



The future generation of lightweight materials? A life cycle assessment of fiber-reinforced composite cross car beams

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ABSTRACT

Fiber-reinforced composites offer promising lightweight alternatives for automotive applications, yet comprehensive life cycle assessments (LCAs) comparing them with conventional metal components remain limited. This study presents the first cradle-to-grave LCA evaluating a recyclable multi-material glass-fiber-reinforced polymer (GFRP) composite cross car beam (CCB) against an aluminium reference, considering 11 CML midpoint impact categories with explicit composite EoL modelling under different scenarios. The study has been conducted as part of a larger research project aimed at supporting the development of a more sustainable GFRP composite CCB. The composite redesign achieves lower cradle-to-grave impacts across 10 of 11 categories, with reductions of 35–37 % in toxicity-related impact categories and 8–16 % in Global Warming Potential. Ozone Depletion Potential represents the only trade-off (~12–13 % increase), attributable to proxy-based inventory data. Despite replacing ~40 % of the aluminium mass, residual aluminium supply for the hybrid composite structure dominates upstream impacts, while end-of-life (EoL) recycling credits prove decisive for resource depletion categories. These results indicate that environmental performance in hybrid multi-material composite architectures is governed by metal substitution, scrap minimization, and EoL recycling quality - conditions increasingly decisive as powertrains electrify and electricity grids decarbonize.

1. Introduction

The automotive sector remains among the most environmentally consequential industries, driven by a global passenger vehicle fleet that has nearly quintupled over the past five decades [1]. Correspondingly, impacts arise across the entire automotive value chain: road transport accounts for approximately one-fifth of global carbon dioxide (CO₂) emissions and is a dominant contributor to EU urban air pollution (~57 % of total nitrogen oxide (NO_x) and ~29 % of all particulate matter (PM) emissions), whereas automotive manufacturing is resource-intensive, consuming ~12 % of global steel and ~18 % of aluminium, while generating ~5 % of global industrial waste [1,2].

In response to these pressures, environmental performance has become an important constraint for vehicle manufacturers, reinforced by tightening CO₂ and pollutant regulations, end-of-life (EoL) and recyclability targets, and shifting consumer preferences toward energy-efficient, low-emission vehicles [3,4]. Consequently, several strategies

have emerged, including fuel efficiency improvements in internal combustion engine vehicles (ICEVs), hybridization and electrification of powertrains, aerodynamic optimization, the integration of autonomous driving technologies, and, increasingly, lightweight design. Lightweight design is particularly attractive as it simultaneously reduces material demand in manufacturing and energy consumption in operation. In the operation phase, this reduction arises from lower rolling and acceleration resistances at reduced vehicle mass, which decreases fuel or electricity consumption and associated use-phase emissions [1,3]. At the fleet level, however, these component-level benefits are partly offset by the ongoing trend toward larger and heavier passenger vehicles, reinforcing the need to realise mass reductions wherever technically feasible [5].

Among lightweight materials, fiber-reinforced polymer (FRP) composites are gaining attention in the automotive sector due to their low density, high modulus, corrosion resistance, and favourable strength-to-weight ratios [6]. In particular, carbon- and glass-fiber-reinforced polymers (CFRP/GFRP) enable substantial mass reductions compared

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Abbreviations

ADP	Abiotic Depletion Potential	FRP	Fiber-Reinforced Polymers
ADP _{elements}	Abiotic Depletion Potential – Elements or Mineral Resources	FU	Functional Unit
ADP _{fossil}	Abiotic Depletion Potential – Fossil Resources	GF	Glass-Fiber
AP	Acidification Potential	GFRP	Glass-Fiber-Reinforced Polymer
BEV	Battery Electric Vehicle	GWP	Global Warming Potential
CCB	Cross Car Beam	HTP	Human Toxicity Potential
CED	Cumulative Energy Demand	ICEV	Internal Combustion Engine Vehicle
CF	Carbon-Fiber	LCA	Life Cycle Assessment
CFF	Circular Footprint Formula	LCI	Life Cycle Inventory
CFRP	Carbon-Fiber-Reinforced Polymers	LCIA	Life Cycle Impact Assessment
CF-SMC	Carbon Fibre Sheet Moulding Compound	MAETP	Marine Aquatic Ecotoxicity Potential
CML	Centrum voor Milieukunde Leiden (Life Cycle Impact Assessment Method)	MM4R	Multi-Material for Recycling (Project Acronym)
CO ₂	Carbon Dioxide	NO _x	Nitrogen Oxide
DE	Germany	ODP	Ozone Depletion Potential
EAF	Electric Arc Furnace	OEM	Original Equipment Manufacturer
EoL	End-of-Life	POCP	Photochemical Ozone Creation Potential
EP	Eutrophication Potential	PP	Polypropylene
ERV	Energy Reduction Value	SI	Supplementary Information
ETP	Ecotoxicity Potential	TETP	Terrestrial Ecotoxicity Potential
EU	European Union	TTW	Tank-to-Wheel
FAETP	Freshwater Aquatic Ecotoxicity Potential	WLTP	Worldwide Harmonised Light-Duty Vehicles Test Procedure
		WTT	Well-to-Tank
		WTW	Well-to-Wheel

with steel and even aluminium [3,7]. However, the cost of continuous-fiber reinforced composites has limited widespread uptake, motivating cost-efficient multi-material concepts. These concepts can be implemented through hybrid structural architectures that combine torsion- and bending-stiff hollow profiles, providing high stiffness at low mass, with flat or sheet-like components that facilitate joining, mounting interfaces, and functional integration. Thermoplastic FRPs are particularly suited to such high-volume architectures when processed by fast-cycle routes such as organo sheet thermoforming and press-and-injection overmoulding, enabling cycle times below 1 min. While thermoplastic sheet-injection moulding hybrid structures are already in series production, the integration of hollow profiles made of FRP remains unrealised despite their potential for scalable, highly integrated lightweight structures [8]. Addressing this gap is a central objective of the multi-material design for recycling-ready lightweight structures (MM4R) research project, which develops and evaluates a redesigned cross car beam (CCB), a cockpit structural component supporting the steering column, airbags, and instrument dashboard [7].

Yet, the shift toward such multi-material lightweight architectures changes not only the component's material composition but also the associated manufacturing routes and EoL management relative to conventional metal-based lightweight components. Therefore, while lightweight design reduces use-phase emissions, these gains may be offset by higher production impacts from advanced material processing as well as increased EoL burdens arising from limited recyclability and potential downcycling, thereby eroding, or even reversing, the net environmental benefit. Accordingly, a life-cycle perspective and multi-impact category assessment are essential to avoid burden shifting from one phase to another in the product life cycle and to capture trade-offs across impact categories beyond climate change alone [4,9]. Life cycle assessment (LCA) provides a systematic method for quantifying environmental impacts across the full life cycle of product systems [10]. It is widely established in the automotive sector as a decision-making supporting tool, particularly in early product development, where it supports robust comparisons between design alternatives [2,4].

In this context, a substantial body of LCA literature exists on lightweight vehicle designs; however, important gaps remain in comparing

newly developed multi-material FRP composite components against conventional metal components under a comprehensive life-cycle scope and impact-category coverage. A limited subset of studies performs explicit composite-metal comparisons [3,9,11–14], whereas most of the literature instead compares alternative composite-based lightweight concepts [4,15–21], evaluates manufacturing routes for composite parts [22,23], compares lightweight metal solutions [24–26], or focuses on composite recycling in isolation [27]. The few existing composite-metal benchmark studies typically evaluate a restricted impact category set related to Global Warming Potential (GWP) and Cumulative Energy Demand (CED) [3,9,11–13]. The only two studies that broaden the impact assessment remain constrained by incomplete EoL representation: Wegmann et al. (2022) extend the impact assessment to endpoint damage categories, but do not model EoL [9], whereas Freire et al. (2025) evaluate a broad set of midpoint impact categories yet apply a cradle-to-gate system boundary, thereby excluding explicit EoL recycling routes (e.g., mechanical recycling, pyrolysis) or any dedicated recycling allocation scheme [14]. Furthermore, these gaps are echoed for crossmember structures, where available LCA studies remain sparse and not transferable to newly developed components like the MM4R CCB: Cecchel et al. (2018) and Suski et al. (2024) examine only metal-based crossmember components [28,29], while Stelzer et al. (2022) compare a thermoset carbon-fiber sheet moulding compound (CF-SMC) drivetrain crossmember with an aluminium counterpart, however, involving different manufacturing processes and serving a different structural function than the CCB, and without addressing composite recyclability at EoL [30]. Consequently, a cradle-to-grave, component-specific LCA of a CCB that directly compares a conventional lightweight aluminium solution against a recyclable multi-material FRP composite-based solution with explicit EoL recycling route modelling and trade-off analysis across relevant impact categories remains absent. In summary, while prior work addresses individual aspects of composite lightweight LCA - whether restricted to specific impact categories, limited to cradle-to-gate boundaries, or omitting composite EoL recycling - no existing study combines a comprehensive cradle-to-grave assessment for a direct composite-metal CCB comparison.

This study addresses these gaps by presenting the first cradle-to-grave LCA of the redesigned CCB within the MM4R project, benchmarking the conventional aluminium reference component of the Porsche 911 Carrera (Type 992) against this innovative, recyclable GFRP-based alternative. The reference CCB is primarily manufactured from aluminium and steel sheets, whereas the MM4R CCB features a more complex, hybrid structure, incorporating a hollow profile, organo sheets (woven glass-fibre fabric in a polypropylene matrix), and injection-molded granulate, all composed of glass-fiber (GF) and polypropylene (PP) composites, replacing ~40 % of aluminium [7]. High-resolution primary data, supplemented by targeted literature-based secondary data, enable detailed modelling of both the production system and composite EoL scenarios, including alternative recycling pathways. Additionally, the use phase is modelled using the LightImpact approach previously demonstrated for the MM4R case study, providing the first WLTP-aligned, vehicle-specific energy reduction values (ERVs) to quantify mass-induced fuel and electricity savings [1]. These validated use-phase inventories are embedded into the comprehensive cradle-to-grave LCA of both CCB variants, spanning raw material extraction, production, and explicit EoL recycling scenarios.

Ultimately, this study advances the environmental assessment of automotive lightweight design to recyclable multi-material composite interior structures relevant for high-volume applications, where thermoplastic recyclability, multi-material joining, and functional integration are primary design drivers rather than maximum carbon-fiber-based lightweighting. Thus, the results support evaluating whether these innovative composite components can achieve net environmental benefits over the full component life cycle and therefore constitute a viable next-generation lightweight structural solution.

2. Methods

The comparative LCA was conducted in accordance with ISO 14040 and ISO 14044, which standardize the LCA method as a four-phase framework comprising (i) Goal and Scope, (ii) Life Cycle Inventory (LCI), (iii) Life Cycle Impact Assessment (LCIA), and (iv) Interpretation [10,31]. In line with this framework, the present methods section describes the goal and scope phase and the LCI, while the LCIA modelling results and their interpretation are presented in the results and discussion sections, respectively. All goal and scope decisions underpinning the comparative assessment are carefully specified, including the definition of system boundaries, the functional unit (FU) and reference flow, the LCIA characterisation method, the scope of impact categories, the modelling software, and EoL allocation.

