



CHALMERS

Application of Structural Batteries in EV Quadricycles

Life cycle assessment and design strategies for
sustainable integration in vehicles

Bachelor's Degree Project in Mechanical Engineering

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SUMMARY

This thesis investigates the integration of structural battery composites (SBCs) in lightweight electric vehicles with a focus on the EU L6e-class quadricycle category. SBCs are multifunctional materials that combine load-bearing and energy storage capabilities offering the potential to significantly reduce vehicle weight, improve energy efficiency, and lower life cycle emissions. The aim of this research is to provide theoretical technical design guidance for application of future SBC technology in lightweight electric vehicles. This was investigated through a literature review covering the emerging field of structural battery composites, lightweight electric vehicles (particularly quadricycles) and eco-design principles. A weight reduction analysis was conducted to assess the potential of SBC integration in specific vehicle components and to inform future design strategies. A screening life cycle assessment was used to investigate the potential environmental implications when integrating SBCs and to analyze potential greenhouse gas emission reductions. The findings show that SBC integration has the potential to significantly reduce component and vehicle weight, while also improving vehicle efficiency. If future production emissions are reduced, SBCs could also lower the overall life cycle emissions of electric vehicles.

Key words: L6e Quadricycle, Structural Battery Composite (SBC), Lightweight EV, Eco-Design, Multifunctional materials, Weight reduction, Sustainable vehicle technology, Lightweighting.

List of Abbreviations

| Abbreviation | Definition |
|---------------------|---------------------------------|
| ABS | Acrylonitrile Butadiene Styrene |
| CAD | Computer aided design |
| CADC | Common Artemis Driving Cycles |
| CAGR | Compound Annual Growth Rate |
| CFRP | Carbon Fiber Reinforced Polymer |
| ERV | Energy Reduction Value |
| EU | European Union |
| EV | Electric Vehicle |
| FEM | Finite Element Method |
| GFRP | Glass Fiber Reinforced Polymer |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| HSLA | High-Strength Low-Alloy |
| ICE | Internal Combustion Engine |
| LCA | Life Cycle Assessment |
| LFP | Lithium Iron Phosphate |
| LIB | Lithium-Ion Battery |
| LMT | Light Means of Transportation |
| PP | Polypropylene |
| SBC | Structural Battery Composite |
| TSFS | Swedish Transport Agency |
| ZEV | Zero Emission Vehicle |

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1. Introduction

Structural batteries are an emerging technology combining composite materials with lithium-ion battery (LIB) energy storage capabilities. This innovation enables lightweight solutions by integrating energy storage directly into vehicle structures, offering potential for "massless" energy storage applications. Such advancements could significantly benefit small electric vehicles (EVs), including quadricycles, by reducing weight, improving energy efficiency, and lowering emissions.

1.1 Study Motivation and Context

Structural battery composite (SBC) technology is in its early stages of development. Ongoing research at Chalmers University of Technology, led by figures such as Leif E. Asp, is advancing the field. However, the technology remains at a low technology readiness level, and its full environmental impact over the lifecycle is not yet well understood. Early assessments through Life Cycle Assessment (LCA) have been made (Hermansson et al., 2023) and are crucial to guide its sustainable development and integration into EV applications. Since the technology is still in its early stages, it will likely take time before it reaches commercial or industrial application. This means that the applications of SBCs will have to be envisioned and environmental impacts of these applications assessed.

1.2 Aim

The aim of this thesis is to investigate and guide the application of structural battery composites in the design of lightweight electric vehicles, with a particular focus on the EU L6e quadricycle category. As urban congestion increases and demand rises for compact, energy-efficient vehicles, driven by trends such as e-commerce and parcel delivery, there is a growing need for vehicle designs that minimize weight while maximizing functional efficiency and environmental performance.

This study focuses on carbon fiber composites with integrated energy storage capability, allowing the material to serve simultaneously as a structural component and a lithium-ion battery. These multifunctional composites present a novel opportunity to reduce overall

vehicle weight and battery volume, which in turn may extend driving range and reduce life cycle greenhouse gas emissions.

The project is positioned within the broader context of the European Commission's Strategy for Low-Emission Mobility, which promotes transport electrification and decarbonization by targeting reductions in CO₂ emissions. Among its priorities is the development of small and light smart electric vehicles, such as battery-electric quadricycles. In alignment with these goals, this thesis assesses the prospective development and application of structural battery technology in such vehicles. A notable example of this trend is the Citroën Ami, which has recently been added to the Free2Move car-sharing fleet.

The research aims to generate knowledge about the design feasibility of using SBCs in small electric vehicles. In particular, it seeks to apply LCA to quantify the climate impact of substituting conventional materials and battery systems with SBCs, and to evaluate their suitability based on structural performance, energy density, and multifunctionality. The goal is to identify design strategies and components where SBC integration offers the greatest benefits, supporting future development of sustainable, low-emission mobility solutions in line with the European Commission's strategy for clean and smart urban transport.

1.3 Limitations

This study applies a simplified LCA approach using available data from comparable materials and components. Due to the low technology readiness level of SBCs, specific performance and environmental data are limited. Proxy data were used where necessary, which affects the relevance of the results to future applications.

The study did not include direct input from manufacturers or users of SBCs or relevant EV systems. Time constraints restricted broader industry engagement and user feedback collection. Instead, relevant insights were collected through academic journals, industry and technical reports.

No physical materials were tested as there is no large-scale production of SBCs. Consequently, no experimental validation through physical prototyping or testing was conducted, meaning that this is a highly theoretical project. The project's theoretical nature relies on CAD-based visualizations and FEM simulations to explore integration and structural performance.

The environmental evaluation uses a screening LCA to estimate production and use-phase emissions. This method supports early-stage assessments but is not standardized or exhaustive. Scenario modeling was based on assumed future conditions to explore potential system-level outcomes.

Cost aspects were discussed qualitatively. No detailed cost calculations were conducted due to the lack of industrial-scale data for SBCs, limiting conclusions on economic feasibility.

1.4 Specification of the issue being investigated

To clarify the scope of this study and communicate its expected outcomes, the aim has been translated into five specific deliverables. These deliverables form the core structure of the project and have been systematically researched, analyzed, and discussed throughout the report.

- Firstly, the report provides a comprehensive overview of the current state of structural battery composites and lightweight electric vehicles, with a particular focus on the L6e category of quadricycles. This included reviewing LCA results, technological studies, and the application of eco-design tools. Key trends in materials, design strategies, and environmental performance were analyzed using academic journals, technical reports, and industry publications.
- Secondly, an evaluation of sustainability-focused design methodologies was conducted, including the use of Eco-Design Checklists. The relevance and effectiveness of these methodologies in guiding sustainable vehicle design were assessed in the context of SBC integration and quadricycle applications.
- Thirdly, insights from the literature review and methodology evaluations informed the selection of specific vehicle components where SBC integration could offer significant benefits. Candidate components were chosen based on structural functionality, environmental impact potential, and material properties. CAD modelling (CATIA V5) along with FEM modelling and simulations in Ansys Granta EduPack software, ANSYS, Inc., 2021 (www.ansys.com/materials) were used to evaluate technical feasibility and validate structural performance.

- Fourthly, a screening LCA was conducted to evaluate the environmental impacts of SBC implementation in lightweight EVs. The analysis covered both the production and use phases, focusing primarily on greenhouse gas emissions. The multifunctional nature of SBCs was modeled by accounting for their potential to replace both structural materials and parts of the battery system. Component-specific scenarios were created to explore how different material substitutions affect emissions, particularly when integrating SBCs into components like rims, chassis pipes, or battery casings. This allowed exploration of both individual component design and integration within full quadricycle concepts.
- Finally, an analysis was performed to assess the environmental and technical performance of different SBC applications. Metrics such as emissions-per-weight saved and material efficiency ratios were used to identify optimal cases for SBC use. Sensitivity analysis examined the effects of changes in energy density, GWP during the production phase and grid emission intensity. Based on these insights, strategic recommendations were developed for effective SBC implementation and areas for future research were outlined.

2. Background

This chapter provides an overview of the primary issues pertaining to the implementation of SBCs in light electric vehicles, with a special focus on quadricycles. The analysis begins with an investigation of the SBC technology, including its structure, application and future improvements. After this it covers the history of quadricycles before proceeding to examine the L6e vehicle category, covering design features, regulatory framework, and marketplace. Lastly, the chapter presents the fundamentals of eco-design and sustainability-driven product development with emphasis on the practices and tools employed to facilitate environmentally conscious design decision-making. Collectively, these subjects provided the theoretical background and contextual framework for technical concept development and environmental analysis conducted in this research.

2.1 Structural battery composites

SBC or structural battery composites is an emerging technology within the field of energy storage. As the quest for maximising Lithium ion battery energy density continues in order to maximize vehicle range, SBC is a different take on the same problem. Instead of making batteries that are heavy and with high energy density you utilize materials with dual functionality such as carbon fibre to perform other tasks than just energy storage while also still providing energy storage capacity. For example replacing the roof of an electric car with structural batteries would provide weight savings from the carbon fibre replacing the structural roof and would allow downsizing of the main battery pack due to the added energy storage from the SBC. This has been demonstrated in studies that show that using structural batteries can lead to significant system-level mass savings (Johannisson et al., 2019). The idea behind SBCs is to have a multifunctional composite material that is able to perform several functions at once, in this case being a structural component and storing energy. Recent breakthroughs by researchers at Chalmers University of Technology show the potential in SBC (Chaudhary et al., 2024).

2.1.1 Structure and Function of SBC

Carbon fibre is frequently utilized for negative as well as positive electrodes in structural battery cells (Chaudhary et al., 2024). SBCs are manufactured using lithium ion phosphate

coated carbon fibre as the positive electrode and pristine carbon fibre for the negative electrode.

Currently the cells are only in lab scale production and are produced in a series of steps; first the electrodes are prepared, the pristine carbon fibre negative electrode has a copper current collector attached and is placed on a working surface, the separator commonly made from cellulose-based separators, such as Freudenberg or Whatman models is placed on top of the negative electrode and the positive electrode is placed on top with a aluminium current collector attached that will act as the battery terminals together with the copper current collector from the negative electrode side. Afterwards the whole pack is placed into a pouch and resin is used to laminate the battery together.

Utilizing carbon fibre for its structural and electrochemical performance is the key behind the excellent performance of the Chalmers-developed structural battery composites and this is what gives the battery its strength and also enables the deposition of lithium ion phosphate on the carbon fibre which in turn enables the energy storage function. The separator is taken straight from current lithium ion batteries and enables the cell to function without shorting in between the two electrodes just like how it would function in a lithium ion battery.

2.1.2 Applications and Use Case Potential

Applications for structural battery composites are almost endless and they can be used for any application where reducing the weight of a battery powered product would be of interest. Anything from consumer electronics to electric cars to electric passenger aviation. (Chaudhary et al., 2024)

Firstly the potential within the automotive industry for applying structural batteries in electric vehicles is very promising. Recent research (Johannisson et al., 2019) shows that by just replacing the roof of an electric car with a structural battery you can achieve a weight reduction of 20% compared to a carbon fibre roof and compared to a steel roof its a 62% weight saving. So exploring the application of structural battery composites in lightweight EVs like our thesis work will have the potential to show some considerable weight reductions and thus efficiency increases.

Aerospace is another sector where structural battery composites have been viewed as having massive potential. Electrification of the aviation sector is currently facing big issues with

current battery technology limitations in energy density and current electric aircraft do not have the range or efficiency to perform longer flights. Applying structural battery composites into the design of aircraft shows great potential for reducing weight and increasing range and efficiency of electric aviation. In theory you could replace entire wings with structural batteries and massively reduce the required amount of batteries and give the aircraft way better range. (Kühnelt et al., 2022)

The primary challenge facing structural batteries is their low energy density, which is currently only 20% of that of traditional lithium-ion batteries. This limitation has made the technology less appealing to industry leaders, as integrating it into existing designs would require a fundamental shift in their approach to electric vehicle development. Given the complexity and cost of such a transition, the minor performance gains do not justify the investment.

For example, replacing a vehicle's roof with structural battery composites could reduce overall weight by more than 20% (Johannisson et al., 2019). However, this improvement alone is not significant enough for companies to allocate resources toward an unproven technology that has yet to see widespread adoption.

Integrating SBCs into real-world applications presents several challenges, including scalability, cost, and long-term durability. Mass production remains a hurdle, as manufacturing processes must be adapted to accommodate new materials. Additionally, the high initial investment and uncertainty regarding long-term performance create financial risks for manufacturers.

Another big short-term challenge is the electrical performance outside of just battery capacity. Charge cycles in current models can result in up to a 50% capacity loss over 500 cycles. Since the technology is based on similar principles to lithium-ion batteries, it is hoped that similar improvements can be applied to SBCs. Another drawback with the current composite cells is the specific voltage which limits the usefulness of the batteries for applications where a high voltage draw is required such as in most vehicle applications. Our current focus with the thesis work however is for quadricycles which typically do not have the high power draw from high output electric motors like what is currently used in most if not all electric cars. Either way this is also being looked into and the goal for the research team is to have the specific voltage up to 200W/kg which is still very low compared to

lithium ion or other types of batteries which will undeniably limit future uses that have high power draws if you want to exclusively use structural battery composites. However using a lithium ion battery pack as well will allow you to use that to be able to provide the power necessary to, for example power a high power electric motor.

Despite these challenges, SBCs offer promising opportunities in terms of sustainability and technological advancement. By reducing vehicle weight, they can improve energy efficiency and extend range, ultimately decreasing reliance on large battery packs. Furthermore, advancements in composite materials and manufacturing techniques could enhance durability and energy density over time, making SBCs a viable alternative in the future.

