions in the End-of-Life Vehicles Directive and the CRMA so that circular-economy performance, not only production and use-phase performance, enters the standard.

4.2.4 A Phased Roadmap

The seven principles above describe what the standard should look like once built; this section sets out the sequence for building it.

Phase 1 (2026–2029): make life cycle reporting under Article 7a mandatory and verified (principle 2), without yet making it compliance-determining. Standardize the assumptions and data requirements behind that reporting, the system boundaries, functional units and grid-intensity scenarios used, drawing on the determinants Chapter 2 identifies as the main source of cross-study variation, so that submissions from different manufacturers are actually comparable rather than only individually well documented. Secondary data is acceptable in this phase provided its quality and representativeness are disclosed alongside the reported figure, consistent with the primary-data preference set out in principle 5. The primary-data share required should rise deliberately rather than by default, and should be understood as applying to the foreground system – the processes specific to the vehicle under study – rather than the background system of generic, shared supporting processes (electricity grids, common raw-material processing) where secondary data from public databases will remain necessary regardless of phase. Within the foreground system, Phase 2 should make primary data mandatory first for the highest-impact-share components this chapter has already identified, battery cells and steel foremost among them, both of which already have dedicated reporting channels through the Battery Regulation and CBAM respectively that this requirement can build on rather than duplicate. Secondary data remains acceptable for the remaining foreground components in Phase 2. Phase 3 should extend the mandatory-primary-data list further as reporting infrastructure matures, with each phase's review checkpoint serving as the point at which that list is revisited and, where data availability justifies it, expanded. Co-invest in the open life-cycle-inventory database (principle 5), and align the resulting reporting requirements with the Battery Regulation, CRMA and CSRD rather than creating a sixth parallel reporting regime.

Phase 2 of this roadmap (2029–2032): replace the flat 1.3× super-credit and flat 10% steel/fuel cap with the conditional, performance-based crediting described in principle 3, keyed to the verified carbon intensity each manufacturer's Phase-1 reporting has by then established. Extend life cycle-parity accounting to grid electricity as set out in principle 4, closing the electricity/fuel accounting asymmetry once comparable grid-intensity data is available. This is also the point at which the review clause in principle 6 should be exercised for the first time, adjusting thresholds and scope in light of what the data actually shows rather than what was assumed in 2026.

Phase 3 (2032 and beyond): phase in binding life cycle-based compliance thresholds alongside the existing tailpipe metric, rather than replacing it outright, using the performance-based crediting structure from Phase 2 as the mechanism by which those thresholds are applied. Integrate end-of-life and recycling data (principle 7) into the compliance framework once reporting under the End-of-Life Vehicles Directive and the CRMA has matured enough to support it. A second review checkpoint, structured like the 2029 review, should be built into this phase too, so the standard keeps tightening as data quality and coverage improve rather than freezing at whatever state it reaches by 2032.