2.1. Goal and scope

The goal of this LCA is to quantify and compare the environmental impacts of two variants of a CCB, a structural automotive component that supports the steering column, airbags, and instrument dashboard while enhancing safety and comfort through energy absorption and

vibration reduction [32]. The comparison includes a conventional state-of-the-art aluminium component and the MM4R redesign, both implemented in the Porsche 911 Carrera (Type 992) vehicle platform. The intended LCA application is decision support for component development, specifically to evaluate whether the MM4R redesign, developed under recyclability-oriented design requirements, delivers a net environmental benefit over the entire life cycle. In addition to the overall impact comparison, the assessment identifies environmental hotspots and trade-offs associated with the redesign, with emphasis on material substitution, changes in production requirements, mass-induced use-phase energy effects, and EoL treatment.

Ultimately, in order to capture drivetrain sensitivity within the use-phase, the comparison is also performed for the CCB variants implemented in the gasoline-fuelled ICEV configuration and in a hypothetical battery-electric vehicle (BEV) configuration [33]. Fig. 1 depicts CAD representations of the assessed CCB variants, with (a) illustrating the aluminium reference design with local steel sheet reinforcements and (b) the MM4R design, which partially replaces aluminium and is associated with an overall vehicle mass reduction of ~5 %.

2.1.1. Functional unit

The functional unit is defined as one CCB fulfilling the structural and integration requirements of the Porsche 911 Carrera (Type 992) vehicle platform over a service life of 200,000 km, with no replacement. The lifetime mileage is aligned with the range presented in the current automotive product category rules and draft guidance [34,35] as well as established original equipment manufacturer (OEM) LCA practice [36–38]. Functional equivalence between the two design variants is ensured by defining the CCB as a structural component implemented in a specific vehicle platform, meaning that both variants meet the same mechanical performance requirements and are validated against standardized engineering procedures for stiffness, crash-related behaviour, vibration behaviour, and platform integration. The corresponding reference flow is one CCB (either the aluminium reference or the composite MM4R design) installed in one Porsche 911 Carrera (Type 992) vehicle to fulfil the functional unit.

2.1.2. System boundary

A cradle-to-grave system boundary was considered, covering raw material supply, component manufacturing, the vehicle use phase, and EoL treatment. Use-phase contributions were taken from prior case-study modelling, considering a well-to-wheel (WTW) system boundary for evaluating burdens attributable to the mass difference between the CCB designs, including both well-to-tank (WTT) processes (fuel or electricity provision as well as distribution) and tank-to-wheel (TTW) processes related to in-vehicle energy conversion (fuel combustion in the ICEV configuration or electricity conversion during BEV operation) [1]. The EoL stage accounts for recycling, including different routes for the composite variant, as well as landfilling, modelled according to market-based treatment shares.

Figs. 2–4 illustrate the modelled system boundaries through sankey

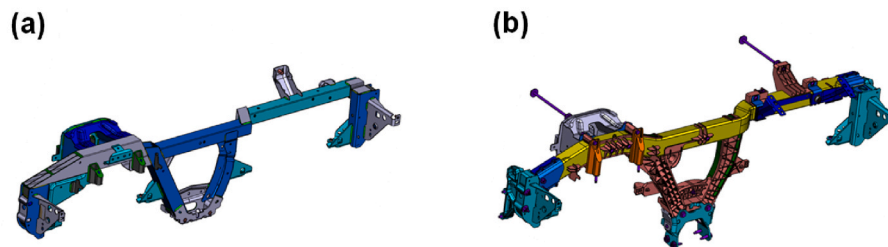


Fig. 1. Schematic illustration of the assessed CCB variants: (a) aluminium reference design and (b) MM4R design.

Colour key — (a): aluminium sheet = grey, blue/turquoise; steel reinforcements = green; (b): aluminium sheet = grey, blue/turquoise; steel reinforcements = dark green; GFRP hollow profile = yellow; GF/PP organo sheets = green; injection-molded GF/PP granulate = rose/brown. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

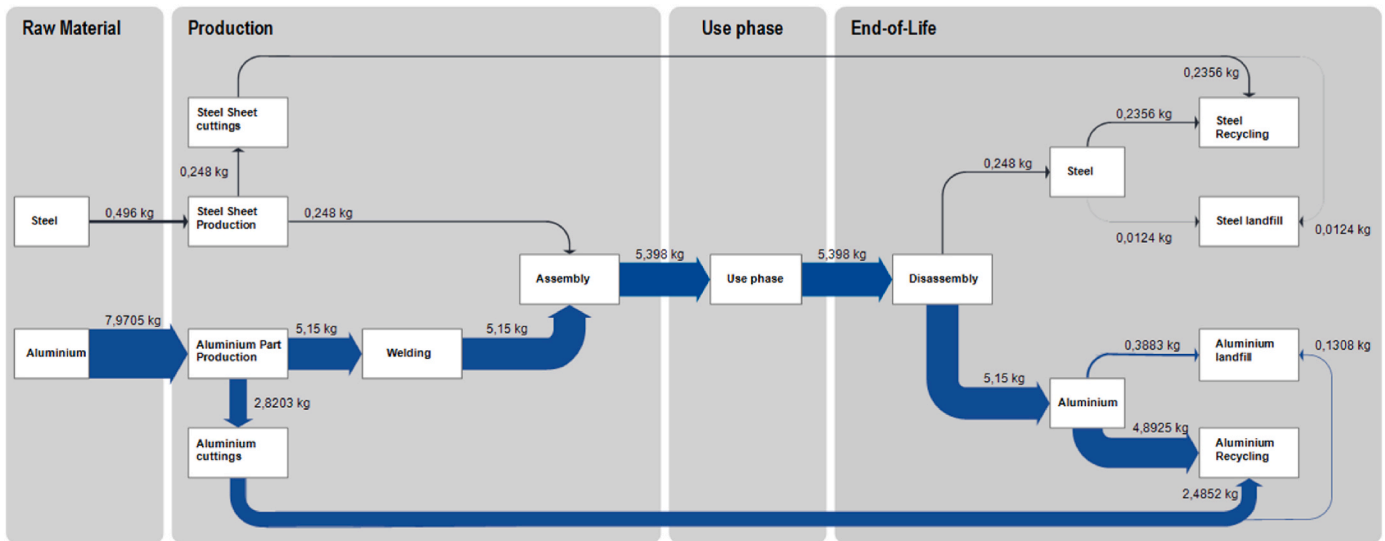


Fig. 2. Aluminium reference CCB Sankey - foreground process and mass-flow diagram.

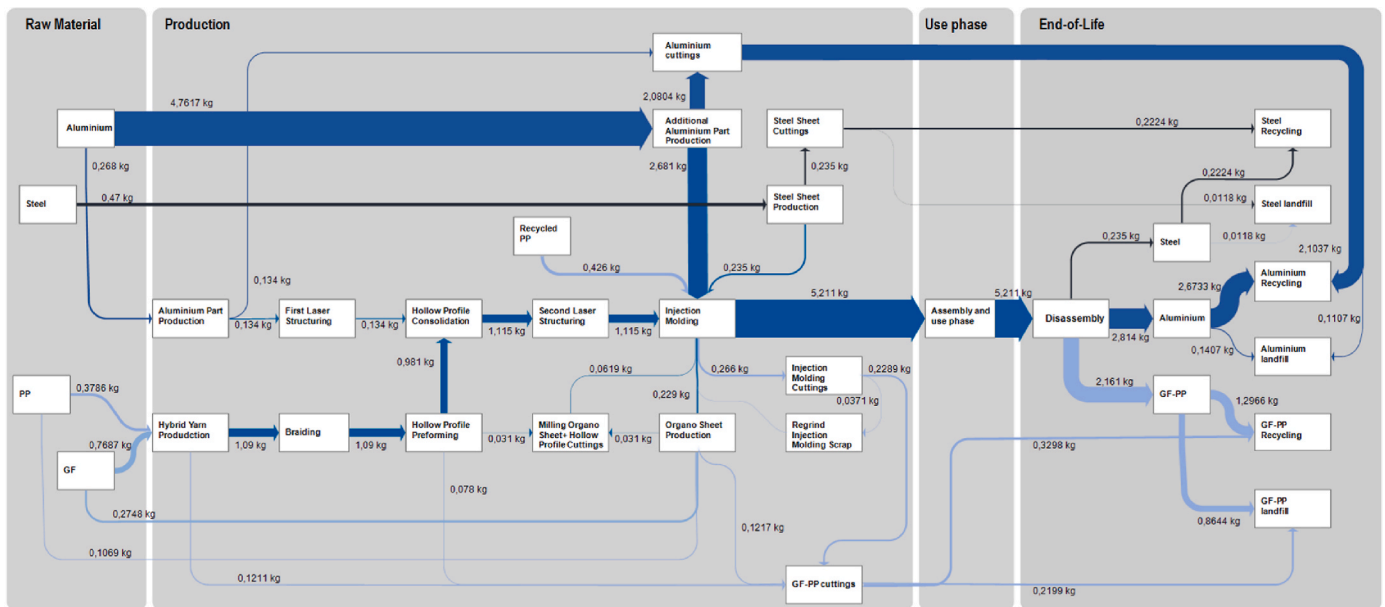


Fig. 3. MM4R CCB Sankey (maximum scrap) - foreground process and mass-flow diagram.

diagrams showing material inputs, mass balances, and the main process steps for the aluminium reference design and for the MM4R design under two alternative composite production scrap assumptions. For visual clarity, the diagrams are restricted to material flows of the foreground product system; quantitative energy and auxiliary inputs (electricity, thermal energy, process water, EoL substitution credits, and ancillary chemicals) for each foreground unit process are reported in full in the LCI (see Section 2.2). The minimum scrap scenario represents an optimized manufacturing case with low cutting waste and reduced material losses, whereas the maximum scrap scenario reflects a conservative assumption with higher production waste rates, leading to increased primary material demand and associated upstream burdens. Foreground and background processes required to produce and treat the CCB variants are included within the system boundaries, including auxiliary materials and chemicals, energy, and water. In contrast, infrastructure, buildings, and production equipment are excluded due to insufficient robustness in allocating across multi-use facilities and limited data availability. Furthermore, transport processes are excluded

using a cut-off criterion, as their contribution was assessed to be below 5 % of total impacts and thus not decisive for the comparative outcomes. Ultimately, assembly and disassembly of the CCB are assumed to be performed manually, entailing negligible energy and material inputs. These processes were consequently represented in the LCA model with zero environmental burden attributed to the assembly and disassembly operations themselves.