2.1.3 Performance Targets and Development Roadmap

Collaboration with the research group at Chalmers in SBC development indicated that their goal is to achieve two-thirds of the energy density of current lithium-ion batteries while also significantly improving other performance metrics essential for commercial viability. Additionally, they aim for structural battery composites to reach two-thirds of the elasticity modulus of standard carbon fiber composites and one-third of their tensile strength, all within the next one to four years.

Reaching these performance benchmarks would greatly enhance the appeal of structural batteries, making them a more viable alternative for industry leaders and vehicle manufacturers. Such advancements could encourage companies to explore integration, as the technology would offer a more compelling balance between structural integrity and energy storage. Reaching that level of performance would make SBCs commercially viable despite current limitations in power density, as the benefits of integration would justify supplementing them with higher-density batteries like conventional LFP.

2.2 Quadricycles

Quadricycles are four-wheeled light vehicles that serve as a compromise between motorcycles and regular cars, which is an economical mode of transportation, especially in cities. They are supposed to be inexpensive, lightweight, and fuel-efficient, and their application as a means of transportation in urban settings and for short distance travel is becoming ever more popular.

2.2.1 History of Quadricycles

The idea of quadricycles originated in the early 20th century, a time when light motorized quadricycles were created as affordable substitutes for conventional automobiles. Nevertheless, the contemporary quadricycle became more popular in the late 20th century and early 21st century because of growing urbanization and the demand for eco-friendly modes of transport (United Nations, 2015).

In Europe, nations such as France and Italy have a long history of quadricycle dominance, especially in suburban and rural regions, where they provide a viable alternative to larger vehicles. The establishment of regulatory frameworks, such as EU Regulation No. 168/2013, has enabled the standardization of quadricycles through their classification into two categories: light (L6e) and heavy (L7e) categories (EUR-Lex, 2013).

The increase in urban populations has intensified transportation challenges such as congestion, parking shortages, and emissions, making quadricycles a viable alternative (Çelik & Topaç, 2023). Today, the quadricycle market and especially the electric versions is growing with the drive of environmental concerns, government promotion of electric cars and consumer demand for affordable urban mobility solutions. Even with this, today's market lacks standardization in design and strong competitors in the automobile segment (Faria & Moura, 2016).

2.2.2 Design Priorities and Urban Functionality

New quadricycles prioritize compactness and light weight, making them perfectly suited for limited urban conditions. With the capacity to seat one or two individuals, their small enclosed bodies are engineered for low production costs and optimal energy efficiency, along with offering little protection from the weather (Koca et al., 2015).

Although there are both electric and ICE versions, the trend has accelerated in favor of EV quadricycles with the shift to tighter emissions regulations and the demand for sustainable mobility solutions. Automakers are increasingly resorting to battery-electric versions to achieve urban emissions targets and changing transport policies (European Commission, 2024).

Weight minimization is a fundamental design strategy in this development because it directly influences the energy consumption of EVs. It is particularly crucial for small vehicles with small battery capacity. In fact, it has been found that light vehicles have the potential to reduce urban travel time by up to 50% compared to conventional vehicles, once again showing their merit in future urban mobility (Santucci et al., 2016).

2.2.3 EU L6e Quadricycle Classification and Regulations

L6e vehicles were introduced under EU Regulation No. 168/2013 to create a clear and uniform classification for lightweight quadricycles, aiming to facilitate the use of low-emission, environmentally friendly vehicles while ensuring safety standards across member states. Under EU Regulation No. 168/2013, L6e vehicles are classified as lightweight quadricycles with the following characteristics (EUR-Lex, 2013):

- Maximum speed: 45 km/h
- Maximum curb weight: 425 kg (excluding battery weight for electric models)
- Maximum dimensions:
 - Length: 3,000 mm (3.0 m)
 - Width: 1,500 mm (1.5 m)
 - Height: No specific restriction
- Power output:
 - L6e-A (Light Road Quadricycle): Open vehicles without an enclosed driver's cabin, limited to 4 kW (4,000 W) continuous power.
 - L6e-B (Light Moped Car): Enclosed vehicles with up to three doors, limited to 6 kW (6,000 W) continuous power.

According to the EU Battery Regulation (EU) 2023/1542, batteries used in L-category vehicles are classified as Light Means of Transport (LMT) batteries if they weigh 25 kg or less. If the battery exceeds 25 kg, it is classified as an EV battery. This distinction is important when considering the integration of structural battery composites, as it may influence both regulatory treatment and design strategies depending on the battery's classification.

While these regulations provide a common framework across the EU, each country can add its own requirements for things like licensing, safety standards, and road use. For instance, in

most EU countries, operating an L6e vehicle requires a special type of driving license. For example, in several countries drivers can operate L6e vehicles with a moped or motorcycle license, while in others a dedicated light vehicle license is required. The minimum age for driving L6e vehicles also varies but is typically set at 16 or 18 years old, depending on the country.

2.2.4 Lightweight Materials and Structural Considerations

Quadricycles use an assortment of different light materials in order to optimize weight reduction while keeping the structure intact. Aluminum is preferred in the making of chassis structures because of its cost effectiveness and strength to weight ratio (Koca et al., 2015).

For body panels, interior components, and casings, quadricycle designs frequently use thermoplastics, polymer blends, and other lightweight synthetic materials in addition to metals and high-performance composites. These materials support cost control while providing corrosion resistance, ease of manufacturing, and flexibility in shaping complex geometries. As part of sustainability-driven development, the use of recycled or bio-based polymers is also being investigated, especially in models that are more affordable or urban in nature. Weight, cost, manufacturing feasibility, and regulatory compliance must all be balanced within the limitations of compact EV design when selecting materials.

The design of lightweight vehicles is being improved by recent developments in materials science, with research concentrating on mass reduction while maintaining structural performance and safety (Fantuzzi et al., 2021; Ferraris et al., 2019). Specifically, hybrid material strategies are becoming more popular, such as integrating bio-composites into non-structural components or combining CFRP with aluminum. As lightweight EV development continues to move toward more sophisticated, environmentally friendly material solutions, these strategies seek to strike a balance between cost, sustainability, and mechanical performance.

2.2.5 Market Trends in Urban EVs

The quadricycle market has changed considerably in the last ten years, mainly due to the growing demand for green urban mobility solutions. As traffic congestion in cities rises and emission regulations become tighter, the popularity of small and light vehicles such as quadricycles keeps rising. Subsidies and incentives provided by the government for electric quadricycles have further enhanced their increasing popularity, and they have become the choice of city inhabitants for affordable and effective transportation means (Santucci et al., 2016).

Despite their advantages, there are several constraints to the widespread use of light electric vehicles (LEVs), including quadricycles. High initial purchase cost is one of the main barriers, especially in the case of electric ones where battery cost has a big impact on the overall price. Moreover, there may be insufficient support infrastructure including charging stations and safe, segregated travel lanes to facilitate their integration with existing urban transport systems. Environmental conditions, in particular low temperatures, can also degrade battery performance and travel distance (Hyvönen et al., 2016).

According to a survey conducted in Finland, about 50% of the respondents were interested in adopting LEVs for intra-urban commuting. The key drivers are improved individual mobility, simplicity, low cost, and the environmental issue. Nonetheless, concerns including the high purchase price, safety in winter time, and lack of charging infrastructure still play an important role in customers' decision-making (Hyvönen et al., 2016). Policy incentives, infrastructure investment and improvements in battery technology can mitigate these barriers, facilitating a faster diffusion of LEVs in urban settings.

Market prediction suggests that the worldwide quadricycle market, comprising both ICE and electric variants, should witness considerable development over the forthcoming years. The market size is projected to hit approximately \$18.6 billion in 2021 and continue growing to reach \$41.6 billion by 2030, registering a Compound Annual Growth Rate (CAGR) of 9.36 percent over the forecast period. Most of that growth is now attributed to battery technology advancements, incentives from government that are incentivizing or legislating a low-emission vehicle uptake, and consumer demand for smaller options for urban mobility (Spherical Insights & Consulting, 2023). While these figures represent the total market, a

substantial share of the projected growth is driven by the rising adoption of electric quadricycles.

2.2.6 Innovations and Electrification in Quadricycle Technology

Traditionally, quadricycles are available in both ICE and electric versions. The trend, however, is moving towards EVs due to various factors like increasingly stringent emission regulations and increasing demand for urban mobility solutions. The automotive sector is seeing a dramatic shift away from ICE quadricycles, with manufacturers placing greater emphasis on battery-electric vehicles in an effort to achieve sustainability goals and regulatory imperatives to curb carbon emissions. This is especially relevant as cities seek to minimize pollution and provide cleaner options for short-distance traveling (European Commission, 2024).

The manufacture of battery-electric quadricycles is greatly influenced by significant improvements in battery technology, resulting in increased energy density, range, and efficiency. Advances in terms of solid-state batteries, rapid-charging systems, and high-energy lithium-ion batteries are making electric quadricycle production increasingly resilient and reliable. As battery technology continues to evolve, manufacturers will be in a position to provide even more viable alternatives for urban commuters who use the vehicles for daily mobility (European Commission, 2024).

However, there remain several obstacles to widespread adoption of electric quadricycles. Charging infrastructure remains a key challenge, particularly in rural or underserved areas where charging stations may be sparse. In response, governments and policymakers are stepping in to address these issues by expanding public and private charging networks and offering financial incentives for both consumers and manufacturers (European Commission, 2024).

In addition to these technical advancements, a new emerging concept in eco-friendly quadricycle design is represented by the Zero Energy Vehicle (ZEV) model, for example, the CERYAN L6e electric vehicle. Developed as a prototype, the CERYAN features solar panels incorporated into the design to capture renewable energy, thereby minimizing the use of external charging systems (Celtek et al., 2024). This innovative approach not only addresses

the challenge of charging infrastructure but also represents a significant step toward reducing the overall energy consumption of urban mobility solutions.

The CERYAN L6e has an advanced energy management system that offers two modes: SPORT and ECO. The ECO mode aims to optimize the efficiency of the vehicle to suit urban use where resource preservation is vital, while the SPORT mode boosts the performance of the vehicle but decreases the efficiency. This two-mode system signifies an important milestone in the use of quadricycles in various driving situations and consumer preferences to balance performance and sustainability harmoniously (Celtek et al., 2024).

The CERYAN concept supports innovative technologies such as the use of passive balancing battery management systems, highly efficient power electronics, and the use of a modular battery architecture that together promote the vehicle's energy efficiency and operational flexibility. The technologies enable the vehicle to be upgraded and maintained easily, ensuring the vehicle's adaptability to future energy solutions (Celtek et al., 2024).

2.3 Eco-Design

Eco-design, or ecological design, is a process for product and service development that minimizes the environmental effect along the entirety of the life cycle. It emphasizes sustainability thinking from the beginning of the design process and works by weighing ecological and economic factors to create responsible solutions. The key principles are efficiency in the use of resources, minimizing waste, utilization of renewable resources, and designing for durability, recyclability, and energy efficiency (European Commission, 2023).

Eco-design emerged as a response to growing environmental concerns in the 1970s and was driven forward by publications like Ian McHarg's *Design with Nature* (1971), which promoted ecological planning. By the 1990s, industry norms and law progressively incorporated sustainability and formal training courses in eco-design began to be available (Kallipoliti, 2018).

Environmental policy worldwide has also had an impact on eco-design. The UN Conference on the Human Environment in 1972 led to the formation of environmental agencies (United Nations, 1972), and the 1992 Earth Summit's Agenda 21 emphasized sustainable resource management (United Nations, 1992). Most recently, the EU's *Ecodesign for Sustainable Products Regulation* (2023) has further supported sustainability by promoting energy

efficiency, durability, and recyclability of products (European Commission, 2023). Today, eco-design is a key factor of sustainable innovation in business sectors. It is now used in developing cost-saving, effective, and environmentally friendly solutions.

2.3.1 Core Principles and Approaches in Eco-Design

Traditionally, Eco-design can be broadly categorized based on the following principles; the efficiency in the use of resources, minimizing waste, utilization of renewable resources, and designing for durability, recyclability, and energy efficiency. All of these principles aim for the reduction of emissions, waste and toxicity. It is a system to improve and acknowledge all of the stages of a product life, from development to its end of life (European Environment Agency, n.d.). However, eco-design can also be seen as a mindset, one that continually reminds developers of the broader impact of their design, material and production choices while encouraging consumers to seek out and prioritize environmentally friendly products.

Eco-design is not just a singular improvement but a whole system that requires life cycle modelling, which includes all processes from material extraction to end-of-life management. Tools such as Life Cycle Assessment (LCA) are crucial in this process, helping designers understand the environmental impact of a product at every stage. Eco-design has for a long time influenced the shifting away from a linear take-make-waste approach toward more sustainable systems. Eco-design has largely focused on improving resource efficiency as a central strategy. One prominent example is Design for Environment (DfE), which promotes the use of more sustainable materials and manufacturing processes during product development (Ecochain, 2024).

The developments in Eco-Design have influenced the designing of a product, for example, with the goal to minimize its resource input, both the amount of material used and the energy needed for extraction is sought out to be lowered and in doing so lower the overall emission output. This can be achieved in several ways, it can be designing a product or component that meets the requirements but in a way that minimizes the amount of material in use. It could also be done by changing the material used and in doing so being able to make the same product with less material (Allwood & Cullen, 2012). These are methods of investigating ways to make more from less and is a crucial mindset throughout Eco-Design.