This sequencing is deliberate. It does not ask the EU to abandon a tailpipe metric it has spent over a decade building administrative capacity around. It asks the EU to build a second, life cycle-based layer alongside it, using data infrastructure that already exists or is already being built for other purposes, and to let that layer take on regulatory weight only once it has been tested and found non-discriminatory. The methodology, the data infrastructure and the political consensus for this second layer largely exist today. What has been missing is a sequence for putting them together. Running two parallel compliance metrics indefinitely would add regulatory burden without adding regulatory bite, particularly once the life cycle standard is doing the substantive work; the burden of justification lies with keeping the tailpipe metric, not with retiring it; the default expectation should therefore be that this second layer eventually replaces the tailpipe metric outright, not that the two continue to operate side by side indefinitely. This is not merely a matter of regulatory tidiness. A framework that continues to rely on tailpipe compliance alone effectively bets the sector's entire climate contribution on a single lever, the drivetrain transition, with no mechanism to compensate if that lever underperforms — a risk the Commission's own proposal for a multi-annual compliance mechanism for 2030–2032 (see Section 3.2), allowing a shortfall in one year to be offset by over-performance in another, already acknowledges implicitly. One recent estimate puts the gap in concrete terms: at the EU's stated pace of e-mobility adoption, the passenger-car sector would deliver only around 80 million tons of the roughly 188 million tons CO_2-eq reduction needed by 2030, with combustion vehicles still making up 78% of the fleet on the road that year (Tang et al., 2023).A more concrete way to frame the decision is to tie it to a specific, checkable condition rather than a fixed calendar date: at the Phase 3 review checkpoint, the case for retiring the tailpipe metric should be assessed against how much of vehicle compliance the life cycle standard is by then actually determining, not against how many years have passed since 2026. If life cycle-based thresholds have become the binding constraint for the large majority of manufacturers by that point, maintaining a separate tailpipe metric adds administrative complexity without adding regulatory bite, and retiring it becomes the more defensible default. If life cycle-based thresholds are still binding for only a minority, continued parallel operation remains the more cautious choice, and the same question should be asked again at whatever the next review checkpoint turns out to be. The same review checkpoints should also revisit the geopolitical dependency picture across all pathways together, energy-carrier imports and battery raw materials alike, rather than only the e-fuel and biomass side flagged in Section 4.3, so that the roadmap's assumptions keep pace with a risk picture that is likely to keep shifting.

4.3 Further Considerations: Geopolitics, Security, and the Allocation of Scarce Alternative Fuels

Security-policy consequences belong alongside ecological, economic, technological and innovation-policy ones in a study of this scope. The pathway in Section 4.2 deliberately focuses on verified life cycle results, in particular reductions in GHG emissions that would enhance the sustainability of the automotive sector, rather than favoring any single drivetrain, fuel, material route, of life cycle phase in advance. It does not, on its own, resolve a further question that sits alongside it. Irrespective of the regulatory framework adopted, some sustainability-relevant resources are limited in absolute quantity over the long term, and how limited resources are allocated across sectors is itself a legitimate policy question that a purely technical standard cannot fully answer.

This applies with particular force to e-fuels and other synthetic, renewable-based liquid and gaseous fuels. Renewable-energy expansion is itself a lever, not a fixed pie to be divided: the efficiency argument against e-fuels above assumes a constant or slowly growing supply of renewable energy. It is correct as far as it goes. It does not address the allocation question below, which arises for geopolitical and structural reasons rather than being about renewable-electricity volume alone. These considerations ultimately need to be weighed against climate mitigation pathways in other sectors too, a point to which we return in Section 4.4.