2.1.3. LCIA method, scope, and software

The LCIA is carried out by implementing the developed LCIs in LCA for Experts (formerly GaBi), version 10.9.1.19, with the Sphera Professional Database with Extensions, content version 2022.2, a software tool widely applied in automotive LCA practice [39–41]. Within this software, environmental impacts were quantified using the CML 2001 characterisation method (August 2016 update), evaluating a set of midpoint impact categories frequently used for automotive applications [2] and consistently recommended for comparative automotive product assessments [1,42–44], in line with the methodological approach set out

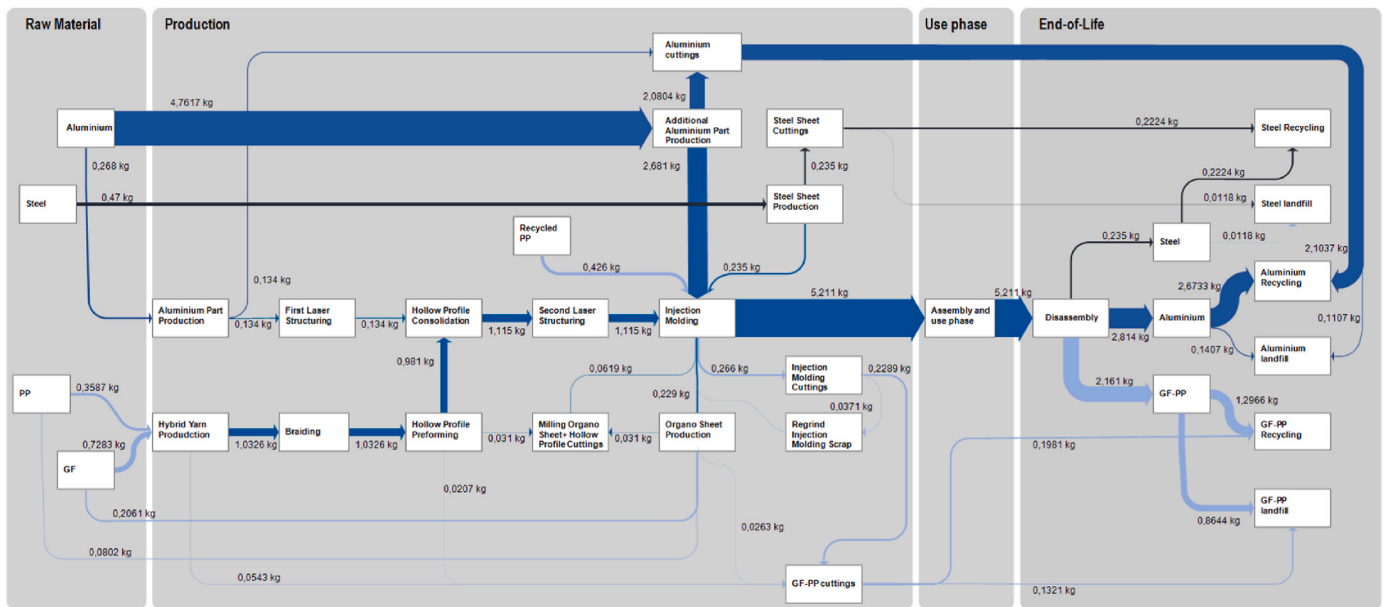


Fig. 4. MM4R CCB Sankey (minimum scrap) - foreground process and mass-flow diagram.

in ISO 14040/14044 and illustrated in ISO/TR 14047 [10,31,45]. The selected impact categories comprise: GWP, Ozone Layer Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion Potential (ADP), Human Toxicity Potential (HTP), and Ecotoxicity Potential (ETP) [44].

2.1.4. Allocation

Allocation at EoL represents a decisive methodological choice in comparative LCAs, as it determines how recycling-related burdens (e.g., impacts associated with recycling operations or disposal) and credits (e.g., avoided impacts due to avoided primary material production through substitution) are distributed between the product life cycle generating recyclable material and the subsequent life cycle using secondary material. To ensure a robust and transparent comparison between the aluminium reference and the MM4R composite CCB design, EoL modelling was implemented with a 50:50 allocation, i.e., impacts and credits associated with recycling are shared equally between the supplying and receiving life cycles [46,47]. This choice positions the assessment between the 0:100 “avoided burden” approach (crediting avoided virgin material production based on system expansion) and the 100:0 “cut-off” approach (assigning recycling benefits entirely downstream), both of which are widely applied in existing studies. Notably, avoided-burden crediting requires the explicit assumption that secondary material substitutes virgin material in an expanded system and, where applicable, that such credits are corrected for quality losses (downcycling) - assumptions that are particularly uncertain for open-loop composite recycling pathways with variable material properties and outlet markets [46]. Finally, while the Product Environmental Footprint guidelines proposed by the European Commission recommend the Circular Footprint Formula (CFF) as a parameterised intermediate solution, its implementation requires additional market- and quality-related parameters, which can increase uncertainty and methodological complexity for non-standard material streams [47]. Against this background, the 50:50 shared-responsibility approach was retained as a pragmatic and transparent approximation where such parameter uncertainty is high.

2.1.5. Scenarios

To examine how key processes and modelling choices influence the results, the LCA was additionally evaluated under a set of scenario

combinations. The scenario analysis addresses relevant variability in (i) background energy supply, (ii) composite production scrap, and (iii) EoL treatment options for the composite variant, while also considering all scenarios under the two drivetrain configurations defined for the use phase (ICEV and BEV). For the electricity supply background process, two electricity supply assumptions were applied: a current German/EU electricity grid mix and a future EU electricity grid mix for 2030, reflecting significant improvements aligned with Paris Agreement-consistent sustainability policies, both sourced from the LCA for Experts database. In the production stage, the MM4R variant was assessed under minimum and maximum composite scrap assumptions (hybrid yarn 5–10 %, preforming 5–10 %, organo sheet 20–40 %), consistent with the ranges provided within the MM4R project and visualized in the system boundary sankey diagrams (see Figs. 2–4). At EoL, the composite variant includes alternative recycling routes, namely mechanical recycling and pyrolysis, representing dominant and emerging thermal pathways discussed in the literature [48,49], while applying a typical market-based treatment split of 60 % recycling and 40 % landfilling without energy recovery [50]. In contrast, no scenario variation was applied for the metal parts, which were modelled considering 95 % recycling and 5 % landfilling. Aluminium scrap was considered to be treated via a rotary furnace route, as this process is specifically applied for contaminated or alloyed aluminium scrap and therefore represents the appropriate recycling technology [51–53]. Steel was modelled as recycled via electric arc furnace (EAF) steelmaking, reflecting the most relevant recycling pathway reported in the literature [53–55]. All evaluated scenario combinations are summarized in Table 1.

2.2. Life Cycle Inventory

The LCI quantifies the input–output flows of all relevant foreground and background processes associated with the two assessed CCB variants (aluminium reference and MM4R). The inventory was compiled separately for each life-cycle stage (raw material supply, production, use phase, and end-of-life) and for each design variant. Foreground processes (i.e., processes explicitly modelled for the CCB product system) were parameterised primarily using primary data from MM4R project partners; remaining foreground gaps were addressed using secondary datasets from LCA for Experts and, where required, ecoinvent. Background processes (i.e., generic upstream supply processes such as energy

Table 1
Overview of evaluated LCA scenario combinations.

Vehicle Type	Composite Cuttings	Electricity Grid Mix	Composite Recycling
BEV	low (hybrid yarn 5 %, preforming 5 %, organo sheet 20 %)	DE/EU	mechanical
		EU 2030	pyrolysis
	high (hybrid yarn 10 %, preforming 10 %, organo sheet 40 %)	DE/EU	mechanical
		EU 2030	pyrolysis
ICEV	low (hybrid yarn 5 %, preforming 5 %, organo sheet 20 %)	DE/EU	mechanical
		EU 2030	pyrolysis
	high (hybrid yarn 10 %, preforming 10 %, organo sheet 40 %)	DE/EU	mechanical
		EU 2030	pyrolysis

and material provision) were represented using database datasets, prioritising those representative of Germany; where unavailable, European and then global datasets were applied. For the EU-2030 electricity scenario, European average datasets were used preferentially for all secondary database processes to maintain consistency with the regional scenario definition, noting that these datasets do not reflect future 2030 scenarios. The complete inventories, including process descriptions, quantified process flows, dataset selections, and underlying process assumptions (e.g., dataset proxies or estimated recycling shares), are reported in the Supplementary Information (SI), [Table S1–S11](#). Subsequently, the key inventory choices for each life-cycle stage are summarized.

2.2.1. Raw material extraction LCI

The raw material supply inventories for the aluminium reference CCB and the MM4R CCB are reported in [SI Tables S1 and S2](#), respectively. These are based on MM4R-provided primary mass and composition data and include the additional inputs required to balance process-dependent production cuttings generated during manufacturing. Fixed cutting-rate estimates were applied to aluminium and steel sheet parts, whereas composite semi-finished products in the MM4R design were modelled using MM4R-provided minimum–maximum scrap ranges that reflect early-stage product development variability.

In terms of material composition, the reference CCB is dominated by aluminium sheet (~95 %) with local steel sheet reinforcements (~5 %). To reflect subsequent forming routes, the LCI virgin aluminium inputs were differentiated by intended processing, i.e., into aluminium sheet (deep drawing) and aluminium ingot (extrusion and die casting).

The MM4R CCB design replaces a substantial share of the metal content with GFRP (PP/GF) composites (~40 %), while the remaining parts that cannot be substituted are aluminium sheet (~55 %) and steel sheet (~5 %). Composite constituent ratios were parametrized explicitly in the LCI on a mass basis (wt%): hybrid yarn and organo sheet were estimated to contain ~30 % PP and ~70 % GF, whereas the moulding granulate was assumed to contain ~70 % PP and ~30 % GF. For moulding granulate, only ~21 % of PP and ~25 % of GF were considered as virgin inputs in the raw material supply LCI; the remaining share originates from internally recovered organo sheet and hollow-profile production cuttings as well as injection-moulding regrind and is therefore accounted for in the production inventory rather than as primary material supply. Notably, as no direct dataset for GFRP organo sheet production was available, a CFRP organo sheet proxy dataset was recalculated by substituting CF with GF, accounting for the resulting density change while maintaining a constant fiber volume fraction and total mass. The recalculation is documented in [SI Table S3](#) and

referenced in [SI Table S2](#).

2.2.2. Production phase LCI

The manufacturing inventories are reported in [SI Table S4](#) (reference CCB) and [SI Table S5](#) (MM4R CCB). Compared with the metal reference, the MM4R CCB requires a more complex, multi-step manufacturing process as composite semi-finished products are produced and subsequently integrated into a single hybrid module. Accordingly, the production LCI for the MM4R CCB includes the composite-specific chain and its integration steps, detailing all dataset selections and assumptions in the SI. In the MM4R production process, a PP/GF hollow profile, organo sheets, and injection-moulding granulate are combined in an integrated press-and-injection moulding step: pre-heated organo sheets and the hollow profile are placed in the tool, the organo sheets are pressed to shape, and then both components are overmoulded using injection moulding. The hollow profile is manufactured from side-by-side PP/GF hybrid yarn by braiding sleeves, stacking them on a core to form a preform, and consolidating under variothermal processing (i.e., cyclic heating and cooling of the tool to melt and re-solidify the PP matrix under pressure [56,57]); while aluminium sheet inserts are laser-structured prior to joining to enable mechanical connection without additional bonding agents. In parallel, organo sheets are produced by stacking and pressing PP/GF textile layers, followed by stamping, where cutting scrap is collected for moulding-granulate preparation. Key foreground operations (braiding, preforming, laser structuring, variothermal consolidation, granulate preparation, and injection moulding) were parameterised using primary project data, whereas remaining steps for both variants were modelled using secondary datasets and literature-based assumptions (including hybrid-yarn and organo sheet production, recycled PP supply, and upstream/auxiliary processes).