Product design is not the only way of developing a product with regards to environmental impact, the usage of sustainable materials, e.g., biodegradable, recycled or low-impact materials can be a way of ensuring that waste can be minimized and environmental harm reduced. Another way of decreasing the environmental impact is delaying a product's end of life. This can be accomplished by enhancing its quality and functionality, repairing components when they fail instead of replacing them, and reusing or upcycling it at the end of its use (Allwood, 2012). Others mean that delaying a product's end of life can be achieved with the design of a “Timeless” product that has a perceived value and engaging the user in an emotional bond that endures (Chapman 2009, as cited in Lockrey et al 2022).

Furthermore, design for disassembly and reuse is one of the primary notions focused on rendering various products repairable, refurbishable, or repurposable once they reach the end of their life cycle. The principle is upheld through the implementation of modular product designs, which enable the replacement of easy-to-replace components, thus contributing to the extension of product lives and the successful reduction of generated wastes. It is notable that the majority of aged components are usually recycled, despite the fact that they could be reused directly without being subjected to recycling processes in the first place (Allwood, 2012).

2.3.2. Emerging Eco-Design Models and Circular Economy Strategies

The principles of Eco-Design have long been guided by the philosophy of eco-efficiency that focuses on resource efficiency and toxicity reduction by making more from less. However, the focus is once again shifting, now towards eco-effectiveness. This approach is essential for achieving long-term sustainability in the built environment. While eco-efficiency focuses on reducing environmental harm, eco-effectiveness seeks to create a net positive impact by developing regenerative systems (Braungart, McDonough, & Bollinger, 2007). The eco-effectiveness mindset is aligned with the principles of a circular economy because it demands systems in which waste is deliberately designed out and materials are continually reused or regenerated, thereby conserving and ecosystems renewed rather than depleted (Webster, 2021).

Eco-efficiency works to optimize resources with the view to reducing its impacts, for example, reducing material use and enhancing energy efficiency. While it slows down degradation, it does not tackle the underlying causes of pollution and waste. Recycling often

results in downcycling, and reducing toxins may not fully eliminate harm (Allwood, 2012). Eco-effectiveness is the contrary, going further than just trying to reduce negative effects and attempting to yield positive ecological and social results. Its origins are closely related to the Cradle-to-Cradle (C2C) approach, which supports regenerative design strategies (Braungart et al., 2007). The C2C philosophy believes that waste must be used as a nutrient, constantly circulating through biological or technical cycles without ever losing integrity or function over a long period of time. Energy should be obtained from renewable resources, reducing dependence on fossil fuel and enabling systems that are self-sustaining without depleting resources (Sustainability Guide, n.d.). Moreover, eco-effectiveness encourages diversity, integrating natural and cultural elements to generate flexible and adaptive environments.

One such approach is biodesign, which is a rapidly growing practice that expands on the biomimicry principles. It works by incorporating living organisms as a foundation for components and material sources within product design, thus leveraging biological systems for sustainable and innovative solutions. It is a practice that seeks to work with nature to create products and systems such as compostable materials, energy-harvesting technologies, and organic computers using bacteria, algae, and other biologically sourced materials (Grushkin, 2021). This makes it a particularly interesting complement to the C2C philosophy, where waste can serve as a nutrient, continuously circulating through biological or technical cycles.

Expanding on this eco-friendly approach, green and blue economies also further emphasize the integration of environmental principles into economic principles to encourage sustainability and increase efficiency in resources. Both of these include concrete strategies for addressing climate change mitigation and practicing sustainability principles with material outcomes. The green economy is defined as an economy that promotes human well-being and social justice and substantially reduces environmental risks and ecological deficits. It primarily aims at sectors such as energy, transport, agriculture, and forestry, and promotes low-carbon, resource-efficient, and socially inclusive economic development. On the other hand, the blue economy builds on the principles of the green economy but focuses more on the marine and coastal resources. It aims to harness ocean-based resources sustainably while ensuring the health of marine ecosystems within industries like fisheries, aquaculture, marine tourism, renewable ocean energy, and biotechnology (Commonwealth Foundation, 2016).

2.3.3. Eco-Design Aided Tools

An eco-design checklist is among the most effective tools enabling the application of eco-design principles in practice by helping designers to progressively assess and improve the environmental performance of the product from the early phases of the product life cycle to the end-of-life.

One widely used eco-design checklist, originally developed by Brezet and van Hemel (1997) and later adapted by Delft University of Technology usually includes material considerations, promoting the use of recyclable, renewable, or environmentally friendly materials and discouraging harmful ones (Delft University of Technology, n.d.). It also promotes energy efficiency in both production and product use, as well as the design of products for durability, modularity, and ease of disassembly to support repair, reuse, and recycling (Diehl et al., 2001).

The checklist supports connecting product development with circular economy goals, emphasizing that design decisions must consider end-of-life scenarios such as reuse, remanufacture, or material recovery. It also focuses on the user, encouraging designs that facilitate responsible energy use and maintenance over the product's operational phase (Hauschild et al., 2018).

The eco-design checklist has a well-organized form; thus, it can be a useful tool to support decision-making processes for eco-design, and is one of the decision-making tools suitable for integration with other environmental impact assessment tools such as Life Cycle Assessment (LCA). It is most valuable in the early stages of design, when decisions bear the most impact on a product's environmental footprint (Hauschild et al., 2018). Through integrating such criteria in design activities, the checklist tends to reduce resource use, emissions, and achieve more sustainable innovation in various sectors (Diehl et al., 2001).

3. Methodology

The methodology for this project is structured around five key deliverables and includes a literature review, evaluation of design methodologies, technical concept development, LCA and strategic recommendations. The project involved applying and building upon existing knowledge in structural battery technology, LCA methodology and relevant tools to support the evaluation of proposed concepts.

3.1 Literature review

The work began with a literature review and information gathering about current lightweight electric vehicles with a main focus on EV quadricycles. This was done by conducting a thorough review of the current literature surrounding lightweight electric vehicles within the category of L6e with a focus on EV quadricycles. The literature review mainly draws from academic journals, industry reports and technical reports. The review prioritized high project relevance, recent publication dates, and an emphasis on urban environments.

Academic journals provided insights into technological trends and performance data. Industry reports highlighted market trends, competitive landscapes, and material innovations, while technical reports detailed engineering specifications, safety standards, and energy efficiency metrics. Standards and regulations defined classifications, performance criteria, and compliance requirements. Benchmarking was used to compare top lightweight EV models, and environmental lifecycle data was analyzed to evaluate their carbon footprint, recyclability, and overall energy impact. By combining these sources, a well-rounded understanding of the current landscape of lightweight EVs was achieved.

The literature review also investigated eco-design principles and sustainable design methods, focusing on how they have shaped the development of lightweight electric vehicles. It explored general principles of eco-design and sustainability to understand how environmental considerations can be integrated into the design process. This included evaluating how manufacturers incorporated sustainable materials, lightweight structures, and energy-efficient design strategies to meet regulatory and environmental targets.

The review also investigated manual eco-design strategies, including step-by-step methodologies such as an Eco-Design Checklist (EcoDesign Circle, n.d.). This checklist could be tailored to address specific areas of improvement in lightweight vehicle design,

focusing on reducing raw material usage, minimizing manufacturing waste, and enhancing end-of-life recyclability.

A systematic approach was applied to the literature review to secure an accurate and reliable review, using keyword searches in databases such as Scopus, Google Scholar, IEEE Xplore and Google Patents to get a wide variety of good data. Sources were evaluated based on relevance, recency, and credibility, ensuring a balanced perspective from academic and industrial viewpoints.

3.2 Technical Concept Development

Based on the findings from the previous step, a series of technical designs and concepts for SBC applications in EV quadricycles was developed. Using the information gathered, components of the EV quadricycle that were suitable for the application of the structural battery technology were established. This included components that were a suitable match considering the different mechanical properties of the materials as well as potential environmental hot-spots of the current structure.

The Citroën AMI was selected as a reference vehicle due to its simplicity, availability of data, and relevance within the L6e category. To initiate the analysis, rough volume estimates of the components were made, guided by the vehicle's simple, box-like geometry. The volume was simplified and calculated based on the vehicle's dimensions and educated assumptions on the thickness and rough measurements, (e.g. 1100 x 900 x 3 for the roof of the quadricycle). CAD models were also developed in CATIA V5 (Dassault Systèmes, 2011) to conceptualize and assess SBC components. This made it easy to calculate volumes, to do preliminary weight analysis, and to earmark interesting candidates for more detailed study.

The different materials for the components were identified with help of the literature review and the relevant material properties were established in a table using the material data software Ansys Granta EduPack (ANSYS, Inc., 2021). EduPack is a material selection software used to compare mechanical and environmental properties of different materials, supporting decisions in sustainable design. This was done to provide a clear and organized foundation from which the weight saving assessment could be developed.

For validation purposes, FEM simulations were performed with the help of the Ansys program on components that had significantly different mechanical properties compared to

the SBC, such as the steel components. FEM, applied through the software ANSYS, enables virtual testing of structural performance under mechanical stress, allowing evaluation of strength, deformation, and safety factors of design concepts. Certain load cases were used on individual components, for example a central load of 2000 N on the rim and a bending load of 10,000 N applied to the midspan of a chassis pipe. These simulations assessed the structural viability of SBC substitutions and provided input on where geometry modifications were needed to achieve similar mechanical properties.

An iterative process was used to ensure that designs were not overstressed, such as von Mises stress, while not using excessive material. The various parts were subsequently designed to minimize weight without compromising structural adequacy.

3.3 Life Cycle Assessment

To support the screening life cycle assessment conducted in the project, time was dedicated to developing a broad and fundamental understanding of life cycle assessment methodology. The aim was to deepen our understanding of LCA by focusing on its core principles, structure, and common applications. Instead of emphasizing specific software tools, we prioritized building a solid conceptual foundation for applying LCA in the context of this study.

As part of the methodology, data gathered from the literature review and expert insights obtained through personal communication with researchers in the SBC field were compiled in Table 3. These inputs were used to fill knowledge gaps where published data was lacking and to inform key assumptions, such as projected energy density and mechanical properties. This was done to provide a clear and organized foundation from which the streamlined screening assessment could be developed. The table served as a reference point for relevant climate impact data and underlying assumptions, helping to ensure consistency and transparency in the early stages of the analysis. Although not a formal life cycle inventory, this step was crucial for scoping the assessment and supporting informed, qualitative comparisons aligned with the goals of a screening LCA.

To support this evaluation, LCA-relevant data for structural battery composites was primarily sourced from recent studies (Hermansson et al., 2023; Sieti et al., 2024), ensuring alignment with the functional context of the selected components. In cases where specific data for the quadricycle's lithium iron phosphate (LFP) battery was unavailable, generic datasets were

used instead. These were compiled from peer-reviewed LCA studies, providing representative values for both cradle-to-gate and use-phase emissions.

As a simplified and early-stage method, the screening LCA enabled the identification of key life cycle phases and parameters relevant to sustainability. However, the approach also has notable limitations. It was not conducted according to formal standards such as ISO 14040 and was instead based on general literature values, eco-profile data, and secondary material databases. Emission estimates and component comparisons were derived from table-based calculations rather than standardized life cycle inventories. While the precision and reproducibility of the results are limited, all input values and assumptions used in the analysis have been reported in Table 3 to ensure transparency and enable replication. Additionally, since SBC technology is still under development, input data may change significantly as production processes evolve, necessitating updates to the assessment in future studies.

Using the knowledge gained and data gathered, a streamlined screening LCA was conducted with a main focus on greenhouse gas emissions. This was done to provide an insight into the sustainability, effectiveness and multifunctionality of the structural battery composites in these types of vehicles.

The analysis began by evaluating the production phase of key vehicle components, comparing the original material and the lithium-ion battery equivalent with the SBC alternative. This was done using eco-profiles for materials and cradle-to-gate GHG emissions data for commercial LiFePO₄(LFP) batteries sourced from a literature review (Botejara-Antúnez et al., 2024; Kim et al., 2023; Ellingsen et al., 2017). Given the multifunctional nature of SBC, making it capable of replacing both structural materials and integrated battery components, the environmental impact of the substitution was assessed accordingly.

After conducting the production phase analysis, the use phase of the electric quadricycle was then incorporated to account for the larger life cycle effects of employing SBCs. Energy demand in such vehicles is closely related to their mass, particularly in urban driving conditions characterized by frequent acceleration and deceleration. Therefore, minimizing vehicle weight is important to enhance the energy utilization and to reduce the operational emission. To examine the effect of this, an energy reduction value (ERV) for the vehicle class was applied whereby the specific driving nature of quadricycles is considered since they

typically include more stop-and-go urban driving. The resulting analysis aimed to quantify the potential reduction in energy consumption and corresponding greenhouse gas emissions over the electric quadricycle's lifetime.

3.4 Integration and Evaluation

To deepen the evaluation, additional metrics such as emission-per-weight-saved and material efficiency ratios were calculated. This allowed a more complex knowledge of the trade-offs involved and helped pinpoint where SBC might present constraints in the automotive environment or offer the greatest environmental benefits. The material efficiency ratios revealed which material substitutions yielded the highest weight savings per kilogram of SBC used. Meanwhile, the emissions-per-weight-saved metric indicated which material substitutions delivered the most effective weight reduction relative to the associated increase in greenhouse gas emissions and thereby highlighting the most environmentally efficient use cases for SBC across different vehicle components.

These calculations were supported by data extracted from CAD models, which provided accurate estimates of component volumes and geometries. This information was essential for quantifying material use and served as the foundation for modeling the environmental impact of replacing conventional materials with structural battery composites. By linking structural design and environmental assessment, the study evaluated the effects of different SBC integration scenarios on both mechanical performance and environmental impact.