- Production capacity for e-fuels depends not only on renewable-electricity volume but on electrolyzer manufacturing capacity, plant siting, the availability of sufficient water, and international supply agreements, each with its own lead times and bottlenecks. These lead times determine not only whether capacity exists at all, but how fast it can be built up to relevant scale. An abundance scenario for renewable electricity does not automatically translate into an abundance scenario for delivered e-fuel volumes on the near- or medium-term horizon relevant to this White Paper's regulatory timeframe.
- Biomass-based fuels face an analogous but distinct constraint: land, not electrolyzer capacity, is the binding resource. The area available for energy-crop or agricultural-residue biomass production competes with land needed for food production, a competition sharpened by a growing world population and rising per-capita demand for land-intensive foods as incomes rise in developing economies. Climate change adds a further constraint on the supply side, as shifting precipitation patterns, heat stress and soil degradation affect the productivity of the same agricultural land the biomass supply depends on. Up to 849 million hectares of natural land, an area larger than the current EU territory, could be degraded by 2050 on current land-use trends, further tightening this constraint (UNEP, 2014). Chapter 2's analysis of the biogenic-carbon-neutrality assumption is the LCA-methodological expression of this same constraint. The claim should not be misread as indicating a settled methodological consensus: carbon-neutrality claims for biogenic carbon are a simplified accounting convention, not a physical fact, and remain contested within the LCA literature itself, not only in this White Paper's own argument. What is not in dispute is the practical implication: biomass is not a free, infinitely available substitute for fossil carbon, and a pathway that allocates it as though it were, risks the same kind of hidden trade-offs against which we have argued regarding tailpipe-only metrics.
- The KIT/DBFZ study (Toedter et al., 2026), commissioned by BMW Group, estimates a substitution potential for carbon-neutral fuels covering 38–55% of EU fuel demand by 2030, rising to 67–107% by 2040, from European feedstocks alone. Industry funding does not by itself disqualify this estimate: it was produced by a recognized technical institute using a documented methodology, and dismissing it on funding grounds alone would be no more rigorous than citing it uncritically. What the figure does depend heavily on is the same kind of assumption running through this section: how much renewable-energy capacity and biomass feedstock will actually be available, and how it is allocated across competing uses. Within this picture, first-generation biodiesel (FAME) and hydrotreated vegetable oil (HVO100) should not be treated as interchangeable: their feedstocks, land-use implications and life cycle emissions differ enough that characterizing "biofuels" as a single, uniformly marginal-benefit category understates the range of outcomes the literature actually reports. This distinction matters even more given where the Brussels debate has actually moved: current discussion focuses less on fuels grown as dedicated energy crops, which is where the land-use and food-competition concerns above apply most directly, and increasingly on fuels made from forestry residues, waste oils and other biogenic residual streams, for which those same concerns apply only in a substantially weaker form. A different constraint applies to this residual-stream pathway instead: the same, comparatively limited pool of forestry residues and waste oils is frequently claimed by multiple studies and multiple sectors at once, so headline substitution-potential figures for any single sector should be read as a share of a constrained, shared resource rather than as dedicated capacity.
- The KIT/DBFZ study points toward a credible additional defossilization lever in alternative fuels, alongside electrification, provided its findings and underlying assumptions hold up to further independent, detailed and scientifically sound scrutiny; the priority now is to conduct that verification, not to dismiss the lever before it has been tested.

- The EU's own Renewable Energy Directive III (EU, 2023) already puts a regulatory ceiling on how much of this biomass and e-fuel potential can realistically reach passenger cars specifically. In force since November 2023, RED III requires transport to source 29% of its energy from renewables by 2030 (or a 14.5% GHG-intensity reduction), with a 5.5% sub-target for advanced biofuels and RFNBOs (including e-fuels) and a roughly 7% cap on conventional food- and feed-based biofuels. These EU-wide ceilings apply across all transport modes, reinforcing rather than replacing the land- and capacity-based constraints above, unless EU countries start importing e-fuel at scale with accompanying risks.
- Import-dependency risks are not only an issue for e-fuels and biomass, but also for to battery raw materials. Lithium, graphite and rare earths are concentrated in extraction and, more importantly, in processing capacity dominated by China, a dependency the Critical Raw Materials (CRM) Act is meant to address but has not yet resolved. Any pathway compared on life cycle terms should weigh this dependency alongside the energy-carrier dependencies discussed above, rather than treating geopolitical risk as a concern that only arises for e-fuels. This is not a hypothetical risk: China accounts for more than 90% of global graphite processing capacity and over 80% of mid- and downstream battery manufacturing capacity. On 9 October 2025 announced export controls spanning battery cells, cathode precursors, anode materials and battery production equipment across the lithium-ion supply chain (Kim et al., 2025). These political risks due to extremely high market concentration during one or more stages of the CRM supply chain is actually far greater than for fuels: e-fuel and biomass production capacity is geographically diversified, with North America and Europe each accounting for roughly 46–48% of the global e-fuel market by value and China a comparatively minor contributor (Fortune Business Insights, 2026). China's own green-fuel output was about 8 million tons of oil equivalent in 2025, per the National Energy Administration's China Green Fuel Development Report 2026. On current evidence, the battery pathway's exposure to single-country geopolitical disruption is the larger of the two risks. The EU's Electrification Action Plan (European Commission, 2026), published 17 July 2026, sets an indicative target of raising electricity's share of final energy consumption from 23% today to 46% by 2040, and explicitly identifies vehicle-to-grid (V2G) technology as a mechanism for bringing measurably more renewable electricity into vehicle charging, through a proposed framework of regulatory sandboxes and living labs for V2G pilot projects, alongside a Tripartite Agreement on Energy Storage that has already yielded pledges of 30–35 GW of stationary storage capacity for 2026–2028. This White Paper's electricity-accounting principle (principle 4) would need to accommodate V2G's emerging role as measurable, verifiable renewable-electricity input as this framework develops.
- Certain sectors have no realistic alternative to liquid or gaseous fuels, for reasons of energy density and existing infrastructure: aviation and heavy-duty long-haul transport cannot, in the foreseeable future, be electrified with current or foreseeable battery technology. This shared constraint does not by itself determine priority between sectors: aviation's renewable-fuel demand is already binding and rising under ReFuelEU Aviation (Regulation (EU) 2023/2405) — a mandatory SAF blending share of 6% by 2030 and 70% by 2050, including a synthetic-e-fuel sub-mandate rising to 35% — for a sector with no electrification alternative at all, whereas passenger cars already have a viable, scalable alternative in battery-electric drivetrains. That difference, not sector size alone, must be an important consideration in any allocation debate. Whatever the outcome of that allocation debate, the size of the existing passenger-car fleet is itself a reason alternative fuels cannot be set aside for this sector: with a large stock of internal-combustion vehicles still years away from retirement, defossilizing the transport sector in time requires deploying these fuels in the existing fleet too, at least for the transition period until the drivetrain shift is complete. This fleet-size consideration holds regardless of how quickly the passenger-car sector's own drivetrain transition ultimately proceeds. This is a

