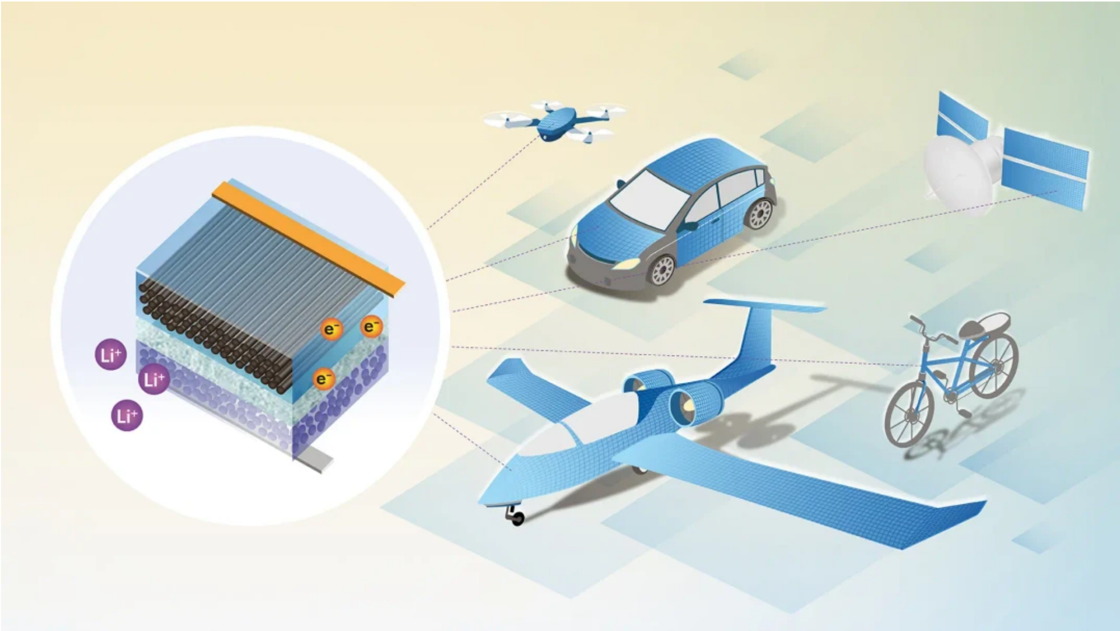
CHALMERS
UNIVERSITY OF TECHNOLOGY



Screening Life Cycle Assessment of Upscaling Structural Battery Composite Production

Master's thesis in Sustainable Energy Systems

SUVEER BALAJI

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
www.chalmers.se

Master's thesis 2025

Screening Life Cycle Assessment of Upscaling Structural Battery Composite Production

SUVEER BALAJI

Department of Technology Management and Economics
Division of Environmental Systems Analysis
Chalmers University of Technology
Gothenburg, Sweden 2025

Screening Life Cycle Assessment of Upscaling Structural Battery Composite Production
SUVEER BALAJI

Supervisor: Dr.Natalia Sieti
Examiner: Prof.Magdalena Svanström

Master's Thesis 2025
Department of Technology Management and Economics
Division of Environmental Systems Analysis
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 (0)31-772 1000

Cover: Structural Battery Composite Production, Chalmers University of Technology Student Portal

Gothenburg, Sweden 2025

Screening Life Cycle Assessment of Upscaling Structural Battery Composite Production

SUVEER BALAJI

Department of Technology Management and Economics
Chalmers University of Technology

Abstract

Structural batteries are composite materials which incorporate lithium-ion battery (LIB) cells to bear mechanical loads as well as receive and release electrical energy. This multi-functionality of structural batteries helps to reduce weight significantly as separate entities for structural support and energy storage are not required unlike in the case of conventional battery technologies. The structural battery is seeing growing demand in transportation systems, consumer electronics and biomedical applications. However, the structural battery technology is currently being implemented only at laboratory scale. The measures and challenges associated with physically scaling structural battery composite production are uncertain.

This study focuses on evaluating environmental impacts when considering scenarios related to physically scaling the production of structural battery composites (SBC) from laboratory scale to pilot scale using screening life cycle assessment (LCA). The scenarios in relation to varying electrolyte to epoxy resin composition of SBC were built, developed and analyzed in this study.

The results from modelling of scenarios showed considerable increase in climate change impacts, ecotoxicity (terrestrial) impacts, ozone depletion, ionising radiation and water use impacts when structural battery composite production was physically scaled from laboratory to pilot scale. The environmental hotspots determined from the study were the use of carbon fibers, production of certain structural electrolyte constituents, consumption of electricity in production processes as well as electrolyte infusion and curing processes. The report also explains the gaps in research and recommendations for future research in relation to scaling SBC production to minimize environmental impacts associated with these processes.

Keywords: LCA, Batteries, Engineering, Sustainability, Scenario Analysis

Acknowledgements

I wish to express my utmost gratitude to Dr.Natalia Sieti, the supervisor and Professor Magdalena Svanström, the examiner for the Master thesis and Johanna Xu, Research Assistant in Industrial and Materials Science division, for their continuous support and guidance throughout the course of the thesis work.

I would like to sincerely thank a group of Master students consisting of Erik Gunnarsson and Suvidhi Kasliwal, whose thesis work in relation to composite material recycling was used as reference for gathering information related to structural battery composite recycling.

I would like to extend my gratitude to Chalmers University of Technology for not only providing the valuable opportunity to work on a relatively important topic for the Master thesis but also provide a great work environment and most importantly my family and peers for their constant support and efforts in providing insights on the thesis work.

SUVEER BALAJI, Gothenburg, December 2025

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

Table 0.1: List of Acronyms

Acronym	**Definition**	**Acronym**	**Definition**
AP	Acidification Potential	LIB	Lithium-ion batteries
CED	Cumulative Energy Demand	LIS	Lithium Sulphur batteries
CF	Carbon fibers		
CFC	Chlorofluorocarbon	ODP	Ozone Depletion Potential
CFRP	Carbon Fiber Reinforced Plastics		
CNT	Carbon nanotubes	PMFP	Particulate Matter Formation Potential
DCB	Dichlorobenzene	POFP	Photochemical Ozone Formation Potential
DES	Deep Eutectic Solvents	RDP	Resource Depletion Potential
SBC	Structural Battery Composite		
FBC	Fluidized Bed Combustion	SBE	Structural Battery Electrolyte
GHG	Greenhouse Gas emissions	SHC	Specific Heat Capacity
GWP	Global warming Potential	SIB	Sodium-ion batteries
LCA	Life Cycle Assessment	SSB	Solid-state batteries
LCI	Life Cycle Inventory	TETP	Terrestrial EcoToxicity Potential
LCIA	Life Cycle Impact Assessment	TRL	Technology Readiness Level
LFP	Lithium Iron Phosphate	VARI	Vacuum assisted resin infusion

Nomenclature

Below is the nomenclature of parameters that have been used throughout this thesis. These represent the metrics in which inventory data was calculated as well as the constituents used in the preparation of structural battery composites.

g	grams
kg	kilograms
m	meter
mm	milli-meter
rpm	rotations per minute
g/cm^3	grams per cubic centimeter (density)
cm^3	cubic centimeter (volume)
$J/(g°C)$	Joules per gram per degrees Celsius (specific heat capacity)
°C	degrees Celsius (temperature)
hp	horse-power (mechanical power output)
MJ	Mega Joules (heat and electricity)
kJ	kilo Joules (heat and electricity)
kWh	kiloWatts per hour (electricity consumption)
GWh	Gigawatts per hour (electricity consumption)
kBq	kilobecquerel (radioactivity)
Mt	Mega tonnes (mass)
$LiTf_2N$	Lithium bis (trifluoromethylsulfonyl)imide
PC	Propylene Carbonate
$EMIM\text{-}Tf_2N$	1-Ethyl-3-methylimidazolium bis (trifluoromethylsulfonyl)imide
HTFSI	Bis(trifluoromethanesulfonyl)imide