In the attempt to analyze the sensitivity and accuracy of the technical and environmental consequences resulting from the incorporation of the SBC into the vehicle structure, a sensitivity analysis was conducted. Parameters such as energy density, global warming potential (GWP), and grid emission factors were selected based on their relevance to core eco-design principles of minimizing resource use, lowering lifecycle emissions, and optimizing functionality. These parameters reflect both the physical properties (such as energy density) and the functional performance (such as emissions reduction potential) of SBCs, enabling a more thorough assessment of their suitability for vehicle integration. With a systematic variation of these parameters, the effects of various possible scenarios on the overall weight, energy use, and emissions of the vehicle over its lifetime was evaluated. This kind of analysis offers valuable insight into the extent to which material property changes and

conditions can affect the viability and environmental gains associated with SBC incorporation.

Starting the evaluation with the SBCs energy density, the effects on the weight savings and carbon emissions could be calculated for different scenarios. The original energy density value of 100 Wh/kg was based on expert expectations provided via personal communication with Prof. Leif Asp (2025), a leading researcher in the field of structural battery composites, and this was adjusted to account for potential scenarios such as future technological advancements, see Table 1. This allowed for the account of how realistic or optimistic expectations would change the performance of the system. For instance, even in a conservative scenario with a real-world tested energy density of 48 Wh/kg, SBCs still achieved weight reduction, demonstrating that the material is beneficial even in initial applications.

To explore how different assumptions affect the environmental performance of SBCs, three GWP scenarios were defined based on available data. The conservative value (266 kg CO₂-eq/kg) is based on current lab-scale production data provided via personal communication (2025), while the moderate and optimistic values (100 and 19 kg CO₂-eq/kg) were derived from forward-looking estimates in the literature (e.g., Hermansson et al., 2023; Sieti et al., 2024). These values are used in the sensitivity analysis and are not based on actual results but rather represent plausible future development scenarios.

Table 1. Sensitivity analysis input values for energy density and global warming potential (GWP) of structural battery composite materials, based on literature data and expert communication.

| Scenario | Energy Density (Wh/kg) | GWP (kg CO ₂ -eq/kg) |
|--------------|------------------------|---------------------------------|
| Conservative | 48 | 266 |
| Moderate | 100 | 100 |
| Optimistic | 150 | 19 |

The values above were utilized in calculating the breakeven point at which integration of SBC would result in net emissions reductions. Threshold values were established for various base materials (e.g., 46.9 kg CO₂-eq/kg for aluminum) and utilized in informing material substitution decisions within the concept assessment process.

In order to account for regional differences in energy production and their effect on use-phase emissions, grid emission intensity factors were incorporated into the analysis. Sensitivity to national grid GHG intensities revealed that the savings in emissions from vehicle lightweighting vary considerably by nation of operation. For example, savings of emissions during use were much greater in Poland due to a more carbon-intensive grid than in countries such as Sweden, where low-emission electricity means use-phase benefits are small. This deployment-context-specific analysis adds to the generalizability of the findings by illustrating how environmental effects vary across deployment locations.

4. Results

This chapter presents the results of the study, combining insights from the literature review with data gathered through technical concept development, environmental assessment, and structural analysis. It contains conclusions about weight reduction, emissions impact, sensitivity analysis, and component-level viability. Results are intended to determine the feasibility and possible environmental advantages of incorporating structural battery composites into lightweight electric vehicles, particularly electric quadricycles, by using a screening life cycle assessment in accord with structural evaluations

4.1 Key Findings from Literature

The literature review provided critical input for understanding the current state of structural battery composites and their relevance to lightweight EV design. Key findings highlighted the performance characteristics of SBCs, their integration challenges, and opportunities for multifunctional design. The review also contextualized the role of quadricycles in sustainable urban mobility and emphasized eco-design principles as essential to guiding material selection and informing the life cycle perspective applied throughout the project. These insights shaped the scope of the technical exploration and supported the development of design strategies discussed in later sections.

4.1.1 Design-Relevant Takeaways from Structural Battery Composite Research

Current SBCs have significantly lower energy density than conventional lithium-ion batteries, which limits their feasibility in high-power applications such as full-sized EVs. However, for low-power platforms like L6e quadricycles, where motors are limited to a maximum continuous power output of 6 kW (Transportstyrelsen 2019), this constraint is less critical. This makes SBC integration more viable in terms of energy demand.

Current SBCs have much lower energy density compared to conventional lithium-ion batteries. This limits their use in high-power applications but remains acceptable for low-power platforms like L6e quadricycles.

Major design challenges include low energy density, voltage limitations, scalability issues, and limited cycle life. As a result, hybrid systems using both SBCs and traditional batteries are currently a more realistic approach.

These takeaways have directly shaped the technical integration strategy and component-level analysis presented in the following sections.

4.1.2 Implications for Technical Concept Development

To contextualize the design considerations for SBC integration, it is important to understand the characteristics and variation within the current electric quadricycle market. Modern quadricycles prioritize compact dimensions, low weight, and simplified safety features, with most models utilizing electric powertrains designed for urban environments. Their small size and reduced curb weight make them ideal candidates for weight-sensitive design improvements such as SBCs. However, limited space also restricts battery size, which in turn reduces driving range. This challenge underscores the importance of lightweighting strategies to improve energy efficiency and compensate for smaller battery capacities (Çelik & Topaç, 2023).

Table 2 summarizes the specifications of a range of electric quadricycles currently on the market, highlighting the diversity in design approaches. Differences in weight, battery capacity, range, and cost reflect varied manufacturer priorities, from affordability to performance and urban mobility optimization.

Table 2. Specifications of representative modern electric quadricycles

| Model | Vehicle Weight (kg) | Battery Capacity (kWh) | Battery Weight (kg) | Range (km) | Motor Power (kW) | Top Speed (km/h) | Price (euro) | Reference |
|---------------------------|---------------------|------------------------|---------------------|----------------|------------------|------------------|----------------------------|-------------------|
| Renault Twizy 45 | 450 i.b | 6.1 | 98 | 120 | 4 | 45 | (replaced by mobilize duo) | (Renault, n.d.) |
| Renault Twizy 80 | 450 i.b | 6.1 | 98 | 100 | 4 | 80 | (replaced by mobilize duo) | (Renault, n.d.) |
| Renault MOBILIZ E DUO | 495 i.b | 10.3 | 83 | 161 | 5.6 | 45 | €9,990 | (Renault, n.d.) |
| MOBILIZ E DUO 80 Evo | 507 i.b | 10.3 | 83 | 160 | 7.4 | 80 | €12,500 | (Mobilize, n.d.) |
| Citroën Ami | 471 i.b | 5.5 | 46 | 75 | 6 | 45 | €9,080 | (Citroën, n.d.) |
| Microlino 2.0(L7e) | 496/513/530 i.b | 5.5 / 10.5 / 15 | N/A | 93 / 177 / 228 | 12.5 | 90 | €16,617 | (Microlino, n.d.) |
| Microlino Lite (L6e) | 496 i.b | 5.5 / 11 | N/A | 200 | 6 | 45 | €18,686 | (Microlino, n.d.) |
| Silence S04 (L6e variant) | 425 e.b | 5.6 / 11.2(2 × 5.6) | 41 / 82(2 × 41) | 80 / 175 | 6 | 45 | €13429/€16223 | (Silence, n.d.) |
| Silence S04 (L7e variant) | 435 e.b | 11.2 (2 × 5.6) | 82 (2 × 41) | 157 | 14 | 85 | €18,837 | (Silence, n.d.) |
| Aixam City | 425 i.b | 5.44 | | 75 | 6 | 45 | €14,399 | (Aixam, n.d.) |
| Aixam Coupe | 425 i.b | 7.44 | | 130 | 6 | 45 | €17,999 | (Aixam, n.d.) |

Note.

ib - including battery, *eb* - excluding battery

Material selection plays a key role in achieving performance goals in quadricycle design. Composites, and particularly carbon fiber-reinforced plastics (CFRP), have gained popularity due to their high stiffness and impact resistance. Studies show that replacing steel chassis parts with CFRP can reduce weight by up to 50%, while CFRP suspension arms can increase stiffness by 78% compared to aluminum (Koca et al., 2015; Carello & Airale, 2014). Despite

their performance benefits, CFRP components remain expensive and require advanced manufacturing techniques such as resin infusion or autoclave curing (Fatima, 2024).

In light of this, manufacturers and researchers are also exploring alternative composite materials that strike a balance between mechanical performance, cost, and environmental impact. Basalt fiber and para-aramid (Kevlar) composites, for example, have shown promising results in terms of durability and impact resistance while offering lower environmental footprints compared to conventional materials. These alternatives, though less common in automotive applications, represent potential future directions for material substitution in lightweight EVs (Boria & Pettinari, 2014).

4.1.3 Eco-Design and LCA-Driven Parameters

To guide the evaluation of SBC integration in electric quadricycles, a set of sustainability-oriented parameters was developed based on the eco-design principles introduced earlier. These included minimizing material use, maximizing multifunctionality, and reducing life cycle emissions during both production and use phases.

Weight reduction was a central parameter, given its direct impact on energy efficiency and use-phase emissions. Material selection was also informed by eco-design criteria, emphasizing the substitution of conventional components with multifunctional ones to reduce part count and simplify assembly. This aligns with design-for-disassembly strategies discussed in the literature, supporting potential recyclability and maintenance over time.

The streamlined screening LCA emphasized the importance of reconsidering material and component integration in the design of sustainable vehicles. The integration of SBCs not only reduces the total mass of the vehicle, but also removes the need for separate structural and energy storage systems by combining both functions into a single material. This multifunctional approach shows strong potential to reduce both production- and use-phase emissions, supporting the role of SBCs in advancing low-emission transportation technologies.

The Eco-Design Checklist, together with the eco-profile data used in the screening LCA, supported the early methodological framing and guided material selection and component simplification strategies. This concept-based approach provided a practical foundation for

evaluating the sustainability of emerging SBC applications. Findings from the screening LCA contributed to prioritizing which vehicle components are most promising for SBC integration, based on weight-saving potential and emission impact. It also offered early indications of the performance and feasibility of the technology when applied to EV quadricycle components. The results were strengthened by incorporating FEM simulations and cradle-to-gate GWP data from Ansys, which together provided technical validation and environmental insight. This combined method proved useful for assessing the potential of SBCs as multifunctional materials in lightweight electric vehicle design.

4.2 Data Gathering

To conduct a reliable analysis, a series of data collection was needed. The data collection was mainly focused on mechanical properties as well as environmental impacts. Most of the data was secondary, retrieved from established sources such as the Granta EduPack database and peer-reviewed studies (e.g., Hermansson et al., 2023). Granta EduPack was selected for its extensive material data relevant to the studied vehicle components.

The collected data, summarized in Table 3, was used to evaluate trade-offs in both mechanical performance and carbon footprint when substituting traditional materials with structural battery composites.

Table 3. Mechanical Properties and Environmental Impact Data for Traditional Materials and Structural Battery Composites

| Material | Property | Value | Unit | Reference |
|----------|----------------------|-------|---------------------------|--|
| SBC | Density | 1690 | kg/m ³ | (Hermansson et al., 2023) |
| | Elastic Modulus | 76 | GPa | (pers. comm., 2025) |
| | Tensile strength | 300 | MPa | (pers. comm., 2025) |
| | Specific energy | 100 | Wh/kg | (pers. comm., 2025) |
| | Climate Impact (GWP) | 266 | kg CO ₂ -eq/kg | (pers. comm., 2025) |
| Steel | Density | 7870 | kg/m ³ | (Ansys, 2024a) |
| | Elastic Modulus | 200 | GPa | (Ansys, 2024a) |
| | Tensile strength | 600 | MPa | (Ansys, 2024a) |
| | Climate Impact (GWP) | 3.07 | kg CO ₂ -eq/kg | (Ansys, 2024a) |
| Aluminum | Density | 2740 | kg/m ³ | (Ansys, 2024b) |
| | Elastic Modulus | 70 | GPa | (Ansys, 2024b) |
| | Tensile strength | 370 | MPa | (Ansys, 2024b) |
| | Climate Impact (GWP) | 13.2 | kg CO ₂ -eq/kg | (Ansys, 2024b) |
| ABS | Density | 1080 | kg/m ³ | (Ansys, 2024c) |
| | Elastic Modulus | 2.9 | GPa | (Ansys, 2024c) |
| | Tensile strength | 50 | MPa | (Ansys, 2024c) |
| | Climate Impact (GWP) | 3.87 | kg CO ₂ -eq/kg | (Ansys, 2024c) |
| LFP | Specific energy | 150 | Wh/kg | (pers. comm., 2025) |
| | Climate Impact (GWP) | 39 | kg CO ₂ -eq/kg | (Botejara-Antún ez et al., 2024; Kim et al., 2023; Ellingsen et al., 2017) |

4.3 Component-Level Evaluation in a Reference Vehicle

In order to assess the feasibility of the application of structural battery composite in light electric vehicles, a component wise analysis was carried out taking the Citroën AMI as a reference vehicle. The study concentrates on major components and examines potential weight savings, structural considerations, as well as the multifunctional advantages including the SBC technology integration.

4.3.1 Weight Reduction Analysis

This case study investigates the application of SBCs in the components of a typical EV quadricycle, comparing it to conventional materials for the original parts. The aim is to study the multifunctionality of the SBC, evaluating how the SBC integration affects overall vehicle weight while simultaneously contributing to the energy storage of the system. Because of its multifunctional nature, SBC enables weight savings not only through direct material substitution but also by providing battery capacity that offsets the weight of the traditional lithium-ion battery pack in the EV.

