FULL STUDY

ALUMINUM IN BATTERY ELECTRIC VEHICLES (BEVS) A LIFE CYCLE ASSESSMENT

Authored By:

Sphera

Marshall Wang, Sr. Mgr., Sustainability Programs, The Aluminum Association

July 2025

Client:	**The Aluminum Association**
Title:	**Aluminum in Battery Electric Vehicles (BEVs) – A Life Cycle Assessment Report**
Report version:	v1.0
Report date:	04/30/2025

On behalf of Sphera Solutions, Inc., and its subsidiaries

Document prepared by

Hassana Elzein		HElzein@sphera.com
Senior LCA Consultant	30 April 2025	
Matou Chingsubam		mchingsubam@sphera.com
Associate Consultant	30 April 2025	

Quality assurance by

Christoph Koffler		CKoffler@sphera.com
Technical Director	30 April 2025	

Under the supervision of

Sean Daley
Consulting Director, Americas

Table of Contents

List of Figures

List of Tables

List of Acronyms

AA	Aluminum Association
ADP	Abiotic Depletion Potential
AP	Acidification Potential
ATG	Aluminum Transportation Group
BEV	Battery Electric Vehicle
BOM	Bill of Materials
BWC	Blue Water Consumption
CA	Canada
CFRP	Carbon Fiber Reinforced Polymer
CML	Centre of Environmental Science at Leiden
CN	China
CUV	Crossover Utility Vehicle
EIA	US Energy Information Administration
EoL	End-of-Life
ELV	End-of-Life Vehicle
EP	Eutrophication Potential
FEV	FEV Consulting
GHG	Greenhouse Gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies (Argonne, US DoE)
GWP	Global Warming Potential
HV	High Voltage
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCA FE	Life Cycle Assessment for Expert
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

MLC	Managed LCA Content
MJ	Megajoule
NMC	Nickel Manganese Cobalt
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone Depletion Potential
OEM	Original Equipment Manufacturers
PED	Primary Energy Demand
PHS	Press Hardened Steel
PM	Particulate Matter
POCP	Photochemical Ozone Creation Potential
RER	Region Europe
RNA	Region North America
SFP	Smog Formation Potential
SUV	Sports Utility Vehicle
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UHSS	Ultra High Stainless Steel
UN	United Nations
US	Unites States of America
VOC	Volatile Organic Compound

Glossary

Life Cycle

A view of a product system as "consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal" (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land, and water.

Life Cycle Assessment (LCA)

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040:2006, section 3.2)

Life Cycle Inventory (LCI)

"Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO 14040:2006, section 3.3)

Life Cycle Impact Assessment (LCIA)

"Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO 14040:2006, section 3.4)

Life Cycle Interpretation

"Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (ISO 14040:2006, section 3.5)

Functional Unit

"Quantified performance of a product system for use as a reference unit" (ISO 14040:2006, section 3.20)

Allocation

"Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO 14040:2006, section 3.17)

Closed-loop and Open-loop Allocation of Recycled Material

"An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties."

“A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.” (ISO 14044:2006, section 4.3.4.3.3)

Foreground System

“Those processes of the system that are specific to it … and/or directly affected by decisions analyzed in the study.” (JRC, 2010, p. 97) This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background System

“Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good….” (JRC, 2010, pp. 97-98) As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Critical Review

“Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment” (ISO 14044:2006, section 3.45).

Executive Summary

The Aluminum Association (AA) represents aluminum producers in the United States of America and Canada ranging from primary production to value-added products to recycling as well as suppliers to the industry. The association is the industry's leading voice, representing companies that produce the majority of the aluminum ingots and aluminum products shipped and transformed in North America (United States of America and Canada). The Aluminum Association membership plays a crucial role in the shift observed over the recent years in the lightweighting and electrification of vehicle fleets in the North American and worldwide markets.

The demand for battery electric vehicles (BEVs) is expected to grow in the future (Ducker Calisle, 2023). City Vehicles make up the majority of BEVs in the sales fleet today, and Family Crossover vehicle is expected to dominate in 2030 (FEV Group, 2022). To better understand the potential environmental impacts of aluminum in BEVs, the Aluminum Association commissioned Sphera Solutions, Inc. ("Sphera") to perform a cradle-to-grave life cycle assessment (LCA) of two conceptual BEV design scenarios – "Status Quo" and "Aluminum Optimized" for the reference model year of "2025" and "2030". The study focuses on two types of BEVs: a City Vehicle (sedan) and a Family Crossover (SUV).

The conceptual BEV designs are the result of a previously published study known as "Aluminum Value in Battery Electric Vehicles" (refer to as the FEV Study). That study was sponsored by the Aluminum Association and conducted by an automotive engineering service provider FEV Group GmbH. It focused on analysing the economic costs of aggressive aluminum intensive lightweight design concepts (Aluminum Optimized) in comparison to relatively moderate lightweighting design concepts (Status Quo) for BEVs.

Both the Status Quo and the Aluminum Optimized design scenarios involve lightweight design of vehicles with aluminum or other materials to replace heavier steel components or systems. The difference is that the Status Quo, or baseline scenario, refers to the "natural market adoption of lightweight materials and an overall decline in vehicle weight over time," while the Aluminum Optimized scenario focuses on "a more aggressive lightweighting scenario in the future, with aluminum substituting steel at different levels for each BEV segment in 2025 and 2030" – under the condition in which it is engineeringly feasible and cost-benefit to do so (FEV Group, 2022).

The LCA examines and compares the potential environmental impacts of different future design options defined in the FEV study. The future in the FEV study was represented by the "model years" of 2025 and 2030 relative to the "baseline model year" of 2021. From a chronological point of view, the 2030 designs have lower vehicle weights than the 2025 designs. From the design option perspective, the Aluminum Optimized designs reduce vehicle weight by 9% for both the 2025 and 2030 model years for City Vehicles compared to the Status Quo designs. For the Family Crossover, the weight reduction of Aluminum Optimized design is 5% in 2025 and 11% in 2030 compared to the Status Quo.

The LCA covers the potential environmental impacts from raw material extraction through manufacturing, use, and end-of-life stages of the vehicles. The functional unit of the study is the transportation service provided by a BEV of the same vehicle class over a lifetime driving distance of 200,000 miles. The study's primary data is from the vehicle design concepts in the FEV study. Secondary data is largely from the Sphera's MLC databases (2024.1).

The potential environmental impacts are based on the following inventory and impact categories:

Table ES 1: Impact categories and their corresponding acronyms, units and sources

Impact Category	Acronym	Unit	Source
Global Warming Potential (GWP100, excluding biogenic CO_2)	GWP100 fossil	kg CO_2-eq.	IPCC AR6
Ozone Depletion Potential	ODP	kgCFC11-eq.	TRACI 2.1
Primary Non-Renewable Energy Demand	PEDnr	MJ LHV	MLC LCI
Acidification Potential	AP	kg SO_2-eq.	TRACI 2.1
Eutrophication Potential	EP	kg N-eq.	TRACI 2.1
Smog Formation Potential	SFP	kg O_3-eq.	TRACI 2.1
Particulate Matter	PM	kg PM2.5-eq.	TRACI 2.1
Blue Water Consumption	BWC	kg	MLC LCI

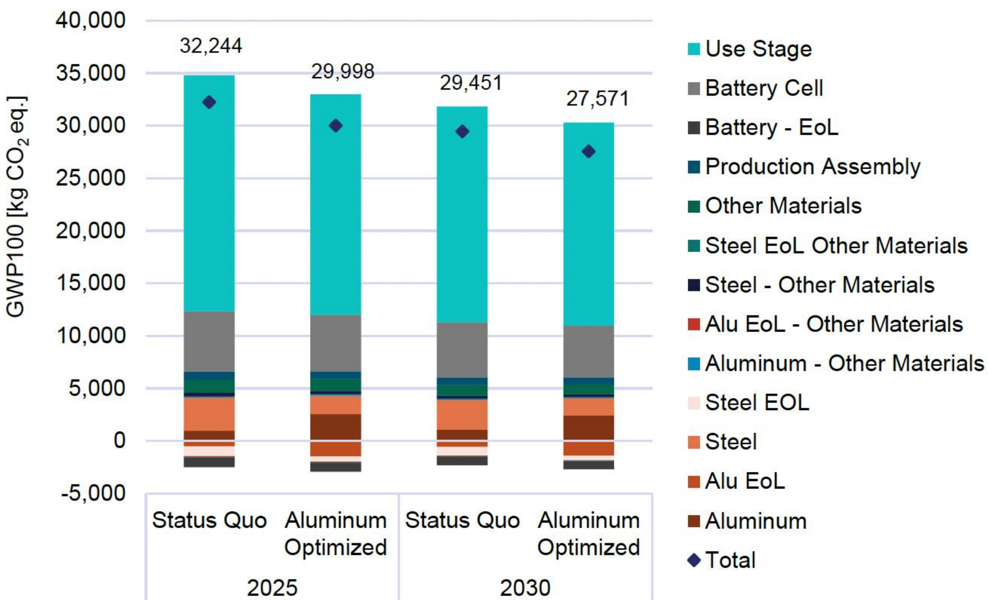
The results of the LCA show that lightweighting BEVs with aluminum contributes to reductions in the life cycle environmental footprint of the vehicles. The most reductions come from Aluminum Optimized designs for both vehicle types and both model years. The overall footprint reduction can be attributed to two major factors: reductions in the footprint of battery manufacturing and reductions in the footprint during the vehicle's use-phase. The study confirms the critical role of aluminum in helping build lighter and cleaner vehicles for the future. It recommends that stakeholders take into consideration the importance of the full life cycle impact when making decisions.

As a snapshot, Figure ES 1 shows the absolute contributions to the cradle-to-grave GWP100 by materials and life cycle stages for City Vehicles. The study findings indicate that:

- Compared to the 2025 designs, the 2030 designs reduce the GWP100 by 9% and 8% for Status Quo and Aluminum Optimization, respectively.
- Compared to the Status Quo, the Aluminum Optimized designs reduce GWP100 by 7% for 2025 and 6% for 2030.
- The reduction in GWP100 due to both lightweight design and battery technology evolution can be as much as 14% between the 2025 Status Quo and the 2030 Aluminum Optimized designs.

Across all scenarios for City Vehicles, the use phase (driving) consistently contributes the most to GWP100, accounting for almost 60% of the total. In the vehicle production phase, the results show that battery cells are the largest absolute GWP100 contributor. When excluding the production of battery cells, the Aluminum Optimized designs increase the cradle-to-gate production phase GWP100 by 2% and 1% for 2025 and 2030, respectively. This underscores the importance of looking beyond the modestly higher carbon intensity of aluminum during the production phase and focusing on the entire life cycle as well as secondary effects such as drivetrain downsizing in lightweighting LCA studies.

Figure ES 1: Contributions of materials and life cycle stages to GWP100 per City Vehicle with a lifetime mileage of 200,000 miles

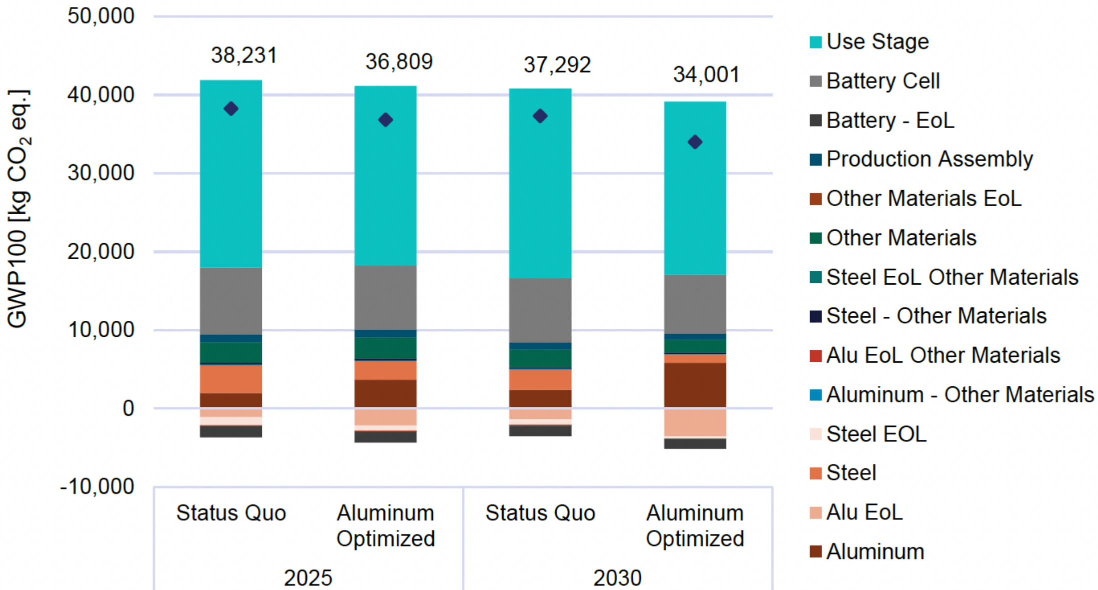


Similarly, Figure ES 2 shows the absolute contributions to the cradle-to-grave GWP100 by materials and life cycle stages for the Family Crossover vehicles. The study findings indicate that:

- Compared to 2025, the 2030 designs reduce GWP100 by 2% and 8% for Status Quo and Aluminum Optimization, respectively.
- Compared to the Status Quo, the Aluminum Optimized designs reduce GWP100 by 4% and 9% for 2025 and 2030, respectively.
- The reduction in GWP100 due to both lightweight design and battery technology evolution can be as much as 11% between the 2025 Status Quo and the 2030 Aluminum Optimized designs.

Across all scenarios for Family Crossover vehicles, the use stage contributes 50% to 55% to GWP100 across all model years and designs. In the production phase, the results show that battery cells are again the largest contributor, despite moderate battery downsizing due to lightweighting. Excluding the production of battery cells, Aluminum Optimized designs increase the cradle-to-gate production phase GWP100 results by 8% and 17% for 2025 and 2030, respectively. This again underscores the importance of looking beyond the carbon intensity of a material's production phase and focusing on the full life cycle impact of the vehicle in lightweighting LCA studies.

Figure ES 2: Contributions of materials and life cycle stages to GWP100 per Family Crossover with a



lifetime mileage of 200,000 miles

Overall, the contribution analysis shows a similar pattern of hotspots for both vehicle types and model years. Aluminum Optimized vehicles offer advantages in reducing the overall GWP100 through vehicle weight reduction that leads to a reduced battery size and fuel efficiency gains. In other impact categories, the Aluminum Optimized vehicles reduce PEDnr, AP, PM, and BWC compared to Status Quo vehicles. Further analysis shows that the break-even point for Aluminum Optimized Family Crossover vehicles compared to the Status Quo occurs at around 40,000 miles. For City Vehicles, the break-even point is already achieved during the production phase itself, i.e. the cradle-to-gate GWP100 is lower for the Aluminum Optimized designs than for the Status Quo designs. This is the result of a modest increase in the footprint of the vehicle's construction materials offset by a reduction in the footprint of the production of battery cells due to smaller battery sizes.

1. Goal of the Study

The Aluminum Association (AA) represents aluminum producers in the United States of America and Canada, ranging from primary production to value added products to recycling as well as suppliers to the industry. The association is the industry's leading voice, representing companies that produce the majority of the aluminum ingots and aluminum products shipped and transformed in North America (United States of America and Canada). The Aluminum Association membership plays a crucial role in the shift observed over the recent years in the lightweighting and electrification of vehicle fleets in the North American and worldwide markets.

The demand for battery electric vehicles (BEVs) is expected to continue to grow through 2030 and beyond. City Vehicles make up the majority of BEVs in the sales fleet today, but Family Crossover vehicle is expected to dominate by 2030 (FEV Group, 2022). To better understand the potential environmental impacts of aluminum in BEVs, the Aluminum Association commissioned Sphera Solutions, Inc. ("Sphera") to perform a cradle-to-grave life cycle assessment (LCA) of conceptual future BEV designs based on a previously published study that was focused on examining the economic costs of lightweighting BEVs. Conceptual designs were represented by the "Status Quo" and "Aluminum Optimized" scenarios, and the "future" was represented by "model years" of 2025 and 2030 relative to the "baseline year" of 2021.

Therefore, the goal of this LCA is to assess the potential environmental impacts of lightweighting BEV bodies with aluminum intensive designs in comparison to steel intensive designs based on design concepts for different timeframes (2025 and 2030 model years) from a previously published vehicle lightweighting cost-optimization study.

Given the fact that this LCA is completed in 2025, readers should be reminded that the model years referred here were simply adopted from a previously published study, and that the vehicle designs are simply a representation of future design concepts of a certain class of vehicles. Neither the model year nor the design itself represent a real timeline or a specific product in the market.

The main audiences of the LCA study include AA members, customer groups, policy makers, the research and investment community, and others who have an interest in the topic. The results will be used to identify design solutions using aluminum products, and to foster discussion around future lightweighting choices in the automotive industry, and the Aluminum Association's place in supporting that effort. The study is intended to be used in comparative assertions between BEV designs with increased aluminum content, and it is to be disclosed to the public.

The study has been conducted according to the requirements of the International Organization for Standardization (ISO) 14044 (ISO, 2006) and has undergone critical review by a panel of independent experts in accordance with ISO/TS 14071:2014. The critical review statement can be found in Annex A.

2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1 Product Systems

In North America, as the automotive market readies for a wave of electrified powertrains and BEVs, aluminum is emerging as the preferred choice of materials because of its ability to reduce vehicle weight – extending vehicle range and mitigating some of the mass added by heavy components like batteries (aluminum.org, 2022). A design evolution to multi-material vehicle construction would help drive aluminum to increase its market penetration. Aluminum content per vehicle is expected to rise to meet the needs of future electric vehicles (Ducker Calisle, 2023).

Aluminum growth in the automotive market is driving innovation and enabling automakers to differentiate from competitors. Aluminum saturation in vehicle doors, hoods, trunk lids, body-in-white parts, and chassis applications are key areas for automotive lightweighting.

The product systems under the LCA study include two types/classes of BEVs, a City Vehicle (sedan), and a Family Crossover (SUV) as described by The Aluminum Association (AA) and FEV Group GmbH ("FEV") in their 2022 study "Aluminum Value in Battery Electric Vehicles" (hereby referred to as the "FEV study") (FEV Group, 2022). The choice of these classes was based on the sales and production data available in the ATG-commissioned Ducker studies using global data input (Ducker Frontier, 2020).

Figure 2-1: Vehicle classes under the study

The two vehicle classes represent a significant cross-section of BEV fleet during the FEV study's baseline model year, which was 2021. The FEV study considered current and future trends in vehicle weight reduction, cost, aluminum application, BEV range, performance expectations, and battery and powertrain cost and efficiency to determine if aluminum solutions will remain economically viable throughout the current decade.

To conduct the LCA, vehicle design concepts and data contained in the FEV study are used as the foundation for the assessment (FEV Group, 2022). The study was sponsored by the Aluminum

Association and conducted by the FEV Group, a global engineering service provider for the automotive and transportation industries.

The FEV study examined the production cost implications of BEV lightweighting. Two hypothetical lightweighting scenarios were analysed with corresponding design simulations: Status Quo and Aluminum Optimized. Both the Status Quo and the Aluminum Optimized scenarios involve lightweight design of vehicle bodies with aluminum or other lightweight materials to replace heavier steel components or systems. The difference is the Status Quo, or baseline scenario, refers to a “natural market adoption of lightweight materials and an overall decline in vehicle weight over time,” while the Aluminum Optimized scenario focuses on “a more aggressive lightweighting scenario in the future with aluminum substituting steel at different levels for each BEV segment in 2025 and 2030” (FEV Group, 2022). Under the Status Quo, expected performance improvements in areas such as range are attributed to vehicle weight reduction, but improvements in battery technology through 2030 are also a main driving factor. Under the Aluminum Optimized scenario, these range and battery technology improvements are expected to occur. At the same time, a more aggressive lightweighting design with aluminum replacing steel can help further reduce the size of the battery and e-motor, improve vehicle performance, and save overall costs for consumers.

Using the vehicle design data from the FEV cost study, this LCA assesses the potential environmental impacts of those design simulations for both types of vehicles. It focuses on evaluating the impacts of lightweighting both at the chronological level and across design scenarios. At the chronological level, results for vehicle model years 2025 and 2030 are compared within each design scenario – either Status Quo or Aluminum Optimized. Across scenarios, the Status Quo and the Aluminum Optimized are compared. From Status Quo to Aluminum Optimized designs, weight reduction for City Vehicle in 2025 is projected to be 9%, and a similar reduction of 9% is projected in 2030. For Family Crossover vehicle, weight reduction from Status Quo to Aluminum Optimized is projected to be 5% in 2025 and 11% in 2030.

The representative vehicle models for each class in the FEV study were based on benchmarking data in the BEV fleet in 2021. Material compositions of those models were based on tear-down data and expert estimation by the FEV team. Table 2-1 lists the vehicles from which data were used to inform the baseline material compositions (FEV Group, 2022).

Table 2-1: Vehicles class descriptions

Technical Specifications	City Vehicle	Family Crossover
Description	Compact 4-door hatchback sedan	Mid-size 4-door hatchback crossover utility vehicle (CUV)
Benchmark vehicles (current model year)	Hyundai Ioniq Volkswagen ID.3	Ford Mustang Mach-E Audi E-Tron

Building on the benchmark vehicle models for each class listed in Table 2-1, the designs for 2025 and 2030 are based on FEV’s observations and cost-optimization regarding to past trends in the electric vehicle fleet and future directions and expected targets including lower overall vehicle weight, increase in battery energy density, and increase in range and vehicle efficiency. FEV prioritized vehicle range and efficiency over performance (i.e. acceleration) during its design simulations. In total, eight scenarios were analysed, considering the Status Quo and Aluminum Optimized scenarios for each vehicle class for the model years of 2025 and 2030 (Table 2-2 and

Table 2-3). It is important to note that there are no claims of equivalence between the vehicle classes under study. Comparisons are made only within the same vehicle class between the Status Quo and the Aluminum Optimized design options for the two future model years, as well as between the near-term model year and the longer-term model year.

The potential environmental impacts are assessed based on factors such as vehicle weight, material compositions, battery chemistry, capacity, and masses, as well as vehicle use stage electricity grid mix, fuel economy, and expected end-of-life pathways. The Status Quo scenario represents less aggressive lightweighting design options to reduce the weight of the benchmarked vehicles listed in Table 2-1. The Aluminum Optimized scenario represents more aggressive lightweighting options and has higher aluminum content compared to the Status Quo. The Aluminum Optimized designs in combination with the assumed improvement in energy densities of battery cells lead to smaller batteries and improved fuel economy. By 2030, it is expected that weight reduction and energy density improvement will continue to be the focus, and that battery technology will continue to improve.