structural fact about the sectors involved, not a scenario assumption, and it is a materially different kind of argument from the scarcity-versus-abundance debate above.

- Import dependency, for both feedstocks and finished fuels, raises the same security-policy questions already familiar from debates over fossil-fuel and CRM dependency (see Section 3.6 on the Critical Raw Materials Act; see also Arezki et al., 2026). To the extent that e-fuels are imported from outside the EU, their availability to EU passenger-car users may be subject to the same kinds of geopolitical risks the European Union is trying to reduce through the CRMA and related instruments (though possibly involving different non-EU countries). Building policy around an assumption of abundant, freely tradable e-fuel supply for passenger cars would sit uneasily alongside that broader strategic-autonomy objective. The EU's Carbon Border Adjustment Mechanism (CBAM) adds a further, LCA-adjacent dimension to this picture: from 2026, CBAM requires importers of steel, aluminum and several other carbon-intensive inputs, all directly relevant to automotive supply chains, to report the embedded emissions of those materials, calculated using life cycle-type accounting. An LCA approach is not merely compatible with this development but close to indispensable for it: manufacturers and suppliers already need this kind of data to comply with CBAM, independently of this White Paper recommendations for Regulation 2019/631. It further strengthens our argument that the reporting infrastructure, needed for a life cycle approach to automotive GHG emissions, is already being built for other reasons.

4.4 Closing This Chapter's Argument

The evidence summarized in Section 4.1 shows that, although the use phase remains the largest single contributor to most vehicles' life cycle emissions, a tailpipe-only metric is not able to capture a vehicle's full climate impact, and that the data needed to do so is not collected consistently across global supply chains. Section 4.2 sets out what closing that gap would concretely require, using infrastructure and consensus that already exist rather than starting from nothing. None of the three objections most likely to be raised against the proposed pathway (complexity, competitiveness, or implementation difficulty), survives critical scrutiny in light of what this study actually proposes. The proposed path to adopting a life cycle-based approach would reuse existing reporting, reward rather than penalize manufacturers who already measure their footprint, and is phased specifically to manage implementation risk. The open question is not whether a life cycle-based standard is achievable or justified; Section 4.1.4 shows the capabilities, the scope and the political willingness are already largely in place. The open question is whether the EU can convert this emergent consensus into a life cycle-based regulatory approach before another investment cycle passes it by.