The analysis starts by comparing the components with the same volume without regards to any mechanical property differences, this is done to get a more generic overview of the potential weight savings from each component. Table 4 presents the component-wise comparison of original materials and their structural battery composite (SBC) replacements. It works by calculating the weight of each component by using the density of its conventional material and the estimated volume, and comparing it to the weight of a SBC component with the exact same volume. Using this, a preliminary weight difference is shown with regards to the simple change of material. To further analyze the multifunctionality of the SBC material the SBCs weight is multiplied with its specific energy to show the energy capacity of each component. This is then compared to a traditional LPF battery and the weight equivalent of LPF that the SBC capacity replaces is deduced and in doing so the total weight savings for each component can be calculated.

Table 4. Component-wise comparison of original materials and SBC replacements for selected parts without component changes. Conditional formatting is used to visually indicate the relative performance. Green corresponds to values with a positive effect while red corresponds to values with a negative effect, yellow/orange represents moderate or marginal changes.

| Components | Dimensions (mm) | Orig material | Orig weight (kg) | Volume (dm3) | SBC weight (kg) | Weight savings (kg) | SBC capacity (kWh) | LFP equivalent (kg) | total weight savings |
|------------------|-----------------------|---------------|------------------|--------------|-----------------|---------------------|--------------------|---------------------|----------------------|
| Roof | 1000x900x3 | Aluminum | 8.1 | 3.0 | 5.1 | 3.06 | 0.507 | 3.38 | 6.44 |
| Door 1x | | Aluminum | 4.1 | 1.5 | 2.5 | 1.53 | 0.254 | 1.69 | 3.22 |
| Chassis singular | | | | | | | | | |
| 0,5m pipe | 30x500x3 | Steel | 1.0 | 0.127 | 0.2 | 0.78 | 0.021 | 0.14 | 0.93 |
| 13" Rim 1x | | Steel | 3.7 | 0.47 | 0.8 | 2.90 | 0.079 | 0.53 | 3.43 |
| Interior panels | | ABS plastic | 6.9 | 6.6 | 11.2 | -4.29 | 1.115 | 7.44 | 3.15 |
| Battery Casing | 700 x 300 x 200 | Aluminum | 10.8 | 4.0 | 6.8 | 4.08 | 0.676 | 4.51 | 8.59 |
| Body panels | 7.5M ² x 2 | ABS plastic | 15.0 | 15.0 | 25.4 | -10.35 | 2.535 | 16.90 | 6.55 |
| Seats | 681x667x500 | ABS plastic | 3.0 | 3.0 | 5.1 | -2.07 | 0.507 | 3.38 | 1.31 |
| TOTAL: | | | 52.6 | | 56.9 | -4.35 | 5.69 | 37.97 | 33.61 |

The initial analysis shows some clear patterns, switching heavy materials, e.g. steel components with a high density, accumulates a big direct weight saving from the switch of material. Among the materials evaluated, aluminum is the only viable result from the table. This is due to its comparable structural integrity to the steel battery casing, which allows for a straightforward material swap without the need for design modifications to maintain structural performance.

When replacing a steel part most of the weight savings comes directly from the material swap due to the big difference in density. However, this is an oversimplification, as it does not account for the fundamental structural differences between steel and SBCs. Unlike steel, SBCs generally exhibit lower stiffness and strength, which necessitates design modifications to maintain structural integrity. This often involves increasing the component's volume or altering its geometry to compensate for the reduced mechanical performance. Consequently, a

more detailed analysis was required to realistically estimate both the weight and performance implications of substituting steel with SBCs.

4.3.1.1 Volume optimization

However, the analysis becomes more complex when comparing SBCs to other common materials used such as ABS plastic; the direct material substitution results in an increase in weight due to SBC’s higher density. Nevertheless, this is compensated with regards to the high volume of material, resulting in a substantial battery capacity and, ultimately, net weight savings when considering the replacement of the conventional battery pack.

This outcome prompted further consideration regarding volume optimization. The possibility of minimizing SBC component volume to the minimum necessary to satisfy structural requirements, increasing weight savings and minimizing the material. However, such a reduction in volume would also lower the available battery capacity, resulting in an offset of the multifunctional benefits and weight savings from displaced LFP batteries. A quick analysis suggests that decreasing the SBC component’s volume reduces both its weight and energy capacity. Although this lowers the battery replacement potential, the reduced material mass can lead to an even greater total weight saving compared to the original configuration as seen in Table 5.

Table 5. Weight saving comparison between different volumes

| Components | Orig material | Orig Weight (kg) | Orig Volume (dm ³) | SBC Volume (dm ³) | SBC Weight (kg) | Weight savings (kg) | SBC Capacity (kWh) | LFP Equivalent (kg) | Total Weight Savings |
|---------------------|---------------|------------------|--------------------------------|-------------------------------|-----------------|---------------------|--------------------|---------------------|----------------------|
| Interior panels | ABS plastic | 6.9 | 6.6 | 6.6 | 11.2 | -4.3 | 1.1154 | 7.44 | 3.15 |
| New interior panels | ABS plastic | 6.9 | 6.6 | 3.04 | 5.1 | 1.7 | 0.51376 | 3.43 | 5.2 |

4.3.2 Structural Performance Considerations

This analysis was done by creating a more detailed 3D model in CAD for those parts and using FEM analysis in ANSYS to roughly calculate how much extra material is needed. This issue also arises when replacing a weaker material with SBC. In the case of ABS to SBC the SBC is denser and stronger than the ABS and if the design remains unchanged the SBC

component will be much heavier before you account for the energy storage. However, calculations indicate that by reducing the volume of SBC to match the structural performance of the weaker material ABS, the resulting decrease in material mass can lead to an even greater overall weight reduction compared to the original configuration.

4.3.2.1 Component redesign

A technical design approach was used to develop both a wheel rim and a 0.5-meter section of chassis pipe. In the case of the rim a load case was chosen with 2000N load in the center hub of the wheel with a pressure of 0.248MPa acting on the outside of the rim where the tire would be as well as a fixed support acting in all 4 bolt holes on the rim. Using this load case and FEM analysis the design was tweaked to be stronger with respect to equivalent von Mises stress (see Figure 1 & 2).

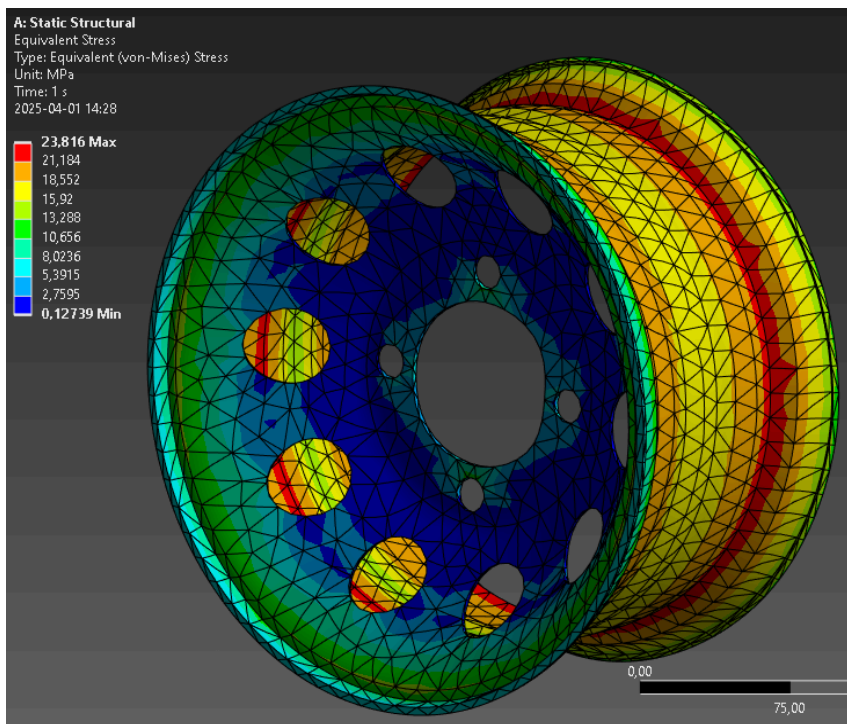


Figure 1. Von Mises Stress Distribution in Original Steel Rim

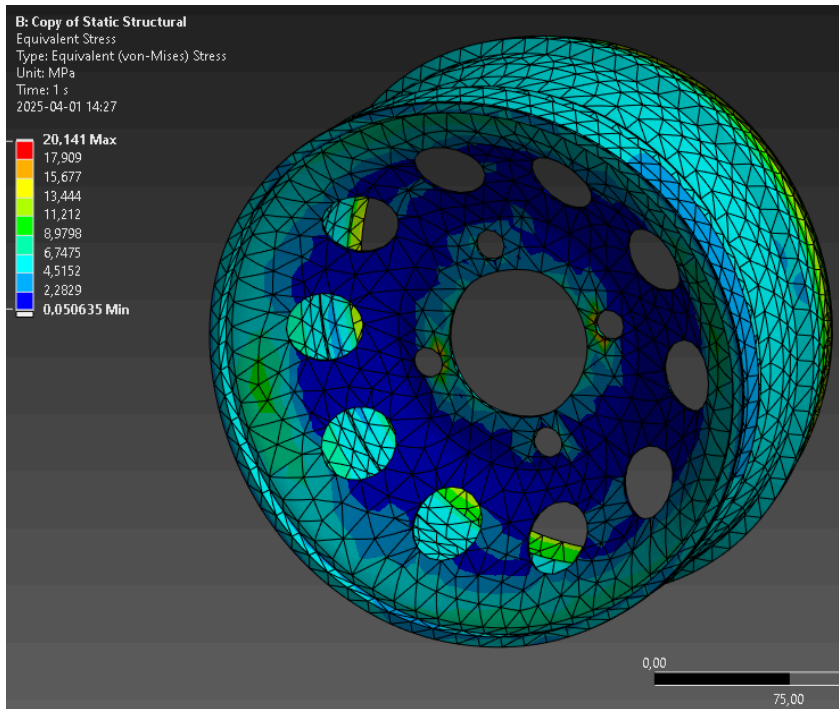


Figure 2. Von Mises Stress Distribution in Adjusted SBC Rim

The redesigned rim reduced the equivalent stress from 27MPa to 20 MPa compared to 23MPa in the original steel rim. To accomplish this, twice as much material was used which in turn resulted in a lower weight reduction. Interestingly, the weight reduction is not linearly proportional to the amount of material used. For example, in the case of the rim, doubling the material usage reduced the total weight savings per rim from 3.3 kg to 2.9 kg—a difference of only 0.4 kg.

This analysis should be relevant for most cases when you are replacing a stronger material with SBC and shows that even if additional material is needed for the same strength the multifunctional nature of the SBC means that you can still get a substantial weight saving.

A similar analysis was performed for the 0.5 M long chassis pipe, which showed very similar results. Since the pipe was considered to be steel, like the rim the projection was that by increasing the volume of the component the mechanical performance could be matched while still achieving a weight reduction due to the multifunctionality and lower density of SBC compared to steel. The load case for the chassis pipe involved fixing both ends and applying a perpendicular load of 10000 N at the midpoint. This setup simulated bending conditions similar to those experienced in a typical vehicle frame (see Figure 3).

Through iterative adjustments in ANSYS, the geometry of the SBC pipe was modified to ensure that the maximum von Mises stress showed similar results to the steel . The optimized design resulted in a 54% increase in volume compared to the original steel pipe, yet the final weight was still reduced by approximately 0.89 kg opposed to the original 0.93kg weight reduction without the structural performance considerations (see Figure 4).

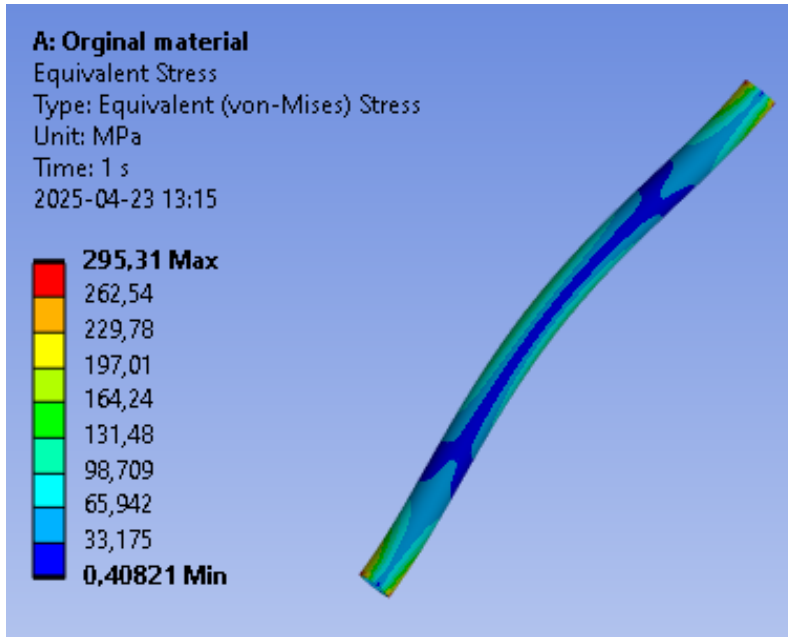


Figure 3. von Mises stress distribution in original steel pipe

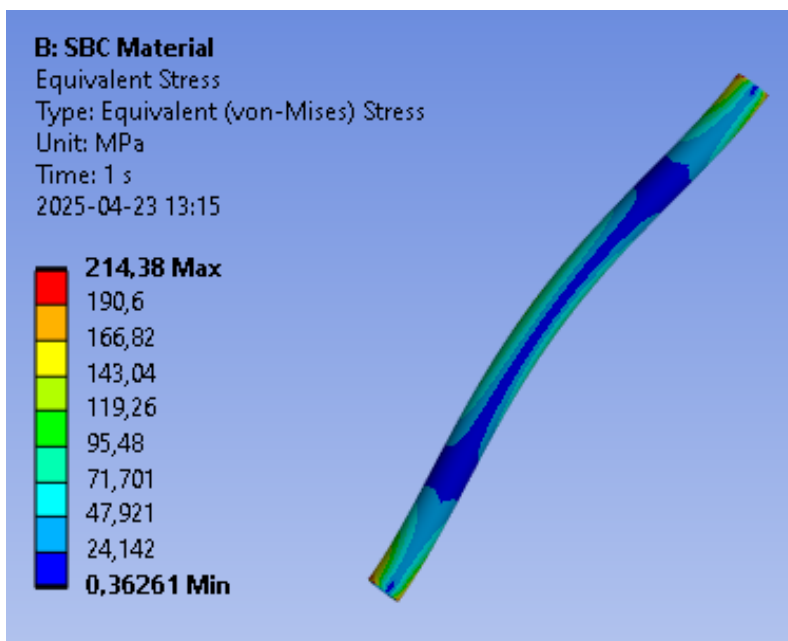


Figure 4. von Mises stress distribution in adjusted SBC pipe

These findings support the idea that while the use of SBC may require more material to meet structural requirements, its lower density and multifunctionality can still provide notable weight savings. Although various components are subjected to distinct loads and stresses depending on their environments, this analysis demonstrates that replacing conventional materials with SBC is feasible and would not be constrained by structural performance if the correct design considerations are taken.