Contents

List of Figures

List of Tables

1 Introduction

The transition from use of fossil fuels to renewable energy sources for generating electricity for transportation and industrial applications is rapidly taking place and is expected to reduce environmental impacts to a large extent. Siraj et al. (2023) cites common battery technologies such as lithium ion batteries (LIB) present challenges related to significantly high battery weight, increased space utilization in vehicles and increased risk of environmental impacts due to mining and extraction of heavy metals such as lithium and cobalt, despite a high share of merits such as high energy density of batteries and enhanced performance in vehicle applications, mentioned in Erakca et al. (2023). This paves way for the introduction of alternative battery technologies like structural batteries, sodium-ion batteries (SIB), solid-state batteries (SSB) and other battery technologies.

Zackrisson et al. (2019) mentions structural batteries not only bear mechanical loads but also store electrical energy. This battery technology has been found to be a promising alternative to conventional battery technologies due to its multi-functionality. Studies are being conducted to incorporate the use of structural batteries in electric vehicles, aerospace systems, marine systems, consumer electronics and biomedical applications (Jin et al. (2023)). This technology has been currently implemented at laboratory scale. Studies with focus on developing and improving this technology at laboratory scale are being done at Chalmers University of Technology. While efforts are being made at present to improve the structural battery technology in terms of composition and design at laboratory scale, the large scale implementation of this technology is in development and this thesis aims towards understanding the feasibility of the technology in terms of multifunctional performance and environmental performance.

Medicharla and Rao (2024) explains the challenges associated with structural battery composite (SBC) production such as trade-off in the multi-functional performance of batteries i.e. the drop in a certain set of properties due to improving another set of properties, need for research in alternate cathode and electrolyte materials, high initial costs for SBC manufacturing and difficulty in SBC recycling. These aspects represent a gap in research and development of structural battery technology and must be addressed to ensure the technology is reliable and sustainable in the future.

In this study, a screening life cycle assessment (LCA) is performed which includes assessing different scenarios and quantifying the environmental impacts associated with SBC production. The survey of literature relevant to LCA framework and structural battery technologies, defining the goal, scope and methodology of the LCA study, modelling of scenarios, analyzing environmental impacts and proposing recommendations on improving SBC production form the major steps performed in this thesis work.

1.1 Aim

The thesis aims to identify, build, develop and analyze scenarios of varying electrolyte composition and assess environmental impacts associated with physically scaling SBC production using screening LCA method. Physical scaling refers to comparison of SBC production at laboratory and pilot scales on the basis of energy consumption and environmental impacts. In addition to the objectives stated, the thesis also aims to provide recommendations for scaling SBC production for future research and development with focus on minimization of environmental impacts.

1.2 Research Questions

The thesis aims to provide more understanding on production of structural battery composites (SBC) by answering the research questions mentioned below.

1. What is the influence of change in composition of structural battery electrolyte (SBE) on the environmental performance of SBC?

2. Do the results obtained by performing a life cycle assessment align with the information on impact categories from earlier LCA studies?

3. What are the primary technical and environmental barriers which must be addressed in relation to physically scaling SBC production from laboratory to pilot scale ?

4. What are the key recommendations for reducing environmental impacts due to production of SBC for future research and development?

2

Background

2.1 Structural Battery Composites and Carbon Fiber Reinforced Plastics

2.1.1 Overview of Structural Battery Composites

Structural battery composites (SBC) are specific advanced materials used to build a structural battery. The **anode** terminal, commonly comprised of carbon fibers, due to excellent mechanical properties and good electrical conductivity, act as load bearing structures and the **cathode** terminal, commonly composed of coated carbon fibers, serve as pathway for electron movement and as reinforcement for enhancing mechanical properties of structural batteries. The **separator** material prevents short circuits by avoiding contact between anode and cathode terminals. Structural battery composites are designed by stacking alternate layers of anode and cathode electrodes with separator material placed in between the layers followed by embedding the laminate structure in a **structural battery electrolyte** (SBE) matrix at vacuum conditions. SBC can bear mechanical loads as well as store and release electrical energy. The modelling of SBC in this study excludes anode, cathode and separator materials and merely focuses on modelling of the SBE components. The components of SBE modelled in this study are explained in the later sections of the report.

Medicharla and Rao (2024) explains the utilization of SBC significantly reduces the weight as opposed to using conventional battery technologies as the materials used in SBC design are involved in the functionality of the SBC structure. The cost of maintaining these structures and reduced material use in the long run support the large scale use of SBC. The article also explained challenges with respect to scaling SBC production being trade-off in multi-functionality, high initial costs for manufacturing and difficulty in recycling i.e. separating active materials from structural matrix.

The development of alternative cathode materials, automated active material production and future SBC designs with greater energy density (greater than 300 Wh/kg), cycle life (more than 2000 cycles) and structural stiffness are prospects in relation to SBC production to be considered for future study purposes. The implementation of such measures at quicker pace and substantial investments in materials and manufacturing equipment would drive SBC towards higher TRL (technology readiness level) and large scale implementation.

2.1.2 Structural Battery Electrolyte

Structural Battery Electrolyte (SBE) is a bi-phasic composite critical for the functioning of structural batteries. While the solid phase of SBE helps to distribute mechanical loads, the liquid phase allows transport of ions between the anode and cathode electrodes. The solid phase of SBE comprises the structural polymer matrix (made of epoxy resins and curing agent) and the liquid phase of SBE consists of liquid electrolyte mixture (combination of lithium salt, ionic liquid and organic solvent). Detailed information on the constituents of SBE modelled in this study are mentioned below.

The structural polymer matrix is composed of two types of epoxy resins: Bisphenol-A-type epoxy resin (E-51) and aliphatic glycidyl ether (AG-80) epoxy resin. The former provides mechanical strength to the matrix while the latter improves flexibility and toughness as well as maintains thermal stability of the structural matrix. A polyether amine based curing agent, Jeffamine D-400 converts the liquid epoxy resin mixture into rigid cross-linked polymer matrix structures. These materials constitute the structural polymer matrix which imparts mechanical functionality to the SBC. The combination of ionic liquid, solvent and lithium salt yields the electrolyte which imparts electrochemical functionality to the SBC. The ionic liquid used to enhance ionic conductivity in the polymer matrix in this study is 1-Ethyl-3-methylimidazolium bis (trifluoromethylsulfonyl)imide i.e. EMIM-Tf_2N. The solvent used to improve lithium ion mobility between the anode and cathode electrodes is propylene carbonate (PC). The lithium salt used in this study was Lithium bis (trifluoromethylsulfonyl)imide, $LiTf_2N$, which acts as a source of lithium ions required for the functioning of the structural battery. The information on the SBE constituents was extracted from Yu et al. (2017).