This chapter's own argument stops short of resolving the assumption dependency Section 4.2.2 identifies as the pathway's central methodological condition: applying a common basis to every pathway compared is necessary, but this White Paper does not itself fix what every value within that common basis should be. Resolving that is the task of an independent consequential LCA study, to which have referred in this paper as the follow-on project. It is worth specifying what that follow-on project needs to address. The core principles guiding the follow-on study chapter should be the same as used throughout this paper: Fostering a regulatory approach that will be unbiased, scientifically sound, and workable. A methodology that is rigorous but carries a disproportionate reporting burden is not workable and therefore would not actually deliver more sustainable technology deployment in practice; the task is to resolve these questions as simply as the underlying science allows, not as elaborately as it could in principle support.

- A harmonized system boundary and functional unit. As documented in Chapter 2, LCA studies vary in whether they include end-of-life treatment at all, and in how they define the functional unit (per vehicle, per kilometer, per passenger-kilometer); the follow-on project needs to fix one cradle-to-grave boundary and one functional unit and apply them across every option compared, not just across drivetrains.

- Explicit, multiple electricity-mix and grid-intensity scenarios, modeling scarcity and abundance of renewable-energy supply side by side, with stated probabilities or ranges where possible, so the pathway's dependence on which scenario materializes can be quantified rather than argued over qualitatively.
- A single, justified allocation methodology, for example cut-off versus avoided-burden allocation for recycled materials, applied consistently rather than reporting a range drawn from studies that used different methods.
- Standardized vehicle lifetime and mileage assumptions, based on primary, EU-representative fleet data rather than a synthesis of differing assumptions.
- End-of-life and recycling pathway modeling, the least developed lever in the current literature and reporting alike, using realistic, prospective end-of-life and recycling rates rather than current-day rates.
- Feedstock and production-pathway assumptions for biofuels and e-fuels, including explicit treatment of indirect land-use change and of the biogenic-carbon qualification flagged in Section 4.1.1, resolving the FAME/HVO100 distinction and the assumptions behind the KIT/DBFZ study (Toedter et al. 2026, commissioned by BMW Group), which estimates a substitution potential for carbon-neutral fuels covering 38–55% of EU fuel demand by 2030 and 67–107% by 2040 from European feedstocks alone, on a primary-data basis rather than accepting or dismissing that estimate on funding grounds alone.
- A genuinely consequential, not only attributional, modeling approach. This White Paper is a literature synthesis of predominantly attributional studies; the follow-on project should model how the market and supply chain actually respond to a given regulatory change, the only way to answer how much additional GHG-reduction potential could be unlocked by expanding renewable-energy capacity rather than treating supply as fixed.
- A governance mechanism for updating these assumptions and data over time, tied to the review checkpoints in Section 4.2.4, so grid intensity, feedstock availability and production-capacity assumptions are revisited on the same cycles as the regulatory thresholds themselves. It is worth noting that today's g/km standard already differentiates targets by vehicle weight through its mass-based utility parameter M0 (Regulation (EU) 2019/631, Annex I), historically by 3.33 g/km per additional 100 kg for passenger cars; this differentiation necessarily disappears once the fleet-wide target is set to zero, a consequence worth flagging explicitly for any successor metric that might reintroduce a comparable adjustment.
- Whether the EU's current end-of-life-vehicle recycling system can actually deliver recycled materials in the quantity and quality a life cycle-based standard would reward. Principle 7 above assumes recycling data becomes available; it does not establish that the underlying recycling infrastructure is adequate to supply high-quality recyclate at scale, which is a separate empirical question the follow-on project should address directly.
- Design principles for effective and efficient regulation beyond the LCA question, covering incentive design, protection for early movers, and the effect of a regional standard on a global market. This White Paper merely identifies the open questions concerning these design issues rather than answering them.

Two of the points above are worth sketching as concrete starting points rather than left as unspecified list items, though neither is developed here as a finished proposal.