Table 6 shows the components selected for further study for emissions impact. In order to easily observe and compare the most efficient material to replace a ratio of total weight savings / SBC weight used was utilized. With this ratio it is observed for steel that each kg of SBC results in a final weight saving of 2.7 kg which is the best ratio out of all materials. Second place is aluminum that results in a 1.25 kg weight saving for each kg of SBC and for the ABS plastic interior this value is near a 1:1 ratio at 1.02. This ratio is used because it is interesting to maximize the amount of material saved while minimizing the SBC material used from an eco design standpoint.

Table 6. Component-Level Evaluation in a Reference Vehicle after structural adjustments

| Component s | Orig material | Orig weight (kg) | Volume (dm ³) | SBC weight (kg) | Weight savings (kg) | SBC capacity (kWh) | LFP equivalent (kg) | Total Weight Savings |
|--------------------------|---------------|------------------|---------------------------|-----------------|---------------------|--------------------|---------------------|----------------------|
| Roof | Aluminum | 8.1 | 3.0 | 5.1 | 3.1 | 0.507 | 3.38 | 6.4 |
| 5m Adjusted Chassis pipe | Steel | 10 | 1.960 | 3.31 | 6.69 | 0.331 | 2.21 | 8.90 |
| 4x Adjusted Rim | Steel | 14.8 | 4.60 | 7.8 | 7.0 | 0.777 | 5.18 | 12.2 |
| Adjusted interior panels | ABS plastic | 6.9 | 3.0 | 5.1 | 1.8 | 0.514 | 3.43 | 5.2 |
| Battery Casing | Aluminum | 10.8 | 4.0 | 6.80 | 4.00 | 0.680 | 4.53 | 8.53 |
| TOTAL: | | 50.6 | | | 22.5 | 2.8094 | 18.73 | 41.23 |

4.4 Emissions impact

4.4.1 Production phase

In order to study the environmental impact of a theoretical replacement from a traditional material to SBC, a graph was established based on the data presented in Table 6 that includes the tweaking of the components after structural performance considerations. In order to estimate the increase in emissions when switching to SBC, its multifunctional properties need to be accounted for. This is done by comparing the SBC to both the original material of the component and the lithium-ion batteries that the SBC can replace. In Table 7, the comparison is made for a selection of the components that were previously compared. These components, such as rims, chassis pipes, and roof panels were chosen based on the diversity of their original materials, to illustrate how SBCs perform across different substitution scenarios. Not all components were included, as the focus was placed on those offering distinct material contrasts to provide a clearer and more representative analysis.

Table 7. Screening LCA results in the application of EV quadricycle components

| 4x Rim | Steel | LFP Battery | SBC | Total change |
|--|--------------|--------------------|------------|---------------------|
| Quantity (kg) | 14.8 | 5.20 | 7.8 | -12.20 |
| GHG Emission Impacts, kg CO ₂ -eq | 45.4 | 202.8 | 2074.8 | 1826.6 |

| Chassis pipe 5m | Steel | LFP Battery | SBC | Total change |
|--|--------------|--------------------|------------|---------------------|
| Quantity (kg) | 10 | 2.20 | 3.3 | -8.90 |
| GHG Emission Impacts, kg CO ₂ -eq | 30.7 | 85.8 | 877.8 | 761.3 |

| Interior | ABS | LFP Battery | SBC | Total change |
|--|------------|--------------------|------------|---------------------|
| Quantity (kg) | 6.9 | 3.40 | 5.1 | -5.20 |
| GHG Emission Impacts, kg CO ₂ -eq | 26.7 | 132.6 | 1356.6 | 1197.3 |

| Roof | Aluminium | LFP Battery | SBC | Total change |
|--|------------------|--------------------|------------|---------------------|
| Quantity (kg) | 8.1 | 3.4 | 5.1 | -6.4 |
| GHG Emission Impacts, kg CO ₂ -eq | 106.9 | 132.6 | 1356.6 | 1117.1 |

| Battery casing | Aluminium | LFP Battery | SBC | Total change |
|--|------------------|--------------------|------------|---------------------|
| Quantity (kg) | 10.8 | 4.53 | 6.8 | -8.53 |
| GHG Emission Impacts, kg CO ₂ -eq | 142.6 | 176.8 | 1808.8 | 1489.4 |

Due to the fact the only GWP value for the SBC material is for lab-scale production (a very inefficient process with high losses) the value is higher than similar materials such as carbon fibre or lithium ion. Larger-scale production typically benefits from economies of scale, leading to lower per-unit energy consumption and material waste. For example, in automated production lines, material utilization can be optimized, and energy-intensive steps such as curing or molding can be shared across batches, reducing emissions per component.

In the case of a GWP of 266 kg CO₂-eq/kg for the production of SBC it is concluded that for the weight reduction of 41.23kg the emissions are increased by 6391.7 CO₂. Which means for every one kg saved the emissions are increased by 155 kg CO₂-eq.

By dividing the emissions with the kg saved for each component a clear pattern emerges, components that were originally steel such as the chassis pipe and rims have the lowest CO₂-eq increase for each kg saved at 85.5 kg CO₂-eq shown in Table 8. The aluminium parts are second best with an increase of 174.5 kg CO₂-eq for each kilo saved. This is expected due to the densities of each material, a ratio was also calculated based on each kg saved vs how many kg of SBC where used, this will logically relate closely to the densities of each material but because of the structural performance considerations it will now more accurately describe show the potential weight savings for each kg of SBC. The kg saved per kg SBC value can also be used to evaluate the economic feasibility of substituting a given material with SBC, as it provides an approximate estimate of the amount of SBC required to achieve a specific weight reduction.

Table 8. kg CO₂-eq Savings and Weight Replacement Ratios for SBC Substitution in Vehicle Components

| Ratio | 5m Chassis pipe (steel) | Roof (Aluminum) | Interior (ABS) |
|-------------------------------------|-------------------------|-----------------|----------------|
| kg CO ₂ -eq per kg saved | 85.54 | 174.54 | 230.25 |
| kg saved / kg SBC | 2.70 | 1.25 | 1.02 |

The standing for each material is that Steel has the lowest GHG emissions per kg switched and the highest kg saved per each kg of SBC, with aluminium coming in at a close second with 174 and 1.25 respectively and in last place the ABS at 230 kg of CO₂-eq per kg saved and a kg saved/ kg SBC ratio of 1.02.

4.4.2 Use phase

While the production phase of the different materials may vary in emissions impact, the unique multifunctionality of the SBC material has shown a significant decrease in the overall weight of the vehicle. When analyzing the component changes in Table 6, a total weight reduction of 41.23 kg was observed, corresponding to a 9.2% decrease in vehicle mass. Of this, 18.73 kg of weight savings comes from the SBC replacing part of a 25 kg lithium iron phosphate (LFP) battery, which is one of two modules in a full 46 kg battery pack. This highlights the multifunctional advantage of SBCs, as they not only substitute structural

materials but also partially replace traditional battery mass, contributing meaningfully to overall weight reduction and enhancing vehicle efficiency.

This weight reduction has a direct influence on the energy consumption of the vehicle during its operational life. According to multiple studies, vehicle energy demand is closely linked to its mass, especially in urban driving cycles where acceleration and deceleration are frequent (Freyermuth et al., 2014). Reducing mass therefore contributes to increased energy efficiency and, consequently, lower greenhouse gas (GHG) emissions during the use phase.

For this study, the Common Artemis Driving Cycles (CADC) were employed, with a focus on the Artemis Urban Cycle to represent the typical operational conditions of electric quadricycles. The Artemis Urban Cycle is specifically designed to simulate city driving, characterized by frequent stops, idling, low-speed acceleration, and deceleration. It runs for approximately 993 seconds (16.5 minutes), covering a distance of 4.6 km at an average speed of 16.4 km/h (DieselNet, n.d.). This cycle effectively reflects the real-world usage patterns of electric quadricycles, which are primarily intended for urban environments.

To estimate this effect quantitatively, the energy reduction value (ERV) had to be established for the case of the quadricycle. The ERV often reflects on the size of the vehicle, increasing as the vehicle increases. Studies have shown that for a vehicle within the N1 class weighing approximately 3500 kg, the ERV under the Artemis Urban Cycle was 1.42 kWh/100 kg * 100 km. It also showed that for a smaller car weighing approximately 1500 kg the ERV was 1.2 kWh/100 kg * 100 km under the same conditions (Sandrini et al. 2024). Using this information, an energy reduction value of 0.83 kWh/100 kg * 100 km was estimated to be viable for a 471 kg (weight of Citroën Ami including batteries) quadricycle under the Artemis Urban Cycle. This means that for every 100 kg of vehicle mass reduced, the vehicle consumes approximately 0.83 kWh less energy per 100 km driven.

Assuming the electricity grid to be 210 gCO₂-eq/kWh, which has been shown to be the average Greenhouse gas emission intensity of electricity generation output per kilowatt-hour in the European Union in 2023 (European Environment Agency, 2024), and a lifetime distance of the vehicle of 100,000 km which is about a third of the lifetime distance of a Tesla Model 3 (Kane, 2024) an estimation of the operational emissions can be calculated.

Based on an estimated vehicle energy consumption of 73 Wh/km for a Citroën Ami, the weight reduction leads to an improvement in efficiency, translating to an energy saving of 341.4 kWh over the vehicle's lifetime. This corresponds to a reduction of approximately 71.7 kg CO₂ in operational emissions.

This stage of the evaluation underscored the importance of rethinking material and component integration in the design of sustainable vehicles. The SBC exemplifies this approach by combining structural integrity and energy storage within a single material, thereby reducing the total vehicle mass and eliminating the need for redundant systems. This integration not only lowers operational and production emissions but also illustrates that meaningful emission reductions can be achieved beyond cleaner energy sources or manufacturing methods. By uniting structural function, energy storage, and lightweighting, SBC technology presents a promising avenue for advancing low-emission transport solutions.

4.5 Sensitivity

This sensitivity analysis examines the impact that variations in the most significant parameters, such as the energy density and GWP of Structural Battery Composite material, have on the overall weight savings, energy use and emissions profile of the vehicle. Changes in SBCs energy density can impact the vehicles weight and energy efficiency, while changes in its GWP (kg CO₂-eq/kg) impact lifecycle emissions associated with vehicle production. By changing these parameters, as well as driving cycle assumptions, we can gain a better insight into their impact on the vehicle's environmental impact.

4.5.1 Energy density

The energy density of structural battery composites is expected to reach between 70–100 Wh/kg within the next one to four years, based on performance targets communicated by researchers at Chalmers. This value represents a future development target rather than current performance levels. As previously stated a value of 100 Wh/kg was chosen for this report. By revising the calculations for different values of energy density the sensitivity to energy density changes can be calculated.

In the theoretical case of a 30Wh/kg increase to 130 Wh/kg the increase is 13.6% which shows that for each wh/kg increase in energy density the weight savings improve by roughly 0.45% and the same appears true for a decrease. In the case of a 30Wh/kg decrease to an

energy density of 70 Wh/kg; a 13.6% decrease in weight savings is observed (see Figure 5). If the energy density would improve to the level of LFP at 150 Wh/kg there is a 22.7% increase in weight savings (see Figure 5). The current energy density of real-world tested structural battery composites (SBCs) is approximately 48 Wh/kg. At this performance level, the overall weight savings are reduced by only 23.6%. Notably, even when replacing ABS plastic, one of the least favorable materials to substitute in terms of density, the SBC still achieves a weight reduction of 3.43 kg. This is made possible by halving the component volume to match the structural performance of the original plastic part.

