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To cite this article: E Jansson *et al* 2026 *IOP Conf. Ser.: Mater. Sci. Eng.* **1342** 012070

IOP Conf. Series: Materials Science and Engineering **1342** (2026) 012070
doi:10.1088/1757-899X/1342/1/012070

Enabling Scalable Structural Battery Composite Production: Key Considerations and Possibilities

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Abstract. Extended electrification in transport and product segments requires lightweight and energy-efficient solutions that also allow for increased design flexibility. Structural battery composites meet these needs by combining mechanical load-bearing capability with energy storage in a single multifunctional material. This study focuses on structural battery composites made from carbon fiber reinforced polymer (CFRP) and evaluates their manufacturing methodology. Using a SWOT analysis framework, the manufacturing process was analyzed with respect to production scalability, manufacturing possibilities, and the triple bottom line—covering environmental, social, and economic sustainability.

The analysis identified key strengths in flexibility and design freedom, but also weaknesses such as high initial costs, labor-intensive workflows, and limited recyclability of materials. The results indicate that the current method is suitable for low-volume, highly customized production, while large-scale implementation is restricted by process sensitivity and high material costs. To progress toward industrial-scale manufacturing, future development should focus on automation, sustainable material alternatives, and improved recyclability to enable a scalable and environmentally viable production process.

1. Introduction

Extended electrification within transport and product segments is requested to ensure future energy efficiency and environmental sustainability [1]. Together with the trend toward higher customization [2], this requires products to be lighter and subject to fewer geometrical constraints. To address this, new energy storage solutions can be developed that are free from the design limitations of conventional cylindrical or prismatic battery cells, which currently require enclosures with high load-bearing capacity to protect the cells that are vulnerable to significant impacts. Recent technologies, such as multifunctional materials, are suitable for these new requirements, as they can serve multiple purposes without compromising functionality [3]. Structural battery composites are a multifunctional material that both carry mechanical load and store electric energy [3]. By integrating the functionality of the enclosure with the battery cells, it enables improved energy efficiency by overall weight reduction [4]. Additionally, it offers greater design freedom, supporting the development of future innovative solutions in products and transportation.

Structural batteries can be made from various materials; however, this paper focuses on those made with carbon fiber reinforced polymer (CFRP) composites and their associated manufacturing method. Structural composite materials are an emerging technology, but not enough attention has been given to manufacturability and scalability. These aspects are essential to ensure that development progresses in a direction that supports industrial scale manufacturing and enables smoother transition towards commercial production, particularly important since composite manufacturing remains labor-intensive and requires skilled workers to guarantee quality. Despite the demonstrated multifunctionality of structural batteries, current production methods remain highly labor-intensive, energy-demanding, and difficult to scale [6]. Addressing these challenges is essential to transition from laboratory prototypes to industrial-scale manufacturing, as a part of commercialization of structural battery composite technology. The conducted analysis considers production scalability, manufacturing possibilities, and the triple bottom line- including environmental, social and economic sustainability- using a SWOT analysis framework to evaluate both internal and external factors. The findings aim to highlight key factors for guiding the future development of structural battery composites towards practical use.

2. Background

2.1 Structural battery composites

A structural battery is a multifunctional material that combines the ability to carry mechanical loads with the capability to store electric energy [4]. Carbon fiber is commonly used as both an electrode material and a high-performance structural reinforcement, making it well suited for this purpose [5]. Consequently, the positive and negative electrodes are made from carbon fiber and coated with lithium iron phosphate ($LiFePO_4$, LFP) [3]. The separator consists of a glass fiber sheet, which provides additional structural integrity and enhances the energy density of the cell. While polymers can function as both a structural matrix and an electrolyte [5], the liquid electrolytes are mixed with Bisphenol A (BPA) monomer resin to create the structural battery electrolyte (SBE). Owing to its multifunctional properties, the SBE enables the carbon fiber components to simultaneously provide mechanical load-bearing functionality and electrical conductivity. The elastic modulus has been measured to exceed 75 GPa when tested in parallel to the fiber direction, while having an energy density of 30 Wh kg^{-1}.

2.2 State of the art

The structural battery composites are manufactured in three main steps: assembly, resin infusion, and curing. All steps are currently performed and measured manually for each cell, which limits throughput and increases labor costs. The latest version uses resin infusion under dry argon atmosphere to apply the SBE mixture [6], the infusion process therefore ensures that the cell attains both mechanical performance and conductivity. Once cured, this results in a stiff and lightweight construction [7]. In earlier versions, the separator and electrodes were impregnated with the SBE using a pipette, resulting in higher variability and lower repeatability [6]. While infusion requires skilled workers to achieve high quality, it is a more repeatable process than manual impregnation. In addition, infusion allows for laminating multiple cells in the same batch, ensuring more consistent quality across batches while also increasing throughput in the manufacturing process.