Two LCI assumptions are particularly relevant for transparency: (i) hybrid yarn manufacturing could not be modelled as a unit-process with explicit primary or secondary energy and material data due to data gaps; instead, the environmental impact was approximated by subtracting the impacts of two secondary datasets (“glass fiber, direct rovings” and “glass fiber, assembled rovings” from the Sphera database), thereby representing the additional processing required to merge fibers in hybrid yarn production; (ii) in-process scrap recovery is explicitly included: cuttings from organo sheet and hollow-profile production are milled and directly reused in moulding granulate production, alongside purchased recycled PP and injection-moulding regrind. The resulting recycling burdens and substitution credits for avoided virgin PP/GF inputs are handled consistently with the 50:50 shared-responsibility allocation, as stated in the goal and scope.

2.2.3. Use phase LCI

The use-phase inventories were derived using the LightImpact approach previously developed and applied to the same MM4R CCB case study, quantifying mass-induced changes in fuel or electricity demand under the WLTP driving cycle via energy reduction values (ERVs). In line with the component-level FU, total vehicle operation is not modelled; instead, the ERV-based model is used to attribute the incremental, mass-induced WTW energy demand to the respective CCB design and scale it to lifetime mileage. The LightImpact study documents and justifies the full set of case-specific, user-definable model inputs, including standardized constants, vehicle- and component-specific parameters, and WLTP-dependent variables. In the present study, this published and documented approach for the MM4R case study is adopted as a modular use-phase sub-model within the cradle-to-grave assessment to ensure robust state-of-the-art ERV derivation [1].

The LightImpact inventories are implemented within the SI as (i) region-specific WTT fuel/electricity provision datasets and (ii) TTW operation processes. For the ICEV configuration, TTW emissions are represented by a customized combustion process parameterised with literature-average exhaust emission factors, whereas for the BEV

configuration, TTW exhaust emissions are set to zero, consistent with [SI Tables S6–S9](#). Separate inventories are provided for the reference and MM4R CCB under ICEV and BEV configurations, as well as for the defined regional electricity/fuel scenarios (DE/EU and EU 2030 for electricity). A key case-study assumption documented in *LightImpact* concerns the BEV representation: as no Porsche 911 Carrera (Type 992) BEV model exists, a Porsche Taycan (Type J1) proxy is used for model calibration [1].

2.2.4. EoL LCI

The EoL inventories are reported in [SI Table S10](#) (reference CCB) and [SI Table S11](#) (MM4R CCB). In both cases, dismantling is assumed to be manual with negligible energy and material demand, yielding separated material streams (aluminium and steel for the reference CCB; aluminium, steel, and PP/GF composite for the MM4R CCB). This assumption is consistent with standard automotive EoL treatment practice, in which manual component removal constitutes a preliminary step prior to shredding in accordance with ISO 22628, and where the environmental burden of the EoL stage is governed by downstream material reprocessing rather than the dismantling operation itself [58, 59]. The assumption is further substantiated by the recyclability-oriented design of the MM4R CCB, which avoids adhesive bonding and utilises laser-structured joining surfaces to facilitate non-destructive material separation without the need for specialised tooling or significant energy input. In addition, production cuttings that are not recovered during manufacturing and are sent for EoL treatment are included in the EoL inventories. All recycling processes and routes are represented using secondary datasets (i.e., PP and aluminium recycling) and, where required, literature-based modelling (including EAF-based steel recycling, composite mechanical recycling, and composite pyrolysis), as documented in the SI. The environmental burdens of EoL recycling and the substitution credits for avoiding primary material production are consistently modelled using the 50:50 allocation approach, i.e., recycling-related impacts and benefits are shared equally between the supplying and receiving life cycles.

For the MM4R composite material stream, the inventory differentiates between mechanical recycling and pyrolysis, documenting specific assumptions for each process. Mechanical recycling is characterised by electricity demand for the input process and a two-fraction output structure, consisting of fiber-rich and resin-rich components [49,60]. Therefore, this process includes credits for avoided production of virgin composites and avoided production of talc, as detailed in [SI Table S11](#). Pyrolysis is modelled using average energy demands from literature for pre-treatment and the process itself, yielding an output composition of 64.25 % solid, 28.41 % oil, and 7.33 % pyrolysis gas [61,62]. The oil and gas fractions receive substitution credits for crude oil and natural gas, respectively, while the solid product is credited as a replacement for virgin glass-fiber production.

3. Results

The LCIA was conducted for the aluminium reference and MM4R CCB variants within the defined study scope, and based on the compiled LCIs and the scenarios defined in [Table 1](#). The LCI was modelled and the LCIA was carried out using LCA for Experts and the integrated CML midpoint characterisation method, evaluating all 11 CML midpoint categories to fully cover the impact categories deemed relevant to the study's scope. The results for all life cycle stages (raw material extraction, production, use phase, and EoL) are first summarized across each impact category to identify life-cycle stage hotspots and evaluate the robustness of the findings under varying scenarios. A more detailed analysis is then presented for GWP, as it is the most frequently reported impact category in automotive lightweight LCA studies, relevant for climate-related product development targets, and strongly influenced by factors such as material substitution, energy-intensive processing, use-phase energy demand, and EoL credits [2,13,14]. Finally, the

comparative performance of the MM4R CCB is evaluated against the reference CCB by analyzing the percentage improvements in best- and worst-case LCIA outcomes. This evaluation aims to highlight the impact categories that consistently show improvements, as well as those that reveal trade-offs or do not demonstrate any relative improvement when compared to the reference CCB.

3.1. LCIA outcomes across impact categories and best-worst case scenarios

[Fig. 5](#) presents the cradle-to-grave LCIA results for both CCB variants, with separate graphs for each of the 11 impact categories. For each impact category, results are presented for four modelling configurations, namely the MM4R CCB and the aluminium reference CCB under ICEV and BEV drivetrain assumptions. To maintain readability, only the best-case and worst-case results for each configuration are derived from the scenario combinations defined in [Table 1](#). These scenarios vary background energy and material supply (regional dataset assumptions), composite scrap rates, and the composite EoL recycling route. Consequently, each impact-category graph displays eight scenario groups (MM4R–ICEV, MM4R–BEV, reference–ICEV, reference–BEV; each as a best- and worst-case scenario). Presenting all scenario results for each configuration would yield 32 plotted outcomes per impact category; therefore, solely the numerical values from the LCIA are provided in the additional SI CCB LCIA results file.

Notably, best- and worst-case results are determined separately for each impact category by screening the results of all scenario combinations for a given configuration and identifying the minimum and maximum cradle-to-grave totals. As the influence of background energy/material supply datasets, composite cuttings, and the composite EoL route differs across impact categories, the scenario combination yielding the minimum or maximum result is not necessarily consistent across categories. For the majority of impact categories, best-case outcomes are obtained under the EU-2030 electricity mix combined with low cuttings and mechanical recycling. While low cuttings consistently yield the lowest impact results as reduced scrap lowers the associated raw material processing burden, the best-case scenario is not universal across specific energy/material background processes or recycling routes. For example, for most impact categories in the MM4R CCB BEV configuration, the best-case result is obtained under the EU-2030 electricity mix with mechanical recycling and low cuttings; however, for AP the best-case result for the same configuration occurs under the current DE/EU electricity mix with low cuttings and mechanical recycling, whereas for ADP_{elements} the best case occurs under the EU-2030 electricity mix with low cuttings and pyrolysis. Accordingly, best and worst cases should be interpreted as the minimum and maximum results within the modelled scenario space for each impact category, rather than as a single scenario that is uniformly best or worst across all impact categories.

To support interpretation of these results, [Fig. 5](#) visualises the results in a consistent, life-cycle-stage-resolved format across all impact categories. Raw material extraction, production, and EoL are reported as discrete stage contributions (each shown as best- and worst-case values), whereas the use phase is displayed as a cumulative, mileage-dependent contribution. This representation enables direct identification of the life cycle stages that drive the total impact and clarifies how scenario-dependent differences evolve over the component lifetime. At 0 km, the plotted totals therefore reflect only the non-use stages, meaning that any differences between the MM4R and reference CCB at the start of life arise from upstream processes (raw material supply and component manufacturing) and capture the effects of material substitution, manufacturing requirements, and the corresponding composite cuttings and background dataset assumptions. At the end of life (200,000 km), the graphs additionally incorporate the EoL stage as a net contribution, including recycling burdens and substitution credits, such that the final values represent the complete cradle-to-grave totals under the