2.1.3 Carbon Fiber Reinforced Plastics

SBC, in this study, has been modelled as a modification to traditional carbon fiber reinforced plastics (CFRP) i.e. composite materials produced due to infusion of structural electrolyte into layers of carbon fibers. Carbon Fiber Reinforced Plastics (CFRP) are composite materials made of a polymer matrix (made of epoxy or polyester) reinforced with carbon fibers. The microstructure of carbon fibers in CFRP contains graphitic crystallites which are not only responsible for the material's mechanical properties but also allow flow of lithium ions. CFRP imparts mechanical properties when used in applications as opposed to structural battery composites (SBC) which are multifunctional in nature.

2.2 Theoretical Background of Life Cycle Assessment

2.2.1 Life Cycle Assessment

The method used to analyze the environmental impacts associated with scaling SBC production from laboratory to pilot scale is screening life cycle assessment (LCA). The environmental impacts due to a process or product can be studied using LCA. The steps performed in a LCA study are listed below.

1. Goal and Scope Definition
2. Life Cycle Inventory Analysis (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation of Results

2.2.2 Goal and Scope Definition

Defining the objectives of the study and the system to be studied form the first step of a life cycle assessment. The **goal of a study** must explain the contextual aspects such as the reason for study, the product or system based on which the study is carried out and the people who would be influenced by the study.

The **scope of study** must explain the modelling aspects such as functional unit, the foreground and background processes of the study and system boundaries with respect to time horizon and geography of study. **Foreground processes** are process activities directly related to the product or process being studied and are often under the control of the persons performing the LCA study while **background processes** refer to secondary activities in a product life cycle such as transport of raw materials and waste treatment and are generally not directly controlled by the persons performing the LCA study.

Functional unit is a term based on which the inputs, outputs and environmental impacts are scaled to and forms as a basis for comparing results from the life cycle assessment performed. A **life cycle flowchart** illustrating all processes and flows included in the life cycle of a product or process is constructed in a LCA study. This would help the readers to understand the system boundaries and sections of the system under study. The scope of a study can commonly be a **cradle-to-gate or cradle-to-grave** study. A cradle-to-gate study considers environmental impacts due to steps from extraction of raw materials to manufacturing of a product while a cradle-to-grave study considers environmental impacts due to steps from raw material extraction through use phase to end-of-life (EoL) of the product.

2.2.3 Life Cycle Inventory Analysis

Inventory data collection and analysis forms the second step while performing a LCA study. Life cycle inventory (LCI) required for modelling of scenarios are usually extracted from literature sources and online LCA databases. The inventory data normally includes information related to input and output materials used, energy use in different processes and values of emissions resulting from different processes. The values obtained are then normalized with respect to the functional unit chosen for the study.

2.2.4 Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) refers to the translation of LCI into potential contribution to environmental impacts. The impact categories which would be considered in a LCA study would be chosen based on the significant change in results observed post modelling of the scenarios and information from literature. The inventory data such as emissions from a process are categorized into different impact categories and characterization factors for the emissions are assigned based on the potential to contribute to significant environmental impacts.

2.2.5 Screening Life Cycle Assessment

A screening LCA provides an overview of environmental impacts associated with a product or process as opposed to a detailed LCA. A detailed LCA normally involves use and quality assessment of primary data while a screening LCA uses generic or average data for the quantification of environmental impacts. The primary purpose of a screening LCA is to determine the hotspots i.e. materials and processes contributing to significantly high environmental impacts. This type of LCA is performed when a product or process is to be assessed based on environmental performance at a quicker rate.

3
Literature Survey

As the preliminary step of the LCA study, several literature sources were studied. The literature study covered the following aspects:

1. LCA studies performed on emerging battery technologies and scaling battery cell production: This helped to gain understanding of factors contributing to major environmental impacts and select scenarios which would be assessed in this study

2. Information on multi-functional performance of SBC based on change in separator material, change in structural electrolyte composition

3. Stages, energy consumption and environmental impacts associated with carbon fiber production

The findings from literature sources are explained in detail below.

3.0.1 LCA of Battery Technologies

Raugei and Winfield (2019) explains about performing a life cycle assessment (LCA) on the use of lithium cobalt phosphate (LCP) batteries. The study determines the cumulative energy demand (CED) and greenhouse gas (GHG) emissions associated with the production and EoL management of the battery technology as well as compares two battery recycling methods: pyrometallurgical and hydrometallurgical recycling. Cathode material synthesis was found to contribute the most to CED (629 MJ of primary energy) and GHG emissions. Minimum environmental impacts were observed in the cases of anode, electrolyte and separator material use. Hydrometallurgical recycling is less energy intensive (i.e. 148 MJ of primary energy per kWh of battery energy capacity) and generates lesser GHG emissions (reduction by about 8 per cent) as opposed to pyrometallurgical recycling.

The functional unit was decided based on production of structural battery composites (SBC) having optimum values of these properties. The optimum values of properties correspond to results obtained when equal amounts of liquid electrolyte and epoxy resins were used.

Zackrisson et al. (2019) explains a cradle-to-grave prospective LCA performed to assess the environmental impacts due to incorporation of a structural battery in the roof of an electric vehicle. The major environmental impacts were observed from battery assembly, carbon fiber production, battery electrolyte production and cathode material (Lithium Iron Phosphate(LFP)) production stages. A scenario involving two different electricity mixes: European electricity mix and Swedish electricity mix was analyzed to determine the change in environmental impacts due to use of different electricity mixes. The study recommends the use of propylene carbonate (PC) instead of dimethyl methylphosphonate as it would significantly lower chemical risks. It was found that about 11 kWh of electricity and 8 kWh of natural gas were required for producing 1 kg of structural battery. Climate change, toxicity, resource use and Photochemical Ozone Formation (POF) were the impact categories analyzed in this study. Studies on energy consumption showed carbon fiber production and structural battery cell assembly being highly energy intensive processes. Large amounts of GHG emissions were avoided (around 210 kg CO_2-eq in a small EV and 115 kg CO_2-eq in a large EV) due to the use of structural batteries.

Details of a prospective LCA study to analyze environmental impacts due to large scale production and use of lithium sulphur batteries (LIS) are mentioned in Wickerts et al. (2023). The study involves analyzing scenarios related to use of alternative battery electrolyte (lithium triflate instead of lithium bis (trifluoromethanesulfonyl)imide), incorporation of wind power in place of fossil based electricity mix, increased energy density (500 Wh/kg as opposed to the baseline scenario of 150 Wh/kg), doubled cycle life (3000 cycles instead of 1500 cycles) and hydrometallurgical battery recycling method (instead of landfilling). A significant reduction of GHG emissions by 60 % and water use impacts were observed due to incorporation of all these scenarios. Hydrometallurgical recycling recovers lithium but contributes to greater emissions resulting from high energy use.

3.0.2 Transition of Battery Cell Production from Laboratory to Industrial Scale

Liu et al. (2024) explains a comparison of laboratory and industrial scale production of hard carbon (HC) used as anode material for sodium-ion batteries using LCA. A hotspot assessment implied pyrolysis process at laboratory scale proved to be highly energy intensive and contributed to major environmental impacts (global warming potential (GWP), acidification potential (AP) and resource depletion potential (RDP)). The shift in use of fossil fuels to renewable energy sources was found to significantly reduce carbon emissions and acidification impacts. The upscaling of the process to industrial scale proved to be highly efficient as there was a drastic reduction in environmental impacts, more efficient energy consumption and increased throughput.

Knehr et al. (2024) explains the energy consumption in the manufacturing of lithium ion batteries (LIB) at three different production scales: 5, 25 and 50 GWh per year.