The cells are made of CFRP, which is produced from carbon-rich precursor materials that undergo stabilization and carbonization through multiple heat-treatment processes [8]. These processes result in both toxic emissions and high energy consumption [9]. Meanwhile, cell manufacturing is currently conducted in both dry and cleanroom environments, which also have high energy requirements [10]. Throughout the manufacturing process, intoxicating chemicals are used, requiring single-use safety equipment that is disposed of after each batch of cells, contributing to waste and operational cost [9].

The CFRP used in the manufacturing of structural battery composites are recyclable, but currently available options either compromise mechanical properties or are costly and energy intensive. The more sustainable recycling options degrade the fiber properties to the extent that they cannot be reused in structural battery composite applications [11]. The more suitable methods, on the other hand, rely on high temperatures or pressure to break down the epoxy matrix, which raises concerns regarding environmental impact and safety [11]. Meanwhile, the recyclability of the SBE mixture has not yet been investigated, and the available methods for CFRP recycling are therefore not guaranteed to work for this application, representing a critical gap for sustainable process design.

Different cell configurations have been manufactured, demonstrating the ability to enable series and parallel connections [6,7]. The cell layout has been a simple laminate with all cells in the same layer. How the configuration of the cells affects battery performance and integration has not yet been investigated, creating a gap in knowledge for scalable panel-level production. The current research has focused on single cell manufacturing, without considering the process of when the cells will be integrated into structural panels. This will probably change the requirements of the production process, but the impact has not been further researched.

3. Method

This paper presents a SWOT analysis on the manufacturing method of structural battery composites. The data were collected through state-of-the-art literature and observational study during a visit to the laboratory at a Swedish university where structural battery composites are being researched and manufactured. The observational assessment of the current manufacturing process was conducted to track existing practices, identify process variables, and evaluate performance under standard conditions. The observations together with insights from literature acted as the ground for the SWOT analysis that was used to strategically evaluate the strengths, weaknesses, opportunities, and threats of the process. This tool helped assess the current situation from different perspectives while identifying gaps and provide insights for potential improvements [12].

Consideration was given to the scalability of production, the possibilities within the current manufacturing method, and the triple bottom line—environmental, social, and economic sustainability. These aspects were identified through the literature as crucial steps toward increasing the technology readiness level (TRL), which is necessary for commercialization [13]. The scalability of the current production was evaluated by comparing the current state with state-of-the-art literature to identify potential improvements, since designing a process that can be efficiently scaled when demand increases is essential [14]. The manufacturing possibilities were assessed, and the observations were ensured to be supported by literature to keep the study relevant. The structural battery composite process was evaluated to study different industry standards it suited, to enable future commercialization in relevant fields [15]. Furthermore, the triple bottom line was included in the evaluation, as both safety and human integration are necessary to achieve higher TRL levels [16], while sustainability has become an increasingly important factor to address early in technology development [17].

Based on this analysis, responses were developed to ensure that appropriate measures were implemented: leveraging strengths to take advantage of opportunities and mitigate potential threats [14]. Weaknesses were addressed to minimize risks while also identifying opportunities for improvement within the process [14]. The results were then used to determine key considerations and future development opportunities for structural battery composites.

4. Result

4.1 SWOT Analysis

The aim of the analysis was to get a clear view of the current manufacturing method by identifying the key strengths and weaknesses. External factors were also covered to get a view of the necessary improvements and potential to work towards. Table 1 shows the performed SWOT analysis from different perspectives. Where strengths, weaknesses, opportunities, and threats were identified.

Production scalability

The strengths of the manufacturing method and production scalability include improvements that can be relatively easily implemented. These include introducing kitting, jigs and changing certain material to allow smoother handling. In some cases, equipment can be modified to improve handling efficiency and reduce the risk of manufacturing errors [18].

The weaknesses are primarily related to the sensitivity of the process. Part of the procedure must be performed in a dry argon environment, while the entire process must take place in a clean environment [6]. Meeting these requirements demands large initial investments in equipment. Additionally, the process will remain labor intensive as the resin infusion methodology cannot currently be automated [18]. Combined with the high risk of cell damage during manufacturing, these factors limit production scalability [6]. To mitigate this, additional quality controls must be implemented to ensure consistent quality across larger batches.