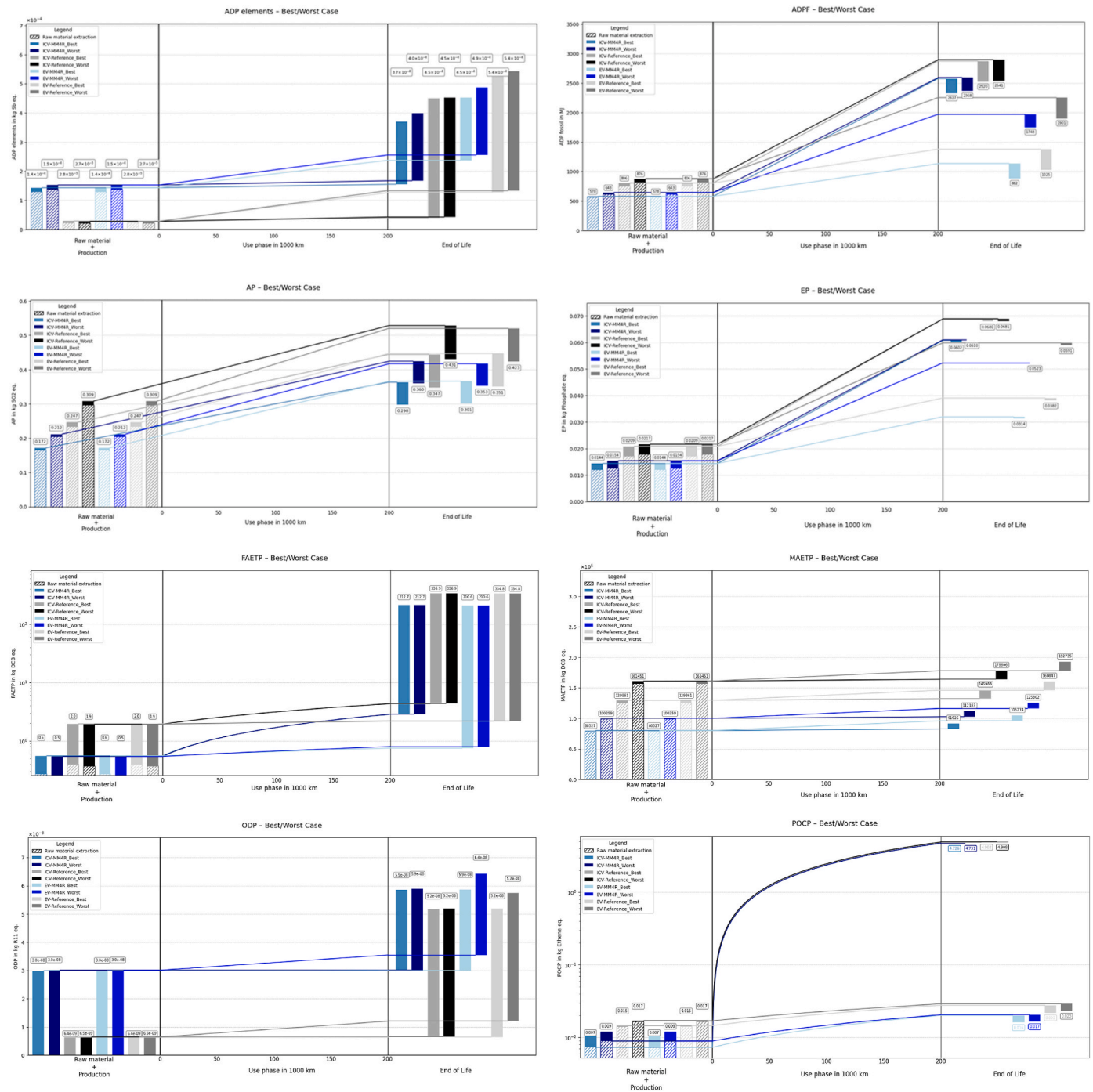


Fig. 5. Cradle-to-grave LCIA results for MM4R and aluminium reference CCBs (ICEV/BEV; best-worst scenarios).

respective best- and worst-case scenarios.

Taken together, the stage-resolved results indicate that the dominant life-cycle stage depends on the impact category and drivetrain configuration. For ICEV (as the current status quo implementation), the use phase represents the largest contribution in 6/11 impact categories for the reference CCB (GWP, POCP, ODP, EP, ADP_{fossil} , Terrestrial Ecotoxicity Potential (TETP)) and in 6/11 categories for the MM4R CCB (GWP, POCP, AP, EP, ADP_{fossil} , TETP). Conversely, for both variants, upstream stages dominate HTP and Marine Aquatic Ecotoxicity Potential (MAETP) (as well as ODP for the MM4R CCB and AP for the reference CCB, both applied in the ICEV configuration), whereas EoL constitutes the largest contribution for $ADP_{elements}$ and Freshwater Aquatic Ecotoxicity

Potential (FAETP). In the BEV configuration, the dominant life-cycle stage shifts away from the use phase, and upstream and EoL contributions become comparatively more influential. Under the current DE/EU electricity-mix assumption, the use phase constitutes the largest contribution in 4/11 categories for the reference CCB (GWP, EP, ADP_{fossil} , TETP) and in 6/11 categories for the MM4R CCB (GWP, POCP, AP, EP, ADP_{fossil} , TETP), while EoL remains the largest contribution for $ADP_{elements}$ and FAETP in both variants. When applying the EU-2030 electricity mix, the use phase becomes non-dominant for the reference CCB (0/11) and remains dominant only for EP, POCP, and TETP for the MM4R CCB (3/11), while upstream stages govern the remaining categories, and EoL dominates $ADP_{elements}$ and FAETP (as well as ODP for the

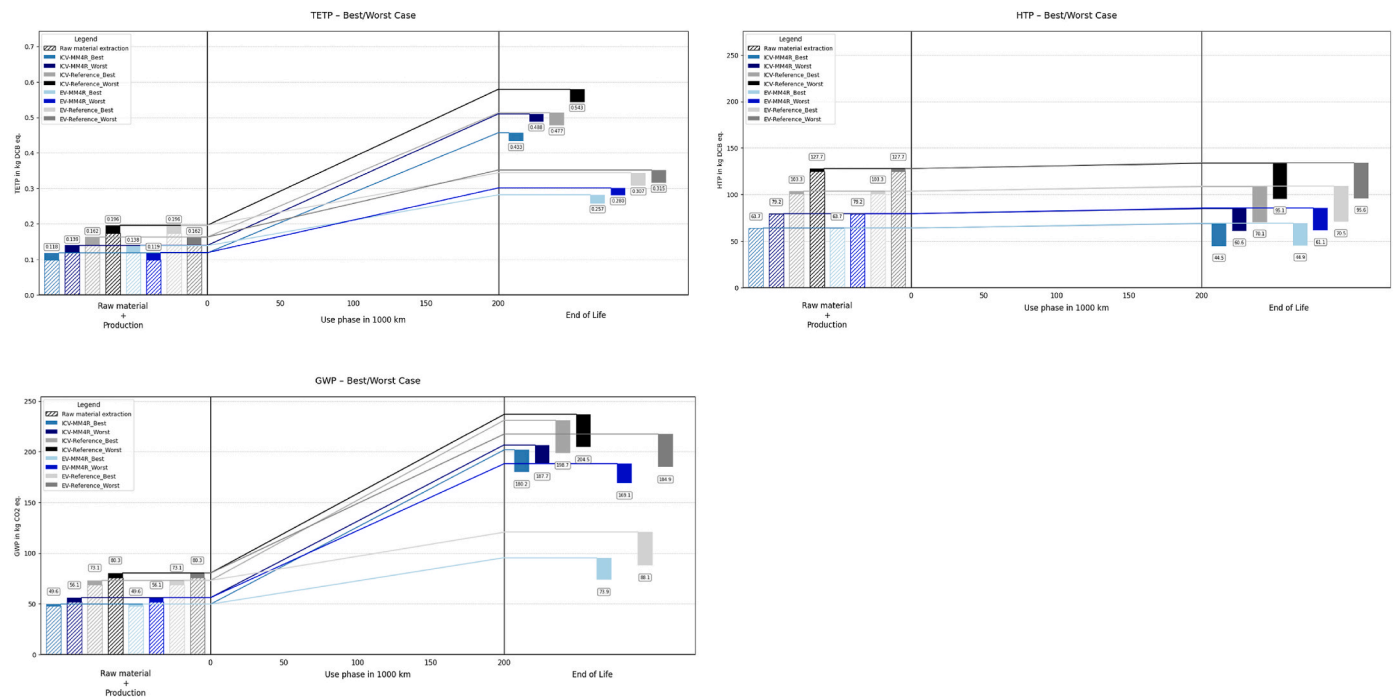


Fig. 5. (continued).

reference CCB).

Furthermore, for 7/11 categories (GWP, POCP, AP, EP, ADP_{fossil}, TETP, HTP), the EoL stage yields net negative contributions due to substitution credits; however, the magnitude of these credits varies between variants, reflecting the composite MM4R design and route-specific composite recycling scenarios (mechanical recycling versus pyrolysis). Consequently, recycling credits do not uniformly reduce cradle-to-grave totals; for ADP_{elements} and FAETP, the EoL stage can become a decisive driver of the final result.

On this basis, the EoL totals in each impact category graph establish the overall comparative ranking across all best- and worst-case scenarios and configurations. Considering both drivetrain configurations, the MM4R CCB design exhibits lower cradle-to-grave totals than the aluminium reference CCB in 10 of the 11 impact categories. ODP constitutes the sole exception and remains higher for the MM4R variant in both ICEV and BEV applications, across both best- and worst-case outcomes. The life-cycle stage-resolved representation further clarifies whether the observed differences are already established at the start of life or emerge over subsequent life-cycle stages. At 0 km use, the MM4R CCB exhibits lower upstream impacts than the reference CCB in 9 of the 11 midpoint categories. ADP_{elements} and ODP are the exceptions, with higher upstream impacts for the MM4R CCB. Over the full cradle-to-grave life cycle, including use phase and EoL, the comparative ranking changes for ADP_{elements}. Although higher at 0 km, the MM4R CCB yields lower cradle-to-grave ADP_{elements} totals than the reference CCB in both drivetrain configurations. In contrast, ODP shows no reversal and remains higher for the MM4R CCB at the EoL.

The best–worst ranges additionally show where the comparative ranking is robust within the modelled scenario space. For ADP_{elements}, FAETP, HTP, MAETP, and POCP, the MM4R CCB worst-case scenarios remain lower impacts compared to the reference CCB best-case scenarios in both drivetrains. In contrast, for GWP, ADP_{fossil}, AP, EP, and TETP (and for ODP, where the MM4R CCB shows higher impacts), the MM4R and reference best–worst ranges overlap in at least one drivetrain configuration, indicating higher sensitivity to scenario assumptions. The magnitude of scenario sensitivity is also impact category- and drivetrain-dependent and is most pronounced in the BEV configuration for electricity-sensitive impact categories, particularly GWP and ADP_{fossil}.

For example, in the BEV implementation, GWP spans ~74–169 kg CO₂-eq for MM4R CCB and ~88–185 kg CO₂-eq for the reference CCB, whereas some impact categories show only minor variation between best and worst cases (best ≈ worst), such as FAETP considering both CCB variants and EP in the ICEV configuration for the reference CCB.

This pattern is mirrored in the ICEV–BEV contrast, which varies widely across impact categories. POCP shows the clearest separation (ICEV totals ~ 4.7–4.9 kg ethene eq versus BEV totals ~ 0.016–0.023 kg ethene eq), and a clear drivetrain effect is also visible in GWP and ADP_{fossil}. By comparison, for toxicity/ecotoxicity impact categories (HTP, FAETP, MAETP), the ICEV and BEV totals are of similar magnitude, indicating a comparatively weak sensitivity to drivetrain choice within the modelled scenario space.

Ultimately, the mileage-dependent use-phase graphs indicate whether a crossover occurs, i.e., whether cumulative use-phase effects offset initial upstream differences. Over the evaluated lifetime range, crossovers are not a dominant feature of the results; instead, increasing mileage mainly changes the magnitude of the difference between variants, depending on impact category and drivetrain configuration.

3.2. GWP hotspot analysis

Building on the multi-impact category comparison, a detailed hotspot analysis is presented for GWP by resolving contributions at the unit-process level within the specified life cycle stages. GWP is widely applied in automotive lightweight LCAs and represents one of the most interpretable impact categories for stakeholders and decision-makers [2,63, 64]. Importantly, this focused analysis is not intended to narrow the assessment to climate change alone: hotspots were screened across all midpoint categories, and the drivers identified for GWP are largely consistent with those observed for the other impact categories, with few deviations documented subsequently.