The study assessed the influence of battery cell design and production volume on energy use. Electrode coating and drying processes were found to be the most energy intensive processes contributing to about 19.6 % of the total energy use followed by cell formation cycling (17 %), building support systems (10.8 %), cooling systems (10.4 %) and dry room operations (10.2 %). It was found that lower energy consumption of battery cells is achieved when the battery cell capacity , active material content and battery cell voltage are higher. These results were helpful in selecting the baseline scenario in relation to structural electrolyte content.

The environmental impacts associated with upscaling of LIB production from laboratory to industrial scale were assessed in Chordia et al. (2021). Comparison on the basis of different cathode materials, electricity mix (South Korean electricity mix and Swedish electricity mix) and battery cell production scales was performed in this study. The impact categories assessed in this study were climate change, acidification potential (AP), resource use and toxicity. A reduction in values of impact categories, shift of environmental hotspots from battery cell manufacturing to raw material extraction and significant reduction in electricity utilization due to production upscaling as opposed to small scale battery cell production were results obtained from this study.

A cradle-to-gate LCA based on upscaling laboratory scale LIB cell production was discussed in Erakca et al. (2023). The impact categories acidification, climate change, resource use and particulate matter formation (PMF) were analyzed in this study. Higher environmental impacts were observed in the laboratory scale case as opposed to industrial scale case due to lower utilization of equipments, higher energy consumption and reliance on German electricity mix having greater share of fossil fuels. Lower emissions due to use of European electricity mix (greater share of renewables), increased throughput, more efficient energy utilization and lower material loss rates were observed in the case of industrial scale LIB cell production.

3.0.3 Structural Battery Technology

The multifunctional performance of structural batteries analyzed has been discussed in Chaudhary et al. (2024). The electrochemical stability and reversibility were determined using cyclic voltammetry. Efficient transfer of lithium ions between anode and cathode terminals and good electrochemical stability and reversibility i.e. stability of electrolyte at optimum voltage range were observed. A major aspect studied was the effect of separator material on the mechanical and electrochemical properties of structural batteries. It was determined from studies that thinner separator materials have greater capacity retention, facilitate better transport of lithium ions, offer lower resistance to ion flow and possess greater values of mechanical stiffness as well as power and energy densities as opposed to thicker separator materials.

The composition, structure and manufacturing of structural batteries has been discussed in Siraj et al. (2023). The anode terminal composed of T800S carbon fibers while the cathode terminal material used was lithium iron phosphate (LFP) coated aluminum foil. A glass fiber separator was used in the study. The article focused on evaluating the performance of structural battery cells produced due to vacuum infusion as opposed to manual production of structural battery cells inside a glove box. The structural battery cells produced using vacuum infusion were found to demonstrate significantly higher multi-functional performance and possess greater energy density (about 41 Wh/kg) and consistency in mechanical and electrochemical properties. However, the poor capacity retention of structural battery cells after considerable number of cycles due to lower ionic conductivity of the structural battery electrolyte (SBE) compared to conventional liquid electrolytes was observed.

The steps involved in the production of carbon fibers, commonly used as anode and cathode material, and environmental impacts associated with carbon fiber production were discussed in Prenzel et al. (2023). LCA by means of hotspot assessment of carbon fiber production in several countries was performed in this study. The production of precursor material acrylonitrile was found to constitute about 37% of GHG emissions due to carbon fiber production. The reliance on fossil fuels for carbon fiber production in countries such as China, Japan and United States was found to be significantly high while the carbon footprint due to carbon fiber production was found to be lower in parts of Europe and United Kingdom where majority of electricity produced was from renewable energy sources.

3.0.4 Production of Structural Battery Composites

The influence of structural electrolyte composition on the multi-functional performance of structural battery composites (SBC) was explained in Yu et al. (2017). The production of structural electrolyte based on varying electrolyte to epoxy resin content and vacuum infusion of structural electrolyte into layers of carbon fibers to produce structural battery composites (SBC) at laboratory scale were discussed in this article. Experimental studies showed a significant decrease in mechanical properties and increase in electrochemical properties of SBC with increase in electrolyte content. The study aimed to modify CFRP specimens to bear mechanical loads as well as release electrical energy. The technical information extracted from this literature source to model scenarios has been provided in the later sections of the report.

4

Methodology

This section provides detailed explanation of individual steps carried out during the course of the thesis work. The work flow is illustrated in Figure 4.1.

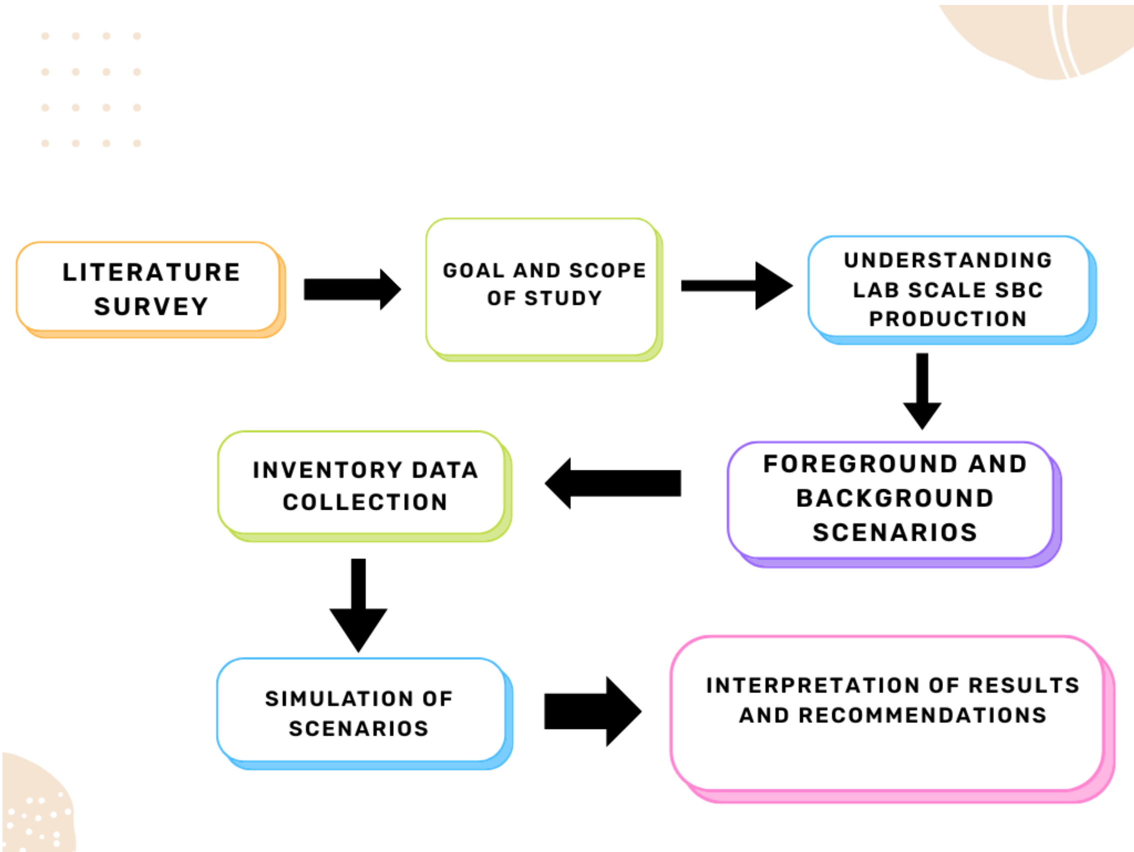


Figure 4.1: Flowchart illustrating the work flow of the study

4.1 Life Cycle Assessment Framework

4.1.1 Goal of Study

The structural battery technology is currently implemented at laboratory scale and research is being done to physically scale the technology to pilot scale. Scenarios related to SBE (Structural Battery Electrolyte) composition were assessed in this study. The goal of the study was to build, develop and analyze these scenarios as well as assess the environmental impacts associated with these scenarios using screening LCA. The thesis also aims to provide recommendations for physical scaling of structural battery composite (SBC) production with focus on minimizing environmental impacts for future research and development purposes.