The opportunities primarily relate to flexibility in production planning, allowing batch sizes and product variations to be easily adjusted [18]. Each batch can be unique, with customizable features according to the customers' needs. The threats are closely connected to the identified weaknesses. Opportunities to reduce costs are limited, and the ongoing demand for high battery volumes will continue. Therefore, small-scale production of highly optimized cells may struggle to remain competitive in a future global market.

Table 1. SWOT Analysis from different perspectives

	Internal		**External**	
	Strengths	Weaknesses	Opportunities	Threats
Production Scalability	Current method allows for easy improvements [a] Allows for quality control through process[a]	High initial cost [a] Requires clean environment [d] High risk of damage to cells through the process [d] Hard to scale manual workflow [a] Most of the process requires a dry argon environment [d]	Modular and flexible method[a]	Hard to reduce costs [a] Low scale manufacturing[a]
Manufacturing Possibility	Few limitations in geometry [c] Lightweight [c]	Expensive method [b] Complex and slow manufacturing [a]	Customizability of products [c] Flexibility between product types[a]	Limited scalability[a]
Triple bottom line	Limited CFRP fibers needed [f] Less thermal danger compared to other battery cells [f]	Environmentally damaging materials used [f] A lot of single use materials [d] Dangerous chemicals used[e]	Potential for environmental improvements when manufacturing methods improves [b]	Limited recyclability of materials [b] Expensive method and materials [b]

[a] Vaneeswari N, Sakthivel JC, 2023. High performance carbon fiber composite and its applications. *Man-Made Text India*, **51**, 354–360.

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Manufacturing possibility

The main opportunity lies in the freedom of cell design. The composite material in the cells imposes few design limitations, allowing structural batteries to be produced in a variety of shapes and sizes [20]. Composites also offer a high strength-to-weight ratio, enabling lightweight cells to carry significant mechanical loads [20]. These design freedoms expand the possibilities in battery design and support the development of advanced and competitive electrified products. However, composites and the associated manufacturing methods are expensive and time-consuming, which limits production throughput [19]. Future manufacturing that incorporates full chassis integration may introduce additional complexity to the process.

As trends indicate that customers are requesting greater variation and a wider range of choices when purchasing products [2], structural batteries provide an opportunity to meet this demand. Their flexibility enables design changes to be implemented quickly in production [20].

On the other hand, a key threat lies in the limitations of scaling production. Expansion is currently only feasible by creating parallel workflows, which would require larger facilities and more expensive equipment for each line. This contrasts with streamlining the existing process, which would represent a more cost-effective approach.

Triple bottom line

From the perspective of social, economic, and environmental sustainability, one strength lies in the limited amount of raw material required for the process [9]. However, the material itself is harmful to the environment, and the process relies heavily on single-use materials to maintain the required clean environment and ensure stable product quality [9]. The chemicals used in the manufacturing of structural battery composites also pose risks to both human health and the environment [4].

With improvements in manufacturing methods, the technology could reduce its environmental impact. When carbon fiber recyclability and the reuse of consumables become feasible, the process could significantly lower its environmental footprint [19]. Additionally, the introduction of bio-based epoxy could make production less hazardous for workers. Presently, the CFRP is difficult to recycle without compromising mechanical properties or increasing the environmental impact [19]. Moreover, both the methods and materials used in the manufacturing process are costly. If production remains labor-intensive, the cost of manufacturing structural battery composites will continue to be high.

4.2 Strategical response

The SWOT analysis presented internal and external factors that impact the production of structural battery composites. To correctly respond, an additional version of the SWOT Analysis was used to create actionable items to resolve the threats and act upon the opportunities.

Table 2 shows the recommended actions to improve the scalability and manufacturing methodology of production. The idea is to use the strengths and opportunities to overcome the threats.

Table 2. Response to actions in the SWOT Analysis of the Production Scalability

Production Scalability	Strengths	Weaknesses
Opportunities	Flexible production with short changeover time	Use flexibility to adapt production to lower the risk of errors
Threats	Focus on customizable products in smaller volumes	Ensure high quality workflows to maintain an efficient production and minimize quality issues

The primary opportunity lies in the potential for flexible production processes that enable extensive customization of structural composite cells. Variations in size, geometry, and quantity can be changed without significant changes to the manufacturing process.