The first concerns steel specifically. A fast-track accounting rule for steel, ahead of a general materials-attribution methodology covering every vehicle component, is a tractable starting point precisely because the sector is not diffuse: a comparatively small number of producers supply it, and the production route – blast-furnace/basic-oxygen (BF-BOF), electric-arc-furnace (EAF), or hydrogen-based direct reduction – is already a clean, verifiable distinguishing factor that manufacturers must disclose at the border under CBAM. Such a rule would classify a vehicle's steel content by production route and feed that classification directly into Article 7a reporting as a discrete input, building on the credit mechanism the 2025 Automotive Package already created for steel specifically. It would not need to solve materials attribution for the vehicle as a whole, only this one, already-tractable case.

The second concerns the metric itself. Once a life cycle standard is in place, it is worth asking whether g/km remains the right unit, rather than assuming it should simply be recalculated on a life cycle basis. The most-discussed alternative is an absolute life cycle metric, tons of CO_2e per vehicle over its service life, aligned with a Paris-compatible carbon budget rather than a per-kilometer efficiency figure. The two reward different things: g/km already normalizes for mileage, so it rewards efficiency independent of fleet composition, whereas an absolute-tons metric measures total impact per vehicle and would therefore need a separate size- or segment-based normalization – mileage standardization alone would not resolve this – to avoid systematically penalizing manufacturers with larger-vehicle or commercial-vehicle-heavy fleets regardless of their actual carbon performance. This White Paper does not attempt that normalization here; it is exactly the kind of quantitative, cross-manufacturer modeling question the consequential-modeling item above already flags as work for the follow-on project, not a question a literature-based study can resolve on its own.

A third concerns the geography of fuel production itself. Section 4.3 already notes that e-fuel and biomass production is, at the continental level, considerably less concentrated than battery-material supply — the residual-stream feedstocks discussed there, forestry residues, waste oils and other biogenic residual streams, are inherently regionally distributed rather than concentrated at a small number of sites, unlike the globally concentrated mineral inputs the battery pathway depends on. What remains open is whether pushing this further — toward many small and mid-sized regional facilities rather than production concentrated even within those less-concentrated regions — could offer additional advantages. Geopolitically, such finer-grained decentralization would further reduce exposure to disruption at any single site or supplier. Logistically, shorter transport and distribution routes between production sites and end users could reduce the fuel-supply-chain emissions and infrastructure burden that come with today's more centralized model — the same plant-siting and international-supply-agreement constraints already discussed in Section 4.3 as a source of lead-time risk for e-fuel production capacity. Whether these further advantages materialize in practice, and at what scale, is a priority for future follow-on studies to examine.

A follow-on project addressing these points, held to the same standard of being non-discriminatory, scientifically sound and administrable rather than exhaustive for its own sake, would not simply add another data point to the literature Chapter 2 reviews. It would supply the fixed, common set of assumptions Section 4.2.2 argues is the minimum condition for a fair comparison across pathways, and would be what allows the outcome-based standard in Section 4.2 to move from a principled architecture to an operational one, feeding directly into the 2029 review checkpoint in Section 4.2.4. That is the path this chapter can point to: from the evidence gathered here toward a regulation of sustainability assessment in the transport sector that is fairer in principle and workable in practice.

The evidence gathered in this White Paper points to no methodological or practical obstacle that would make life cycle-based regulation infeasible; what remains are questions of sequencing and detail, not of feasibility. Manufacturers already make decisions — in materials, energy carriers, and recycling — that can meaningfully affect a vehicle's climate footprint, yet none of these currently count toward regulatory compliance. A credible standard should change that: the framework Chapter 1 anticipates and this chapter has now worked out in operational terms, rewarding the better choice at every phase of the life cycle, not only the choice of drivetrain. Steel shows this need not wait for the full framework to arrive: a dedicated fast-track rule for this one material could be introduced comparatively quickly, demonstrating the broader approach in practice. What this requires of the Commission is not a renewed bet on drivetrain transition alone, but a workable regulatory framework that credibly achieves the climate targets already set — and that framework does not need to be invented from nothing: the Commission already holds a mandate under Article 7a to develop a life cycle reporting methodology. Fulfilling that mandate, rather than creating a new one, is the task that remains outstanding.