4.1.2 Scope of Study

The LCA performed in this study is a cradle-to-gate LCA covering steps from raw material extraction to SBC production. Figure 4.2 below depicts a flowchart illustrating the processes studied and modelled along with emissions and energy requirements (heat and electricity) associated with each step of SBC production process studied.

The two phases of structural battery electrolyte (SBE), namely solid phase (comprised of epoxy resins and curing agent) and liquid phase (comprised of ionic liquid, solvent and lithium salt) as well as carbon fibers constitute structural battery composites (SBC) which are modelled in this study. The scope of study does not include the end-of-life management of SBC although findings from literature sources in relation to this aspect are documented and presented in the Discussion and Appendix sections of the report. The materials used in anode and cathode terminals as well as separator are not modelled in this study.

Figure 4.2 illustrates a life cycle flow chart that contains the sequence of steps starting from the extraction of raw materials (structural electrolyte constituents - epoxy resins and liquid electrolyte mixture) to the manufacturing of structural battery composites. The structural battery electrolyte is produced by the synthesis of epoxy resin and liquid electrolyte mixture. Heat is used for preheating the blends obtained depending on the mixture of liquid electrolyte and epoxy resin composition and for curing of SBC. Electricity is used in mixing of the blends, infusion of structural electrolyte into carbon fibers and generating heat required for curing processes. The curing agent is added to the electrolyte-epoxy resin blends in the power mixing step of the process. The blend preheating, shear mixing and power mixing processes constitute the structural battery electrolyte (SBE) production while the electrolyte infusion and curing processes constitute the structural battery composite (SBC) production. The life cycle flowchart was designed based on inventory data modelled for different electrolyte based scenarios on OpenLCA 2.4.1 software.

4.1.3 Functional Unit

This study involves production of structural battery electrolyte (SBE) and production of structural battery composites (SBC). The study also focuses on optimizing the electrochemical properties of SBC.

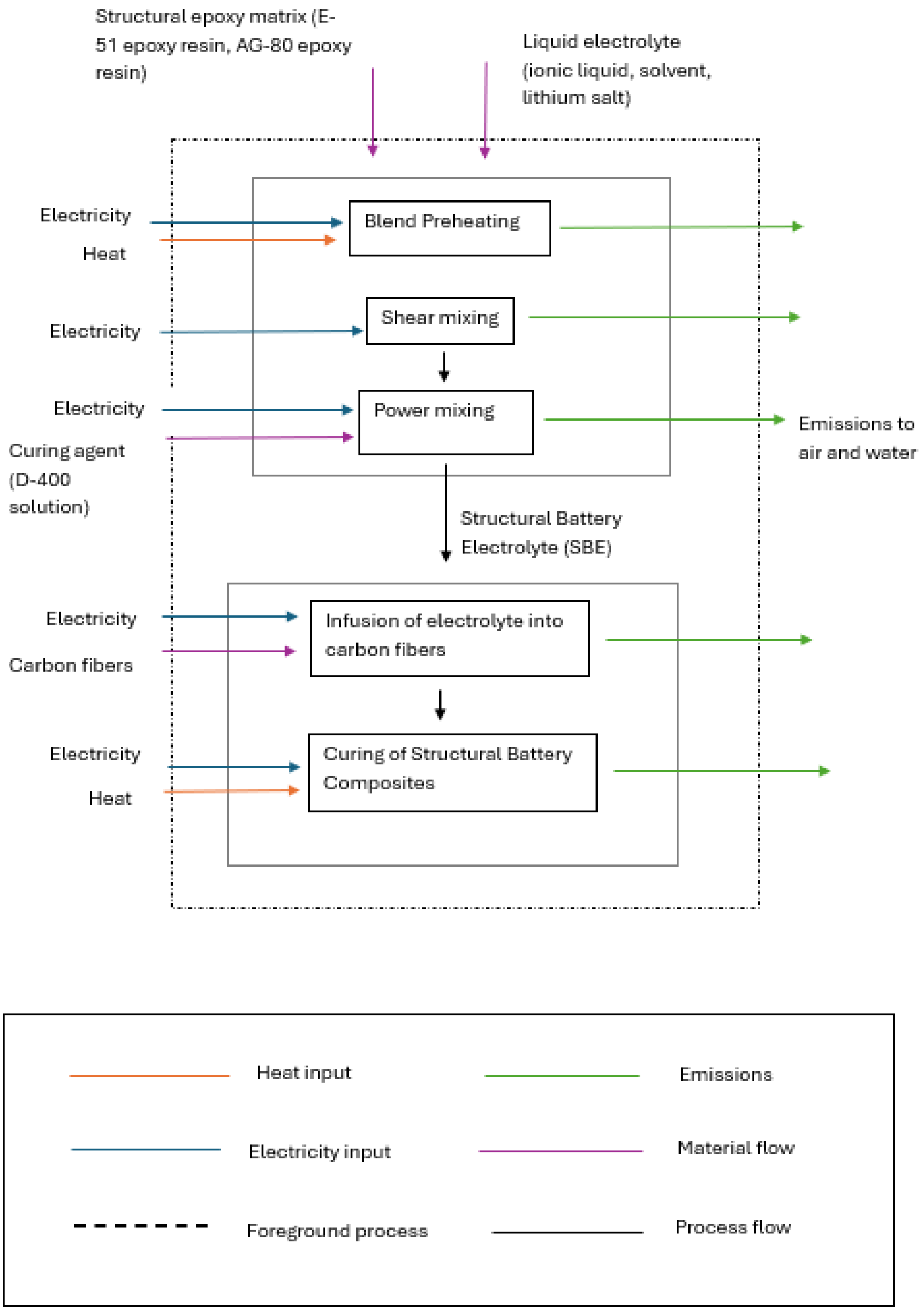


Figure 4.2: Life Cycle Flowchart

The variation in properties of SBC such as mechanical stiffness, ionic conductivity and battery capacity due to increasing liquid electrolyte to epoxy resin content are shown in Table 4.1.

Table 4.1: Variation of mechanical and electrochemical properties of SBC with increase in electrolyte content

Electrolyte-Epoxy resin Composition	Mechanical Stiffness (MPa)	Ionic Conductivity (mS/cm)	Battery Capacity (mAh/g)
75:100	400	0.08	12
100:100	**200**	**0.10**	**25**
125:100	100	0.30	22

Note: The 100:100 ratio represents the baseline scenario where equal mass amounts of liquid electrolyte and epoxy resins were used.

The functional unit was established based on producing SBC having optimum values of these properties. This was observed where equal amounts of electrolyte and epoxy resins were used. Hence the electrolyte to epoxy resin content ratio of 100:100 was selected as the baseline case for comparing the production of SBC with other scenarios at laboratory and pilot scale.

The functional units based on which the inventory data was calculated and modelled and environmental impacts were assessed were producing 1 m^2 and producing 1 kg of SBC with ionic conductivity of 0.1 mS/cm and battery capacity of 25 mAh/g. The reasoning behind the selection of these functional units for the study is provided below.