Table 2-2: City Vehicle scenarios and specifications provided by AA

		2025		2030	
Materials	Unit	Status Quo	Aluminum-optimized	Status Quo	Aluminum-optimized
Vehicle weight	kg	1,521	1,384	1,394	1,265
Acceleration (0-60 Mph)	second	8.7	8.7	10	10
Steel weight	kg	700	408	655	400
Aluminum weight	kg	152	346	167	334
Battery cell weight	kg	244	228	223	210
All other materials	kg	425	402	348	321
Battery cell capacity	kWh	61	57	67	63
E-motor power	kW	157	137	121	110
E-drive range	miles	250	250	300	300
Fuel economy	Wh/mi	244	228	223	210

Table 2-3: Family Crossover vehicle scenarios and specifications provided by AA

		2025		2030	
Materials	Unit	Status Quo	Aluminum-Optimized	Status Quo	Aluminum-Optimized
Vehicle weight	kg	1,882	1,779	1,656	1,480
Acceleration (0-60 Mph)	second	6.3	6.3	7.0	7.0
Steel weight	kg	795	539	603	274
Aluminum weight	kg	292	445	331	618
Battery cell weight	kg	364	348	350	320
All other materials	kg	431	447	372	268
Battery cell capacity	kWh	91	87	105	96
E-motor power	kW	287	256	200	180
E-drive range	miles	350	350	400	400
Fuel economy	Wh/mi	260	249	263	240

2.2 Functional Unit & Reference Flows

In this LCA, the functional unit is defined as the following for all vehicles covered by the study:

The transportation service provided by a battery electric vehicle of the same type/class over a lifetime driving distance of 200,000 miles

An assumed lifetime mileage of 200,000 miles (321,869 km) for each vehicle is in line with the US EPA's regulatory impact analysis for model years 2017-2025 (EPA & DOT, 2012). Accordingly, the reference flow is one vehicle each with the respective specifications listed in Table 2-2 and Table 2-3. There is no omission of any additional functions in comparisons made in this study.

2.3 System Boundary

This study is a cradle-to-grave LCA that begins at raw material extraction and continues through manufacturing of all the different vehicle components such as body, chassis, powertrain, interior, and battery cells, followed by the vehicle manufacturing and its transportation, use stage, and end-of-life. Figure 2-2 shows the system boundary and Table 2-4 lists the processes that are included and excluded from the study.

It is important to note that the manufacturing of more complex components and assemblies (e.g., seats) is excluded due to a lack of manufacturing data and to reduce complexity. As such, the model focusses on the overall material composition of the vehicle combined with generic inventory data on mechanical processing such as injection molding and stamping. This simplification applies equally to all vehicle designs and is therefore not expected to materially affect the conclusions of this study.

Production and maintenance of capital goods and infrastructure have been excluded from the study and are not considered in the system boundary, along with support equipment, human labour and employee commute, BEV distribution, vehicle maintenance, and passive energy drain, either because of their limited relevance or because specific data was unavailable as the vehicle designs do not represent any specific vehicles that are currently in production.

Figure 2-2: System boundary flowchart

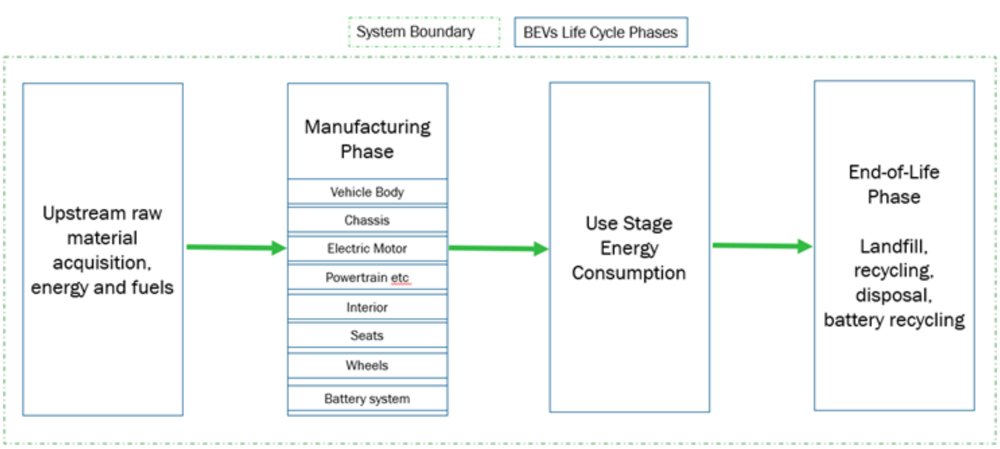


Table 2-4: System boundaries inclusions and exclusions

Included	Excluded
✓ Raw materials production and part manufacturing for steel, aluminum and other major materials such as stainless steel, copper and PVC	× Construction of capital equipment
✓ Transportation of raw materials to manufacturing site	× Maintenance and operation of support equipment (e.g., employee facilities)
✓ Battery pack and cells manufacturing	× Human labor and employee commute
✓ Vehicle assembly	× Infrastructure (roads, charging stations)
✓ Use of auxiliary materials, water, and energy during manufacturing	× Vehicle maintenance (fluids, filters, tires)
✓ Emissions to air, water, and soil during manufacturing	× Passive vehicle energy drain
✓ Use stage	× The manufacturing of more complex components and assemblies beyond their material composition
✓ End-of-life (vehicle dismantling, materials, and battery recycling)	

2.3.1. Time Coverage

The vehicle designs and the material compositions of the designs are intended to simulate the "future", which is symbolically represented by the reference model years of 2025 and 2030. They are based on the projected material substitution for aluminum replacing steel in specific systems and components in battery electric City Vehicles and Family Crossovers, as well as projected developments of battery specifications. The background data for material production, parts manufacturing, vehicle assembly and use (charging) is based on currently available information (2014 – 2024) which reflects the present situation. This LCA is intended to assess the potential environmental impacts of today's design concepts for the future based on today's production processes and technologies. It is not intended to speculate the future.

2.3.2. Technology Coverage

This study intends to cover the technologies associated with the different materials and energy sources utilized to produce, operate, and decommission BEVs sold in the North American (NA) market. The best available secondary data is used where available and proxy data where necessary. The choice of vehicle design concepts for the assessment is based on the FEV study (FEV Group, 2022), with benchmark vehicles representing the NA market in 2021, which is the baseline year of its study. The future of BEV technology is assessed from today's perspective based on a variety of assumptions made by FEV in its cost study.

2.3.3. Geographical Coverage

The study is intended to represent BEVs sold in the North American (United States of America and Canada) market.

2.4 Allocation

2.4.1. Multi-output Allocation

No multi-output allocation is applied in the foreground of the study.

Multi-output allocation in the background data follows the requirements of ISO 14044, section 4.3.4.2, and was taken from the Managed LCA Content (MLC, 2024.1) database, which is documented online at https://sphera.com/life-cycle-assessment-lca-database/.

2.4.2. End-of-Life Allocation

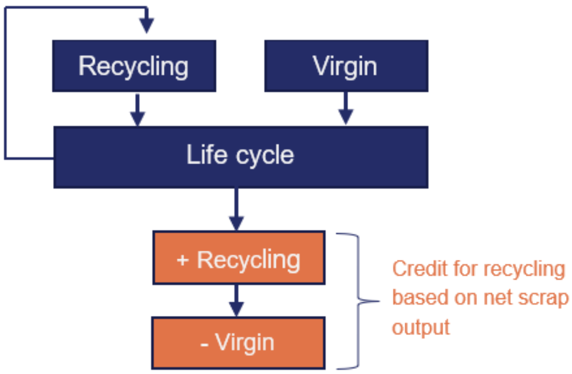
End-of-Life allocation follows the requirements of ISO 14044, section 4.3.4.3. Such allocation approaches address the question of how to assign impacts from virgin material production processes to material that will be recycled and used in future product systems.

The study uses an embodied burden approach as described by Koffler & Finkbeiner (Koffler & Finkbeiner, 2018). While similar to the widely used substitution approach, the recycling credit awarded under the embodied burden approach represents the original burden of primary material production that is "embodied" in the scrap material being recycled rather than the inventory of the substituted, market-average primary material. Compared to the substitution approach, a key advantage of this approach is that the embodied burden credit does not rely on specific substitution rates which are based on the technical substitutability of the recovered secondary material compared to its primary counterpart. Material substitutability is often hard to quantify with accuracy when the exact end-use application of the recycled material under study is unknown. To overcome the uncertainty associated with material substitutability and substitution rates, the embodied burden approach applies a "relay race" rationale to EOL recycling in which the original primary material burden is handed off from one product system to the next regardless of substitutability and substitution rate.

As such, the same life cycle inventory used to represent the burden of primary material in the manufacturing phase (i.e., the embodied burden) is used to credit EOL recycling. For aluminum, this is the inventory of North American primary aluminum consumption mix including domestic production and imports (Wang, 2022). On the other hand, a similar inventory of consumption mix for North American primary steel is not available since the steel industry only provides one standard global inventory for crediting steel recycling (Worldsteel Association, 2021). As a result, this standard dataset is used to model the EOL stage of steel, while the manufacturing stage uses regional specific North American steel production inventories published by the American Iron and Steel Institute (AISI, 2021).

This EOL allocation approach further includes a net scrap calculation where scrap materials consumed in semi-fabrication are not associated with any burden from a cradle-to-gate perspective but are instead subtracted from aluminum and steel scraps collected for recycling over the life cycle of the aluminum and steel parts, including manufacturing scraps. Only the remaining “net scrap” of the product system as a whole is modelled as being recycled in the EOL stage to determine the overall amount of secondary material to be credited. The net scrap calculation helps avoid double counting (Figure 2-3).

Figure 2-3: Schematic representation of the embodied burden approach



The same allocation approach is applied to EoL recycling throughout the model, including for the recycling of the battery (see also section 3.7).

In cases where materials are sent to waste incineration, they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. Credits are assigned for recovered electricity and heat outputs using the regional grid mix and thermal energy from natural gas.

In cases where materials are sent to a landfill, they are linked to an inventory that accounts for waste composition, regional leakage rates, landfill gas capture as well as utilization rates (flaring vs. power production). A credit is assigned for power output using the regional grid mix.

The choice of methodology for EoL recycling allocation could have a potential impact on the results of the study. For this reason, a scenario analysis is conducted in Section 0 to show the difference in results between the embodied burden approach and a cut-off approach.

2.5 Cut-off Criteria

No cut-off criteria are defined for this study. As summarized in the section 2.3, the system boundary was defined based on relevance to the goal of the study. For the processes within the system boundary, all available energy and material flow data have been included in the LCA model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

The choice of proxy data is documented in Chapter 3.

2.6 Selection of LCIA Methodology and Impact Categories

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-5. Finally, it is determined that human toxicity and ecotoxicity impacts are of low relevance to the product under assessment. Human toxicity and ecotoxicity impacts often involve greater uncertainties compared to other categories. Therefore, excluding these categories can help conduct a more targeted analysis and maintain a higher level of confidence in the reported results.

Table 2-6. **Error! Reference source not found.**TRACI 2.1 has been selected as it is currently the only impact assessment methodology framework that incorporates US average conditions to establish characterization factors (Bare, 2012) (EPA, 2012).

Global warming potential (GWP) and non-renewable primary energy demand (PEDnr) were chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be the most pressing environmental issues of our time. Since TRACI 2.1 uses outdated characterization factors from IPCC's 4th Assessment Report (AR4), the global warming potential impact category is assessed based on the current characterization factors taken from the 6th Assessment Report (IPCC, 2021) for a 100-year timeframe (GWP100) including climate-carbon feedback as recommended by the UNEP Life Cycle Initiative GLAM project (Life Cycle Initiative, 2017). It should be noted that there is no scientific justification for selecting 100 years over other timeframes. If indicated, a scenario analysis using GWP20 values may be carried out to assess the influence of this factor considering the mix of long- and short-lived climate forcers emitted over the life cycle of the product.

Due to the absence of relevant amounts of bio-based materials in the product systems, both biogenic CO_2 removals and emissions as well as CO_2 emissions due to land use change have been excluded from consideration. Please note that any biogenic CH_4 emissions are still included since atmospheric CO_2 that is re-released as CH_4 emissions contributes to global warming almost as much as fossil CH_4.

Eutrophication, acidification, particulate matter, and photochemical ozone creation potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burdens associated with commonly regulated emissions such as NO_x, SO_2, VOC, and others.

The *Montreal Protocol on Substances that Deplete the Ozone Layer* was implemented in 1989 with the aim of phasing out emissions of ozone-depleting gases. The protocol has been ratified by *all* members of the United Nations – an unprecedented level of international cooperation. With a few exceptions, the use of CFCs, the most harmful chemicals have been eliminated, while a complete phase-out of less active HCFCs will be achieved by 2030. As a result, it is expected that the ozone layer will return to 1980 levels between 2050 and 2070. In addition, no ozone-depleting substances are emitted in the foreground system under study. For these reasons, ozone depletion potential is not considered in this study.

Blue water consumption, i.e., the anthropogenic removal of water from its watershed through shipment, evaporation, or evapotranspiration has also been selected due to its high political relevance. The United Nations (UN) estimates that roughly a billion people on the planet do not have access to improved drinking water, which entails a variety of problems around ecosystem quality, health, and nutrition (UNICEF/WHO, 2019).

The present study excludes the assessment of resources as there remains no robust, globally agreed upon method - or even problem statement - for assessing mineral resource inputs in life cycle impact assessment. One may further argue that the concern regarding the depletion of scarce resources is not as much an 'environmental' one, but rather about the vulnerability of markets to supply shortages. These shortages, in return, are driven by various factors that are not captured well by current metrics. Accordingly, resource criticality has emerged as a separate tool to assess resource consumption (Nassar, et al., 2012; Graedel & Reck, 2015). As a complete criticality assessment is out of scope for this work and the environmental emissions associated with the production and consumption of these resources are captured by the other impact categories, the study at hand excluded the assessment of abiotic resources.

Table 2-5: Impact category descriptions

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP100)	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	(IPCC, 2021)
Acidification Potential (AP)	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg SO_2 equivalent	(Bare, 2012) (EPA, 2012)
Eutrophication Potential (EP)	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg N equivalent	(Bare, 2012) (EPA, 2012)

Ozone Depletion Potential (ODP)	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants.	kg CFC-11 equivalent	(Bare, 2012) (EPA, 2012)
Smog Formation Potential (SFP)	A measure of emissions of precursors that contribute to ground-level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground-level ozone may be injurious to human health and ecosystems and may also damage crops.	kg O_3 equivalent	(Bare, 2012) (EPA, 2012)
Human Health Particulate Air (PM)	A measure of emissions from a subset of criteria pollutants, i.e., particulate matter and precursors to particulates, and their impact on human health. Particulate matter is a collection of small particles in ambient air which have the ability to cause negative human health effects including respiratory illness and death.	kg $PM_{2.5}$ equivalent	(Bare, 2012) (EPA, 2012)

Finally, it is determined that human toxicity and ecotoxicity impacts are of low relevance to the product under assessment. Human toxicity and ecotoxicity impacts often involve greater uncertainties compared to other categories. Therefore, excluding these categories can help conduct a more targeted analysis and maintain a higher level of confidence in the reported results.

Table 2-6: Other environmental indicators

Indicator	Description	Unit	Reference
Primary Energy Demand (PEDnr)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ (lower heating value)	(Guinée, et al.,
Blue Water Consumption (BWC)	A measure of the net intake and release of fresh water across the life of the product system. This is not an indicator of environmental impact without the addition of information about regional water availability.	Liters of water	(Sphera Solutions Inc.,

It shall be noted that the above impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

As this study intends to support comparative assertions to be disclosed to third parties, no grouping or further quantitative cross-category weighting has been applied. Instead, each impact is discussed in isolation, without reference to other impact categories, before final conclusions and recommendations are made.

2.7 Interpretation to be Used

The results of the LCI and LCIA were interpreted according to the Goal and Scope. The interpretation addresses the following topics:

- Identification of significant findings, such as the main process step(s), material(s), and/or emission(s) contributing to the overall results
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions, limitations, and recommendations

Note that in situations where no product outperforms all of its alternatives in each of the impact categories, some form of cross-category evaluation is necessary to draw conclusions regarding the environmental superiority of one product over the other. Since ISO 14044 rules out the use of quantitative weighting factors in comparative assertions to be disclosed to the public, this evaluation will take place qualitatively and the defensibility of the conclusions therefore depends on the authors' expertise and ability to convey the underlying line of reasoning. Different authors may come to different conclusions based on the same set of results.

2.8 Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regard to the goal and scope of the study under given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modelling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artifacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to

provide enough transparency with this report so that third parties are able to approximate the reported results. This ability may be limited by the exclusion of confidential primary data and access to the same background data sources.

- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope. The goal is to use the most representative primary data for all foreground processes and the most representative industry-average data for all background processes. Whenever such data were unavailable (e.g., no industry-average data available for a certain country), best-available proxy data were employed.

An evaluation of the data quality with regard to these requirements is provided in Chapter 5 of this report.

2.9 Type and Format of the Report

In accordance with the ISO requirements (ISO, 2006), this document aims to report the results and conclusions of the LCA completely, accurately, and without bias to the intended audience. The results, data, methods, assumptions, and limitations are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

2.10 Software and Database

The LCA model was created using Life Cycle Assessment for Experts (LCA FE) 10.9 Software system for life cycle engineering, developed by Sphera Solutions, Inc. The Managed LCA Content (MLC, 2024.1) LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

2.11 Critical Review

The international standard ISO 14044 (ISO, 2006) requires that a review panel of at least three independent experts conduct comparative assertions critical review of an LCA report that is intended to be released to third parties. The main goals of such a critical review are to provide an independent evaluation of the LCA study and consider the input of the reviewer on how to improve the study's quality and transparency. The goals of a critical review are to ensure that:

- the methods used to carry out the LCA are consistent with ISO 14040 and 14044,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study
- the study report is transparent and consistent

The study report is reviewed by a panel of three independent experts including Dr. Roland Geyer (University of California, Santa Barbara), Dr. Tom Gloria (LCA Consultant), and Dr. Yuan Yao (Yale

University). The Critical Review Statement can be found in Annex A. The Critical Review Report containing the comments and recommendations of the review panel as well as the practitioner's responses is available upon request from Aluminum Association (AA) in accordance with ISO/TS 14071:2014.

3. Life Cycle Inventory Analysis

3.1 Data Collection Procedure

Primary data for vehicles including weight, bill of materials, and battery details was provided primarily by FEV Group based on a 2022 cost study (FEV Group, 2022). The FEV study did not breakdown steel and aluminum by product forms and manufacturing techniques which are important for LCA since different product forms and manufacturing techniques will lead to differences in life cycle inventory of the same material. To solve the data gap on detailed material breakdown, additional assumptions were made to facilitate the assessment with the assistance of a team of experts from the Aluminum Transportation Group (ATG) of the Aluminum Association.

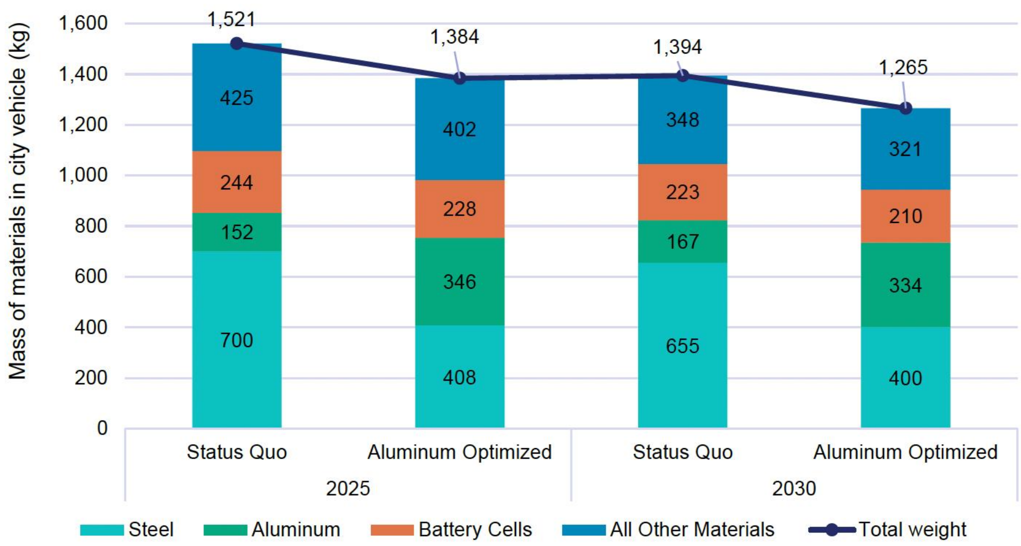
To specify the material composition of the 'Other Materials' category not further specified in the FEV study, three research papers by the GREET team at Argonne National Laboratory (ANL) were used to arrive at the percentage contribution of materials (J.C. Kelly, October, 2020; Kelly, October, 2022; Burnham, July 2012). Data was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. If gaps, outliers, or other inconsistencies occurred, Sphera engaged with the data provider to resolve any open issues.

3.2 City Vehicle

3.2.1. Overview of City Vehicle

City Vehicles are compact, 4-door hatchback sedans. The study examines City Vehicles across two future design scenarios for the model years 2025 and 2030: the Status Quo, which is a less aggressive lightweighting design option resulting in a steel-intensive vehicle, and an Aluminum Optimized design, which lightweights the vehicle more aggressively with more aluminum parts and subsystems being used to replace steel components. As shown in Figure 3-1, the Aluminum Optimized design more than doubles the aluminum content, while the steel content is reduced by 39% to 42%.The 2030 model is 8.3% to 8.6% lighter than the 2025 model for the Status Quo and Aluminum Optimized designs, respectively, while the Aluminum Optimized vehicle reduces weight by 9% compared to the Status Quo in both model years. This reduction in vehicle weight leads to a decrease in the battery cell weight and battery capacity, resulting in improved fuel economy as shown in Table 2-2.