Let us be direct about what this White Paper does and does not conclude. It does not conclude that battery-electric drivetrains are, or should be treated as, the only lever that matters for defossilizing road transport. The evidence reviewed here shows a genuine, quantifiable efficiency advantage for BEVs on average — but it also shows that materials, energy carriers, and end-of-life management each contribute independently to a vehicle's actual climate performance, regardless of drivetrain. A regulatory framework that rewards only the drivetrain choice, however well-intentioned, will miss the contribution the rest of the life cycle could make. That is the reality this White Paper asks regulators, and manufacturers, to face.

5 Conclusion

This paper makes above all a two-part conceptual contribution. First, any law, regulation, or public policy that seeks to achieve the greatest possible reduction in the transport sector's contribution to climate change should focus on defossilization rather than decarbonization — that is, the removal of fossil carbon from automotive emissions. Second, since greenhouse gas emissions occur across the entire life cycle of vehicles, comprehensive defossilization of the transport sector requires an LCA approach rather than an exclusive focus on use-phase emissions via tailpipe regulation. Regulation (EU) 2019/631 currently conflates defossilization and decarbonization, and it conflates tailpipe emissions with emissions over the life cycle of vehicles. This study develops the scientific basis underpinning these recommendations.

Chapter 2's LCA analysis and Chapter 3's regulatory and political analysis converge on the same answer from different starting points: tailpipe accounting carries the risk of merely shifting GHG emissions from one life cycle phase to another, and fails to acknowledge the further levers, beyond the drivetrain, that can contribute to lowering emissions. A broad evidence base on potential defossilization measures already exists, as does the capability for comprehensive assessment of actual emission-mitigation measures, using the by-now well-developed toolset of Life Cycle Assessment (LCA). The same holds for the political willingness to move toward an LCA-based approach. What has been missing is not evidence, and not even consensus on the direction of travel, but a regulatory framework that translates the goal of defossilization into a workable metric.

Chapter 4 sketches a path towards such a framework: a phased, principle-based pathway that reuses existing reporting infrastructure rather than creating a new bureaucratic burden. Seven principles guide its design, among them building on existing regulatory frameworks rather than a parallel regime, replacing flat credits with performance-based crediting keyed to verified carbon intensity, and closing the accounting asymmetry between electricity and fuel. These principles are then sequenced into three phases: making life cycle reporting mandatory without yet making it compliance-determining; introducing performance-based crediting once that reporting has produced a comparable dataset; and, from 2032, phasing in binding life cycle-based compliance thresholds. The chapter closes by scoping the specific technical questions that a comprehensive follow-on study, foreseen from 2027, will need to resolve.

For the ongoing revision of Regulation (EU) 2019/631, two findings from this analysis are especially salient. First, life cycle-based reporting can be introduced without waiting for a fully harmonized assessment methodology, by building on Article 7a and existing knowledge and methods, including initiatives such as Catena-X and the Battery Regulation's digital product passport. Second, doing so does not require declaring any one drivetrain the "winner": the evidence in Chapter 2 shows that, despite the undeniable central importance of the drivetrain – and even though one drivetrain, i.e., BEV, under current conditions in the EU has the efficiency edge – vehicle, material, and energy-carrier choices as well as the thorough implementation of CE strategies together can deliver significant mitigation contributions in a transition period. Applicable EU regulations should reward that contribution rather than assume it away, judging outcomes across the entire life cycle of vehicle rather than focusing only on the drivetrain during the use phase, following the defossilization logic set out above.

Defossilization, not decarbonization, is therefore the standard this White Paper recommends the revision of Regulation (EU) 2019/631 should adopt. The follow-up study will provide harmonized data required for it. The evidence for it, and the political opening to begin building the architecture for it, already exist.

This is not a conclusion that any single drivetrain is the only lever that matters for defossilization; it is a conclusion that the standard should reward every lever that genuinely contributes — drivetrain included, but not alone.

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