To avoid quality issues, improvements to the existing process steps are essential. Ensuring high quality structural battery composites is critical, as the manufacturing method does not allow for post-production corrections.

Table 3 presents an overview of the manufacturing possibilities and highlights the critical aspects to consider in the further development of structural battery composites.

Table 3. Response to actions in the SWOT Analysis of the Manufacturing Possibility

Manufacturing Possibility	Strengths	Weaknesses
Opportunities	Focus on complex products with weight limitations	Limit product scope to industries that allow for long lead time and are not cost sensitive
Threats	Focus on customizability in lower volumes	Explore alternative material composition to improve manufacturability

Structural battery composites are best suited for products with weight restrictions and complex geometries. These features set this technology apart, as they allow the unique properties of composite structures to be applied to battery packs, potentially driving meet the needs of industries that can benefit from these characteristics, enabling faster industrialization once both electrochemical and mechanical performance are optimized.

The triple bottom line is presented in table 4, together with the key aspects to focus on when working towards a sustainable material and manufacturing process.

Table 4. Response to actions in the SWOT Analysis of Tripple Bottom Line

Triple Bottom Line	Strengths	Weaknesses
Opportunities	Longevity of technology when meeting future demand of environmental impact and safety requirements	Do the possible improvements to be prepared when the manufacturing method is implemented
Threats	Consider recycled materials to lower environmental impact and cost	Explore options in utensils and material while not compromising the functionality

The focus should be on incorporating recycled or alternative materials into both structural battery composites and their consumables. This has the potential to reduce the environmental impact, as the current process relies heavily on single-use materials. Structural battery composites also hold significant potential for longevity by addressing future demand for lightweight battery structures. Attention should therefore be directed toward preparing advancements in composite manufacturing that enable greater automation and support scalable production.

5. Discussion

The results indicate that the current manufacturing method for structural battery composites demonstrates its main strength in the short changeover time between batches. This allows for high flexibility in both batch size and product variation, made possible by the predominantly manual workflow. Consequently, the method is well suited for low-volume production that requires multiple product variations and can be easily adapted to individual customer needs [19]. However, this also means it is currently not suitable for high-volume industries such as automotive or electronics. Instead, the focus should be directed toward sectors that demand high customization and performance, such as aerospace and defence applications [20]. It is therefore also necessary to investigate the suitability of structural battery composites for use in extreme environments, as the requirements and regulations associated with these fields may significantly influence further development.

Future trends in CFRP part manufacturing are driven by advancements such as automated fiber placement systems, the development of sustainable CFRP materials, and additive manufacturing [21]. These technologies have the potential to enable more cost-effective and sustainable production of CFRP components at higher volumes, directly influencing the manufacturing capabilities of structural battery composites [21]. Improved recyclability of materials and consumables could further expand the relevance of structural battery composites across a wider range of industries and applications. However, the high energy consumption associated with current recycling processes remains a major challenge for large-scale implementation [19]. Moreover, recycling may affect the electrical performance of the carbon fibers used in structural battery composites, which requires further investigation. Determining the feasible proportion of recyclable material and understanding its impact on the mechanical and electrical properties of the cells are key areas for future research.

Future research should explore the integration of part manufacturing into the cell manufacturing process, as this could greatly enhance overall production efficiency. Currently, structural battery composites are manufactured separately and then manually integrated into a laminated component [7]. Combining part lamination and cell fabrication within a single manufacturing tool could significantly reduce cycle times. However, this would require careful consideration of material selection and process composition, making it a critical next step toward scalable production of structural battery composites.

Further investigation into stacking multiple cell layers within a laminate is needed to understand how cell orientation and fiber layup affect the mechanical performance of the final component. Previous applications have included cells within a single laminate layer and in flat geometries [6, 7]. Therefore, research should also examine how single- and multi-curvature designs influence both the electrical and mechanical properties of the cells.

6. Conclusion

This paper reviews current manufacturing methodology and production aspects of structural battery composites and covers the considerations and future possibilities of the technology. It deviates from previous research, which focuses on the multifunction material´s performance electrically and mechanically. Research using LCA analysis has also been done, with the focus on carbon emissions of the entire life cycle, while the current papers cover the triple bottom line from a production scalability perspective. Suggestions on what application to focus on and what areas future research should cover were presented based on the potential of up scaling a future production.

Acknowledgement

This work was supported by VGR under grant no MRU 2024-00381 MAXBATT. The work was carried out within Chalmers' Production Area of Advance. The support is gratefully acknowledged.

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