Figure 3-1: City Vehicle material compositions



3.2.2. Detailed Material Composition

The body and chassis of battery electric City Vehicles are primarily composed of steel and aluminum. Table 3-1 shows a detailed material composition of the City Vehicle for both model years. Table 2 shows a detailed material composition of the "Other Materials" category from Table 3-1. The primary metal content (i.e. 1 – recycled content) of different forms of aluminum and steel products specific to automotive applications is adopted from the MLC database in which the original data was published by AA and AISI (Wang, 2022) (AISI, 2021).

Table 3-1: Material composition of City Vehicle designs

Material Category	Material Details	2025 Status Quo	2025 Aluminum Optimized	2030 Status Quo	2030 Aluminum Optimized	DQI*
Vehicle weight		**1,521**	**1,384**	**1,394**	**1,265**	**Calculated**
Steel						
Steel sheet	Steel - Cold Forming; galvanized	27.8%	16.5%	27.0%	15.6%	Calculated
Stainless steel	Steel - Cold Forming; non-galvanized	9.3%	5.5%	9.0%	5.2%	Calculated
Steel forging	Steel – Ultra High Stainless steel (UHSS)/ Press Hardened Steel (PHS)/other	9.0%	7.4%	11.0%	10.8%	Calculated
Aluminum						
Wrought aluminum	Sheet	2.0%	6.5%	2.3%	6.7%	Calculated
	Extrusion	2.3%	7.6%	2.9%	8.2%	Calculated
Cast aluminum	Casting	5.7%	10.9%	6.8%	11.5%	Calculated
Other materials	**All Other Materials**	28.0%	29.0%	25.0%	25.4%	Calculated
Battery	**Battery cells**	16.0%	16.5%	16.0%	16.6%	Calculated
TOTAL		**100%**	**100%**	**100%**	**100%**	

* measured / calculated / estimated / literature

Table 3-2: Material Composition of 'Other Materials' based on [(Burnham, July 2012);(J.C. Kelly, October, 2020);(Kelly, October, 2022)]

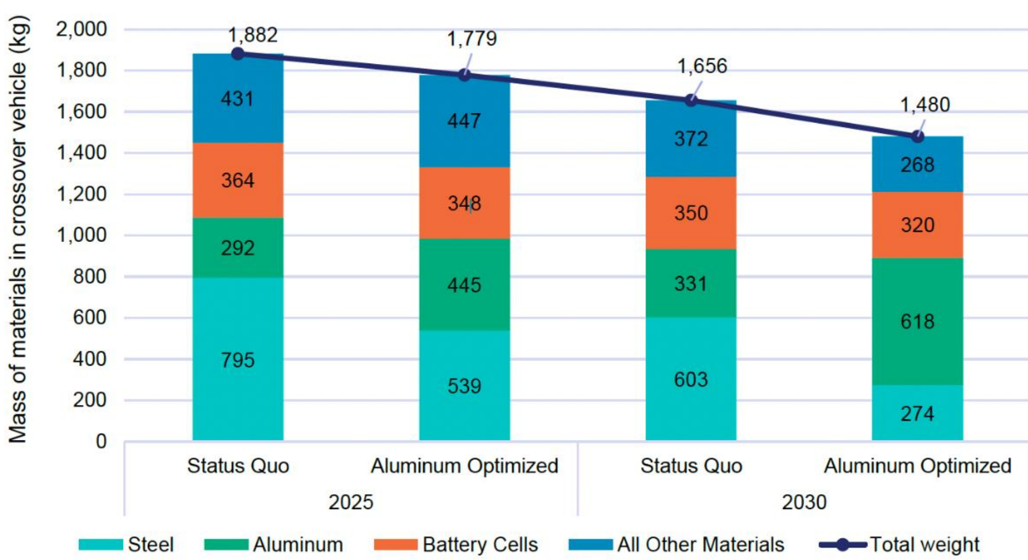
Materials	Percentage
Steels / cast steel / sintered steel	9.6%
Cast aluminum alloys	6.4%
Wrought aluminum alloys	0.9%
Magnesium and magnesium alloys	0.2%
Nonferrous heavy metals, cast and wrought alloys	9.8%
Special metals	0.0%
Thermoplastics & Polymeric compounds	42.7%
Thermoplastics Elastomere & Elastomers / elastomeric compounds	21.0%
Duromers	0.2%
Other materials and material compounds	8.9%
Battery acids	0.0%
Magnet	0.3%
TOTAL	100.0%

3.3 Family Crossover Vehicle

3.3.1. Overview of Family Crossover Vehicle

Family Crossover vehicles are mid-size 4-door hatchbacks. As with the City Vehicle, two future design scenarios are evaluated for the model years of 2025 and 2030: Status Quo and Aluminum Optimized. As shown in Figure 3-2, from a model-year perspective, the 2030 model is lighter than the 2025 model within each of the same design options. From a cross-design-option perspective, the 2025 Status Quo design has 42% steel and only 16% aluminum while the Aluminum Optimized vehicle reduces steel content by 12 percentage points and increases aluminum content by 10 percentage points. The net effect is a 5% vehicle weight reduction. For the model year 2030, the Status Quo design has 36% steel content and 20% aluminum content, while the Aluminum Optimized design has 19% steel content and 42% aluminum content. The net vehicle weight reduction is 11%. These reductions in vehicle weight led to a decrease in the battery cell weight and battery capacity, resulting in improved fuel economy.

Figure 3-2: Family Crossover material compositions



3.3.2. Detailed Material Composition

Table 3-3 shows the material composition of each Family Crossover vehicle model year and design alternative, while

Table ***3***-4 shows a detailed breakdown of the "Other Materials" category. The primary metal content (i.e. 1 – recycled content) of different forms of aluminum and steel products specific to automotive applications is adopted from the MLC database in which the original data was published by AA and AISI (Wang, 2022) (AISI, 2021).

Table 3-3: Material composition of Family Crossover designs

Material Category	Material Details	2025 Status Quo	2025 Aluminum Optimized	2030 Status Quo	2030 Aluminum Optimized	DQI* Measured
Vehicle weight		**1,882**	**1,779**	**1,656**	**1,480**	Calculated
Steel						
Steel sheet	Steel - Cold Forming; Galvanized	24.7%	17.1%	19.2%	8.6%	Calculated
Stainless steel	Steel - Cold Forming; non-Galvanized	8.3%	5.7%	6.4%	2.9%	Calculated
Steel forging	Steel - UHSS/PHS/other	9.3%	7.5%	10.9%	7.1%	Calculated
Aluminum						
Wrought aluminum	Sheet	3.2%	7.7%	4.8%	16.6%	Calculated
	Extrusion	6.7%	11.1%	8.5%	14.2%	Calculated
Cast aluminum	Casting	5.6%	6.2%	6.7%	10.9%	Calculated
Other materials	**All Other Materials**	22.9%	25.1%	22.4%	18.1%	Calculated
Battery	**Battery cells**	19.3%	19.6%	21.1%	21.6%	Calculated
TOTAL		**100%**	**100%**	**100%**	**100%**	

Table 3-4: Summary of Family Crossover 'Other Materials' Compositions

Materials	Family Crossover
Steels / cast steel / sintered steel	5.6%
Cast iron	0.5%
Cast aluminum alloys	6.3%
Wrought aluminum alloys	1.1%
Magnesium and magnesium alloys	0.2%
Nonferrous heavy metals, cast and wrought alloys	9.4%
Special metals	0.0%
Thermoplastics & 5.5 Polymeric compounds	43.8%
Thermoplastics Elastomere & 5.3 Elastomers / elastomeric compounds	24.1%
Duromers	0.4%
Other materials and material compounds	8.1%
Magnet	0.5%
TOTAL	100.0%

3.4 Vehicle Manufacturing

Since there was no primary data (data directly collected through surveying manufacturing facilities) available in this study for vehicle parts manufacturing from raw and intermediate materials, generic background datasets from the MLC database are used to model the manufacturing of parts on a high level. The main manufacturing processes associated with aluminum and steel parts in the body and chassis are discussed below. However, the further manufacturing of more complex components and assemblies involving multiple materials (e.g., seats) was not included in the model due to a lack of data and to reduce complexity. Nevertheless, the involved materials are included in the life cycle inventory model along with the generic manufacturing processes. For a complete overview of raw materials, manufacturing processes, and other background data, please refer to Section 3.8 and Table 3-2.

3.4.1. Steel part manufacturing

Steel (including stainless steel) vehicle parts are manufactured by Original Equipment Manufacturers (OEMs) or their suppliers using semi-fabricated steel, which is either in the form of flat-rolled sheet (often in coil), or in profiles. Parts are then assembled into vehicles in assembly lines.

Sheet coils are either hot or cold rolled and sometimes galvanized. Steel profiles are made through drawing, forging, or other metal working techniques. At OEMs, sheet coil is fabricated into vehicle parts (body and closure) through a blanking and stamping process. The corresponding dataset for the blanking and stamping process in Sphera's MLC database is named "deep drawing", which is a translation from German to English and it is the equivalent to the blanking and stamping process in automotive manufacturing. Steel profiles are usually supplied to OEMs with no further fabrication needed. All the steel parts, together with parts made of other materials, are assembled into vehicles through the assembly process that involves joining, coating, baking, and other necessary finishing steps. The blanking and stamping process is included in the inventory, as is the energy consumption for vehicle assembly. The per-vehicle energy consumption for vehicle production and assembly that contained body welding, painting, and assembly operations is based on energy consumption data reported by Sullivan *et al.* The electricity and thermal energy demand considered in the model is 1.5 MJ per kg vehicle and 3.92 MJ per kg vehicle, respectively (Nakata, 2020), (J.L. Sullivan, 2010).

3.4.2. Aluminum part manufacturing

Aluminum vehicle parts are also manufactured by OEMs or their suppliers using semi-fabricated aluminum, which is either in the form of flat-rolled sheet (often in coil), or extruded, forged, or cast profiles. Parts are then assembled into vehicles in assembly lines.

Aluminum sheets are hot or cold-rolled, and some alloys may be subsequently heat-treated. At OEMs, sheet coil is fabricated into vehicle parts (body and closure) through a blanking and stamping process. The corresponding dataset for the blanking and stamping process in Sphera MLC database is named "deep drawing", which is a translation from German to English and it is the equivalent to the blanking and stamping process in automotive manufacturing. Extruded, forged, or cast profiles are usually supplied to OEMs by aluminum manufacturers with no further fabrication needed. All the aluminum parts, together with parts made of other materials, are assembled into vehicles during the assembly process that involves joining, coating, baking, and other necessary finishing steps. The blanking and stamping process is included in the inventory, as is the energy consumption for vehicle assembly (J.L. Sullivan, 2010).

3.4.3 Manufacturing yield parameters of aluminum and steel products

While the direct energy consumptions of the blanking, stamping, and mechanical assembly processes are included in the inventory, these consumptions are just a small fraction of the overall footprint. For instance, according to a similar study by Rivian, the total energy footprint of "onsite production and logistics", which is the equivalent of the above blanking, stamping, and assembly processes, is only about 8% (Rivian, 2024). The most important process parameter is the material yield, which will determine how much raw or intermediate material is needed per kg of product output. The lower the yield, the more the material is needed, thus the higher the environmental footprint.

Table 3-5 shows the yields of the selected manufacturing processes. It is worth noting that these overall yield factors may be slightly different from one LCA software tool to another. For instance, the Argonne National Lab's GREET Model sets the overall yield at approximately 61 – 65% for the blanking and stamping of steel and aluminum coils for vehicle body-in-white production. The Sphera MLC yield factors are more conservative compared to the GREET Model.

Table 3-5: Key manufacturing process yields for steel and aluminum parts in Sphera MLC datasets

Manufacturing process	Yield %
Steel Part Manufacturing	
Steel sheet deep drawing	54%
Stainless steel deep drawing	54%
Steel forging/Steel turning	74%
Aluminum Part Production	
Aluminum cast machining	91%
Aluminum sheet deep drawing	54%

3.5 Battery Cells

All vehicle designs use the same lithium nickel manganese cobalt oxides NMC 721 battery chemistry. Sphera's proprietary vehicle battery model is used to model the battery cells, which is based on a variety of sources including BatPaC3 (BatPaC 3.1 by Argonne National Laboratory, 2018), Lithium-ion Batteries in the GREET Model (Dai & Dunn, 2019) but not limited to Sphera (Sphera Solutions Inc.,).

In this study, cell production is assumed to be carried out in Poland, which is consistent with the FEV study's benchmark vehicle models (FEV Group, 2022). Production in Poland is based on benchmark data for electric vehicles like the Volkswagen ID.4, Porsche Taycan and Audi E-Tron that use pouch cell batteries. Table 3-6 and Table 3-7 provides battery cell information for City Vehicle and Family Crossover, respectively. Data shows that aluminum optimization in vehicles leads to a reduction in vehicle weights and battery weight. Additionally, the target electric drive range was set to 250 miles in 2025 and 300 miles in 2030 for the City Vehicle, and to 350 miles and 400 miles for the Family Crossover in 2025 and 2030, respectively.

The battery pack includes battery modules (consisting of cells), housing of modules (aluminum), housing of battery pack (steel), thermal energy management system, battery management system, and cables and wiring. For this study, the amount of steel, aluminum, and other materials contained in the housing of modules, housing of battery pack, high voltage (HV) wiring, and thermal and battery management systems are already included in the vehicle's bill of materials. Therefore, the battery model of this study is concentrated on the battery cells. All future battery assumptions (i.e. for 2025 and 2030) were based on the FEV study (FEV Group, 2022) where improvements are expected at the energy density and cost levels.

Table 3-6: City Vehicle battery cell specifications

2025			2030		
Materials	Unit	Status Quo	Aluminum-Optimized	Status Quo	Aluminum-Optimized
Battery Type	-	NMC	NMC	NMC	NMC
Battery Chemistry*	-	721	721	721	721
Battery Cell Weight	kg	244	228	223	210
Battery Capacity	kWh	61	57	67	63

*721 refers to the composition of Nickel; Manganese and Cobalt respectively

Table 3-7: Family Crossover vehicles battery cell specifications

			2025	2030	
Materials	Unit	Status Quo	Aluminum-Optimized	Status Quo	Aluminum-Optimized
Battery Type	-	NMC	NMC	NMC	NMC
Battery Chemistry*	-	721	721	721	721
Battery Cell Weight	kg	364	348	350	320
Battery Capacity	kWh	91	87	105	96

*721 refers to the composition of Nickel; Manganese and Cobalt respectively

3.6 Use Stage

The study aims to reflect the operational impacts of BEV usage within the US. Therefore, the use stage is modelled using the US electricity grid mix. The corresponding electricity dataset from the MLC database represents the US average electricity supply for final consumers, including own electricity consumption, transmission/distribution losses, electricity imports from Canada and Mexico, the national energy carrier mix used for electricity production, the power plant efficiency data, and shares of combined heat and power generation (CHP). Detailed power plant and fuel supply chain models were used, which combine measured emissions (e.g. NOx) with calculated emission values (e.g. heavy metals). The inventory is based on primary industry data and secondary literature data.

As there are no tailpipe emissions, the use stage emissions associated with BEVs arise from the electricity used to charge the battery. Table 3-8 and Table 3-9 summarize the fuel economy calculations for the City Vehicles and Family Crossover vehicles, respectively. The study calculated the total emissions for the lifetime vehicle mileage of 200,000 miles as a function of the fuel economy and battery capacity.

Table 3-8: Fuel economy calculation for City Vehicles

		2025		2030	
Materials	Unit	Status Quo	Aluminum-Optimized	Status Quo	Aluminum-Optimized
E-drive range	miles	250	250	300	300
Battery capacity	kWh	61	57	67	63
Fuel economy	Wh/mi	244	228	223	210

Table 3-9: Fuel economy calculation for Family Crossover Vehicles

		2025		2030	
Materials	Unit	Status Quo	Aluminum-Optimized	Status Quo	Aluminum-Optimized
E-drive range	miles	350	350	400	400
Battery capacity	kWh	91	87	105	96
Fuel economy	Wh/mi	260	249	263	240

3.7 Vehicle and Battery End-of-Life

At the end-of-life stage of BEVs, 95% of the steel and aluminum fractions as well as 100% of the battery cells are assumed to be recycled to recover valuable materials, while the remainder is disposed in a landfill (Table 3-10).

The study considers that battery cells undergo recycling within the US. It is assumed that the distance from end-use to collection is 50 miles, collection to disassembly is 50 miles, and disassembly to the recycler is 1000 miles for a total of 1,100 miles.

NMC battery cell recycling is modelled using a 50/50 mix of pyrometallurgical and hydrometallurgical routes representing the recycling technologies in the US (BatPaC 3.1 by Argonne National Laboratory, 2018). Lithium-ion battery recycling datasets using the two processes are taken from the MLC database (Sphera Solutions Inc., 2024) which is modelled based on Argonne National Laboratory's EverBatt Model as well (Dai & Dunn, 2019).

Table 3-10: Recycling rates of EoL materials

Materials	Treatment	Percent to Treatment
Steel	Recycling	95%
	Landfill	5%
Aluminum	Recycling	95%
	Landfill	5%
Plastics and fabrics	Landfill	100%
Glass	Landfill	100%
NMC battery cells	Recycling via pyrometallurgical	50%
	Recycling via hydrometallurgical	50%

3.8 Background Data

3.8.1. Fuels and Energy

National averages for fuel inputs and electricity grid mixes were obtained from the Managed LCA Content (MLC, 2024.1) databases. Table 3-11 shows the most relevant LCI datasets used in modelling the product systems. Electricity consumption was modelled using national grid mixes that account for imports from neighboring countries.

Documentation for all Managed LCA Content (MLC) datasets can be found at https://sphera.com/solutions/product-stewardship/life-cycle-assessment-software-and-data/managed-lca-content/

Table 3-11: Key energy datasets used in inventory analysis

Energy	Location	Dataset	Data Provider	Reference Year	Proxy?
Electricity	US	Electricity grid mix	Sphera	2020	No
Thermal Energy	US	Thermal energy from natural gas	Sphera	2020	No

3.8.2. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the Managed LCA Content database (MLC, 2024.1).

Table 3-12 shows the most relevant LCI datasets used in modelling the product systems. The various locations considered were the Region of North America (RNA), the Region of Europe (RER), and Canada (CA). For the results, the model mainly used RNA datasets, and the Canadian primary aluminum ingot was used for sensitivity analysis. The AISI's steel datasets excluded the impact of imported steel into the North American region, whereas AA's aluminum datasets accounted for the impact of imported aluminum. Such an imbalance reflects an imperfection in data availability, but the impact is expected to be small. All steel, aluminum and other materials datasets used were cradle-to-gate. Documentation for all MLC datasets can be found at https://sphera.com/life-cycle-assessment-lca-database/.

Table 3-12: Key material and process datasets used in inventory analysis – Steel and Aluminum

Material/ process	Location	Dataset	Data Provider	Reference Year	Proxy?
Steel					
Steel sheet	RNA	Steel cold rolled coil	AISI	2017	No
	RNA	Steel hot rolled coil	AISI	2017	No
	RNA	Steel hot dip galvanised	AISI	2017	No
Stainless steel	RER	Stainless steel cold rolled coil (304)	EUROFER	2014	Geo
Steel forging	RNA	Steel sections	AISI	2017	No
EoL recycling	GLO	Value of scrap	WorldSteel	2022	Geo
Aluminum					
Cast aluminum	RNA	Primary aluminum ingot	Sphera	2016	No
	CA	Primary aluminium ingot	IAI	2015	No
	RNA	Aluminum die-cast product	Sphera	2016	No
Wrought aluminum	RNA	Aluminum automotive extrusion	Sphera	2016	No
	RNA	Aluminum automotive sheet	Sphera	2016	No
EoL recycling	RNA	Recycled aluminum ingot (100% recycled content)	Sphera	2016	No

Table 3-13: Key material and process datasets used in inventory analysis - Other materials

Material/ process	Location	Dataset	Data Provider	Reference Year	Proxy?
Other Materials	CN	Magnesium	Sphera	2023	No
	RER	Copper Wire Mix (Europe 2015)	Sphera	2015	Geo
	RER	Lead primary and secondary mix	ILA	2021	Geo
	GLO	Lead, primary	ILA	2021	No
	US	Acrylonitrile-butadiene-styrene granulate (ABS)	Sphera	2023	No
	US	Glass fibres	Sphera	2023	No
	US	Carbon fiber (CF; PAN-based; HT) - 06	Sphera	2023	No
	US	Polyamide 6.6 granulate (PA 6.6) (HMDA from	Sphera	2023	No

Material/ process	Location	Dataset	Data Provider	Reference Year	Proxy?
		butadiene 67% and acrylonitrile 33%)			
	US	Polycarbonate granulate (PC)	Sphera	2023	No
	US	Polyethylene low density granulate (LDPE/PE-LD)	Sphera	2023	No
	US	Polyester (PET) fabric	Sphera	2023	No
	US	Polyethylene terephthalate fibres (PET)	Sphera	2023	No
	US	Polyethylene terephthalate granulate (PET) via terepht. acid + EG (partially biobased from corn)	Sphera	2023	No
	US	Polyoxymethylene granulate (POM)	Sphera	2023	No
	US	Polypropylene granulate (PP)	Sphera	2023	No
	US	Polystyrene granulate (PS) (approximation)	Sphera	2023	No
	US	Polytetrafluoroethylene granulate (PTFE)	Sphera	2023	No
	US	Polyvinyl chloride granulate (S-PVC)	Sphera	2023	No
	US	Magnet Nd-Fe-Dy-B (low energy demand)	Sphera	2023	No
	US	Tap water from surface water	Sphera	2023	No
	US	Sulphuric acid (37%)	Sphera	2023	No
	US	Lubricants at refinery	Sphera	2020	No
	GLO	Compounding (plastics)	Sphera	2023	No
	GLO	Compressed air 7 bar (medium power consumption)	Sphera	2023	No

Table 3-14: Key material and process datasets used in inventory analysis- Battery cells and waste

Material/ process	Location	Dataset	Data Provider	Reference Year	Proxy?
Battery cells	GLO	Nickel sulphate hexahydrate (NiSO4 6H2O)	Sphera	2022	No
	GLO	Manganese	Sphera	2023	No

Material/ process	Location	Dataset	Data Provider	Reference Year	Proxy?
	GLO	Cobalt sulphate heptahydrate (CoSO4 7H2O)	Sphera	2019	No
	CN	Sodium hydroxide mix (approximation)	Sphera	2023	No
	CN	Ammonia (NH3) without CO2 recovery (carbon dioxide emissions to air)	Sphera	2023	No
	CN	Water (desalinated; deionised)	Sphera	2023	No
	CN	Lithium carbonate (Li2CO3) Spodumene Route (price allocated)	Sphera	2023	No
	CN	Lithium hydroxide monohydrate (LiOH.H2O) from Spodumene	Sphera	2023	No
	GLO	Polyninylidene Fluoride (PVDF)	Sphera	2023	No
	CN	Carbon Black	Sphera	2023	No
Waste	US	Polyvinyl chloride (PVC) in waste incineration plant (0% H2O content)	Sphera	2023	No
	US	Plastic waste on landfill, post-consumer	Sphera	2023	No
	DE	Used oil in waste incineration plant (15% H2O content)	Sphera	2023	No
	US	Municipal Solid Waste Incineration Plant (27.5% H2O content)	Sphera	2023	No
	US	Municipal wastewater treatment (mix)	Sphera	2023	No
	US	Inert matter (Glass) on landfill	Sphera	2023	No
	US	Hazardous waste (statistical average composition) in waste incineration plant (7.2% H2O content)	Sphera	2023	No
	RER	Electrolytic copper secondary (input light copper scrap 90% Cu)	Sphera	2023	No

3.8.3. Transportation

Average transportation distances and modes of transport are included for the transport of raw materials, operating materials, and auxiliary materials to production and assembly facilities.