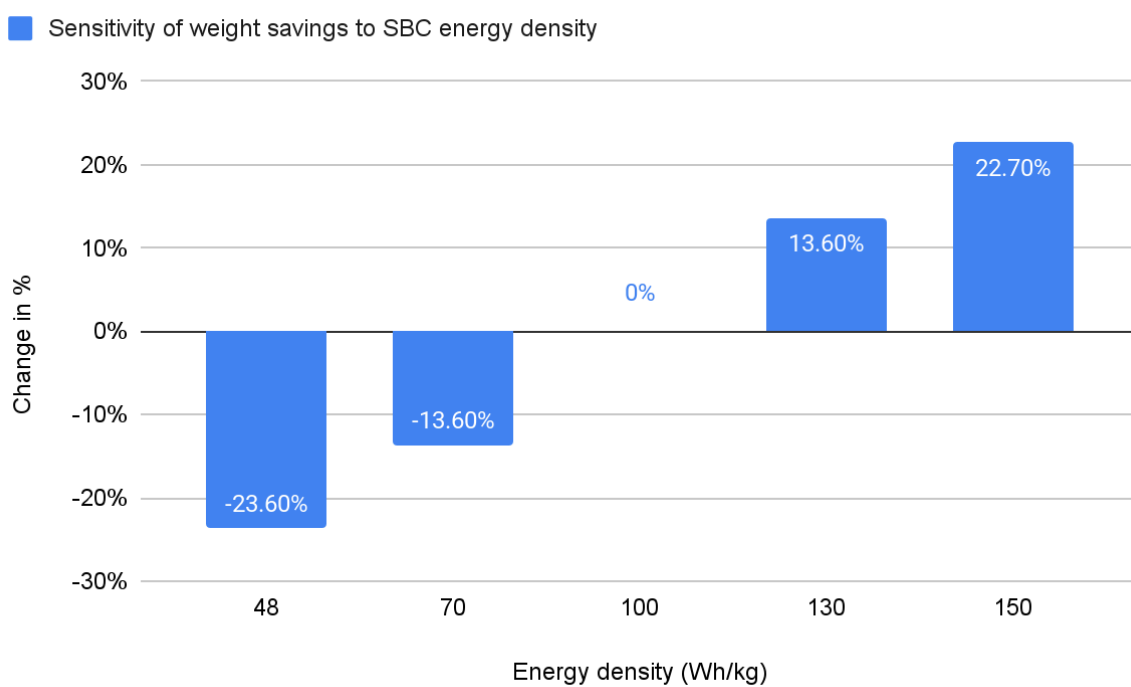


Figure 5. Sensitivity of weight savings of SBC system (difference in weight savings /original weight savings) to SBC energy density (higher percentage means higher weight savings).

The energy density also affects the total CO₂-eq emissions because the increase in energy density means that the same amount of SBC can replace more of the original LFP batteries which in turn reduces the CO₂-eq emissions of the SBC component.

The current CO₂-eq emission for SBC production, as reported in a laboratory-scale LCA (Sieti et al., 2024), reflects an early-stage manufacturing process. These values are expected to decrease with future developments and upscaling of SBC production, as process efficiencies improve and material losses are minimized.

Because of this the impact of energy densities on the total CO₂-eq emissions is very low. In order to still get some interesting results, calculations were made that compared how much the CO₂-eq emissions caused by the LFP battery are reduced since a higher SBC energy density means you replace more LFP batteries for a given component. Calculations show that the percentage change in CO₂-eq emissions from the LFP batteries being replaced is directly proportional to each wh/kg increase/decrease which means,

- A 30 wh/kg decrease in SBC energy density means a 30% increase in LFP battery CO₂-eq emissions
- A 30 wh/kg increase in SBC energy density means a 30% decrease in LFP battery cells CO₂-eq emissions

Because energy density increases, more LFP batteries can be replaced with the same amount of SBC, which in turn reduces the total vehicle emissions because of the now smaller LFP battery.

4.5.2 Climate impact

Since the GWP value is based on laboratory scale production it would be interesting to know what a realistic large scale production GWP value could be for the SBC. Earlier studies have used a GWP for SBC of 19 kg CO₂-eq emissions/kg as an educated guess of CO₂ emissions during SBC production (Hermansson et al., 2023). In the case of the 266 GWP used earlier we can see that the total CO₂-eq emissions when swapping the rims, 5m of the chassis, interior, roof and battery casing is an increase in emissions of 6391kg CO₂-eq. For the case with a climate impact of 19 kg CO₂-eq emissions/kg we get an emissions reduction of 549 kg CO₂-eq for the same change. If it is assumed the real value would be between these two GWP values it would need to be lower than 42 (when accounting for reduction in emissions due to weight saving in use phase) in order to reduce total vehicle emissions. However looking at the different components it is observed that this change occurs at different values depending on what material the original component was made of.

In the case of aluminum this shift from negative impact to positive occurs at a GWP value of equal or less than 46.9kg CO₂-eq. Below are the minimum values for the SBC to reduce the total emissions of the vehicle excluding the use phase.

- **Aluminum:** SBC must have a GWP < **46.9 kg CO₂-eq/kg**
- **ABS plastic:** SBC must have a GWP < **31 kg CO₂-eq/kg**
- **Steel:** SBC must have a GWP < **35 kg CO₂-eq/kg**

In a scenario where the GWP of producing SBC is lower than any of these values, replacing that material will reduce the CO₂-eq emissions of the component.

4.5.3 Grid factor

Electricity production varies significantly by energy mix across different countries, resulting in large disparities in associated greenhouse gas (GHG) emissions. Within the European Union, total GHG emissions continue to decline, driven by policy measures, increased deployment of renewable energy sources, and improvements in energy efficiency. Yet, major disparities among the member states still persist, see Table 9. A few nations, such as Sweden and France, utilize low-carbon energy sources, such as hydropower and nuclear power, to a large extent, which explains their comparatively lower emissions. Others, such as Poland and Bulgaria, continue to rely on coal heavily, and their emission rates are much higher (European Environment Agency, 2024).

Table 9. Disparities of GHG emission intensity of electricity generation between EU countries

| Country | Grid Factor gCO ₂ e/kWh |
|----------|------------------------------------|
| Sweden | 8 |
| Portugal | 119 |
| EU-27 | 210 |
| Germany | 329 |
| Poland | 614 |

These differences will affect the impact of lightweighting of the vehicle. When looking at a country like Poland which is among the highest in the EU, the GHG emission intensity of electricity generation is 614 gCO₂e/kWh which is almost three times higher than the 210 gCO₂e/kWh EU-28 average. Due to these differences in the electricity generation the avoided emissions during the use phase will be greater in a country that relies heavily on fossil fuels such as coal to generate the grid electricity. On the other hand, in countries that rely on low-carbon energy sources such as Sweden, which is among the lowest in the EU, the GHG

emission intensity of electricity generation is only 8 gCO_{2e}/kWh, where the emissions avoided through energy savings from lightweighting are minimal and largely negligible. This is clearly shown in Fig 6, where the three different scenarios are compared, showing that in high-emission countries such as Poland, the emissions avoided in the use phase through lightweighting amount to 209.6 kg CO₂-eq, while in low-emission countries such as Sweden, the reduction is only 2.7 kg CO₂-eq.

Use-phase sensitivity to grid factors

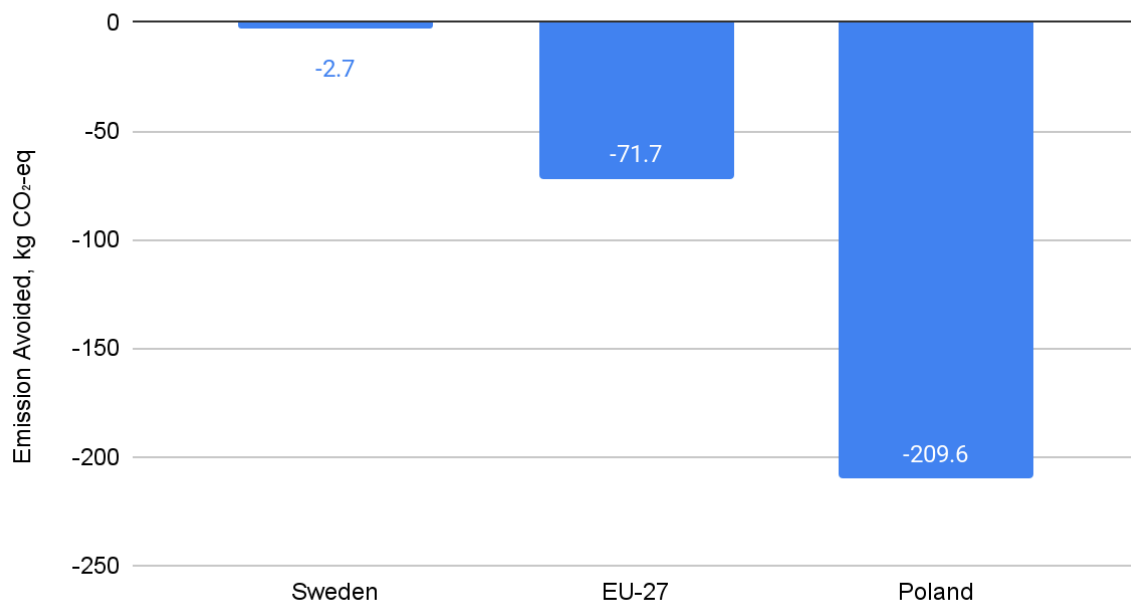


Figure 6. Avoided GHG emission through lightweighting during the use phase for the electric quadricycle in different grid factors

4.6 Summary of Findings

The integration of structural battery composites into lightweight EV quadricycle components demonstrated both environmental and structural viability. Key findings include:

- The integration of SBC led to significant weight losses. This is especially the case when replacing dense materials such as steel and aluminum for example, replacing part of the steel chassis or aluminum body panels such as the roof showed great weight savings for the vehicle.

- SBC's multifunctionality showcased that the component can serve not only as a structural part but also as an energy storage unit, reducing the need for separate battery packs and enabling system-level mass savings.
- Components designed with SBC can contribute meaningfully to energy storage (e.g. Table 6 showing a 2.81 kWh total in the case study), partially replacing the conventional LFP batteries. It even has the potential to replace conventional LFP batteries entirely, either by integrating more vehicle components, increasing energy capacity, or both.
- FEM simulations indicate that with design adaptations the SBC can match the strength of traditional materials such as steel, if the volume is increased and the correct design considerations are taken.
- The sensitivity analysis showed that with the right precautions and an estimated full-scale production of SBC, the SBC integration can yield significant net environmental benefits.
- Despite its high lab-scale production emissions (e.g., 266 kg CO₂-eq/kg for SBC), the use phase emissions can be lowered due to the lightweighting of the vehicle, particularly in regions with carbon-intensive electricity grids.

5. Discussion & Recommendations

This chapter presents a detailed discussion of the key findings, limitations, and broader implications of integrating Structural Battery Composites (SBC) into lightweight electric vehicles, with a particular focus on L6e quadricycles. The interpretation of results highlights the environmental and structural trade-offs associated with SBC adoption, emphasizing material selection, weight-saving potential, and life cycle emissions. A critical analysis of data reliability, production constraints, and eco-design challenges further frames the scope and boundaries of this study. Technical feasibility is explored through targeted component evaluations, leading to practical design recommendations that align with eco-design principles such as modularity, reparability, and material efficiency. Finally, the discussion extends beyond quadricycles, considering the potential application of SBC in larger vehicles and other sectors where weight reduction is vital, such as aerospace. These insights serve as a foundation for strategic recommendations in the subsequent chapter and inform the potential direction of future SBC development and deployment.

5.1 Interpretation of Key Results

There are many factors to consider for the integration of SBC in a vehicle due to its unique multifunctionality. Its multifunctionality allows it to combine two separate systems into one, a structural component with an energy storage. This is the appeal for the use of SBC, as it does not only remove redundant systems but also because it aligns with the eco-design principles of “doing more with less” due to the resource minimization. The technology shows great potential to fulfill its intended function, if the right advancements were to be achieved.

For instance, if the GWP value for large scale SBC production ends up being lower than 31 kg CO₂-eq/kg the appeal of SBC will increase significantly due to the fact that it would make components lighter and more environmentally friendly all while increasing vehicle range and

without reducing component strength. For industry actors this will probably help offset the potential increase in complexity and required change in design approach that swapping to SBC will likely bring. Even a GWP value of 35 or 46.9 kg CO₂-eq/kg could be enough to consider using SBC from an environmental perspective due to the fact that this is when steel and aluminium become climate positive to replace with SBC.

The research has shown that when considering the utilization of SBC, the most weight saving efficient materials to target are dense but strong materials wherever possible. Parts made from steel are the most efficient to replace of the materials looked at in this report, it can however be hard to find components made out of steel to replace, especially in electric quadricycles that already use a lot of aluminium.

The ideal material to swap from an environmental perspective would be aluminium since it has significantly higher emissions than steel and thus helps offset the increase when swapping to SBC and in the case of a lower GWP for SBC results in increased CO₂-eq savings. In general the heavier the material is the better it is to swap as long as structural considerations are taken into account. Even when accounting for the lower strength of the current SBC it is still beneficial to swap from steel over aluminium to SBC from a weight saving perspective even if it loses out in the environmental aspect.

When considering the benefits of the weight savings during the use phase, the avoided emissions in countries like Sweden, where the greenhouse gas emission intensity of electricity generation is as low as 8 gCO₂e/kWh, are almost negligible. Nevertheless, if the weight savings significantly reduce energy consumption, it could allow for a smaller battery pack or serve as a selling point for manufacturers, offering consumers a more cost-efficient vehicle in terms of both purchase and operation.

5.2 Critical Analysis & Limitations

Due to the lack of large-scale production of SBC, limited access to physical materials and reliable environmental data restricted the analytical depth of this project. While personal communications were held with experienced researchers in the field, which helped strengthen the likelihood of reasonable estimations, much of the data used remains uncertain or based on proxy values.

One aspect further limiting the project was time. Gathering real-world data and building detailed scenarios for a more comprehensive LCA would have been too time-consuming within the given timeframe. As a result, a streamlined prospective LCA was selected, focusing on greenhouse gas emissions to quantify prospective scenarios of material substitution. This analysis was complemented by sensitivity assessments to account for uncertainties in key parameters such as energy density, global warming potential, and grid emission factors.