4.1.3.1 Selection of Separate Functional Units

The reference flow for the structural functional unit of 1 m^2 of structural battery composite (SBC) was determined for each electrolyte scenario. This helped in calculating the masses of individual structural electrolyte constituents required for producing 1 m^2 of SBC. The calculations are provided below.

Carbon Fibers

The mass of carbon fibers required to produce 1 m^2 of SBC was calculated using Equation 4.1.

$$\text{Mass of carbon fibers (kg)} = \frac{\text{Area density of carbon fibers (g/m}^2) \times \text{No. of layers of carbon fibers}}{1000} \tag{4.1}$$

The area density of carbon fibers used in this calculation was 250 g/m^2 and four layers of carbon fibers were used in the production of SBC. This information was obtained from Yu et al. (2017) and is also provided in section 4.5.1 of the report.

Structural Electrolyte

The density of structural electrolyte used to produce 1 m^2 of SBC was calculated using values of mass and volume constituted by individual structural electrolyte constituents. Equation 4.2 shown was used to calculate the density of structural electrolyte.

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} \tag{4.2}$$

The mass of structural electrolyte corresponding to each electrolyte scenario was calculated using Equation 4.3.

$$\begin{aligned}\text{Mass of Structural Electrolyte (kg)} = {} & \text{Area consumed by SBC produced } (\text{m}^2) \\ & \times \text{ Thickness of SBC (m)} \\ & \times \text{ (1 - Fiber Volume Fraction)} \\ & \times \text{ Density of Structural Electrolyte } (\text{kg/m}^3)\end{aligned} \tag{4.3}$$

The values of SBC thickness, carbon fiber volume fraction and density of structural electrolyte corresponding to each electrolyte scenario are provided in Table 4.2. The values of SBC thickness and carbon fiber volume fraction corresponding to each electrolyte scenario were extracted from Yu et al. (2017). An average of minimum and maximum values of carbon fiber volume fraction was used corresponding to different ratios of electrolyte-epoxy resin composition. The fiber volume fraction is expressed in percentage.

Table 4.2: Parameter values for determining structural electrolyte mass corresponding to each electrolyte scenario

Parameter	**Lower Electrolyte Scenario**	**Baseline Scenario**	**Higher Electrolyte Scenario**
Thickness of SBC Produced (mm)	1.14	1.13	1.13
Fiber Volume Fraction	0.5785	0.5837	0.5836
Density of Structural Electrolyte (g/cm^3)	1.26	1.29	1.31

Structural Battery Composites

The mass equivalent of SBC (determined from masses of carbon fibers and structural electrolyte) corresponding to 1 m^2 of SBC produced using different electrolyte compositions are shown in Table 4.3. The values are in kilogram (kg).

Table 4.3: Mass equivalent of 1 m^2 of SBC in each electrolyte scenario

Lower Electrolyte Scenario	Baseline Scenario	Higher Electrolyte Scenario
1.609	1.608	1.616

The multi-functionality of SBC is vital for efficient operation in large scale applications i.e. SBC must be robust as well as store sufficient amounts of electrical energy. The properties mechanical stiffness, ionic conductivity and battery capacity are intrinsic properties i.e. properties influenced by mass of liquid electrolyte and epoxy resins. Two separate functional units were chosen in this study to address the multi-functionality of SBC. The structural functional unit (1 m^2 of SBC) helped to assess environmental impacts due to production of SBC having fixed geometry. The functional unit of 1 kg of SBC helped to assess environmental impacts resulting from production of SBC with suitable electrochemical properties.

4.1.4 System Boundaries

4.1.4.1 Boundaries in Relation to Natural Systems

The interaction of the life cycle with the environment begins with the extraction and production of epoxy resins, curing agent and liquid electrolyte constituents such as propylene carbonate (PC), EMIM-Tf_2N and $LiTf_2N$. Water from sources such as rivers and wells are used in the production of epoxy resins AG80 and E51, organic chemicals are used in the production of majority of the constituents and heat as well as electricity used in several stages of SBC production is produced using a variety of energy sources (oil, bio fuels and coal). All of these processes in addition to output flows involve use of natural resources and emissions to air and water.

4.1.4.2 Geographical Boundaries

The two major aspects of this study: structural electrolyte production and structural battery composite (SBC) production are based in Sweden. The Swedish electricity mix is used as the source of electricity in all stages of the processes under study. The heat required for the processes is obtained majorly through industrial processes and district heating. The laboratory scale and pilot scale processes are assumed to take place in Sweden. Carbon fibers are produced using acrylonitrile, heat and deionised water obtained from different regions in Europe and the Swedish electricity mix.

4.1.4.3 Temporal Boundaries

The information on SBC material constituents and their compositions, fiber volume fractions, SBC production processes and electrochemical properties of SBC based on varying electrolyte content were extracted from Yu et al. (2017), published in 2017. The laboratory scale data and pilot scale data for SBC production were modelled to represent the emerging structural battery technology in the year 2025.

4.1.4.4 Boundaries within Technical Systems

The study includes the use of epoxy resins, curing agent and liquid electrolyte in structural electrolyte production and vacuum based structural electrolyte infusion into carbon fibers to produce SBC. The study does not include structural battery cell assembly, extraction and transport of materials required for the production processes, use phase of structural batteries and manufacturing of equipment involved in producing SBC. The technical boundaries have been set in an attempt to simplify the study, being a screening LCA.

4.1.4.5 Impact Assessment Methods

EcoInvent 3.11 database was used to model the scenarios using OpenLCA 2.4.1 software. The life cycle impact assessment (LCIA) method used in this study was the ReCiPe 2016 v1.03 midpoint(H) method. This method analyzes impact categories from a hierarchist perspective.

4.1.4.6 Foreground and Background Scenarios

The foreground processes of this study are the production of structural battery electrolyte (SBE) and production of structural battery composites (SBC). The background processes of this study are generation of heat and electricity, carbon fiber production, assembly of structural battery cell and transport of raw materials produced at different sites to Sweden.

4.1.5 Limitations of Study

The limitations of the study are categorized based on the scope of the study and modelling of inventory data performed in the study.

Scope of study: This study excludes the use phase and end-of-life management of structural battery composites (SBC) and focuses only on the manufacturing of SBC. Hence, the study provides information on the environmental impacts associated with SBC production but does not explain the viability of the technology. The study does not consider the variation in mechanical properties of SBC such as mechanical stiffness with change in electrolyte content.

Modelling aspects: Structural Battery Composites (SBC), in this study, refers to modification of carbon fiber reinforced composites by infusion of structural battery electrolyte (SBE) into layers of carbon fibers. The **modelling of SBE constituents** such as constituents of structural polymer matrix and liquid electrolyte mixture along with carbon fibers are considered while active materials such as materials used in anode, cathode and separator materials, are not considered while performing modelling of scenarios in this study. The study does not consider the environmental impacts due to extraction and use of lithium in SBC production. The **duration of processes** involved in SBE and SBC production were kept constant during calculation and modelling of laboratory and pilot scale SBC production. This is a shortcoming as equipment used in real time would tend to produce SBE and SBC at quicker rates. The **ionic liquid** considered for the production of SBE in this study is EMIM-Tf_2N, which has been found to incur high capital costs when used in laboratory and pilot scale applications. The environmental impacts due to **cooling in laboratory and pilot scale equipment** post curing of SBC are not considered in this study although energy requirements for the cooling process at laboratory and pilot scale processes were determined. The **efficiency of equipment** used in different stages of SBC production was fixed. This is contrary to the real world case where difference in efficiencies of equipment used for SBC production would be observed.