Sphera's MLC datasets were used to model transportation. Truck transportation within the United States was modelled using US truck transportation datasets based on data from EPA's SmartWay program (https://www.epa.gov/smartway). SmartWay collects fleet data—including truck class, fuel consumption, miles driven, etc.—from US fleet carriers and aggregates the data to generate average carbon dioxide (CO_2) emissions for each carrier. Emissions for this dataset are then calculated by averaging emissions for all carriers classified under the given SmartWay vehicle category.

Other emissions are calculated based on EPA MOVES data (https://www.epa.gov/moves). An appropriate MOVES truck type is identified and corresponding emission factors in grams per mile are obtained from the model. Emission factors are separated for short (less than 200 miles) and long haul (above 200 miles) as the latter accounts for "hoteling", i.e., the hours spent in idle mode during breaks.

While no biodiesel has been considered in this study, the diesel consumption is back-calculated from SmartWay CO_2 emissions that factor in biodiesel content from the US Energy Information Administration (EIA) Annual Energy Review under the assumption that diesel is the primary fuel consumed by SmartWay carriers. The fraction of biodiesel calculated from EIA data is also used to split SmartWay CO_2 emissions into fossil and biogenic CO_2.

Table 3-15: Transportation and road fuel datasets

Mode / fuels	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Ship	GLO	Container ship, 5,000 to 200,000 dwt payload capacity, deep sea	Sphera	2023	No
Rail	US	Rail transport cargo - average, average train, gross tonne weight 1,000t / 726t payload capacity	Sphera	2023	No
Heavy Duty Truck	US	Truck - TL/dry van (EPA SmartWay)	Sphera	2023	No
Heavy oil	US	Heavy fuel oil at refinery (0.3wt.% S) Sphera	Sphera	2023	No
Diesel	US	Diesel mix at filling station	Sphera	2020	No

3.9 Life Cycle Inventory Analysis Results

ISO 14044 defines the Life Cycle Inventory (LCI) analysis result as the "outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment". As the complete inventory comprises hundreds of flows, the below table only displays a selection of flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results. The LCI results of all vehicle types are listed in Annex B: Annex **B: Additional Results**

B.1. Life Cycle Inventory Analysis Results.

4. LCIA Results

This chapter contains the results for the impact categories and additional metrics defined in section 2.6. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

4.1 Overall Results

4.1.1. City Vehicles

Table 4-1 shows the characterized LCIA results for each impact category for the Status Quo and Aluminum Optimized City Vehicles for 2025 and 2030. The results indicate that compared to the Status Quo, the Aluminum Optimized designs reduce the GWP100, PED, AP, and SFP impacts by 6% to 10% due to increase in aluminum content in the vehicle bodies. Reductions in the EP and PM impacts in 2025 are 14% and 20%, respectively, but no reduction in 2030. The BWC impact, however, increases ~16% for both model years. The increase in BWC is due to the fact that the majority of primary aluminum consumed in North America relies on hydropower electricity for smelting. When aluminum content increases in the vehicle body, so would be blue water consumption.

It is worth to be reminded that both steel and aluminum production situations are assumed to be the same in this study, regardless of the timeframes of the designs of the vehicles, which are "future" design concepts.

Table 4-1: Cradle-to-grave LCIA results for City Vehicles

		2025		2030	
Impact Categories	**Unit**	**Status Quo**	**Aluminum Optimized**	**Status Quo**	**Aluminum Optimized**
GWP100	kg CO_2 eq.	32,244	29,998	29,451	27,571
PED	MJ	557,156	518,507	508,347	475,942
AP	kg SO_2 eq.	57	53	54	49
EP	kg N eq.	7	6	6	6
PM	kg PM2.5 eq	5	4	4	4
SFP	kg O_3 eq.	857	775	780	708
BWC	kg	149,589	173,197	138,365	161,513

4.1.2. Family Crossover Vehicles

Table 4-2 shows the characterized LCIA results for each impact category for the Status Quo and Aluminum Optimized Family Crossover vehicles for 2025 and 2030. The results indicate that compared to the Status Quo, the Aluminum Optimized designs reduce the GWP100, PED, and SFP impacts by 4% to 12% due to increase in aluminum content in the vehicle bodies. There is almost no reduction in the AP, EP and PM impacts in 2025, but the 2030 model year sees a reduction of these impacts by 13% to 15%. The BWC impact, however, increases 13% in 2025 and 8% in 2030. The increase in BWC is due to the fact that the majority of primary aluminum consumed in North America relies on hydropower electricity for smelting. When aluminum content increases in the vehicle body, so would be blue water consumption. Again, it is worth to be reminded that both steel and aluminum production situations are assumed to be the same in this study, regardless of the timeframes of the designs of the vehicles, which are "future" design concepts.

Table 4-2: Cradle-to-grave LCIA results for Family Crossover vehicles

		2025		2030	
Impact Categories	**Unit**	**Status Quo**	**Aluminum optimized**	**Status Quo**	**Aluminum optimized**
GWP100	kg CO_2 eq.	38,231	36,809	37,292	34,001
PED	MJ	647,823	623,617	633,550	576,768
AP	kg SO_2 eq.	97	96	91	77
EP	kg N eq.	8	8	8	7
PM	kg PM2.5 eq.	7	7	7	6
SFP	kg O_3 eq.	1,139	1,088	1,071	938
BWC	kg water	185,972	210,013	207,685	223,768

4.2 Contribution Analysis

The following subsections detail the cradle-to-gate and cradle-to-grave results for both types of vehicles. It is important to note that all end-of-life results presented include manufacturing scrap (typically considered a part of manufacturing) via the net scrap approach.

4.2.1. City Vehicles

Figure 4-1 shows the contributions to GWP100 by different materials and battery cells from a cradle-to-gate perspective. The battery cells are the most significant contributor to the environmental impacts. This is due to the mining and processing of lithium, cobalt, and nickel. When the battery cells are excluded from consideration in the manufacturing stage, aluminum optimization increases cradle-to-gate GWP100 results by 2% and 1% for 2025 and 2030, respectively.

Figure 4-1: Cradle-to-gate GWP100 contribution analysis for City Vehicles

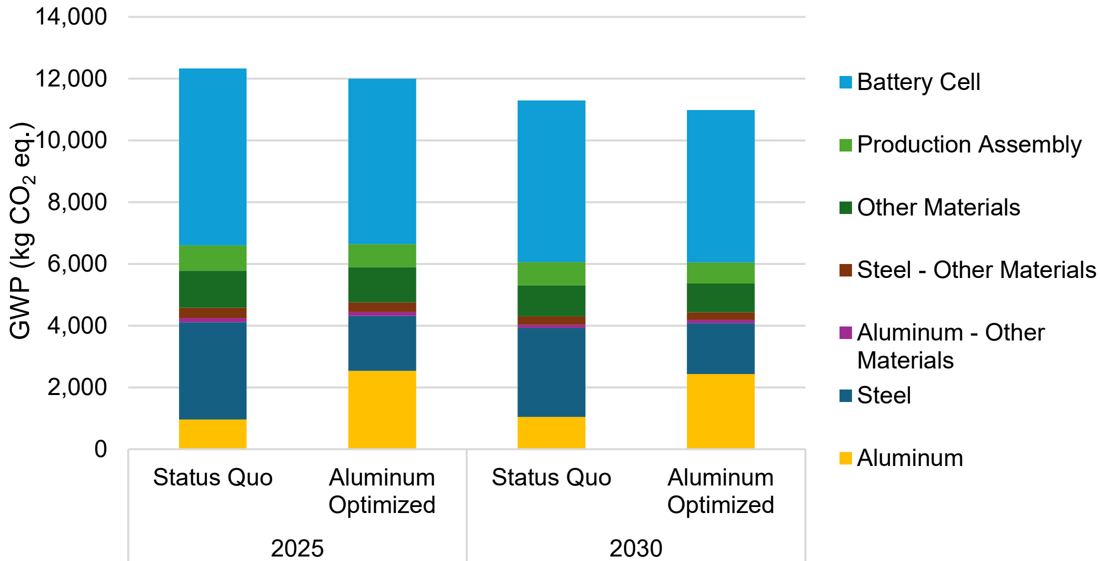


Figure 4-2 shows the contributions of the main life cycle stages for City Vehicles in 2025. The use stage dominates the GWP100 and PEDnr impacts due to emissions from electricity to charge the vehicles. The manufacturing stage contributes the most to other impact categories. The end-of-life stage reduces the life cycle totals via recycling credits, providing significant benefits to AP, PM, and BWC due to the recycling of battery cells, steel, and aluminum while such reductions in SFP and EP impacts are moderate between 5% and 17%.

Figure 4-2: Cradle-to-grave City Vehicle results by life cycle stage in 2025

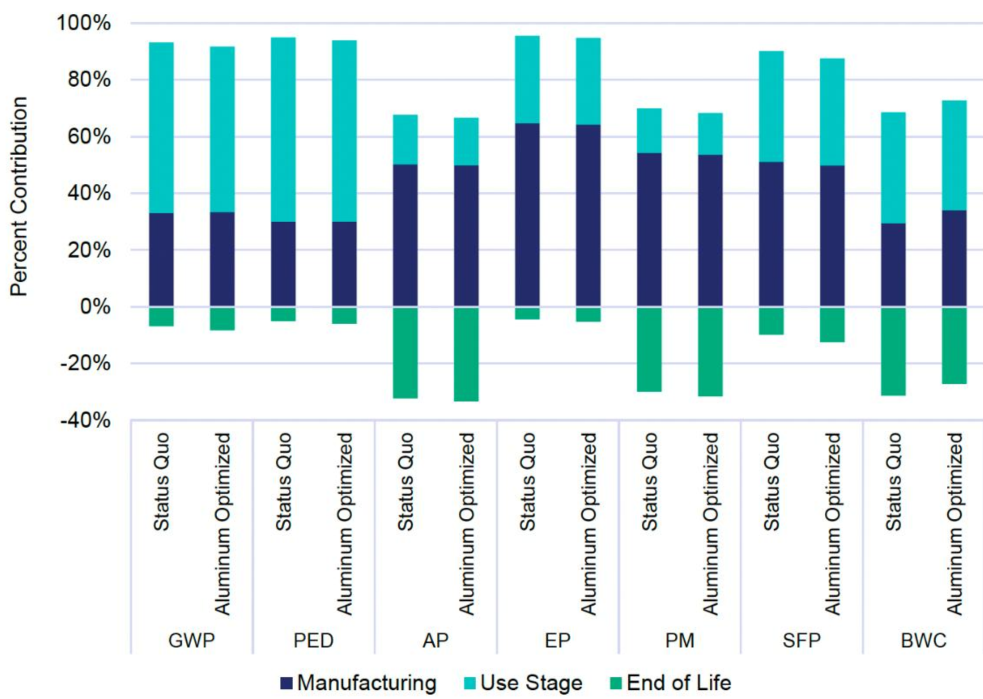
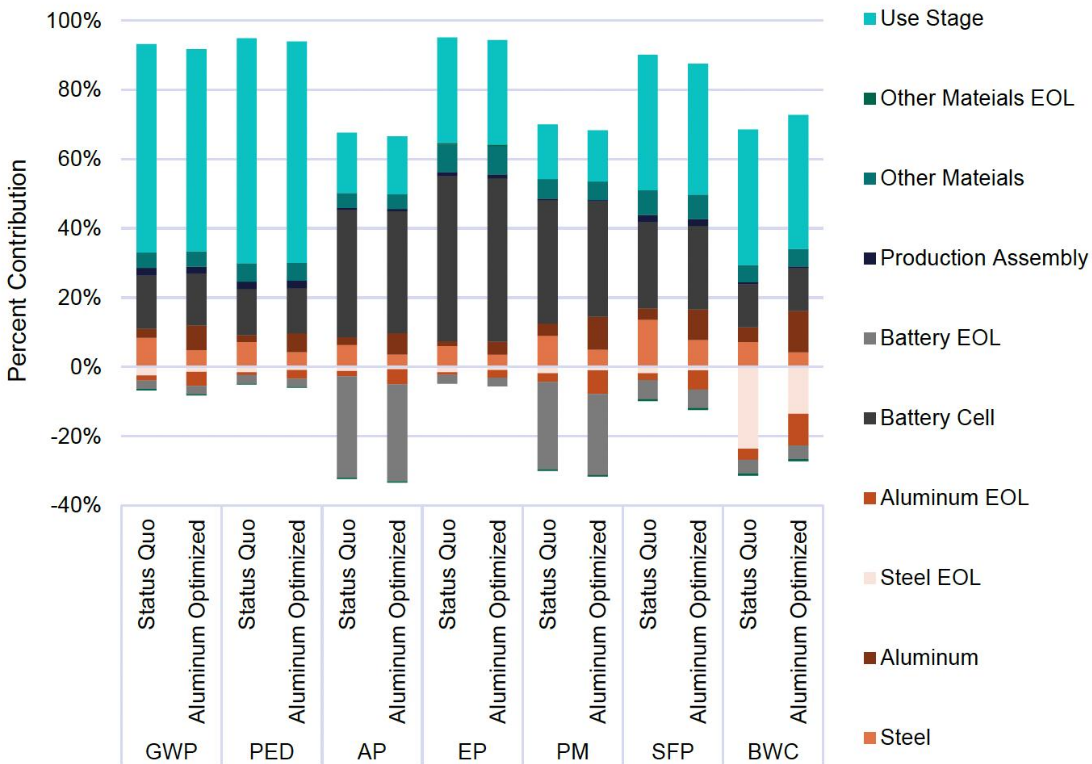


Figure 4-3 presents more detailed contributions from different material categories and life cycle stages to each environmental impact category for the model year 2025 designs for City Vehicles. The battery cells are the second largest contributor to GWP100 and PEDnr after the use stage. Battery cells also dominate other impact categories. The end-of-life treatment of steel, aluminum, and battery significantly reduces AP, PM, and BWC.

Figure 4-3: Cradle-to-grave City Vehicle results by main contributors in 2025



Similarly, Figure 4-4 shows the contributions of the main life cycle stages for the model year 2030 designs for City Vehicles. The use stage again dominates the GWP100 and PEDnr impacts due to emissions from electricity to charge the vehicles. Manufacturing contributes the most to other impact categories. End-of-life stage reduces the overall results, providing significant benefits to AP, PM, and BWC due to recycling of battery cells, steel, and aluminum while such reductions in other impact categories are less than 10%.

Figure 4-4: Cradle-to-grave City Vehicle results by main life cycle stage in 2030

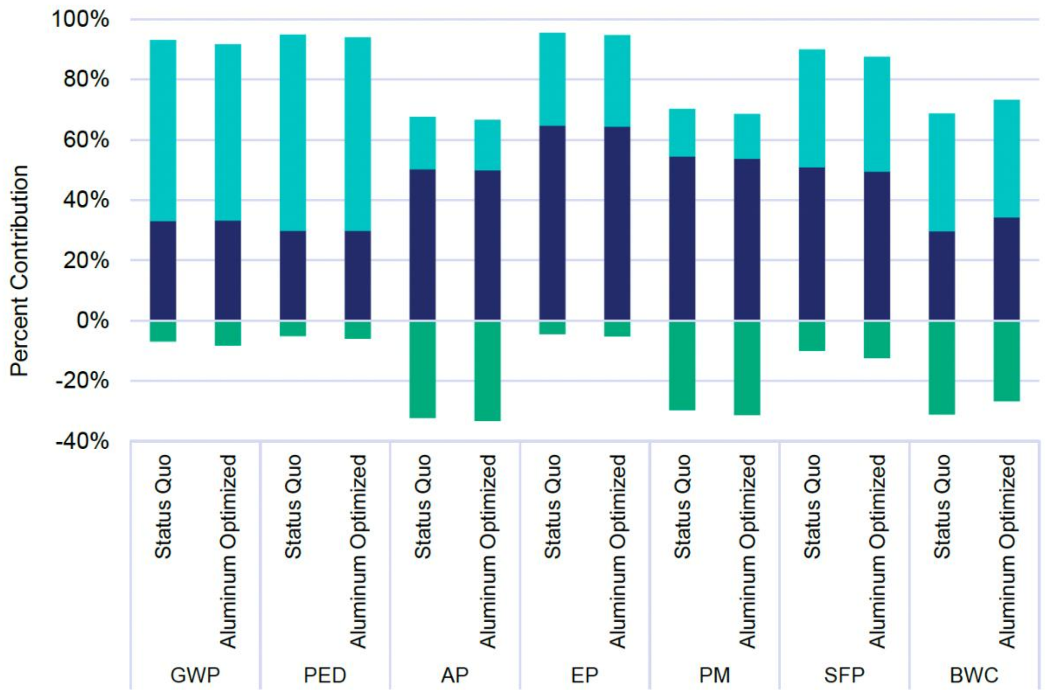
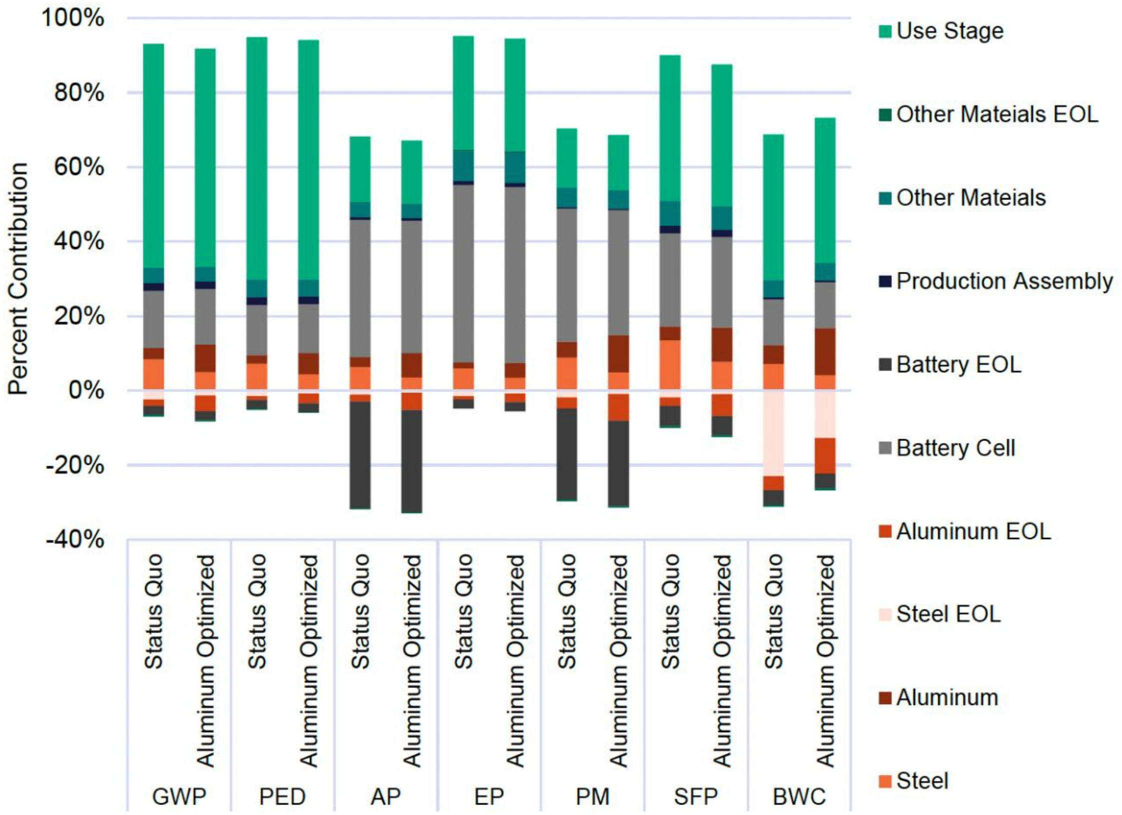


Figure 4-5 presents a more detailed contribution to each environmental impact category from different material categories and life cycle stages for the model year 2030 designs for City Vehicles. The battery cells are the second largest contributor to GWP100 and PEDnr after the use stage. It also dominates other impact categories. The end-of-life treatment of steel, aluminum, and battery significantly reduces AP, PM, and BWC.

Figure 4-5: Cradle-to-grave City Vehicle results of main contributors in 2030



4.2.2. Family Crossover Vehicles

A similar pattern of contributions to the cradle-to-gate impacts is observed for the Family Crossover vehicles. Figure 4-6 shows that at the production phase, battery cells are the most significant contributor to the environmental impacts. On the other hand, unlike the case of the City Vehicle, in which the aluminum-optimized designs help reduce the overall production phase footprint, this actually leads to a moderate increase in GWP100 despite some level of battery downsizing. When the battery cell production and assembly are excluded, Aluminum Optimization increases GWP100 by 8% and 17% for 2025 and 2030, respectively, compared to the Status Quo designs.