In this context, Fig. 5 serves as the starting point for subsequent analysis, illustrating the best- and worst-case cradle-to-grave totals for both CCB variants and drivetrain configurations, including contributions from the raw material supply, component manufacturing, use phase, and EoL treatment. Under the present energy-supply assumptions (i.e., excluding the EU-2030 electricity-mix scenario), the use phase is

the dominant positive contributor to GWP for both the ICEV and the BEV CCB applications. Raw material extraction represents the second-largest positive contribution, underscoring the relevance of upstream material provision. By comparison, the production stage accounts for a smaller share of total GWP for both designs, despite the increased process complexity associated with the MM4R concept. Finally, the EoL stage constitutes a net negative contribution to GWP because recycling generates substitution credits for avoided primary material production, thereby lowering the cradle-to-grave totals relative to the end-of-use values.

Given that EoL yields net GWP credits and that use-phase burdens are driven primarily by the drivetrain-specific energy-conversion context and mass-related energy demand in combination with the assumed background energy supply - factors that are largely external to component-level engineering measures or are technically constrained (e.g., lightweight design) - the hotspot analysis focuses on upstream stages. Accordingly, Fig. 6 disaggregates the raw material extraction and production phases and reports unit-process contributions for the best-case MM4R CCB in the ICEV configuration as a representative reference scenario. This case is selected as an illustrative reference as the rank order of dominant unit processes in raw material extraction and production remains proportionally consistent across the modelled scenarios and configurations, while absolute magnitudes vary with altering background datasets, cuttings, and the composite EoL route.

Within the raw material supply stage of the MM4R CCB (ICEV application and best-case scenario), Fig. 6 (bottom) indicates that GWP is clearly dominated by aluminium-related processes. The largest single contributor is residual CCB aluminium sheet (40.6 kg CO₂-eq), representing the aluminium mass that remains non-substitutable by the composite design and encompasses aluminium supply for deep drawing as well as aluminium ingot used for extrusion. All remaining raw material contributions are comparatively small:

- additional aluminium sheet (laser-structured parts): 2.3 kg CO₂-eq;
- hybrid yarn: 2.0 kg CO₂-eq;
- moulding granulate: 1.3 kg CO₂-eq;
- steel sheet: 1.0 kg CO₂-eq; and
- organo sheet: 0.5 kg CO₂-eq.

Thus, the raw material GWP profile is primarily shaped by the remaining aluminium content and associated upstream supply burdens despite the composite-based substitution in the MM4R redesign. Notably, the same GWP raw-material hotspot structure largely holds across the other impact categories: additional aluminium sheet is also the dominant contributor in all categories except ADP_{elements}. For ADP_{elements}, the hotspot shifts to the composite constituents:

- hybrid yarn: 66.3 mg Sb-eq;
- moulding granulate: 30.0 mg Sb-eq;
- organo sheet: 19.0 mg Sb-eq; and
- additional aluminium sheet: 13.0 mg Sb-eq.

This cross-category consistency supports using GWP as the reference impact category for interpreting upstream hotspots.

In the production stage, Fig. 6 (top) shows a more distributed contribution pattern across an increased number of processing unit processes, while the overall magnitude of impacts remains small relative to the raw materials extraction stage (<1 kg CO₂-eq per unit process). The largest production-stage GWP contributors are hybrid-yarn-related processing (0.67 kg CO₂-eq), consolidation (0.43 kg CO₂-eq), additional aluminium sheet-related processing (0.42 kg CO₂-eq), and injection moulding (0.33 kg CO₂-eq). Other finishing and joining operations (e.g., laser structuring) contribute only marginally. Fig. 6 (top) further indicates negative contributions (credits) within the production balance, attributable to internal recycling and reuse within the production system (e.g., credits associated with moulding-granulate recovery and related recycling steps), which partially offset the positive production burdens in the best-case scenario.

Yet, unlike the raw-material extraction stage, the production-stage hotspot ranking is less uniform across impact categories. Hybrid-yarn processing dominates GWP, ADP (elements and fossil), and ODP; additional aluminium sheet-related operations dominate AP, POCP, and TETP; and recycling of PP dominates EP and the toxicity-related impact categories (HTP, FAETP, MAETP). Still, GWP remains a useful representative metric here, as the largest process contributors (hybrid yarn and aluminium-related operations) recur across the majority of impact categories (7/11), with hybrid yarn processing specifically being the most frequently identified production hotspot.

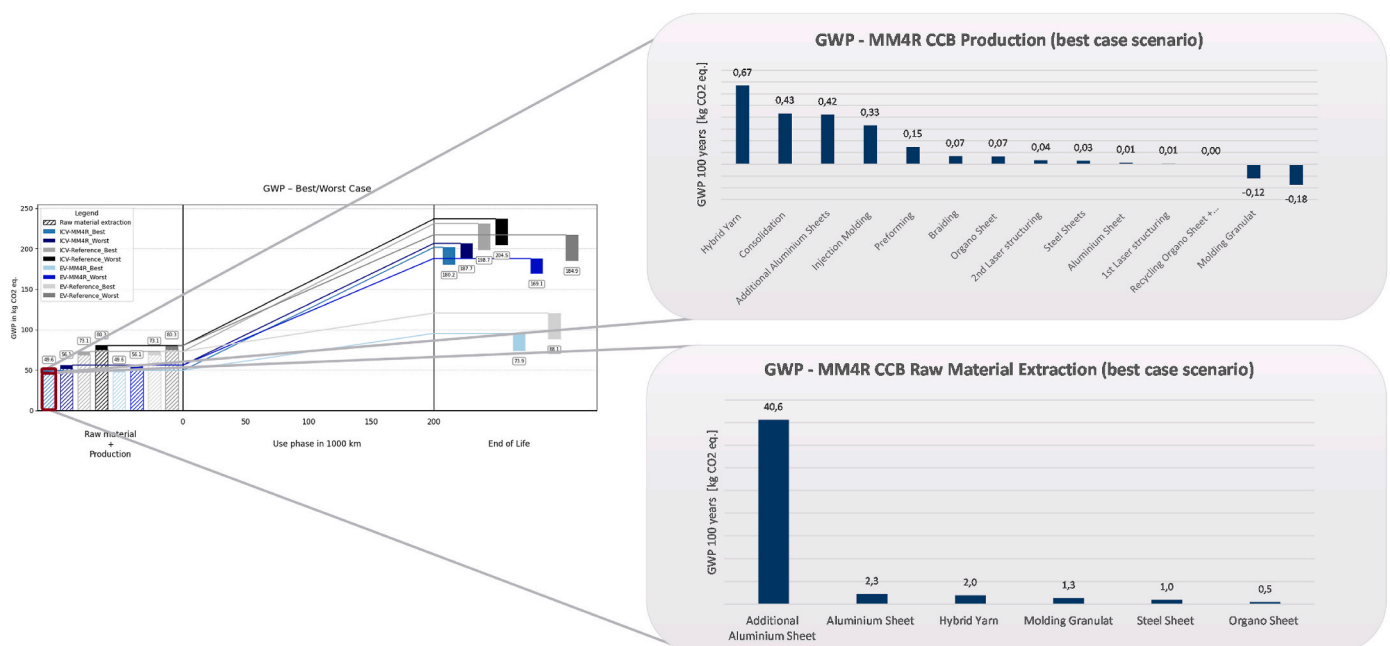


Fig. 6. GWP hotspot analysis.

Taken together, the hotspot results in Fig. 6 confirm that upstream GWP for the MM4R CCB is primarily governed by raw material supply, particularly aluminium-related inputs, whereas the production stage contributes a smaller, multi-process contribution, shaped by composite semi-finished processing and module-integration steps. Combined with the life cycle stage-resolved cradle-to-grave patterns in Fig. 5 - where the ICEV use phase constitutes the largest positive contribution and EoL substitution credits reduce net totals - this unit-process hotspot breakdown provides a transparent basis for identifying the upstream levers that most strongly influence overall results across the modelled scenario space.

3.3. Relative MM4R vs. reference CCB performance and trade-offs

To complement the upstream hotspot screening and its cross-category insights, the analysis is subsequently extended to the relative environmental performance of the MM4R CCB compared with the aluminium reference design. Using the cradle-to-grave totals in Fig. 5, the results are converted into percentage differences. For each impact category and for both the MM4R and reference CCB designs, the full scenario set was screened (background energy supply, composite cuttings, and composite EoL pathway, evaluated under ICEV and BEV drivetrain assumptions), retaining the minimum and maximum cradle-to-grave totals as the design-specific best-case and worst-case outcomes. Fig. 7 reports the resulting relative change of MM4R compared to the reference for (i) best-case vs. best-case and (ii) worst-case vs. worst-case, calculated as:

$$\Delta [\%] = \frac{EI_{\text{reference}} - EI_{\text{MM4R}}}{EI_{\text{reference}}} \times 100,$$

where $EI_{\text{reference}}$ denotes the environmental impact of the reference CCB and EI_{MM4R} the corresponding impact of the MM4R CCB. Positive values, therefore, indicate lower impacts of the MM4R CCB redesign relative to the reference, whereas negative values indicate higher impacts (i.e., trade-offs).

Across the full CML midpoint set, Fig. 7 shows that the MM4R CCB implementation achieves impact reductions in 10 of 11 categories in both the best-case and worst-case comparisons. The only systematic

trade-off is ODP, for which the MM4R CCB-related impacts remain higher than the reference CCB in both comparisons ($\sim -13\%$ in the best-case and $\sim -12\%$ in the worst-case comparison). For all remaining impact categories, the magnitude of improvement varies by category and by the best-versus-worst-case framing. The largest and comparatively most robust relative reductions are observed for the toxicity-related impact categories. Specifically, FAETP improves by $\sim 37\%$ in both comparisons, HTP by $\sim 37\%$ and $\sim 36\%$, and MAETP by $\sim 38\%$ and $\sim 35\%$.

For the remaining impact categories, MM4R improvements are more moderate and, in several cases, more sensitive to the underlying scenario framing. GWP improves by $\sim 16\%$ in the best-case comparison and $\sim 8\%$ in the worst-case comparison, ADP_{fossil} decreases by $\sim 14\%$ (best-case) and $\sim 7\%$ (worst-case), while ADP_{elements} decreases by $\sim 18\%$ and $\sim 10\%$. EP declines by $\sim 18\%$ (best-case) and $\sim 10\%$ (worst-case), and TETP decreases by $\sim 16\%$ and $\sim 10\%$. For AP, the reduction is of similar magnitude in both comparisons ($\sim 14\%$ best-case and $\sim 17\%$ worst-case). POCP exhibits the most pronounced divergence between the two comparisons, improving by $\sim 27\%$ in the best-case comparison but only by $\sim 4\%$ in the worst-case comparison.

Overall, Fig. 7 therefore provides a compact cross-category summary of (i) impact categories in which the MM4R redesign delivers consistently lower impacts than the reference across the modelled scenario space and (ii) categories for which the relative improvement is more contingent on best-versus worst-case conditions. The only impact category showing a consistent trade-off is ODP, while all other impact categories remain favourable for the MM4R CCB design under both comparison scenarios.