4.2 Assumptions made in the Study

The efficiency of all equipments used at different stages of SBC production was assumed to be 80%. The duration for the power mixing and structural electrolyte infusion processes was assumed to be 1 hour for the laboratory and pilot scale production cases. The ambient temperature required for calculating heat requirements for electrolyte-epoxy blend preheating and SBC curing was assumed to be 25 °C. The values of density and specific heat capacity (SHC) of ionic liquid, EMIM-Tf_2N and lithium salt, $LiTf_2N$, were used in calculations based on properties of compounds having similar chemical composition.

4.3 Scenarios selected for the Study

The scenarios assessed in this study are categorized into two types: production of SBC using three different electrolyte-epoxy resin compositions and physical scaling of SBC production from laboratory to pilot scale. The detailed information on these scenarios is provided below.

4.3.1 Structural Electrolyte Composition and SBC Manufacturing

Scenarios assessing the influence of structural electrolyte composition on the environmental impacts were developed and modelled.

The masses of structural electrolyte constituents extracted from Yu et al. (2017) are provided in Table 4.4. The values are expressed in grams (g).

Table 4.4: Mass of Structural Electrolyte Constituents corresponding to electrolyte scenarios - Extracted from literature

Constituent	**75:100**	**100:100**	**125:100**
E51	70.00	70.00	70.00
AG80	30.00	30.00	30.00
D400	73.49	73.49	73.49
EMIM-Tf_2N	128.81	171.75	209.69
PC	1.30	1.74	2.17
$LiTf_2N$	56.14	74.85	93.56
Total Structural Electrolyte Mass (g)	**359.74**	**432.83**	**479.91**

The liquid electrolyte was blended with epoxy resins in compositions corresponding to varying liquid electrolyte to epoxy resin content. The **preheating step** involved blending and preheating of electrolyte and epoxy resins in an oven at 55 °C for 5 minutes. This was followed by **shear mixing** wherein the blends were mixed and stirred at 8000 rpm for one hour. The curing agent was added to the blends followed by stirring in the **power mixing** step. These steps constitute the production of the structural electrolyte.

The SBC were manufactured using **Vacuum Assisted Resin Infusion (VARI)** of the structural electrolyte into the layers of carbon fibers. This was followed by **curing** of SBC produced at three different temperatures and durations: 75 °C for 2 hours, 110 °C for 2 hours and 160 °C for 2 hours. The heating and cooling rates of the curing processes were 2 °C per minute in the case of laboratory scale SBC production.

4.3.2 Physical Scaling of SBC Production from Laboratory to Pilot Scale

The production of SBC was compared in terms of environmental performance at two scales: laboratory and pilot scales. The material requirements to produce SBC remain the same at both scales while the energy requirements vary significantly due to utilization of equipments with different specifications at laboratory and pilot scales. The calculation and modelling of inventory data in relation to this scenario are explained below.

4.4 Inventory Data Collection

Information related to parameters associated with different battery chemistries such as cell voltage, cell capacity and energy density, energy consumed in the form of electricity and heat at different stages of battery cell production and environmental impacts associated with manufacturing, use and end-of-life (EoL) management of battery components from different literature sources were compiled. This was the preliminary step of the life cycle inventory procedure.

The composition of liquid electrolyte, curing material and epoxy resins in terms of mass as well as values of mechanical and electrochemical properties of SBC such as mechanical stiffness, ionic conductivity and battery capacity based on varying electrolyte composition were determined from Yu et al. (2017). These values were used to model structural electrolyte based scenarios.

4.5 Inventory Data Analysis

4.5.1 Carbon Fibers

The properties of T700S carbon fibers such as material density and specific heat capacity were determined from the T700S technical datasheet Toray Composite Materials America, Inc. (2018). The information related to carbon fibers from the technical datasheet and Yu et al. (2017) are mentioned in Table 4.5. The mass of carbon fibers used in SBC production was calculated based on these values.

Table 4.5: Carbon fibers

Property	Value	Unit
Density	1.8	g/cm^3
Specific heat capacity	0.752	J/g°C
Area density	250	g/m^2
Number of layers of carbon fibers	4	layers

4.5.2 Mass, Specific Heat Capacity and Density of Structural Electrolyte Constituents

The values of structural electrolyte constituent properties such as specific heat capacity (SHC) and density required for calculating heat requirements and for modeling the individual steps of structural battery composite (SBC) production were determined from literature sources and online resources. These values are provided in Table 4.6.

Table 4.6: Properties of structural electrolyte constituents

Constituent	**SHC**(J/g°C)	**Density(g/cm^3)**
E-51	1.4892	1.2
AG-80	1.11	1.15 (IOLITEC GmbH (2025))
D-400	1.16	1.03
Propylene Carbonate	1.803	1.2
EMIM-Tf_2N	1.634	1.52 (ChemicalBook (2025b))
Li-Tf_2N	1.28	1.334 (ChemicalBook (2025a))

The volume consumed by each constituent was determined based on the values of mass and density of the constituents using Equation 4.2 provided in section 4.1.3.1 of the report.

The density of the structural matrix (containing epoxy resins, curing agent and liquid electrolyte mixture) was determined using the values of matrix volume and mass of constituents using the same equation.

The mass of structural electrolyte constituents and carbon fibers were determined separately for the production of 1 m^2 of SBC and 1 kg of SBC. The detailed information on these calculations is provided below.

1 m^2 of SBC Production

The masses of structural electrolyte constituents determined using information provided in Table 4.4 and total mass of SBC corresponding to each electrolyte scenario provided in section 4.1.3.1 of the report are provided in Table 4.7. The table represents values before normalization. The calculation of carbon fiber mass required for producing 1 m^2 of SBC is provided in section 4.1.3.1 of the report.

1 kg of SBC Production

The weighted mass of carbon fibers and structural electrolyte constituents were calculated for each electrolyte scenario.

Table 4.7: Mass of Carbon Fibers and Structural Electrolyte Constituents for 1 m^2 of SBC Production

Constituent (g)	**Lower electrolyte scenario**	**Baseline scenario**	**Higher electrolyte scenario**
Carbon fibers	**1000.00**	**1000.00**	**1000.00**
E51	118.57	100.91	90.07
AG80	50.82	43.25	38.60
D400	124.48	105.94	94.57
PC	95.09	107.90	120.39
EMIM-Tf_2N	218.18	247.59	269.82
$LiTf_2N$	2.20	2.51	2.79
Total mass of structural electrolyte produced	**609.34**	**608.10**	**616.25**
Total mass of SBC produced (kg)	**1.609**	**1.608**	**1.616**

The weighted mass of carbon fibers was calculated using values of fiber volume fraction (provided in Table 4.2) and density of carbon fibers (mentioned in Table 4.5). The weighted mass of structural electrolyte was calculated using values of matrix volume fraction and density of structural electrolyte provided in section 4.1.3.1 of the report.

The masses of carbon fibers and structural electrolyte constituents required for producing 1 kg of SBC are shown in Table 4.8. The columns represent mass values of carbon fibers and structural electrolyte corresponding to scenario of lower electrolyte use, baseline scenario and scenario of higher electrolyte use respectively. The table represents values before normalization.