Figure 4-6: Cradle-to-gate GWP100 contribution analysis for Family Crossover vehicles

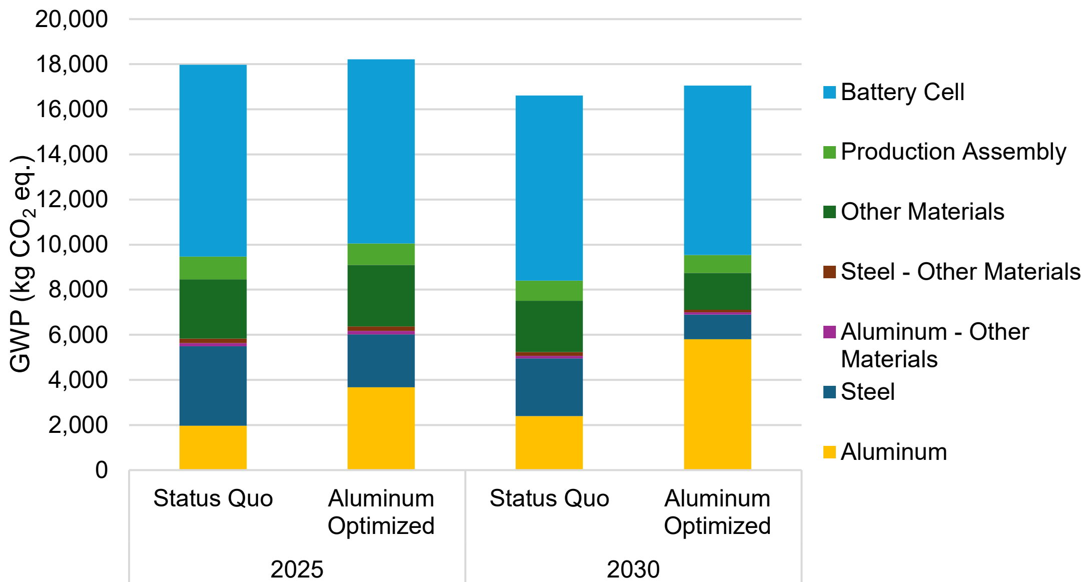


Figure 4-7 shows the contributions to the cradle-to-grave impacts of the main life cycle stages for the 2025 designs. Like the City Vehicles, the use stage dominates the GWP100 and PEDnr impacts due to emissions from electricity to charge the vehicles. Manufacturing contributes the most to other impact categories. The end-of-life stage reduces the life cycle totals via recycling credits, providing significant benefits to AP, PM, and BWC due to the recycling of battery cells, steel, and aluminum, while recycling-led reductions in other impact categories are less than 10%.

Figure 4-7: Cradle-to-grave Family Crossover vehicle results by main life cycle stage 2025

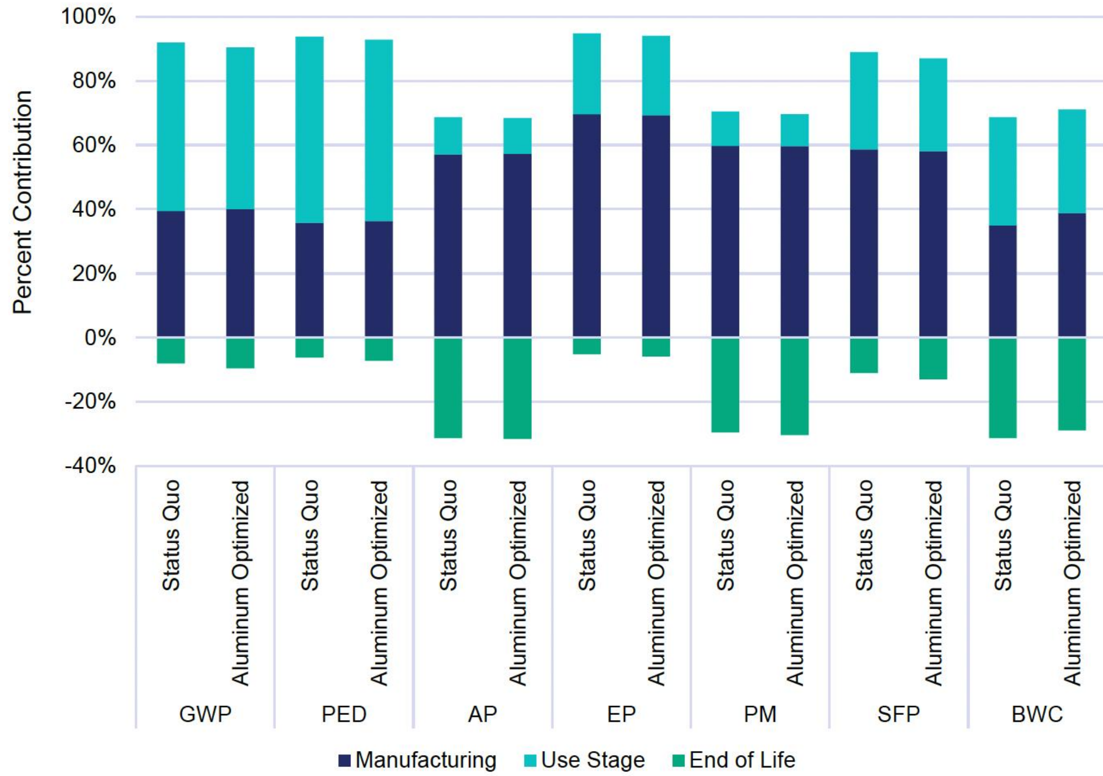


Figure 4-8 shows a more detailed contribution to the full life cycle impacts both by materials and by main life cycle stages for the 2025 Family Crossover vehicle designs. While the use stage dominates GWP100 and PEDnr, the production of battery cells is the second largest contributor to GWP100 and PEDnr, and the largest contributor to the other impact categories. The end-of-life recycling of batteries helps reduce impacts due to recycling credits, particularly for AP and PM.

Figure 4-8: Cradle-to-grave Family Crossover vehicle results by main contributors in 2025

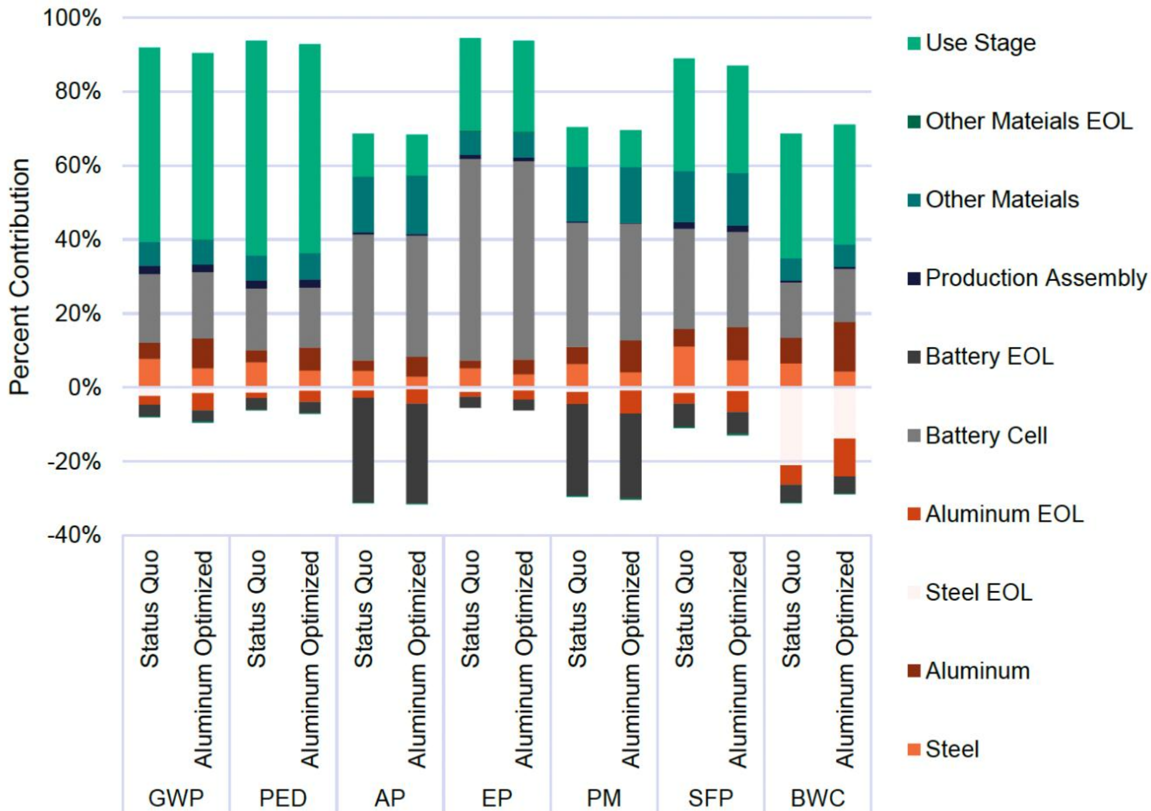
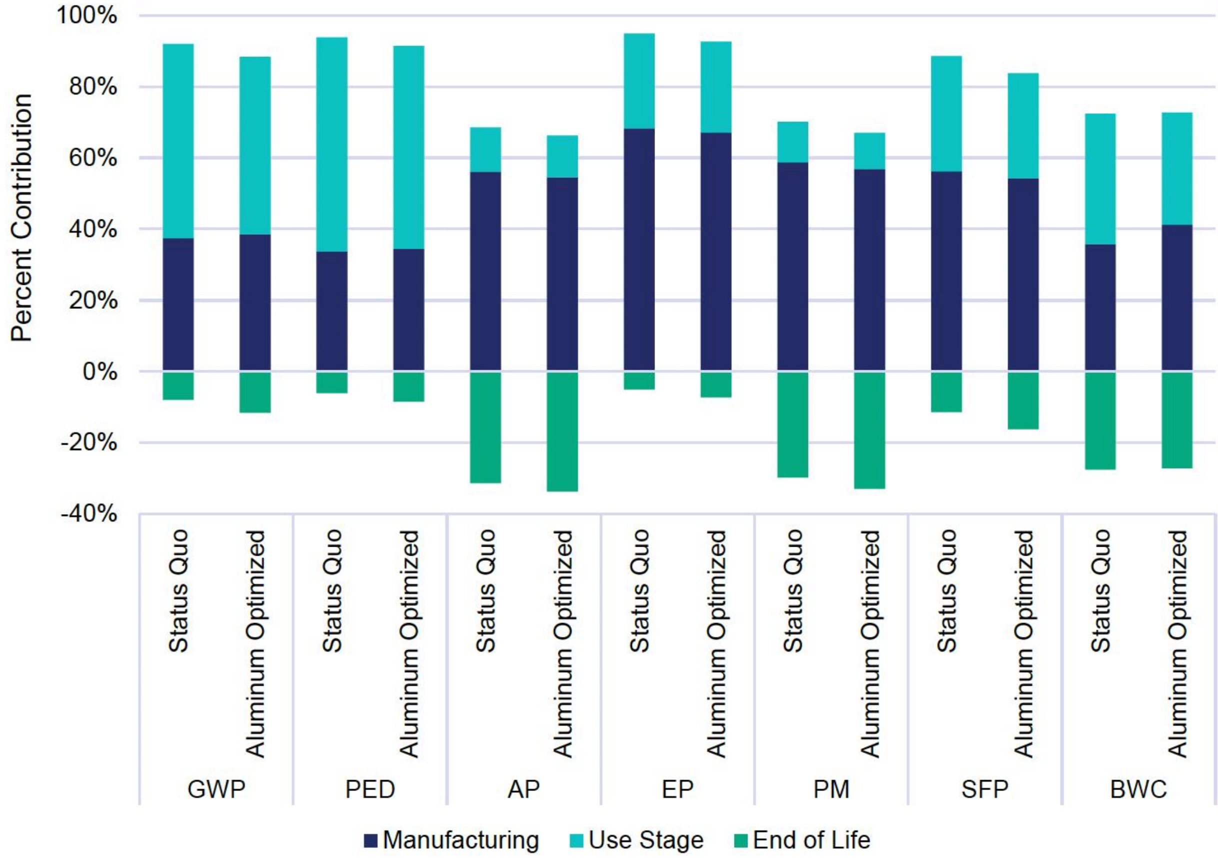


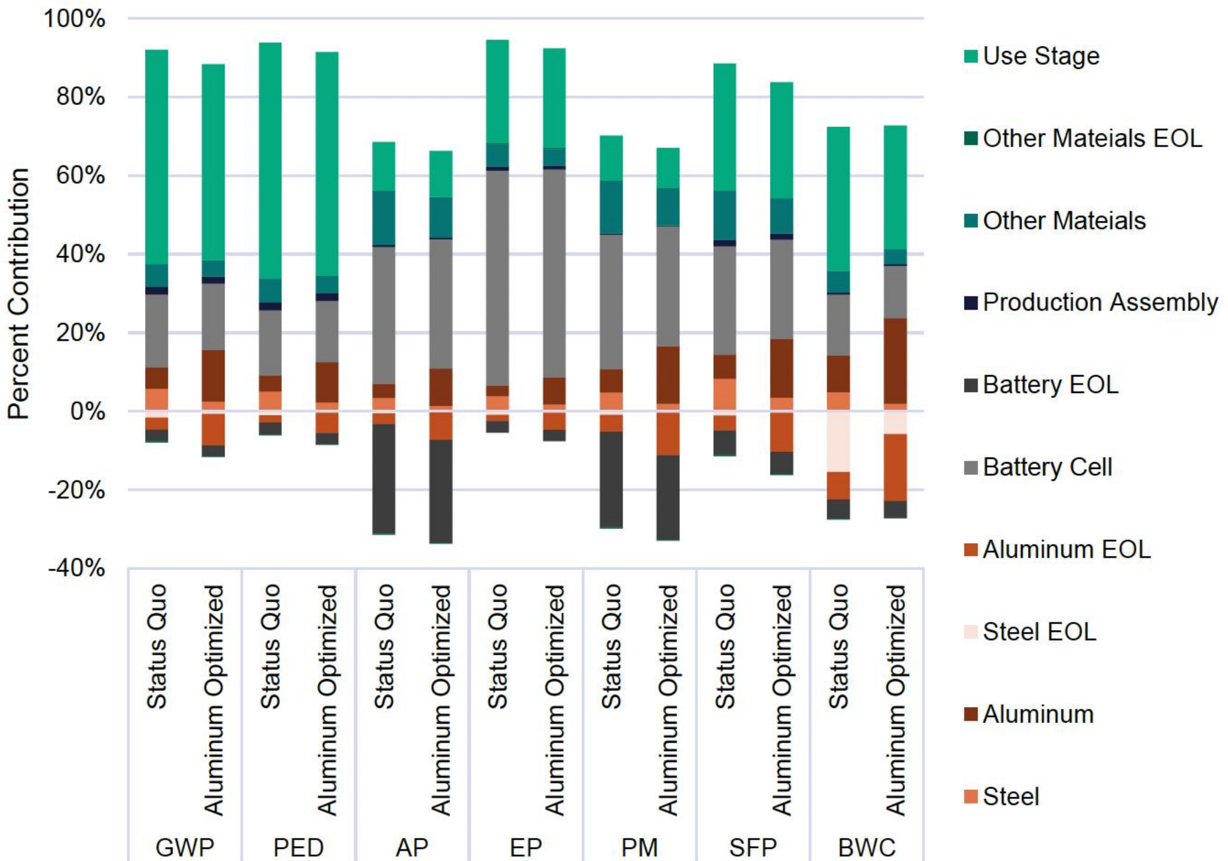
Figure 4-9 shows the contributions to the full life cycle impacts by the main life cycle stages for the 2030 Family Crossover vehicle designs. Like the 2025 designs, the use stage dominates the GWP100 and PEDnr impacts due to emissions from electricity to charge the vehicles. Manufacturing contributes the most to other impact categories. The end-of-life stage reduces the life cycle totals via recycling credits, providing significant benefits to AP, PM, and BWC due to the recycling of battery cells, steel, and aluminum while such recycling-credit-led reductions in other impact categories are less than 16%.

Figure 4-9: Cradle-to-grave Family Crossover vehicle results by main life cycle stage in 2030



Similarly, Figure 4-**0** shows a more detailed contribution from both materials and main life cycle stages to the full life cycle impacts for the 2030 Family Crossover vehicle designs. The pattern is the same as the model year 2025 designs.

Figure 4-10: Cradle-to-grave Family Crossover vehicle results by main contributors for 2030



4.3 Sensitivity Analysis

4.3.1. Lifetime Mileage

Since GWP100 was dominated by the use stage emissions, a sensitivity analysis on the impact of vehicle lifetime mileage was conducted. The GWP100 results are shown in Figure 4-41 and Figure 4-52 for City Vehicles and Family Crossover vehicles, respectively.

With each additional 50,000 miles driven during the vehicle lifetime, GWP100 increases by 20% for the City Vehicles and 18% for the Family Crossover vehicles. This indicates that absolute emissions rise with extended vehicle use. On the other hand, emissions are reduced per mile driven as the emissions from the production stage are distributed over more miles. This results in a lower average emissions rate per mile as shown in and

Figure 4-64 for City Vehicles and Family Crossover vehicles, respectively. The g CO_2 eq./mile GWP100 is reduced by 36% for City Vehicles and 31% for Family Crossover vehicles.

Figure 4-41: Sensitivity of lifetime GWP100 to City Vehicle lifetime mileage

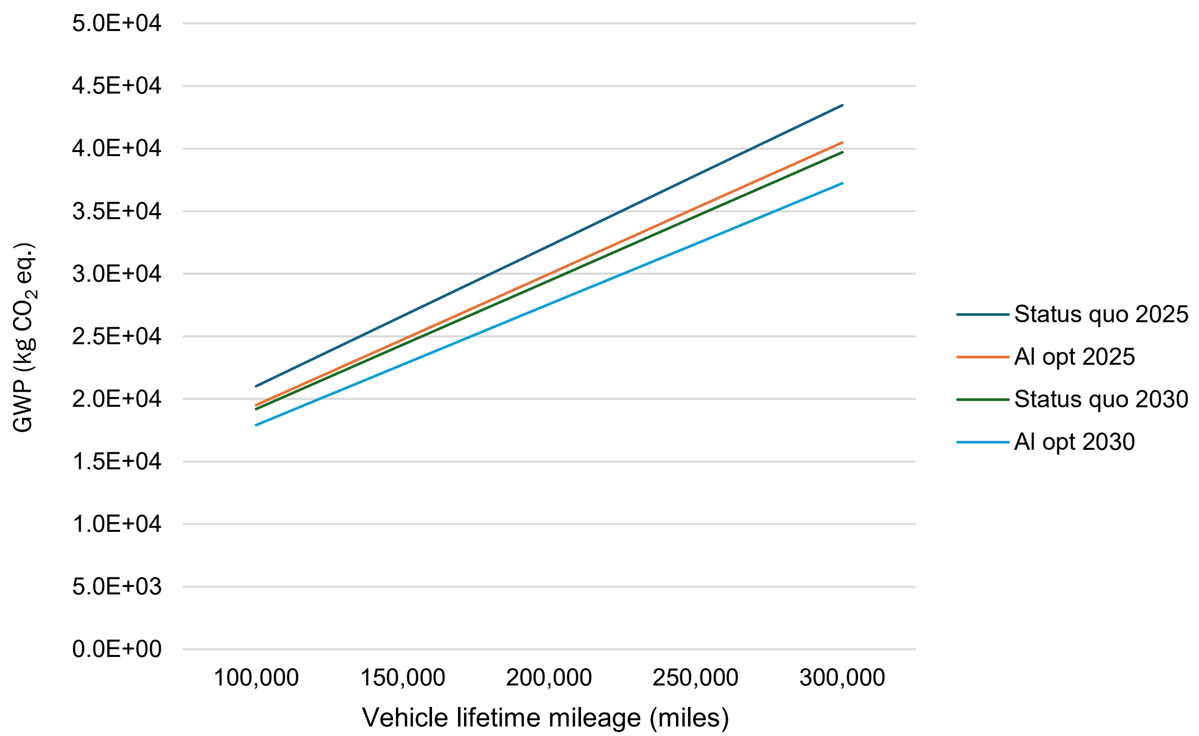


Figure 4-52: Sensitivity of lifetime GWP100 to Family Crossover lifetime mileage

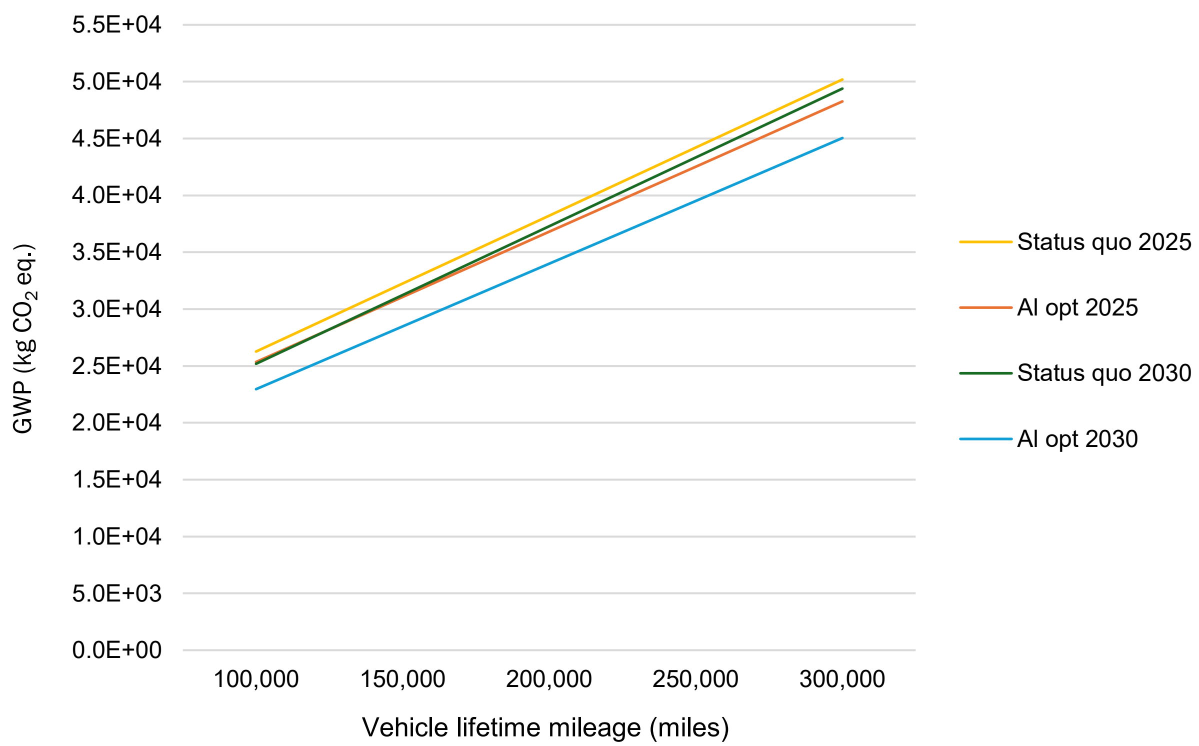


Figure 4-13: Sensitivity of GWP100 per vehicle mile to lifetime mileage for City Vehicles