This approach allowed investigation into the carbon emissions during both the production and use phases of SBCs in a quadricycle application. A more advanced LCA using dedicated software such as OpenLCA could potentially alter the overall environmental conclusions, especially by revealing other relevant environmental trade-offs, such as resource depletion or toxicity potential. Moreover, the end-of-life phase was not included in this study, although existing research (e.g. Hermansson et al., 2023) addresses this topic.

Another important aspect, which falls outside the scope of this project, is the cost dimension of SBC applications. Currently, there is limited research on the production costs of SBC cells. Based on a qualitative comparison between the cost of raw materials in SBCs and materials such as iron used in LFP batteries, SBCs are expected to be more expensive. However, this is difficult to determine precisely, as studies suggest that lignin-based carbon fibres could significantly lower the cost of carbon fibre, especially in the context of future price trends for fossil-based alternatives (Baker, 2013).

Carbon fibre is widely regarded as an expensive material, especially when compared with materials like steel or aluminium. The nature of the SBC material means that the SBC material will potentially be more expensive than its LFP equivalent even when accounting for the reduction in other materials like steel, aluminium and especially ABS plastics.

5.3 Technical Feasibility & Design Recommendations

The application of SBC in a quadricycle can be tricky; there are a lot of factors to account for in the potential components to achieve the desired result. Therefore should an application be viewed from an eco-design perspective. This can be guided by an Eco-design checklist where questions are provided to support the analysis of a product's impact on the environment.

While the application of SBC in quadricycles could help advancements in urban congestion and short-distance commuting, technology is not only confined to a quadricycle application but could show more benefits in other vehicle types.

5.3.1 SBC application recommendations for Quadricycles

A key insight obtained during the project was that the rim component studied in this report was not a suitable option for the application of SBC, due to the rotation of the wheel affecting liquid inside the SBC cells. This input, provided by Leif E. Asp suggests that while this limitation may be overcome in future developments, it currently presents significant challenges. Additionally, rims are exposed to frequent impacts from curbs and road debris, making them prone to damage. Their rotating nature could complicate the extraction of stored energy efficiently, and the proximity to the ground increases the risk of wear, contamination, or leakage in case of composite failure. However the findings are true for any similar steel component such as the chassis pipe which is an ideal material to swap for the component and offers great weight savings per kg of SBC used.

Another key observation is the vulnerability of the structural battery composite in the event of damage or even a crash. In such scenarios, the energy storage function of the SBC may be compromised, rendering the component unusable. Currently it remains uncertain if damaged SBC can be effectively repaired. Consequently, affected parts would likely need to be disposed of or recycled, even if only partially damaged.

To look at it from an Eco-Design perspective, it would be advisable to integrate SBCs into areas of the vehicle that are less exposed to impact during collisions such as the roof or interior. This approach would minimize the risk of material waste and overdesign. Considering the high likelihood of impacts such as crashes or dents in the typical urban operating environment of quadricycles, it is therefore strongly recommended. The integration of SBC into these vehicles from an accident perspective remains a challenge and could potentially be avoided in other vehicle types.

If the application were to be evaluated using an eco-design checklist, any future implementation of SBC components would need to be both detachable and positioned within a serviceable area of the vehicle. This could imply that the suggested application of SBC in parts of the chassis would be less favorable, as such components are typically not designed

for easy disassembly or replacement, thereby conflicting with principles of modularity, repairability, and end-of-life recovery promoted in eco-design.

5.3.2 SBC's Viability for Other Vehicle Types

Structural battery composites show considerable promise within light electric vehicles such as quadricycles. This project focused on the L6e category, which includes vehicles with a maximum curb weight of 425 kg (excluding battery weight for electric models). However, the insights gained are also applicable to related vehicle classes.

SBC integration may be especially advantageous for the L3e category, which includes two- or three-wheeled vehicles like electric motorcycles. Despite the structural limitations of these vehicles, lightweighting and compact energy storage are equally important. If the structural requirements can be satisfied within their smaller frames, SBCs may provide functional and performance advantages given the high sensitivity of L3e vehicles to weight and volume.

A logical progression of the results in this report is the L7e category, which covers quadricycles up to 450 kg curb weight for passenger transportation and 600 kg for goods transportation. The application of SBCs to L7e vehicles is predicted to be comparable, if not identical, to the strategy used for L6e based on the results. However, because of the larger structural surfaces, there may be a greater performance impact.

But the application could range beyond quadricycles, across bigger vehicle classes such as electric cars and trucks. This could potentially help reduce the emissions of both passenger cars and commercial trucks by lightweighting and still keeping the same range, if the GWP during production is low enough there would be savings both during production and use phase helping electric vehicles be even more competitive.

There is an argument to be made that the application of SBCs becomes more beneficial as vehicle size increases. Although larger vehicles may not operate as frequently in urban environments, where lightweighting has a great impact, their Energy Reduction Value (ERV) often scales with vehicle size, meaning that the potential energy savings grow as the vehicle mass increases. Additionally, larger vehicles offer more material volume that can be substituted with SBCs, which can result in greater absolute weight reduction. However, it's important to note that while the total weight savings may be higher, the relative weight reduction (as a percentage of total vehicle mass) could remain similar across different vehicle

sizes. Nevertheless, replacing more material would lower the overall emission to a greater extent in a bigger vehicle if the GWP of SBC would be below the break even points for the relevant materials.

More broadly, the technology is relevant to any domain where weight reduction is critical, such as the aerospace industry. Despite advances in lithium-ion batteries, electric aviation remains limited by the insufficient energy density of current battery technologies (Crownhart, 2022). Recent research has explored the potential of structural batteries to address this limitation and contribute to the viability of electric aviation (Kühnelt et al., 2022). This study proposed performance targets for structural batteries, suggesting that an energy density of approximately 100 Wh/kg and a Young's modulus of around 100 GPa would be required for aviation applications. These are below the targets set by the Chalmers research team within a timeframe of 1-4 years. This implies that if those goals can be met SBC could possibly be utilized in the aviation industry if other issues are solved within the near future and in turn help make the aviation industry climate neutral by enabling longer range electric aircraft. This of course depends on the research team at Chalmers being able to reach those goals because current SBC technology is not yet at that level.

5.4 Strategic Recommendations for Future Work

Future research should collaborate in close cooperation with automotive manufacturers to better align the development of structural battery composites with relevant design, manufacturing, and regulatory requirements. Collaboration directly with industry partners would allow for the possibility of gathering proprietary information, resolving actual design constraints, and gaining feedback on manufacturability and readiness for market. This type of collaboration could also accelerate prototyping and testing of SBC components in existing vehicle architectures, thus fostering incremental design improvements. Moreover, early contact with manufacturers can determine the most promising vehicle segments or parts for the application of SBC, which can potentially accelerate commercialization and guarantee that design innovation addresses both technical requirements and consumer needs.

Building on this, an essential area for future work is the validation of structural performance in full-scale SBC components. As the current technology remains cell-based and largely theoretical, developing and testing full-scale prototypes would provide more accurate

mechanical data and allow for realistic assessments of structural behavior under load. This should include mechanical fatigue tests, crash simulations, and vibration resistance evaluations in real-world conditions, offering deeper insight into durability, safety, and functional integration of SBCs in vehicle systems.

Another important area for future research is conducting a comprehensive LCA of structural battery composites. While the current study primarily collected data from LCA studies for the GWP, a broader LCA would evaluate additional environmental impact categories such as resource depletion, water use, human toxicity, particulate matter formation, climate impact and end-of-life scenarios. This would provide a more comprehensive understanding of the environmental trade-offs of SBC integration in quadricycles and guarantee that carbon emission reductions are not made at the expense of other sustainability indicators.

Additionally, research in the future needs to investigate the repairability/recyclability trade-offs that are inherent to the SBC technology. Since SBCs perform both structural and energy storage roles, their design could make the disassembly, repair, and material recovery at the end of the vehicle's life more difficult. It is crucial to understand the trade-offs in order to inform the development of SBCs that are not just efficient in use but also reasonable with respect to circular economy considerations. Investigating how SBC design choices affect ease of disassembly, component reuse, and material separation could help overcome key barriers to recyclability and support more practical end-of-life strategies.

Furthermore, future work should place greater emphasis on identifying vehicle platforms and application domains which stand to benefit the most from SBC integration. Research should investigate SBC use not only with quadricycles, but also other categories of electric vehicles where design constraints, power demands, and available installation space may be especially well-suited to SBC use. Comparative examination of vehicle structures may identify other components like floor panels, doors, or battery enclosures that are most practical considering the function of storing energy versus structural strength. Incorporating user-focused criteria such as vehicle use patterns, urban driving profiles, and charging behavior will also be important to ensure that SBC integration aligns with real-world mobility needs and enhances overall system efficiency and usability.

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Appendix:

Table A1. Component-Wise Comparison of Original Materials and SBC Replacements

| Component | Material | Density (kg/m ³) | Young's Modulus (GPa) | Tensile Strength (MPa) | Characteristics | Use/Source |
|-------------------|--|------------------------------|-----------------------|------------------------|--|---|
| Chassis | High-Strength Low-Alloy (HSLA) Steel | ~ 7,850 | ~ 210 | 250–550 | Offers a good balance between strength and weight, providing structural integrity while allowing for weight reduction. | Usually used in larger vehicles with higher weight, seen usage in more robust quadricycles, e.g Renault Twizy |
| .Alt | Aluminum Alloy | ~ 2,700 | ~ 70 | 200–600 | Lightweight, corrosion-resistant, good strength-to-weight ratio, aiding in energy efficiency. | Increased usage for quadricycles because of its strength-to-weight ratio. Often mixed with steel, e.g Ligier & Aixam models |
| .Alt | Carbon Fiber Reinforced Polymer (CFRP) | ~ 1,600 | 80–150 | 600–2,500 | Extremely lightweight, high strength-to-weight ratio, excellent fatigue resistance, but costly and complex to manufacture. | More experimental, not an industry standard. It has shown promise in weight reduction while keeping the structural integrity (Koca et al., 2015). |
| Body Panel | ABS Plastic (Acrylonitrile Butadiene | ~1,050 | ~2.28 | ~43 | lightweight, impact-resistant, and rigid | ABS is widely used in L6e quadricycles for body panels, |

| | | | | | | |
|-----------------------|-----------------------------|---------|--------|-----------|---|--|
| | Styrene) | | | | thermoplastic with good dimensional stability and a smooth surface finish, making it ideal for durable and aesthetic components. | bumpers and protective covers, light casings and grilles (e.g., Renault Twizy, Ligier quadricycles) |
| .Alt | Polypropylene (PP) Plastic | ~ 900 | 1.5–2 | 25–40 | Lightweight, cost-effective, and easily moldable, making it suitable for complex shapes and designs. | More of a budget version, probably seen as a complement to ABS in many designs. |
| .Alt | Fiberglass (E-Glass) | ~ 2,580 | ~ 72 | ~ 3,400 | High strength-to-weight ratio, corrosion resistance, and design flexibility. | Is utilized in various components across different vehicle types. Used for body panels in L6e quadricycles, reduce weight while maintaining structural integrity. |
| Suspension | Spring Steel (eg. SAE 5160) | ~ 7,850 | ~ 200 | 724 | High strength and toughness, excellent fatigue resistance, and good elasticity. Suitable for cyclic loading and impact absorption in suspension components. | Commonly used in automotive suspension systems (e.g., leaf springs, coil springs) due to its excellent fatigue strength, toughness, and elasticity. Widely adopted in both traditional and lightweight vehicle applications. |
| .Alt | CFRP | ~ 1,600 | 80–150 | 600–2,500 | Stiff, lightweight, reduces unsprung mass | Experimental suspension arm using CFRP (Carello & Airale, 2014). |
| Battery Casing | Aluminum Alloy | ~ 2,700 | ~ 70 | 200–600 | Lightweight and corrosion-resistant, providing structural support and effective thermal management for | Common choice for battery casings in EVs, offering strength and cooling advantages. |

the battery pack.

| | | | | | | |
|----------------------------|---|---------------------------|-------|---------|---|--|
| Interior Components | Acrylonitrile Butadiene Styrene (ABS) Plastic | ~ 1,050 | 2–2.5 | 40–60 | Durable, easy to mold, and provides a good surface finish, commonly used for dashboards and interior trims. | Commonly used in automotive interiors for components like dashboards, trim panels, and pillar covers due to its good moldability, impact resistance, and surface finish. |
| Seats | Polyurethane (PU) Foam | 30–50 for flexible foams. | N/A | N/A | Provides cushioning and comfort, lightweight, and can be molded into various shapes. | Widely used in vehicle seating for its cushioning, light weight, and flexibility. Found in seat bases, backs, and headrests. |
| Rims | Steel Alloys | ~ 7,850 | ~ 210 | 400–550 | Provides the necessary strength and durability to withstand various driving conditions and loads. | Standard rim material in many low- to mid-cost vehicles due to high strength and affordability. Common in EV quadricycles and small urban vehicles. |
| .Alt | Aluminum Alloy | ~ 2,700 | ~ 70 | 200–600 | Lightweight, corrosion-resistant, good strength-to-weight ratio, aiding in energy efficiency. | Increasingly used in EVs for its lower weight, helping reduce rotational mass and improve energy efficiency. Found in high-efficiency and premium vehicle wheels. |

Source: Authors' compilation based on literature review and data from Ansys Granta EduPack (2024), Koca et al. (2015), and case examples such as Renault Twizy and Ligier quadricycles.

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