4. Interpretation and discussion

The following discussion first interprets the LCIA results by analysing impact-category patterns, life-cycle-stage and unit-process hotspots, and subsequently positions these findings against the existing body of composite-metal LCA literature. Engineering implications for composite lightweight design are then derived, followed by a critical assessment of key limitations and methodological priorities for future research.

4.1. Interpretation of LCIA results

The cradle-to-grave LCIA results confirm that the MM4R CCB redesign yields net multi-category environmental improvements relative to the aluminium reference CCB, while also revealing non-negligible trade-offs and scenario sensitivities that become evident when impact categories beyond GWP are systematically assessed. Within the considered impact-category set and across the screened scenario space, the MM4R variant attains lower cradle-to-grave totals than the reference CCB in 10 of 11 impact categories for both ICEV and BEV applications when the best-case MM4R scenario is compared with the best-case reference scenario and the worst-case MM4R scenario with the worst-case reference scenario. The only systematic trade-off occurs for ODP, where MM4R CCB impacts remain approximately 12–13 % higher than those of the reference CCB in both best-case and worst-case comparisons. However, this performance is not uniformly robust: in a conservative comparison of MM4R CCB worst-case scenario against reference CCB best-case scenario, clear improvements persist only for a subset of impact categories, notably FAETP, HTP, and MAETP, whereas several other categories exhibit small or even reversed differences. Taken together, these findings indicate that the MM4R CCB redesign achieves an overall environmental improvement under consistent and realistic scenario assumptions, but that its interpretation as a “next-generation” lightweight solution must explicitly acknowledge the sensitivity of several impact categories to scenario choices and model uncertainty.

This pattern of results frames the subsequent hotspot analysis and clarifies the role of life cycle stages and individual processes in driving the observed trade-offs.

Improvements of MM4R CCB compared to Reference CCB

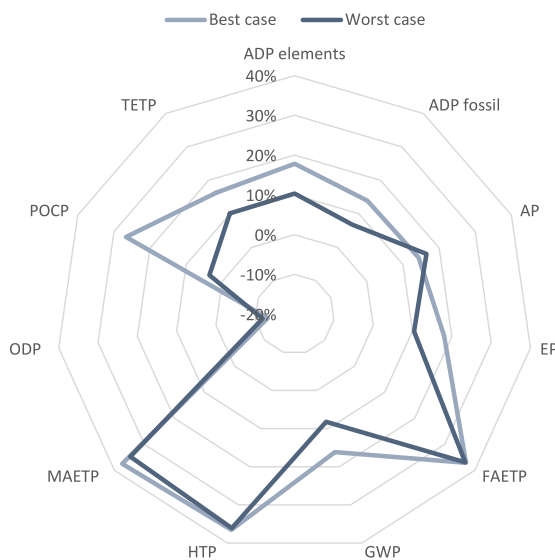


Fig. 7. Relative environmental performance of MM4R vs. reference CCB across the 11 impact categories, with best- and worst-case scenarios screened per category from Table 1 (positive values: improvement; negative values: trade-off).

The ODP trade-off, in particular, is largely governed by composite-specific upstream manufacturing processes. Hybrid-yarn manufacturing is identified as the main contributor to MM4R ODP under the current proxy-based inventory, and the associated burdens are not compensated by mass-induced use-phase savings or end-of-life credits. Specifically, the ODP burden traces to halogenated compounds in the background datasets of the textile-processing proxy, as no additional material or energy inputs are modelled at the foreground level. As this process is represented by a subtractive proxy derived from two aggregated background datasets (assembled vs. direct rovings) rather than primary unit-process data, the resulting ODP estimate is plausibly influenced by inventory representativeness. While the present study does not quantify this sensitivity, recent assessments of composite LCI data quality have documented that proxy-derived and aggregated flows for GF constituents vary substantially across databases, particularly when transparency of the underlying data is limited, or proxies are used in place of primary data [65,66]. Accordingly, the observed ODP trade-off should be interpreted with caution and treated as a signal for targeted primary data collection on hybrid-yarn manufacturing rather than as evidence of an inherent ODP hotspot of thermoplastic GFRP structures. This interpretation points to specific modelling improvements and mitigation options, including the development of primary-energy and auxiliary-material inventories for hybrid-yarn production, optimising hybrid-yarn processing at an industrial scale, and using electricity mixes and suppliers with lower ODP profiles.

Beyond the aggregated cradle-to-grave comparison, the life-cycle-stage-resolved analysis highlights that most impact categories are influenced by a combination of raw-material extraction processes and use-phase contributions, with the relative importance of each stage depending strongly on drivetrain configuration and specific unit-process. For ICEV applications, the use phase is the dominant contributor to GWP and most other impact categories, consistent with established automotive LCA literature, which shows that vehicle operation can account for up to 91 % of the GWP [1]. In this study, mass-induced fuel savings due to the lighter MM4R CCB design amplify upstream advantages so that the GWP difference between the CCB designs grows over mileage. When the CCB is implemented in a BEV, use-phase contributions decline for most impact categories. This reduction is particularly pronounced under the EU-2030 electricity mix for electricity-sensitive categories such as GWP, ADP_{fossil} , and EP. The corresponding key magnitudes are summarized in Table 2. At the same time, some impact categories (e.g., TETP, POCP) show lower BEV use-phase burdens, whereas others (e.g., ADP and ODP) can exhibit higher BEV use-phase contributions under current grid mixes, reflecting trade-offs in upstream renewable electricity generation in those impact categories.

As the relative influence of the use phase diminishes in BEV and renewable electricity scenarios across most impact categories, upstream and EoL stages become more prominent in determining comparative performance. Within this study, the unit-process hotspot analysis reveals that raw-material extraction, rather than production, governs the upstream impacts of both CCB designs. Despite the substitution of roughly 40 % of the original aluminium mass by GFRP composites, the raw-material impacts of the MM4R CCB remain dominated by the residual

aluminium inputs, whose environmental burden stems primarily from electricity demand for Hall–Héroult electrolysis and direct CO₂ from carbon anode consumption [67]. In the best-case MM4R ICEV scenario, non-substitutable aluminium sheet and ingot supply contribute about ~40 kg CO₂-eq, whereas the next-largest raw-material composite contributions (hybrid yarn, moulding granulate, organo sheet) each remain at or below approximately ~2 kg CO₂-eq. This pattern is broadly consistent across most impact categories, with aluminium supply dominating all midpoint categories except $ADP_{elements}$; for $ADP_{elements}$, the hotspot shifts to fiber-containing composite constituents (hybrid yarn, moulding granulate, organo sheet), reflecting the mineral resource inputs embedded in glass fiber production rather than associated energy demand, given that electricity-only production processes contribute orders of magnitude less to $ADP_{elements}$ than the glass fiber datasets themselves. Similarly, for the toxicity-related categories (HTP, MAETP, FAETP), the aluminium dominance is attributable to heavy metal emissions to air and water along the primary aluminium production chain [67]. This indicates that environmental improvements in composite CCB redesign are most effectively achieved by reducing residual aluminium mass where functionally permissible, increasing recycled content, shifting to lower-impact aluminium supply chains, and minimising sheet and semi-finished scrap through process stabilisation and optimization.

In contrast to the strong influence of raw material supply, the production stage demonstrates that increased process complexity in the MM4R CCB manufacturing chain does not translate into proportionally higher burdens. For the MM4R design production-stage, GWP impacts remain in the order of <1 kg CO₂-eq, far below the upstream aluminium supply burden, with the largest contributions arising from hybrid-yarn-related processing, consolidation, additional aluminium-insert processing, and injection moulding. Two aspects of the MM4R CCB manufacturing process chain contribute to this outcome. First, the predominant burdens originate outside of the factory gate, including energy- and material-intensive background processes. Second, in process recovery and reuse of composite cuttings, especially the integration of organo sheet and hollow profile scrap into moulding granulate together with recycled PP and injection moulding regrind, partially offsets production burdens. These findings suggest that design-for-recycling measures implemented already in the production phase, such as closed-loop scrap recovery, are effective levers for improving the environmental performance of composite-intensive lightweight structures.

The EoL stage plays a dual role in shaping the comparative results. On the one hand, both designs benefit from high recycling rates of aluminium and steel, yielding substantial substitution credits for primary material production and reducing cradle-to-grave totals in several impact categories (7/11). On the other hand, for $ADP_{elements}$ and FAETP, EoL impacts become a decisive contributor in both designs, strongly influencing cradle-to-grave totals. For the MM4R design, this highlights the importance of explicitly modelling composite EoL rather than relying on simplified disposal assumptions used in previous studies. While the metal-rich reference CCB benefits from high recycling rates and established secondary markets, the EoL benefits of the MM4R design are dependent on the assumed composite recycling share and the credited substitution product, which differ between mechanical recycling and pyrolysis (e.g., substitution of virgin composites and talc in mechanical recycling, substitution of virgin GF, crude oil, and natural gas in pyrolysis). The observed reversal of $ADP_{elements}$, where MM4R shows higher upstream impacts but lower cradle-to-grave impacts than the reference component due to EoL credits, demonstrates how EoL credits for recycled fibers and matrix substitutes can change component performance for resource-depletion impacts. This underscores the importance of both recycling-ready design strategies (to ensure high-quality recycled outputs) and transparent allocation methods in composite EoL modelling.

Taken together, the cross-impact category hotspot screening further shows that some life cycle stage and specific process drivers are

Table 2
Quantitative summary of GWP-related comparisons.

Comparison	Configuration	GWP change
MM4R vs. aluminium reference, best-case	ICEV	~16 %
MM4R vs. aluminium reference, worst-case	ICEV	~8 %
ICEV vs. BEV use-phase contribution	Current DE/EU grid mix	~12 %
ICEV vs. BEV use-phase contribution	EU-2030 grid mix	~70 %

consistent across impact categories, whereas others are impact category-specific. Considering the MM4R CCB upstream raw material extraction stage, aluminium-related supply remains the dominant hotspot across many impact categories, while the composite manufacturing chain contributes smaller but more distributed burdens, and EoL credits can become decisive for resource as well as toxicity-related impact categories, depending on the recycling route.

4.2. Discussion

When the present findings are positioned against the existing body of LCA literature on composite-metal lightweight components, several recurring patterns and important divergences emerge. The overarching observation is that fiber-reinforced composites are not inherently environmentally preferable to metals. The LCA performance depends on the explicit product system, such as the composite material constituent, manufacturing route, magnitude of mass reduction, drivetrain configuration, and EoL treatment. Direct comparability across studies is further constrained by inconsistent methodological choices, including FUs spanning different component types and service lifetimes from 160,000 to 300,000 km, LCIA methods restricted to GWP and CED, and frequent omission of composite EoL recycling pathways [9,11–14,30]. Within this heterogeneous evidence base, CFRP-metal comparisons yield divergent conclusions. Several studies report higher cradle-to-grave impacts for CFRP, attributing this to the energy intensity of carbon-fiber production [11–13], while others find net environmental benefits where use-phase mass savings are sufficiently large [3,30]. For existing GFRP-metal comparisons, the literature evidence base is more limited but yields equally mixed results: Freire et al. (2025) report consistently higher midpoint impacts for GFRP, whereas Wegmann et al. (2022) find lower GWP and CED. However, both studies omit explicit EoL recycling modelling, constraining their direct comparability with the present cradle-to-grave results and highlighting a critical methodological gap [9,14]. Moreover, the divergence between these two studies illustrates that LCA goal and scope choices significantly influence LCA results.