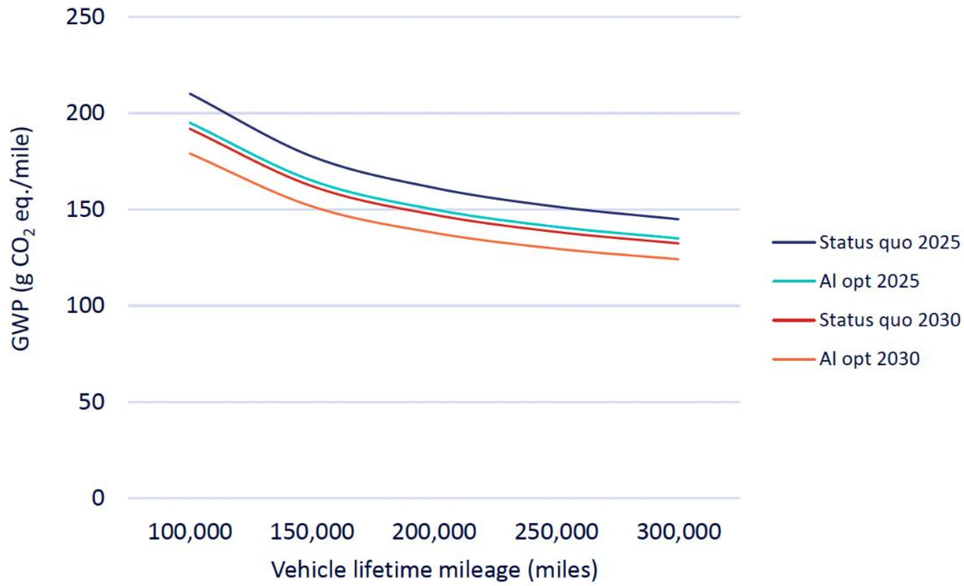
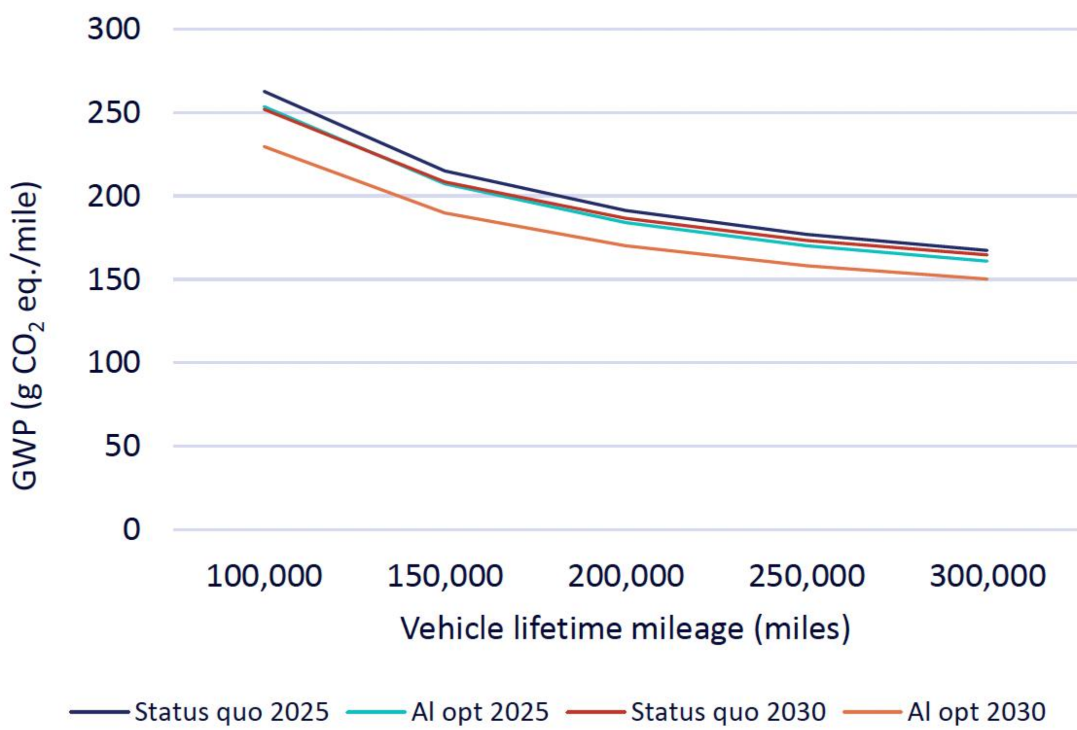


Figure 4-64: Sensitivity of GWP100 per vehicle mile to lifetime mileage for Family Crossovers



4.3.2. Aluminum and steel end-of-life recycling rate

This sensitivity analysis is conducted to evaluate how variations in end-of-life recycling rates for steel and aluminum affect the overall environmental impacts. Given the fact that the study takes a “Net Scrap” approach to deal with recycling allocation, manufacturing scrap is also part of the overall material balance. The analysis varies the EoL recycling rates for both materials at 0%, 50%, and 100%, and compares the findings against the benchmark recycling rate of 95%.

The results in Figure 4-15 and Figure 4-716 show that as the recycling rate decreases, there is an increase in the cradle-to-grave GWP100. The result of the 50% recycling rate scenario falls between those of the 0% and 100% recycling rate scenarios. When comparing the extreme cases, a 0% recycling rate shows a 7% to 15% increase in the total GWP value relative to the 100% recycling rate. This shows that higher recycling rates correspond to lower environmental impacts, with the 50% scenario representing the middle point between the two extremes.

Figure 4-15: City Vehicle sensitivity of total GWP for varying aluminum and stee end-of-life recycling

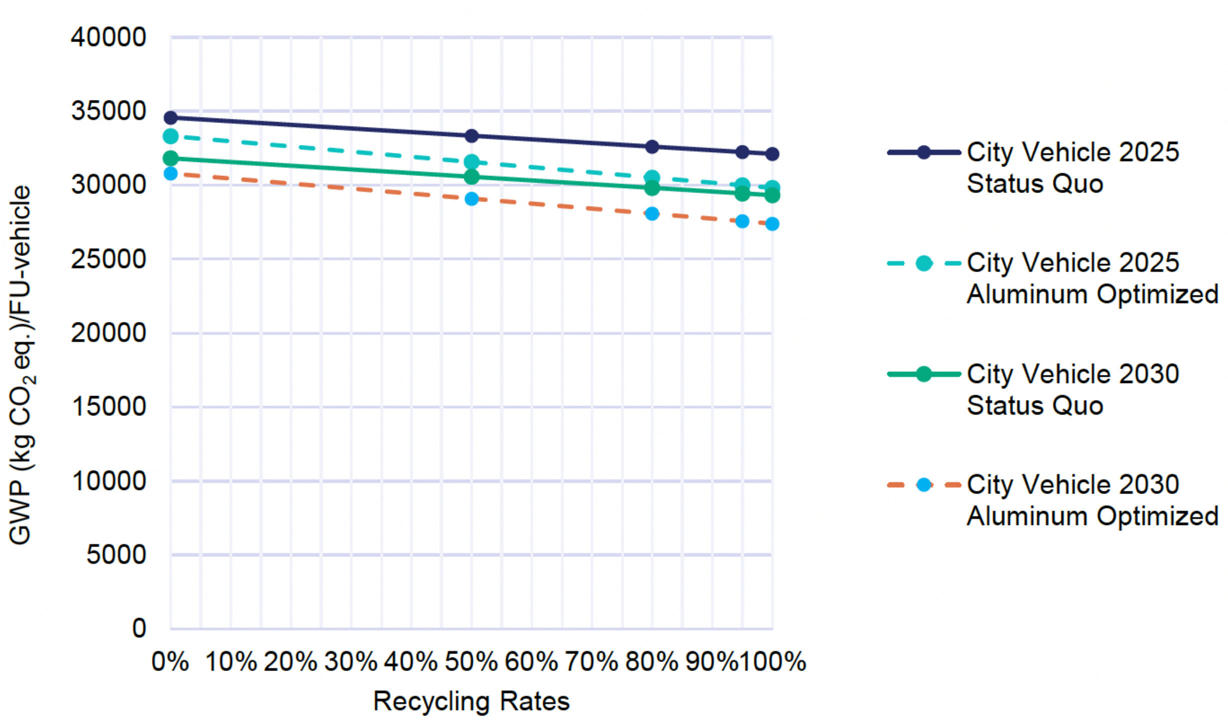
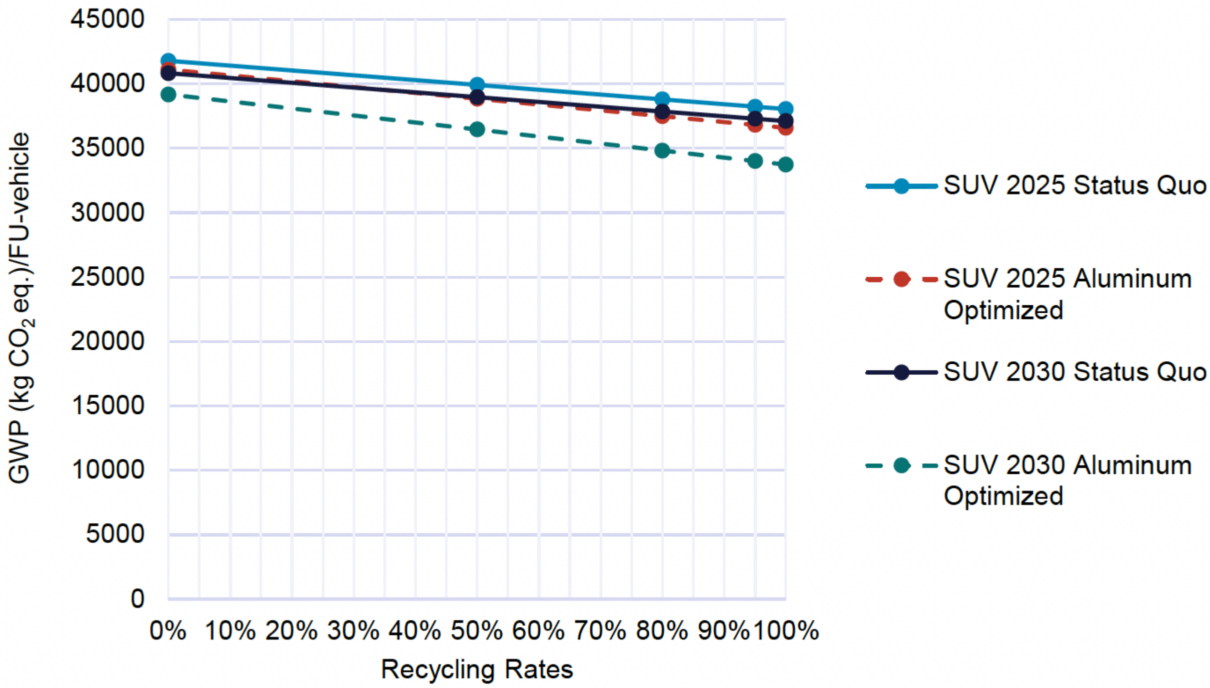


Figure 4-76: Family Crossover sensitivity of total GWP for varying aluminum and steel end-of-life rate

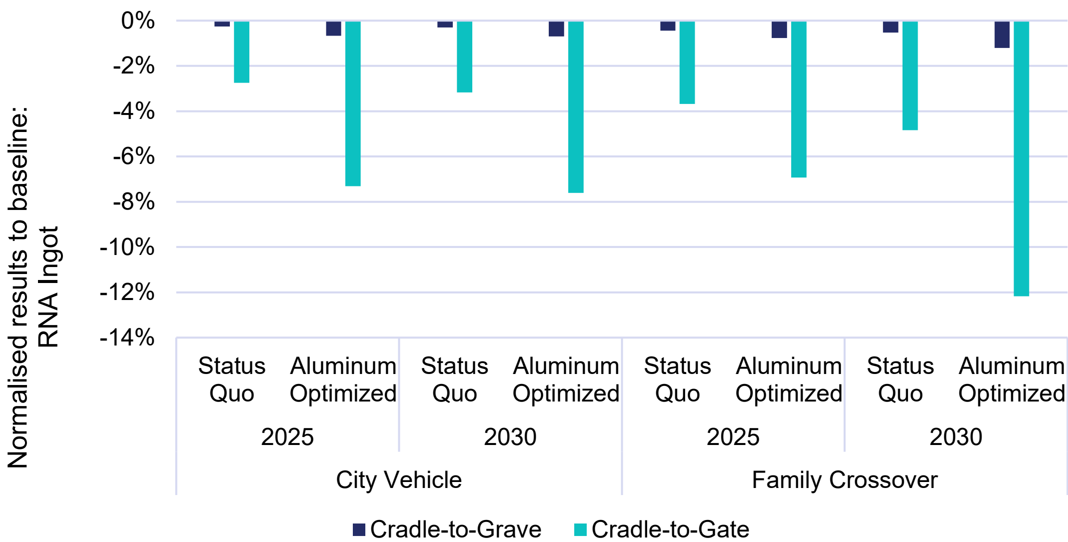


4.3.3. Low carbon footprint aluminum sensitivity analysis

A sensitivity analysis is conducted to evaluate the impact of using low-carbon aluminum by applying the Canadian primary ingot dataset instead of the Region North America (RNA) dataset. Canadian aluminum is produced from hydropower electricity and is among the lowest carbon footprint primary aluminum. The RNA primary aluminum consumption mix dataset contains not only Canadian aluminum but also metals produced in the U.S. and several other countries and regions. The footprint of the Canadian primary ingot is 38% lower than that of the NA consumption mix.

This analysis is solely focused on what low carbon footprint material is available in today's market, and the adoption of such materials wouldn't lead to technological challenges that could compromise the quality and safety of the vehicles. It intends to understand how such a change in material sourcing would affect the overall cradle-to-grave environmental impact. Figure 4-17 indicates that substituting the RNA primary aluminum with the Canadian primary ingot has had a minimal effect on the total cradle-to-grave GWP100 impact. However, at the production stage for the City Vehicle, there is a reduction in the GWP100 impact by 3% for Status Quo and 7% for Aluminum Optimized in 2025, and 3% for Status Quo and 8% for Aluminum Optimized in 2030. For the Family Crossover, the reduction in production stage is 4% for the Status Quo and 7% for the Aluminum Optimized in 2025, increasing to 5% and 12%, respectively, in the 2030 scenarios. This suggests that while the overall lifecycle impact remains largely unchanged, sourcing low-carbon aluminum can reduce GWP100 in the production stage.

Figure 4-17: Sensitivity of GWP100 to using low-carbon Canadian primary aluminum ingots



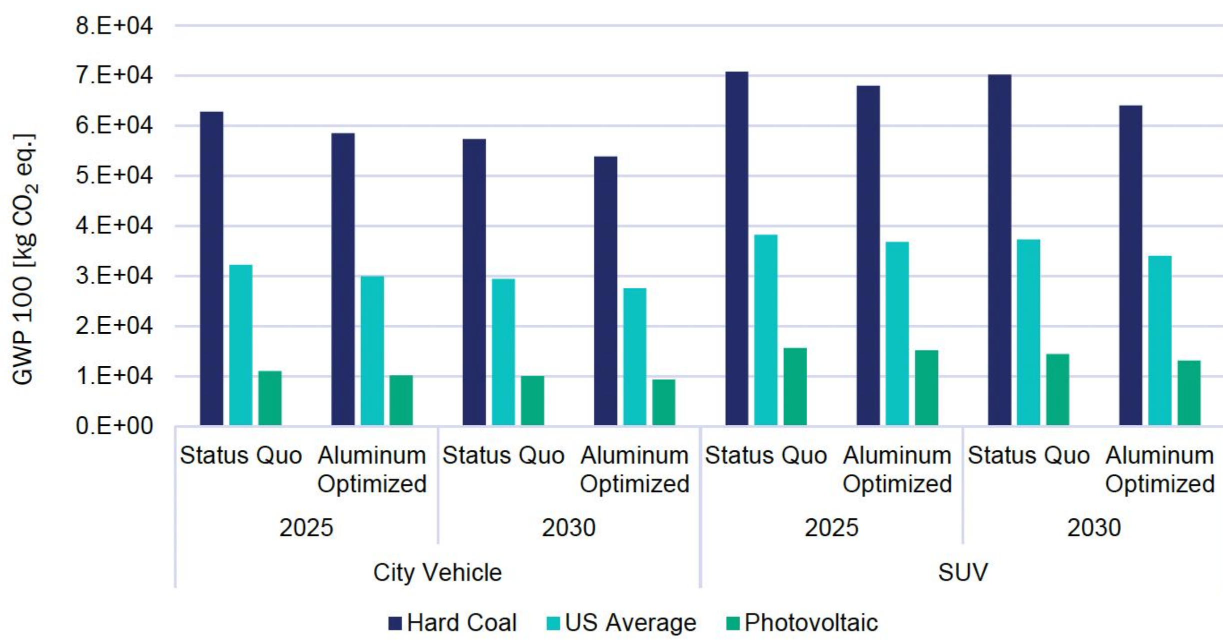
While automotive aluminum product manufacturers can choose to source lower carbon primary aluminum that is both available in the current market and won't lead to any technological challenges at their facilities, the same is not true for steel automotive product manufacturers. The North American primary steel (blast furnace/blast oxygen furnace steel) has already had a low emission intensity compared to the rest of the world. A lower emission intensity steel, which is largely recycled steel based on the electric arc furnace (EAF) technology, has a limited application in automotive manufacturing. It is estimated that less than 10% of automotive applications use EAF steel. For these reasons, this sensitivity analysis does not include low carbon steel as a scenario.

4.3.4. Source of electricity for vehicle charging

Figure 4-18 highlights how a change in the source of electricity for BEV charging could impact the life cycle emissions of the vehicles. From the absolute emission quantity point of view, switching electricity from the US average grid mix to electricity generated by hard coal would lead to an increase in GWP100 by approximately 95% for City Vehicles across all model years and all design scenarios. For Family Crossover vehicles, the increase in GWP100 would be approximately 85% for the 2025 model year design scenarios, and 88% for the 2030 model year designs. If electricity is switched from the US average grid to renewable source generated electricity such as solar, the GWP100 would be reduced by approximately 66% for City Vehicles across all model years and all designs. Similarly, for Family Crossover vehicles, the GWP100 reduction would be 59% for the 2025 model year designs and 61% for the 2030 model year designs.

On the other hand, from a design comparison point of view, which is the goal of this study, a change in the source of charging electricity for BEVs does not lead to any change in the lower environmental impact of Aluminum Optimized designs compared to the Status Quo designs for both vehicle types and both model years. This is largely due to the fact that the increase or decrease in overall emissions as a result of the source change is unanimous, i.e., it is the same percentage of increase or decrease between the Aluminum Optimized and Status Quo designs. Of course, higher or lower emission electricity will change the relative shares of impacts among different life cycle stages, with hard coal electricity significantly reducing the share of impacts during the vehicle production phase, and renewable sourced electricity significantly increasing the share of vehicle production phase impacts.

Figure 4-18: Sensitivity of GWP 100 as a result of change in electricity sources



4.4 Scenario Analysis

The study considers the embodied burden approach, substituting the recycled materials with credits. To understand the impact considering the cut-off approach, a scenario analysis is conducted using the cut-off approach that excludes end-of-life (EOL) recycling credits.

Figure 4-19 and 4-20 show that the results remain consistent between the two approaches with the total impact dominated by the use stage and battery cell. The cut-off approach GWP100 results for city vehicles are 9% to 10% higher compared to the substitution approach, reflecting the impact of removing recycling credits. Similarly, for the family crossover, the GWP100 results are 10% to 14% higher than the substitution approach.

Figure 4-19: Comparison of GWP for city vehicles between embodied burden and cut-off approaches

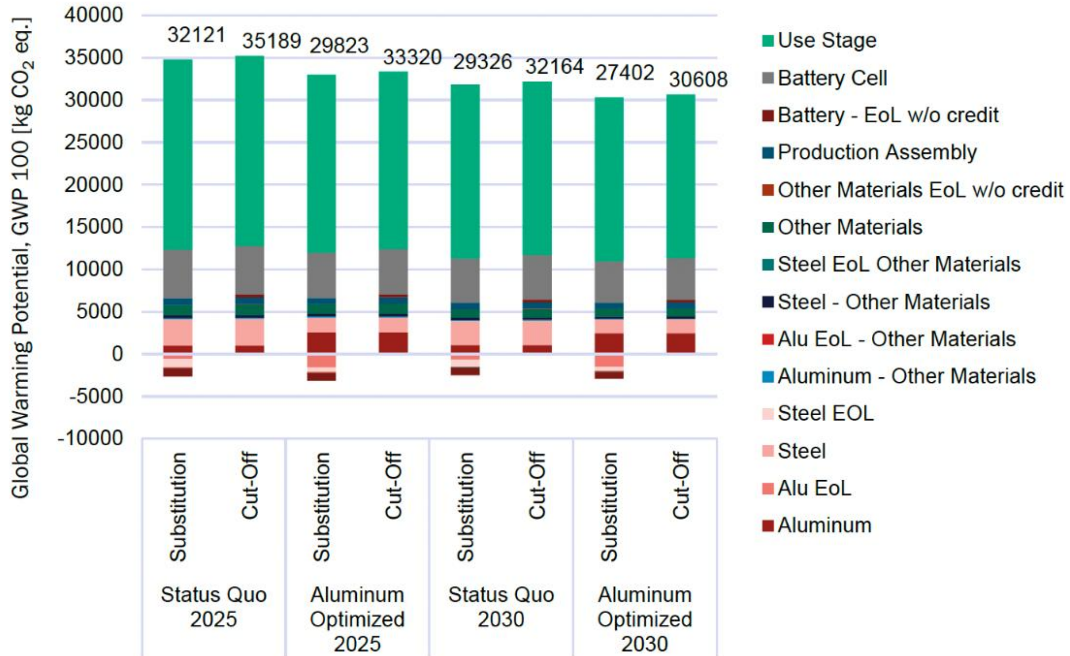
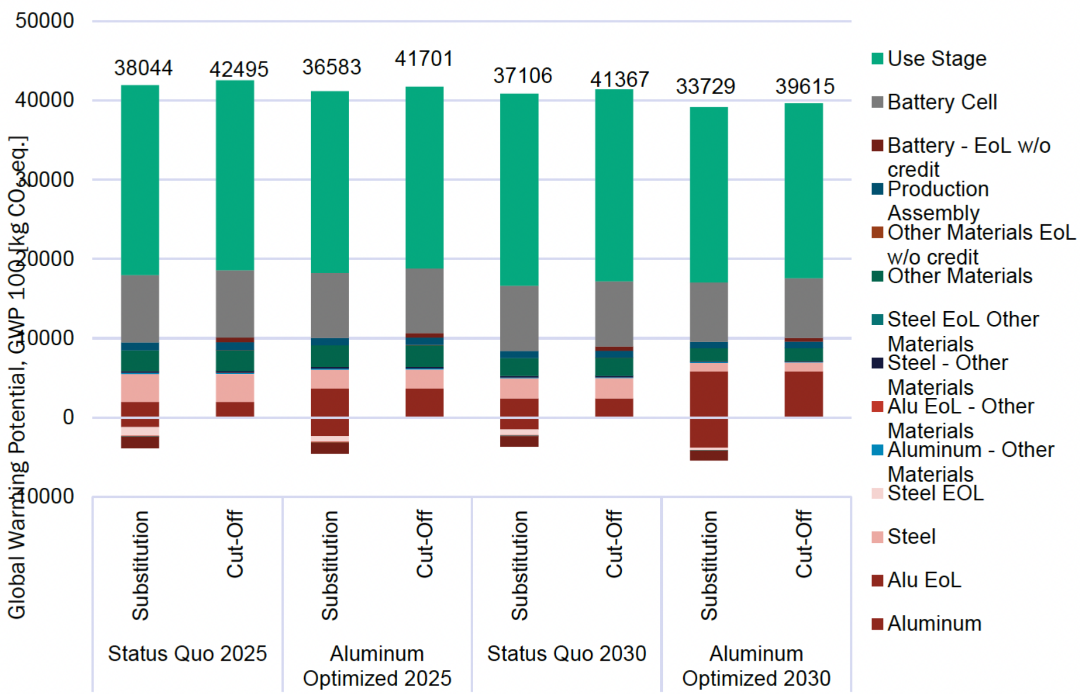


Figure 4-20: Comparison of GWP for family crossover between embodied burden and cut-off approaches



4.5 Uncertainty Analysis

The contribution, scenario, and sensitivity analyses provide an understanding of the key uncertain parameters used in the model. The study shows that compared to the Status Quo, the Aluminum Optimized reduces GWP100 by 7% for City vehicles in 2025 and 6% in 2030. For Family Crossovers, the reduction is 4% in 2025 and 9% in 2030.