Against this backdrop, the MM4R CCB case study advances the state of the art as the first comprehensive cradle-to-grave, multi-impact category benchmark between a conventional aluminium reference CCB and a recyclability-oriented thermoplastic GFRP multi-material CCB redesign. Key distinguishing features include WLTP-aligned use-phase energy modelling via LightImpact, explicit composite scrap variability, alternative composite EoL recycling routes (mechanical recycling and pyrolysis) under a transparent 50:50 allocation, and a broad CML midpoint set of 11 impact categories, directly addressing the methodological gaps identified in prior work.

Within this expanded scope, the MM4R CCB design achieves lower cradle-to-grave totals than the aluminium reference CCB for both ICEV and BEV configurations, demonstrating main hotspots in the raw material supply and use-phase life cycle stages. This outcome diverges from CFRP-focused studies that identify the composite production stage as a hotspot [3,9,11,12,30]. Considering the MM4R CCB, upstream impacts are primarily governed by residual aluminium supply, rather than by the composite material supply processes, which contribute substantially smaller burdens. Additionally, EoL credits prove decisive for resource- and toxicity-related impact categories, notably ADP_{elements}, FAETP, and MAETP, depending on the recycling route applied - an insight absent from studies that omit composite EoL modelling. Taken together, these results support the conclusion that recyclability-oriented thermoplastic GFRP hybrid architectures can constitute a credible next-generation lightweight solution at the component level, provided that residual aluminium-related hotspots, data gaps in composite processing (e.g., hybrid yarn and organo sheet production), and uncertainties in recycling pathways as well as secondary-material markets are resolved in future work.

For OEMs, component developers, and policymakers, these findings indicate that lightweight design is only robustly environmentally

sustainable when material substitution, manufacturing efficiency, and EoL circularity are jointly optimized. The highest-priority environmental levers for the MM4R CCB case study are:

- (i) further substitution of primary aluminium content or substitution toward secondary aluminium supply;
- (ii) systematic scrap minimization with closed in-process recovery loops;
- (iii) the establishment of scalable, quality-assured GFRP composite recycling pathways with viable secondary material markets.

These conditions become increasingly decisive as electrification and grid decarbonization shift environmental relevance away from the use phase toward upstream and EoL stages. Interpretation of the results should nonetheless remain conservative where proxy inventories, pre-serial production data, composite recycling model assumptions, BEV proxy parametrization, and EoL allocation sensitivity introduce unquantified uncertainty.

The present study provides the first comprehensive cradle-to-grave, multi-impact-category LCA comparing a recycling-ready thermoplastic GFRP composite CCB against a conventional aluminium reference CCB, supported by primary foreground data, explicit composite EoL recycling scenario modelling, and a broad set of impact categories. Nonetheless, several methodological as well as data-related limitations constrain the interpretation and generalisability of the reported findings and are discussed below alongside priorities for future research:

- LCI data quality. The foreground inventory combines detailed primary data with adapted secondary datasets and literature-based proxies for specific composite processes, including hybrid-yarn manufacturing, organo sheet production, and the mechanical recycling and pyrolysis routes at EoL. These approximations introduce further uncertainty into impact categories sensitive to fiber processing and thermochemical treatment, particularly ADP_{elements}, ODP, and the toxicity-related impact categories. The ODP trade-off is especially sensitive to the hybrid-yarn proxy, as the proxy relies on two conventional glass-fibre manufacturing datasets (assembled and direct rovings) that may not fully represent the upstream burdens specific to hybrid-yarn processing. Its magnitude may therefore change once primary industrial data and more mature process configurations become available. Acquiring primary or high-resolution secondary LCI data for these processes, therefore, constitutes a key priority for future research, as does validating the substitution assumptions for recycled composite outputs against realistic secondary-material markets.
- Composite CCB production representativeness. Although the manufacturing process had reached a pre-serial development stage and the foreground LCI data were scaled to series-production volumes based on project partner estimations to maintain comparability with the aluminium reference CCB, these scaled values remain approximations. While this approach provides a reasonable approximation, deviations between estimated and actual series-production conditions - particularly regarding energy efficiencies, scrap rates, and process strategies - cannot be excluded and could alter the relative importance of production-stage burdens and the effectiveness of internal scrap recovery. Similarly, the BEV configuration relies on a proxy vehicle (Porsche Taycan, Type 9J1) because no Porsche Carrera 911 (Type 992) BEV variant currently exists, introducing uncertainty in the ERV-based attribution of mass-induced use-phase impacts. The scenario analysis partially addresses these uncertainties by varying electricity mixes, composite scrap rates, and EoL recycling routes; however, a formal uncertainty analysis (e.g., Monte Carlo simulation) was beyond the scope of this study and would be needed to quantify the uncertainty ranges associated with the comparative conclusions.

- Methodological choices. The 50:50 EoL allocation is a transparent compromise between avoided-burden and cut-off approaches, well-suited to open-loop composite recycling where parameter uncertainty is high. Nevertheless, alternative schemes such as the 100:0 cut-off or the CFF could redistribute burdens and credits between life cycles and alter the outcomes in resource- and toxicity-related impact categories. Likewise, the CML midpoint LCIA characterisation method, while consistent with automotive LCA practice, does not capture impact categories such as water scarcity and land use, which are gaining relevance in regulatory contexts. Beyond their implications for the interpretation of the present results, these methodological choices also constrain direct comparability with the existing automotive composite vs. metal component LCA literature, in which heterogeneous FU definitions, assumed service lifetimes (160,000 – 300,000 km), LCIA method scope, and system boundary delineations introduce additional variability into cross-study comparisons.
- Generalisability. The findings are specific to the defined FU, vehicle platform, and scenario space. Whether the observed environmental advantages of the MM4R CCB extend to other components, vehicle architectures, or regulatory contexts depends on continued improvements in composite process data, recycling infrastructure, and secondary-material market development. In this regard, given that residual aluminium supply was identified as the dominant upstream hotspot, future assessments should also evaluate the effect of substituting primary aluminium with secondary (recycled) aluminium on the comparative life cycle results.

Finally, the present assessment addresses only the environmental dimension of sustainability. A comprehensive evaluation of whether recyclability-oriented composite automotive lightweight designs constitute a viable next-generation solution requires the integration of social and economic life cycle perspectives [2]. A prior social life cycle assessment (S-LCA) of the identical MM4R CCB case study indicates that the composite redesign also reduces social impacts relative to the aluminium reference [7]; accordingly, if no adverse trade-offs emerge in economic terms, the case for composite lightweight structures as a next-generation solution is further strengthened.

5. Conclusion

Despite growing interest in composite lightweight design for automotive applications, the question of whether fiber-reinforced composite components deliver net environmental benefits over their full life cycle has remained unresolved, constrained by incomplete EoL modelling and limited impact-category scope in prior work. This study addressed this gap, providing the first comprehensive cradle-to-grave LCA comparing a recycling-ready thermoplastic GFRP composite CCB against an aluminium reference CCB. The following key results emerge from the assessment:

- The composite redesign outperforms the conventional aluminium reference in 10 of 11 impact categories across ICEV and BEV drivetrain configurations.
- Improvements are most pronounced and robust for toxicity-related impact categories (~35–37 % reductions), while climate and energy-resource impact categories also improve consistently but are more scenario-contingent (e.g., GWP reductions of ~16 % in best-case and ~8 % in worst-case like-for-like comparisons).
- ODP constitutes the only consistent trade-off (~12–13 % increase), attributable to proxy-based hybrid-yarn inventory data rather than an intrinsic property of thermoplastic GFRP composites.
- In the MM4R CCB redesign, residual aluminium supply (~55 % of total mass) dominates upstream impacts across nearly all categories, indicating that in partial-substitution architectures the cradle-to-grave footprint is primarily governed by the magnitude and

composition of the residual high-impact metal fraction rather than the composite processing stage.

- In ICEV configurations, mass-induced fuel savings further intensify the upstream advantage of the composite design, while under BEV and low-carbon grid conditions, use-phase contributions diminish progressively and EoL recycling credits - for both metal and composite material streams - become essential, including reversing the MM4R design's upstream disadvantage in ADP_{elements}.

These outcomes should not be interpreted as evidence of a universal environmental improvement with FRP composites over metal-based lightweight components. Rather, the comparative LCA performance was found to be dependent on three co-acting system-specific factors: the degree of primary aluminium substitution within the hybrid architecture, the drivetrain-dependent amplification of mass-induced use-phase energy savings, and the magnitude of EoL credits.

For automotive OEMs and component developers, these results indicate that the environmental case for composite lightweight design is not determined by the composite material substitution alone, but hinges on jointly optimising residual primary aluminium content, in-process scrap recovery, and end-of-life circularity – priorities that become increasingly decisive as vehicle electrification and grid decarbonization progressively shift environmental relevance from the use phase toward upstream material choices and EoL architecture.

Future work should prioritize:

- primary, additional industrially representative process inventories for hybrid-yarn and organo sheet production;
- empirically validated technology-specific recycling yields and substitution relationships for mechanical recycling and pyrolysis;
- systematic sensitivity and uncertainty analysis across allocation approaches, secondary aluminium share scenarios, and additional future electricity scenarios;
- the coupling of LCA with structural optimization and data-driven modelling approaches to enable environmentally informed composite component design at early development stages;
- and extension toward integrated LCSA of composite supply chains.

By establishing a multi-impact category, cradle-to-grave reference framework for recyclable composite automotive structures, this study demonstrates that the environmental contribution of composite lightweight structures will be increasingly determined by upstream material choices and EoL architecture, assessing multiple impact category trade-offs - a finding that calls on automotive sustainability governance to broaden its scope well beyond single-impact category carbon accounting.

CRedit authorship contribution statement

Suzana Ostojic: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paula Effkemann:** Visualization, Validation, Software, Formal analysis, Data curation. **Marzia Traverso:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition. **David Schmidt:** Writing – review & editing, Project administration, Data curation. **Alexander Liebsch:** Writing – review & editing, Project administration, Data curation. **Daniel Wohlfahrt:** Writing – review & editing, Project administration, Data curation. **Robert Kupfer:** Writing – review & editing, Validation, Funding acquisition, Data curation. **Maik Gude:** Supervision, Resources.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Suzana Ostojic, Paula Effkemann, David Schmidt, Alexander Liebsch,

Daniel Wohlfahrt reports financial support was provided by Federal Ministry for Economic Affairs and Energy (BMWE). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.compositesb.2026.113768>.

Data availability

Data will be made available on request.

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