The contribution analysis indicated that the improvements offered by Aluminum Optimized over the Status Quo are primarily driven by the use phase energy consumption and the down-sizing of battery as well as recycling credits. In the scenarios studied, Aluminum Optimized options of both the vehicle types for the model years 2025 and 2030 performed better in terms of GWP, PED, AP, EP, PM except BWC.

The sensitivity analyses further examined how the impacts are affected by every additional 50,000 miles driven during the vehicle's lifetime. The results showed that absolute emissions increase with longer use; however, emissions per mile driven decrease as the high emissions from the production stage are distributed over more miles, resulting in a lower average emissions rate per mile. Additionally, the varying recycling rate of aluminum at the EOL revealed that changing the collection rate of aluminum from 95% to 80% increases GWP100 by less than 2%. The third sensitivity analysis evaluated the impact of using low-carbon aluminum by substituting the Canadian primary ingot dataset for the Region North America (RNA) dataset. This substitution had a minimal effect on the total cradle-to-grave GWP100 impact, although, a reduction in GWP100 was observed at the production stage of both vehicle types considered.

Overall, the cradle-to-grave analysis shows that increasing the aluminum content in vehicles reduces environmental impacts and provides benefits at the end of life. Therefore, the analysis's results appear to be relatively robust despite uncertainties in key modelling parameters and assumptions, specifically mileage, aluminum and steel recycling rates, and aluminum carbon footprint.

5. Interpretation

5.1 Identification of Relevant Findings

The study compares the cradle-to-grave potential environmental impacts of Status Quo and Aluminum Optimized designs for City and Family Crossover vehicles for model years 2025 and 2030. The study examines how increasing the aluminum content relative to steel in BEVs affect their environmental performance through vehicle lightweighting, electric motor downsizing, and drivetrain optimization.

Across all scenarios, the results indicate that, compared to the Status Quo scenario, the Aluminum Optimized City Vehicle designs reduce GWP100 by 7% in 2025 and 6% in 2030. The reduction in GWP100 between the 2025 Status Quo and the 2030 Aluminum Optimized designs is 14%. For Family Crossover vehicles, the reduction in GWP100 from the Aluminum Optimized designs is 4% in 2025 and 9% in 2030, respectively. The reduction between the 2025 Status Quo and the 2030 Aluminum Optimized designs is 11%.

The use stage accounts for 62% to 70% of GWP100 due to emissions from electricity generation to charge the BEVs. Manufacturing contributes the most to other impact categories, while recycling at the end-of-life stage significantly reduces AP, PM, and BWC due to material recovery from the battery cells, steel, and aluminum.

Overall, the cradle-to-grave analysis shows that increasing aluminum content relative to steel in the vehicles reduces the total environmental impacts if the weight savings are leveraged to reduce battery and electric motor size and improve fuel economy rather than to maximize range and vehicle performance.

5.2 Assumptions and Limitations

Three main limitations were identified including the granularity of data, the temporal scope of data and the factors affecting the vehicle performance. Data granularity limitation refers to the reliance of the study on high-level material composition data from a prior FEV report rather than more granular vehicle component level data. The material composition of the “Other Materials” category is based on data extrapolation from research papers of the GREET studies (Burnham, July 2012), (Chris Hart, 2021), (Kelly, October, 2022). Temporal scope limitation refers to the use of material and vehicle production data of the present to assess the potential environmental impacts of vehicle designs for the “future” – the 2025 and 2030 model years. Lastly, the vehicle designs are adopted from the FEV study in which a preselected set of performance parameters such as acceleration, top speed, e-drive range, and battery capacity. Any change in such preselected parameters in design could have a significant impact on the results.

Addressing these data limitations would help shed light on details in designs for lightweighting. However, this is beyond the technical and financial capacity of the LCA study. All we can do here is to caution readers to keep in mind about these limitations.

5.3 Results of Sensitivity, Scenario, and Uncertainty Analysis

5.3.1. Sensitivity Analysis

Four sensitivity analyses were performed to test the sensitivity of the GWP100 results to changes in lifetime mileage, steel and aluminum recycling rates, low-carbon aluminum using the Canadian primary ingot, and source of electricity for vehicle charging. Lifetime mileage analysis shows that as vehicles are driven an additional 50,000 miles, GWP100 increases by 20% for City Vehicles and 18% for Family Crossovers, indicating that absolute emissions rise with longer use. However, emissions per mile decrease because the production emissions are spread over more miles. The average emissions rate per mile is reduced by 36% for City Vehicles and 31% for Family Crossovers. This highlights that maximizing vehicle utilization will reduce average emissions per mile.

Further sensitivity analyses on steel and aluminum recycling rates show that increasing recycling rates will reduce GWP100 while decreasing recycling rates will increase GWP100. For instance, changing the recycling rates of aluminum and steel from 95% to 80% would increase the lifetime GWP100 by less than 2%.

The sensitivity analysis using low-carbon aluminum of the Canadian primary ingot dataset to replace the North American consumption mix dataset shows a minimal effect on the total cradle-to-grave GWP100 and other impact categories. However, it does reduce production-related GWP100 for City Vehicles by 3% for Status Quo and 7% for Aluminum Optimized in 2025, and 3% for Status Quo and 8% for Aluminum Optimized in 2030. For Family Crossover vehicles, the reduction in production stage impact is 4% for the Status Quo and 7% for the Aluminum Optimized in 2025, increasing to 5% and 12%, respectively, in the 2030 scenarios.

Finally, a change of the source of electricity for vehicle charging leads to significant changes in life cycle GWP100. For instance, switching from the US average power mix to coal-fired power would almost double the total emissions. On the other hand, switching from U.S. average power mix to renewable energy power would cut the total emissions by more than half.

While the change of these sensitivity parameters alters the absolute life cycle GWP100 and other impact categories, from a design comparison point of view, which is the goal of this study, the conclusions won't be affected. The Aluminum Optimized designs still have lower overall potential environmental impacts compared to the Status Quo designs for both vehicle types and both model years.

5.4 Data Quality Assessment

Inventory data quality is judged by its precision (e.g. measured, calculated, or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent background LCA information from the Managed LCA Content (MLC, 2024.1) database were used. The LCI datasets from the Managed LCA Content (MLC, 2024.1) database are widely distributed and used with Sphera's LCA FE 10.9 Software. The datasets have been used in LCA models worldwide, in industrial and scientific applications as well as in many critically reviewed and published studies. In the process of providing these datasets, they are cross-checked with other databases and values from industry and science.

5.4.1. Precision and Completeness

- ✓ **Precision:** As the majority of the relevant foreground data are measured data or calculated based on primary information sources of the owner of the technology, precision is considered to be moderately high. All background data are sourced from Managed LCA Content (MLC) databases with documented precision.
- ✓ **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data is considered to be high. All background data are sourced from Managed LCA Content (MLC) databases with documented completeness.

5.4.2. Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail. All background data were retrieved from the Managed LCA Content (MLC) databases which is obtained from various sources including Sphera, The Aluminum Association (AA), American Iron and Steel Institute (AISI), European Steel Association (EUROFER), International Aluminum Institute (IAI), and International Lead Association (ILA).
- ✓ **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modelling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modelling approaches.

5.4.3. Representativeness

- ✓ **Temporal:** All primary data were based on a previous FEV study, which used fleet data from 2021 to simulate designs for 2025 and 2030. All secondary data come from the Managed LCA Content (MLC, 2024.1) and are representative of the years 2017-2023. The study is intended to compare product systems that are simulated by experts for the future based on current data; hence, the background processes are not a prospective representation of the future.

- ✓ **Geographical:** All primary and secondary data were collected specific to the countries or regions under study. Where country-specific or region-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be high.
- ✓ **Technological:** All primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is considered to be high.

5.5 Model Completeness and Consistency

5.5.1. Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete and detailed with regards to the goal and scope of this study.

5.5.2. Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimized by exclusively using LCI data from the Managed LCA Content (MLC, 2024.1) databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.6 Conclusions, Limitations, and Recommendations

5.6.1. Conclusions

The study evaluates the potential life cycle environmental impacts of two design scenarios – Status Quo and Aluminum Optimized – for two types of BEVs for 2025 and 2030: City Vehicle and Family Crossover. The study explores how vehicle lightweighting solutions through increasing aluminum content and battery optimization affect environmental impacts. It excluded other factors affecting its performance such as the motor conditions and aerodynamics.

The result of the study indicates that Aluminum Optimized BEVs help reduce the GWP100 by 7% for 2025 and 6% for 2030 for City Vehicles, and by 4% for 2025 and 9% for 2030 in Family Crossovers. The use stage is the largest contributor to GWP100 and PEDnr across all scenarios due to emissions from electricity to charge the vehicles. Manufacturing contributes the most to other impact categories, while the end-of-life stage helps significantly reduce AP, PM, and BWC due to the recycling of battery, steel, and aluminum.

The BEVs are promising transportation means, however, their advantage over conventional vehicles is highly dependent on the grid used to charge them. Therefore, increasing the share of renewable energy sources is a major factor in the future environmental impact of battery vehicles. Overall, the cradle-to-grave analysis shows that increasing aluminum content in the vehicle reduces impacts and provides benefits at the end-of-life recycling.

5.6.2. Limitations

There are three key factors that significantly contribute to improved vehicle performance and achieving an increase in range for BEVs: aerodynamics (air resistance and stability), engine/motor condition (power and efficiency), and vehicle weight (impact on acceleration and fuel economy). This study, however, only examined the impact of vehicle weight (lightweighting), as per the FEV Study. As such, the results of this LCA are valid for the assumptions made by the FEV. While they provide valuable insights, they cannot be generalized to represent all aluminum-based designs. Specific vehicle designs should be assessed on a case-by-case basis.

Finally, datasets adopted in this study for steel products do not fully reflect the consumption mix in the North American region. Absence of imported steel from other regions could have some effect to the results, both at the production stage and at the EOL recycling stage.

5.6.3. Recommendations for BEV lightweighting

The study could be improved by using more specific data at the component level of the vehicles such as steel, aluminum, and other specific material content in each of the body, chassis, powertrain, and battery systems.

References

(2022). Retrieved from aluminum.org: https://www.aluminum.org/autos-fastest-growing-material-era-electrification

AISI. (2021). *A Life Cycle Assessment Report: "Life Cycle Inventories of North American Steel Products , American Iron and Steel Institute"*. AISI.

Bare, J. (2012). *Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) - Software Name and Version Number: TRACI version 2.1 - User's Manual*. Washington, D.C.: U.S. EPA.

BatPaC 3.1 by Argonne National Laboratory. (2018). *Composition of battery based on BatPaC 3.1 (BatPaC: Battery Manufacturing Cost Estimation - A software tool designed for policymakers and researchers, Version 3.1*.

BSI. (2012). *PAS 2050-1:2012: Assessment of life cycle greenhouse gas emissions from horticultural products*. London: British Standards Institute.

Burnham, A. (July 2012). *Updated Vehicle Specifications in the GREET Vehicle-Cycle Model*. Argonne National Laboratory.

Chris Hart, A. A. (2021). *The Value of ALuminum Llight Weighting in Battery ELectric Vehicles.*

Dai, Q. S. (2019). *EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model.Argonne National Laboratory. Retrived from https://publications.anl.gov/anlpubs/2019/07/153050.pdf*.

Dai, Q., & Dunn, J. C. (2019). *Energy consumption cell manufacturing (incl. battery assembly): Update of Life Cycle Analysis of Lithium-ion Batteries in the GREET Model, Argonne National Laboratory, September 2017*.

Ducker Calisle. (2023). *Ducker ATG 2023 Summary Report*. Retrieved from drivealuminum.org: https://drivealuminum.org/wp-content/uploads/2023/05/Ducker-ATG-2023-Summary-Report-April-2023.pdf

Ducker Frontier. (2020, July). *2 0 2 0 North America Light Vehicle Alumnium Content and Outlook*. Retrieved from drivealuminum.org: https://drivealuminum.org/wp-content/uploads/2022/05/DuckerFrontier-Aluminum-Association-2020-Content-Study-Summary-Report-FINAL.pdf

EPA & DOT. (2012, October 15). *2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule*. Retrieved from Federal Register, 77(199), 62623-63000. Washington, DC: https://www.govinfo.gov/content/pkg/FR-2012-10-15/pdf/2012-21972.pdf

EPA. (2012). *Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) – User's Manual*. Washington, D.C.: U.S. EPA.

FEV Group. (2022). *Aluminum Value in Battery Electric Vehicles*. Retrieved from https://drivealuminum.org/wp-content/uploads/2022/05/FINAL_The-Value-of-Aluminum-Light-Weighting-in-Battery-Electric-Vehicles.pdf

Graedel, T., & Reck, B. (2015). Six Years of Criticality Assessments - What Have We Learned So Far? *Journal of Industrial Ecology*. doi:10.1111/jiec.12305

Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., . . . Huijbregts, M. (2002). *Handbook on life cycle assessment. Operational guide to the ISO standards*. Dordrecht: Kluwer.

IPCC. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 - Agriculture, Forestry and Other Land Use.* Geneva, Switzerland: IPCC.

IPCC. (2021). *Climate Change 2021: The Physical Science Basis.* Geneva, Switzerland: IPCC.

ISO. (2006). *ISO 14040: Environmental management – Life cycle assessment – Principles and framework*. Geneva: International Organization for Standardization.

ISO. (2006). *ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines.* Geneva: International Organization for Standardization.

J.C. Kelly, a. O. (October, 2020). *Update of Vehicle Material Compositions in the GREET® Mode.* Argonne National Laboratory.

J.L. Sullivan, A. B. (2010). *Energy-Consumption and Carbon-Emission Analysis of Vehicle and Component Manufacturing; https://publications.anl.gov/anlpubs/2010/10/68288.pdf.* Argonne National Laboratory.

JRC. (2010). *ILCD Handbook: General guide for Life Cycle Assessment – Detailed guidance. EUR 24708 EN* (1st ed.). Luxembourg: Joint Research Centre.

Kelly, R. I. (October, 2022). *Updates to Vehicle-Cycle Inventory for Select Components of Light-Duty, Medium-Duty, and Heavy-Duty Vehicles.* Argonne National Laboratory.

Koffler, C., & Finkbeiner, M. (2018). Are we still keeping it “real”? Proposing a revised paradigm for recycling credits in attributional life cycle assessment. *Springer Nature*.

Life Cycle Initiative. (2017). *Global Guidance for Life Cycle Impact Assessment Indicators Volume 1.*

Nakata, F. E. (2020). Energy Consumption Analysis for Vehicle Production. MDPI www.mdpi.com/journal/energies.

Nassar, N., Barr, R., Browning, M., Diao, Z., Friedlander, E., Harper, E., . . . Graedel, T. (2012). Criticality of the Geological Copper Family. *Environmental Science & Technology*, 1071-1078.

Sphera Solutions Inc. (2020). *GaBi LCA Database Documentation*. Retrieved from GaBi Solutions: https://www.gabi-software.com/databases/gabi-databases/

Sphera Solutions Inc. (2024). *LCA Database Documentation. Retrieved from Sphera Solutions, Inc.: https://sphera.com/solutions/product-stewardship/life-cycle-assessment-software-and-data/managed-lca-content*.

UNICEF/WHO. (2019). *Progress on drinking water, sanitation and hygiene: 2000-2017: Special focus on inequalities*. New York: United Nations Children's Fund (UNICEF) and World Health Organization.

Wang, M. J. (2022). *A Life Cycle Assessment Repot: "The Environmental Footprint of Semi-Fabricated Aluminum Products in North America"*. The Aluminum Association.

Worldsteel Association. (2021, May). *Life cycle inventory (LCI) study - 2020 data release*. Retrieved from worldsteel.org: https://worldsteel.org/wp-content/uploads/Life-cycle-inventory-LCI-study-2020-data-release.pdf

Annex A: Critical Review Statement

Critical Review of the Study "Aluminum in Battery Electric Vehicles (BEVs) – A Life Cycle Assessment Report", 21 April , 2025:

Commissioned by:	The Aluminum Association
Performed by:	Hassana Elzein, Matou Chingsubam, Christoph Koffler, Sphera Solutions, Inc.
Critical Review Panel[1]:	Dr. Roland Geyer, Professor, (Chair) University of California, Santa Barbara, CA Dr. Tom Gloria, Industrial Ecology Consultants, Newton, MA Dr. Yuan Yao, Associate Professor, Yale University, New Haven, CT
Date:	29 April 2025
Reference	ISO 14044: 2006. Environmental Management - Life Cycle Assessment – Requirements and Guidelines ISO/TS 14071: 2024. Environmental management — Life cycle assessment — Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006

The Scope of the Critical Review

The review panel had the task to assess whether

- the methods used to carry out the LCA are consistent with ISO 14044:2006 and ISO/TS 14071: 2024
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

[1] While the professional affiliations of the peer reviewers have been provided, their effort was personally compensated. Thus, their reviews do not represent any endorsements by their Universities.

The review was performed according to ISO 14044 and ISO/TS 14071 in their strictest sense as the results of the study are intended to be used for comparative assertions to be disclosed to the public.

The extent to which the unit process data are appropriate and representative, given the goal and scope of the study, was determined by a critical review of the available metadata,

i.e. process descriptions, etc. The following data was outside of the scope of this review:

- Detailed material compositions and technical specifications of the vehicles
- Inventory data and models of the unit processes

This is the norm for external LCA reviews. The review is based exclusively on the LCA Report. The reviewers did not have access to the actual inventory models and data.

Critical Review Process

The Critical Review started on January 13, 2025, with the delivery of the first draft of the LCA report. Three rounds of reviews were conducted via online meetings, email exchanges, and a review worksheet.

The critical review process was open and constructive. The LCA commissioner and practitioner were cooperative and forthcoming and addressed all questions, comments, and requests of the review panel to its full satisfaction.

This Review Statement summarizes the review process and its outcome. The full review process is documented in the Review Report, which is available as a separate document and contains all reviewer comments and practitioner responses.

General Evaluation

The defined scope for this LCA study was found to be appropriate to achieve the defined goals. The Life Cycle Inventory models are suitable for the purpose of the study and are thus capable of supporting the goal of the study. All primary and secondary data are adequate in terms of quality, and technological, geographical and temporal coverage. The data quality is found to be mostly high for the most important processes and at least adequate for all others.

Study results are reported using five impact categories from TRACI 2.1, the global warming potentials of the 6th Assessment Report of the IPCC, primary energy demand, and blue water consumption. This selection was found to be appropriate and reasonable in relation to the goal of the study. As a result, the report is deemed to be representative and complete. The study is reported in a transparent manner. Various assumptions were addressed by uncertainty and sensitivity analyses of critical data and methodological choices. The interpretations of the results reflect the identified limitations of the study.

Conclusion

The study has been carried out in conformance with ISO 14044 and ISO/TS 14071. The critical review panel found the overall quality of the report high, its methods scientifically and technically valid, and the used data appropriate and reasonable. The study report is transparent and consistent, and the interpretation of the results reflects the goal and the identified limitations of the study.

Roland Geyer	Tom Gloria	Yuan Yao

Annex B: Additional Results

B.1. Life Cycle Inventory Analysis Results

The Life Cycle Inventory (LCI) analysis result of all vehicle types covered in the study are provided in Table B-1 to Table B-8. The tables only display a selection of flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results.

Table B-1: LCI results of City Vehicle Status Quo scenario (2025)

Type	Flow	Manufacture	Use Phase	End-of-Life	Total
Resources	Water use	2.33E+07	2.16E+07	-1.03E+07	3.47E+07
	Crude oil	7.30E+02	1.80E+02	-1.80E+02	7.30E+02
	Hard coal	1.95E+03	3.80E+03	-6.33E+02	5.11E+03
	Natural gas	1.65E+03	3.54E+03	-7.75E+01	5.11E+03
	Uranium	2.33E-02	2.01E-01	-1.37E-03	2.22E-01
Emissions to air	CO_2	1.12E+04	1.99E+04	-2.37E+03	2.88E+04
	CH_4	3.43E+01	8.21E+01	-4.56E+00	1.12E+02
	N_2O	1.90E-01	2.55E-01	-2.20E-02	4.22E-01
	NO_x	2.00E+01	1.65E+01	-4.24E+00	3.23E+01
	SO_2	5.94E+01	1.32E+01	-4.67E+01	2.60E+01
	NMVOC	3.16E+00	2.55E+00	-3.61E-01	5.35E+00
	CO	1.88E+01	7.66E+00	-1.48E+01	1.16E+01
	PM10	8.42E-01	8.31E-03	-8.29E-01	2.17E-02
	PM2.5	1.54E+00	5.86E-01	-2.38E-01	1.88E+00
	Heavy metals	1.67E+00	6.14E-02	-7.51E-03	1.72E+00
Emissions to water	NH_3	8.44E-01	1.35E+00	-1.41E-01	2.05E+00
	NO^{3-}	2.94E-01	3.55E-02	-1.92E-03	3.27E-01
	PO_4^{3-}	2.36E-01	1.45E-01	5.23E-01	9.04E-01
	Heavy metals	1.34E-02	-4.10E-03	-8.09E-02	-7.16E-02
Emissions to soil	PAH	2.33E+07	2.16E+07	-1.03E+07	3.47E+07
	Heavy metals	7.30E+02	1.80E+02	-1.80E+02	7.30E+02

Table B-2: LCI results of City Vehicle Aluminum Optimized scenario (2025)

Type	Flow	Manufacture	Use Phase	End-of-Life	Total
Resources	Water use	3.15E+07	2.02E+07	-1.82E+07	3.36E+07
	Crude oil	7.13E+02	1.68E+02	-2.23E+02	6.58E+02
	Hard coal	1.68E+03	3.55E+03	-4.97E+02	4.73E+03
	Natural gas	1.62E+03	3.30E+03	-1.36E+02	4.78E+03
	Uranium	2.03E-02	1.87E-01	-1.84E-03	2.06E-01
Emissions to air	CO_2	1.09E+04	1.86E+04	-2.76E+03	2.68E+04
	CH_4	3.23E+01	7.67E+01	-4.50E+00	1.04E+02
	N_2O	1.78E-01	2.38E-01	-3.22E-02	3.84E-01
	NO_x	1.89E+01	1.54E+01	-5.14E+00	2.91E+01
	SO_2	5.79E+01	1.24E+01	-4.62E+01	2.40E+01
	NMVOC	3.08E+00	2.38E+00	-4.37E-01	5.02E+00
	CO	1.41E+01	7.15E+00	-9.05E+00	1.22E+01
	PM10	8.43E-01	7.77E-03	-6.96E-01	1.54E-01
	PM2.5	1.61E+00	5.48E-01	-4.76E-01	1.68E+00
	Heavy metals	1.58E+00	5.74E-02	-7.06E-03	1.63E+00
Emissions to water	NH_3	7.63E-01	1.26E+00	-1.53E-01	1.87E+00
	NO^{3-}	2.73E-01	3.32E-02	-2.33E-03	3.04E-01
	PO_4^{3-}	2.43E-01	1.35E-01	4.73E-01	8.51E-01
	Heavy metals	1.26E-02	-3.83E-03	-7.62E-02	-6.74E-02
Emissions to soil	PAH	3.15E+07	2.02E+07	-1.82E+07	3.36E+07
	Heavy metals	7.13E+02	1.68E+02	-2.23E+02	6.58E+02

Table B-3: LCI results of City Vehicle Status Quo scenario (2030)

Type	Flow	Manufacture	Use Phase	End-of-Life	Total
Resources	Water use	2.22E+07	1.98E+07	-1.01E+07	3.18E+07
	Crude oil	6.62E+02	1.65E+02	-1.65E+02	6.62E+02
	Hard coal	1.77E+03	3.47E+03	-5.67E+02	4.68E+03
	Natural gas	1.50E+03	3.23E+03	-7.51E+01	4.65E+03
	Uranium	2.13E-02	1.83E-01	-1.23E-03	2.03E-01
Emissions to air	CO_2	1.03E+04	1.82E+04	-2.20E+03	2.63E+04
	CH_4	3.10E+01	7.50E+01	-4.16E+00	1.02E+02
	N_2O	1.72E-01	2.33E-01	-2.06E-02	3.85E-01
	NO_x	1.82E+01	1.51E+01	-3.92E+00	2.94E+01
	SO_2	5.43E+01	1.21E+01	-4.16E+01	2.48E+01
	NMVOC	2.87E+00	2.33E+00	-3.31E-01	4.87E+00
	CO	1.69E+01	7.00E+00	-1.32E+01	1.07E+01
	PM10	7.64E-01	7.60E-03	-7.41E-01	3.02E-02
	PM2.5	1.41E+00	5.36E-01	-2.38E-01	1.71E+00
	Heavy metals	1.55E+01	1.21E-02	-7.80E-02	1.54E+01
Emissions to water	NH_3	1.55E+00	5.61E-02	-6.64E-03	1.60E+00
	NO^{3-}	7.65E-01	1.23E+00	-1.27E-01	1.87E+00
	PO_4^{3-}	2.17E-01	1.32E-01	4.39E-01	7.89E-01
	Heavy metals	1.23E-02	-3.74E-03	-7.15E-02	-6.29E-02
Emissions to soil	PAH	2.22E+07	1.98E+07	-1.01E+07	3.18E+07
	Heavy metals	6.62E+02	1.65E+02	-1.65E+02	6.62E+02

Table B-4: LCI results of City Vehicle Aluminum Optimized scenario (2030)

Type	Flow	Manufacture	Use Phase	End-of-Life	Total
Resources	Water use	2.94E+07	1.86E+07	-1.71E+07	3.09E+07
	Crude oil	6.46E+02	1.55E+02	-2.04E+02	5.97E+02
	Hard coal	1.54E+03	3.27E+03	-4.41E+02	4.36E+03
	Natural gas	1.47E+03	3.04E+03	-1.28E+02	4.38E+03
	Uranium	1.87E-02	1.73E-01	-1.67E-03	1.90E-01
Emissions to air	CO_2	9.97E+03	1.72E+04	-2.53E+03	2.46E+04
	CH_4	2.92E+01	7.06E+01	-4.07E+00	9.57E+01
	N_2O	1.62E-01	2.19E-01	-2.98E-02	3.51E-01
	NO_x	1.72E+01	1.42E+01	-4.71E+00	2.67E+01
	SO_2	5.32E+01	1.14E+01	-4.15E+01	2.31E+01
	NMVOC	2.80E+00	2.20E+00	-3.99E-01	4.60E+00
	CO	1.26E+01	6.59E+00	-7.82E+00	1.14E+01
	PM10	7.63E-01	7.15E-03	-6.20E-01	1.50E-01
	PM2.5	1.47E+00	5.05E-01	-4.50E-01	1.53E+00
	Heavy metals	1.43E+01	1.14E-02	-6.96E-02	1.42E+01
Emissions to water	NH_3	1.48E+00	5.28E-02	-6.29E-03	1.53E+00
	NO^{3-}	6.92E-01	1.16E+00	-1.39E-01	1.71E+00
	PO_4^{3-}	2.23E-01	1.25E-01	3.89E-01	7.37E-01
	Heavy metals	1.16E-02	-3.53E-03	-6.80E-02	-5.99E-02
Emissions to soil	PAH	2.94E+07	1.86E+07	-1.71E+07	3.09E+07
	Heavy metals	6.46E+02	1.55E+02	-2.04E+02	5.97E+02

Table B-5: LCI results of Family Crossover Status Quo scenario (2025)

Type	Flow	Manufacture	Use Phase	End-of-Life	Total
Resources	Water use	3.77E+07	2.31E+07	-1.79E+07	4.29E+07
	Crude oil	1.02E+03	1.92E+02	-2.89E+02	9.25E+02
	Hard coal	3.04E+03	4.05E+03	-7.93E+02	6.30E+03
	Natural gas	2.22E+03	3.77E+03	-1.41E+02	5.84E+03
	Uranium	3.12E-02	2.14E-01	-2.57E-03	2.42E-01
Emissions to air	CO_2	1.64E+04	2.12E+04	-3.41E+03	3.43E+04
	CH_4	4.58E+01	8.74E+01	-6.24E+00	1.27E+02
	N_2O	1.13E+00	1.59E-02	-1.52E-02	1.13E+00
	NO_x	3.19E+01	1.76E+01	-6.47E+00	4.30E+01
	SO_2	1.15E+02	1.41E+01	-7.21E+01	5.71E+01
	NMVOC	4.49E+00	2.72E+00	-5.75E-01	6.64E+00
	CO	2.35E+01	8.16E+00	-1.66E+01	1.50E+01
	PM10	1.09E+00	8.86E-03	-1.12E+00	-1.45E-02
	PM2.5	2.20E+00	6.25E-01	-4.40E-01	2.39E+00
	Heavy metals	1.86E+01	1.41E-02	-1.28E-01	1.85E+01
Emissions to water	NH_3	1.96E+00	6.55E-02	-1.62E-02	2.01E+00
	NO^{3-}	1.17E+00	1.44E+00	-2.23E-01	2.38E+00
	PO_4^{3-}	1.15E-03	3.76E-03	-9.22E-05	4.81E-03
	Heavy metals	1.88E-02	-4.37E-03	-1.26E-01	-1.11E-01
Emissions to soil	PAH	3.77E+07	2.31E+07	-1.79E+07	4.29E+07
	Heavy metals	1.02E+03	1.92E+02	-2.89E+02	9.25E+02

Table B-6: LCI results of Family Crossover Aluminum Optimized scenario (2025)

Type	Flow	Manufacture	Use Phase	End-of-Life	Total
Resources	Water use	4.76E+07	2.21E+07	-2.70E+07	4.28E+07
	Crude oil	1.04E+03	1.84E+02	-3.40E+02	8.80E+02
	Hard coal	2.87E+03	3.88E+03	-7.00E+02	6.05E+03
	Natural gas	2.26E+03	3.61E+03	-2.07E+02	5.66E+03
	Uranium	2.93E-02	2.05E-01	-3.02E-03	2.31E-01
Emissions to air	CO_2	1.66E+04	2.03E+04	-4.00E+03	3.30E+04
	CH_4	4.52E+01	8.37E+01	-6.51E+00	1.22E+02
	N_2O	1.18E+00	1.52E-02	-2.08E-02	1.18E+00
	NO_x	3.19E+01	1.69E+01	-7.65E+00	4.11E+01
	SO_2	1.16E+02	1.35E+01	-7.23E+01	5.75E+01
	NMVOC	4.53E+00	2.60E+00	-6.67E-01	6.47E+00
	CO	1.98E+01	7.81E+00	-1.19E+01	1.57E+01
	PM10	1.14E+00	8.48E-03	-1.02E+00	1.28E-01
	PM2.5	2.38E+00	5.98E-01	-7.09E-01	2.27E+00
	Heavy metals	1.92E+01	1.35E-02	-1.20E-01	1.91E+01
Emissions to water	NH_3	1.89E+00	6.28E-02	-1.41E-02	1.94E+00
	NO^{3-}	1.12E+00	1.38E+00	-2.38E-01	2.26E+00
	PO_4^{3-}	1.12E-03	3.60E-03	-1.00E-04	4.62E-03
	Heavy metals	1.85E-02	-4.18E-03	-1.21E-01	-1.07E-01
Emissions to soil	PAH	4.76E+07	2.21E+07	-2.70E+07	4.28E+07
	Heavy metals	1.04E+03	1.84E+02	-3.40E+02	8.80E+02

Table B1- 7: LCI results of Family Crossover Status Quo scenario (2030)

Type	Flow	Manufacture	Use Phase	End-of-Life	Total
Resources	Water use	3.86E+07	2.33E+07	-1.99E+07	4.21E+07
	Crude oil	9.59E+02	1.94E+02	-2.91E+02	8.62E+02
	Hard coal	2.71E+03	4.10E+03	-6.51E+02	6.15E+03
	Natural gas	2.05E+03	3.81E+03	-1.58E+02	5.71E+03
	Uranium	2.77E-02	2.16E-01	-2.71E-03	2.41E-01
Emissions to air	CO_2	1.52E+04	2.15E+04	-3.27E+03	3.34E+04
	CH_4	4.20E+01	8.85E+01	-5.64E+00	1.25E+02
	N_2O	1.06E+00	1.61E-02	-1.65E-02	1.06E+00
	NO_x	2.91E+01	1.78E+01	-6.37E+00	4.05E+01
	SO_2	1.08E+02	1.43E+01	-6.82E+01	5.37E+01
	NMVOC	4.23E+00	2.75E+00	-5.74E-01	6.40E+00
	CO	1.95E+01	8.25E+00	-1.20E+01	1.58E+01
	PM10	1.02E+00	8.96E-03	-9.66E-01	5.99E-02
	PM2.5	2.07E+00	6.32E-01	-5.10E-01	2.19E+00
	Heavy metals	1.60E+01	1.43E-02	-1.17E-01	1.59E+01
Emissions to water	NH_3	1.90E+00	6.63E-02	-1.39E-02	1.95E+00
	NO^{3-}	1.07E+00	1.45E+00	-2.17E-01	2.31E+00
	PO_4^{3-}	1.06E-03	3.80E-03	-9.59E-05	4.77E-03
	Heavy metals	1.77E-02	-4.42E-03	-1.18E-01	-1.05E-01
Emissions to soil	PAH	3.86E+07	2.33E+07	-1.99E+07	4.21E+07
	Heavy metals	9.59E+02	1.94E+02	-2.91E+02	8.62E+02

Table B1- 8: LCI results of Family Crossover Aluminum Optimized scenario (2030)

Type	Flow	Manufacture	Use Phase	End-of-Life	[redacted]
Resources	Water use	5.83E+07	2.13E+07	-3.83E+07	4.13E+07
	Crude oil	9.77E+02	1.77E+02	-3.95E+02	7.59E+02
	Hard coal	2.35E+03	3.74E+03	-5.87E+02	5.50E+03
	Natural gas	2.08E+03	3.48E+03	-2.87E+02	5.27E+03
	Uranium	2.41E-02	1.97E-01	-3.41E-03	2.18E-01
Emissions to air	CO_2	1.56E+04	1.96E+04	-4.74E+03	3.04E+04
	CH_4	3.99E+01	8.07E+01	-6.84E+00	1.14E+02
	N_2O	1.05E+00	1.47E-02	-2.76E-02	1.03E+00
	NO_x	2.82E+01	1.62E+01	-9.02E+00	3.54E+01
	SO_2	1.01E+02	1.30E+01	-6.96E+01	4.43E+01
	NMVOC	4.22E+00	2.51E+00	-7.62E-01	5.96E+00
	CO	1.45E+01	7.53E+00	-6.54E+00	1.55E+01
	PM10	1.11E+00	8.18E-03	-8.96E-01	2.26E-01
	PM2.5	2.44E+00	5.77E-01	-1.04E+00	1.97E+00
	Heavy metals	1.16E+01	1.31E-02	-1.06E-01	1.15E+01
Emissions to water	NH_3	1.73E+00	6.05E-02	-1.11E-02	1.78E+00
	NO^{3-}	9.73E-01	1.33E+00	-2.49E-01	2.05E+00
	PO_4^{3-}	9.24E-04	3.47E-03	-1.00E-04	4.29E-03
	Heavy metals	1.73E-02	-4.03E-03	-1.09E-01	-9.60E-02
Emissions to soil	PAH	5.83E+07	2.13E+07	-3.83E+07	4.13E+07
	Heavy metals	9.77E+02	1.77E+02	-3.95E+02	7.59E+02

B.2. Detailed breakdown of manufacturing stage

Figure B-1 and Figure B-2 show the changes of aluminum contribution to the total manufacturing GWP100 for the City Vehicle in 2025 and 2030. The results show that the battery system is the largest contributor, however, excluding the battery system and production and assembly from the results, the aluminum optimization alternatives increase cradle-to-gate GWP100 by 2% and 1% for 2025 and 2030, respectively. Similar results pattern is seen for Family Crossover as shown in the Figure B-3 and Figure B-4.

Figure B-1: Status QuoDetailed breakdown of Status Quo manufacturing stage GWP contributions for 2025 city vehicles

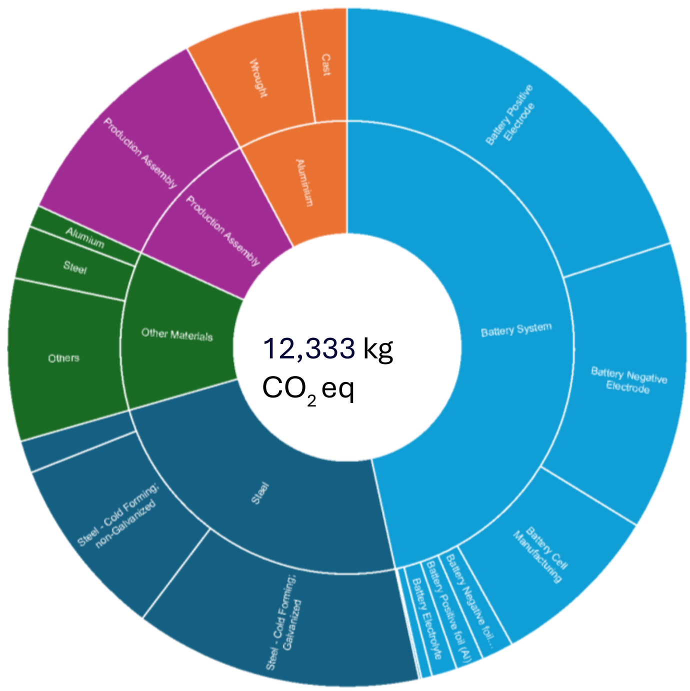


Figure B-2: Detailed breakdown of Aluminum Optimized manufacturing stage GWP contributions for 2025 city vehicles

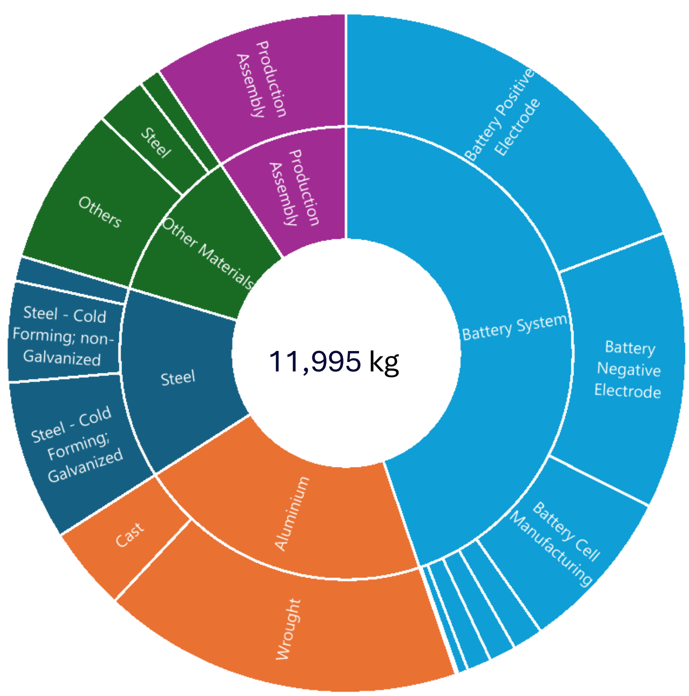


Figure B-3: Detailed breakdown of Status Quo manufacturing stage GWP contributions for 2025 family crossover vehicles Status Quo

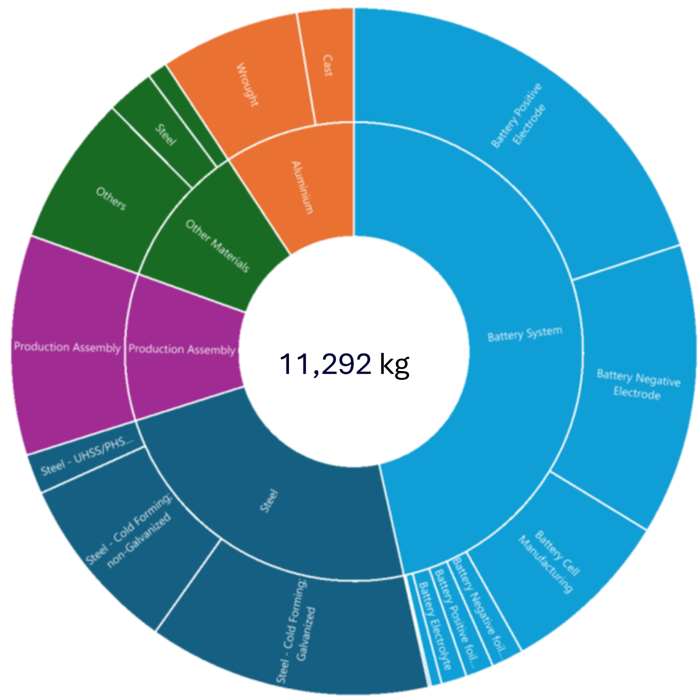
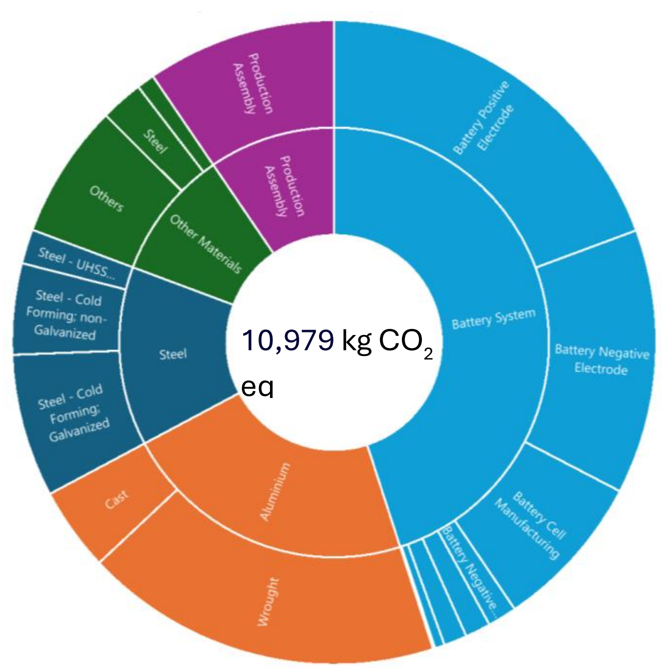


Figure B-4: Detailed breakdown of Aluminum Optimized manufacturing stage GWP contributions for 2025 family crossover vehicles



/ Drive Aluminum

/ @DriveAluminum

drivealuminum.org

DRIVEALUMINUM