4.5.3 Electrochemical Performance Scaling Factor

The values of structural electrolyte constituents and carbon fiber masses as well as electricity requirements for individual steps of structural battery electrolyte (SBE) and structural battery composite (SBC) production were normalized by the electrochemical performance scaling factor. The performance scaling factor for each scenario was calculated using the values of electrochemical properties corresponding to each electrolyte scenario, mentioned in Table 4.1. The performance scaling factor was used to normalize the inventory data corresponding to electrolyte scenarios such that environmental impacts resulting from production of SBC with desired electrochemical properties could be assessed. The scaling factor has been calculated using

Table 4.8: Mass of Carbon Fibers and Structural Electrolyte Constituents for 1 kg of SBC Production

Constituent (g)	Lower Electrolyte Scenario	Baseline Scenario	Higher Electrolyte Scenario
Carbon fibers	**660.76**	**661.34**	**658.26**
E51	66.01	56.20	61.28
AG80	28.29	24.09	26.26
D400	69.30	59.00	64.34
PC	1.23	1.40	1.35
EMIM-Tf_2N	121.47	137.89	130.35
$LiTf_2N$	52.94	60.09	58.16
Total mass of structural electrolyte produced	**339.24**	**338.66**	**341.74**
Total mass of SBC produced (kg)	**1.00**	**1.00**	**1.00**

Equation 4.4.

$$\text{Performance Scaling factor} = \frac{\text{Target value}}{\text{Actual value}} \tag{4.4}$$

The target value refers to values of ionic conductivity and capacity of SBC corresponding to the baseline scenario. The actual value refers to the values of electrochemical properties corresponding to lower electrolyte scenario and higher electrolyte scenario.

A product of ratios of target to actual values of ionic conductivity and battery capacity was calculated for each electrolyte scenario as the performance scaling factor. The calculation of these values for each scenario is provided below.

$$\text{Performance Scaling factor (Lower electrolyte content scenario)} = \left(\frac{0.1}{0.08}\right)\times\left(\frac{25}{12}\right) = 2.604$$

$$\text{Performance Scaling factor (Baseline scenario)} = \left(\frac{0.1}{0.1}\right) \times \left(\frac{25}{25}\right) = 1.00$$

$$\text{Performance Scaling factor (Higher electrolyte content scenario)} = \left(\frac{0.1}{0.3}\right)\times\left(\frac{25}{22}\right) = 0.3787$$

The values of performance scaling factors are presented in Table 4.9.

Table 4.9: Scaling factors

Ratio	Scaling factor
0.75	2.604
1.00	1.00
1.25	0.3787

A higher value of scaling factor implies greater amount of material and energy inputs required to produce SBC having desired electrochemical properties. This would result in greater environmental impacts. A lower value of scaling factor implies lower amounts of material and energy inputs required to produce SBC having desired electrochemical properties. This would result in significantly lower environmental impacts. A higher value of scaling factor was obtained in the lower electrolyte content scenario as the values of electrochemical properties are fairly low compared to the baseline scenario and hence greater amounts of material and energy would be required in order to produce SBC with desired electrochemical properties while a lower value of scaling factor was obtained in the higher electrolyte content scenario as the values of electrochemical properties are higher as opposed to the baseline scenario and hence lower amounts of material and energy would be required to produce SBC with desired electrochemical properties.

4.5.4 Electricity Requirements for SBC Production

The electricity requirements for different stages of structural electrolyte and SBC production were determined using engineering principles and specifications of equipments used in different stages of production at laboratory and pilot scales. The specifications of the equipments required for calculating electricity requirements are provided in Table 4.10 and Table 4.11. These values were obtained prior to normalization using performance scaling factor. The electricity requirements for producing 1 m^2 and producing 1 kg of SBC remain the same. The electricity requirements for curing processes mentioned in the tables below include hold, heating and cooling processes. The other technical specifications of laboratory and pilot equipment discussed in the study are provided in the Appendix section of the report.

The electrical power or rate of electricity consumption of equipments was determined from the specifications of equipment using online resources. In some cases, the power consumption of equipment was determined using Equation 4.5.

$$\omega = \text{RPM} \times \frac{2\pi}{60} \tag{4.5}$$

where:

- ω represents angular velocity ($\mathrm{rad\,s^{-1}}$).

- RPM represents the rotational speed of motor in the equipment (rotations per minute).

The total electrical energy consumed by equipments in each stage of the SBC production was determined using Equation 4.6.

$$E = P \times t \tag{4.6}$$

where:
- E is the electricity consumed in the process (kW h).
- P is the electrical power consumed by the equipment (kW).
- t is the duration of the process (h).

Table 4.10: Specification of Electrical Equipment: Laboratory Scale SBC Production

Process	**Equipment used**	**Power consumption** (kW)	**Duration of process** (hours)	**Electricity consumption** (kWh)
Blend preheating	Laboratory preheating oven (Weiss Technik GmbH (2022))	1.80	0.08	0.18
Shear mixing	Laboratory High shear mixer	0.50	1.00	0.62
Power mixing	Heavy duty power mixer (Cole Parmer) (Col (2003))	0.37	1.00	0.46
Structural electrolyte infusion	Vacuum pump (Polyestershoppen (2025))	0.18	1.00	0.22
Curing	Curing oven (GlobalGilson (2025))	0.85	8.25	15.15

The electricity consumption due to maintaining the temperature for the curing duration (holding), heating and cooling processes, constituting the curing process, are mentioned individually in Table 4.12 and Table 4.13. The duration of each stage of SBC curing process was determined using values of heating and cooling ramp rates and temperatures of curing processes. Equation 4.7 was used to calculate the duration of each stage of SBC curing.

$$t = \frac{T_{\text{end}} - T_{\text{start}}}{R_{\text{heat/cool}}} \tag{4.7}$$

where:

Table 4.11: Specification of Electrical Equipment: Pilot Scale SBC Production

Process	**Equipment used**	**Power consumption** (kW)	**Duration of process** (hours)	**Electricity consumption** (kWh)
Blend preheating	Pilot scale pre-heating oven (Carbolite Gero (2018))	6.00	0.08	0.62
Shear mixing	High shear mixer (Admix, Inc. (2025)	7.46	1.00	9.32
Power mixing	Heavy duty power mixer (LAKIDIS SA (2025))	18.50	1.00	23.12
Structural electrolyte infusion	Vacuum pump (Easy Composites Ltd (2022))	0.55	1.00	0.68
Curing	Curing oven (Despatch (2020))	108.00	7.68	1847.06

- t represents the duration of curing cycle (min).
- T_{end} represents the temperature at which the curing process ends (°C).
- T_{start} represents the temperature at which the curing process starts (°C).
- $R_{\text{heat/cool}}$ represents the rate of heating or cooling of the curing oven ($°\text{C}\,\text{min}^{-1}$).

The heating and cooling rate of laboratory scale curing oven considered was 2 °C per minute. The heating rate of pilot scale curing oven was considered as 4 °C per minute and the cooling rate was considered as 2 °C (Despatch (2020)).

Table 4.12: Curing cycles: Laboratory Scale SBC Production

Curing cycle	Start temp. of cycle (°C)	End temp. of cycle (°C)	Duration of curing (minutes)	Electricity required for curing (kWh)
First curing cycle	25	75	25	2.57
Second curing cycle	75	110	17.5	2.44
Third curing cycle	110	160	25	2.57
Hold time	-	-	360	6.38
Cooling	160	25	67.50	1.19

The values of electricity requirements were normalized using performance scaling factors calculated in section 4.5.3 of the report before modeling of scenarios using OpenLCA.

Table 4.13: Curing cycles: Pilot Scale SBC Production

Curing cycle	Start temp. of cycle (°C)	End temp. of cycle (°C)	Duration of curing (minutes)	Electricity required for curing (kWh)
First curing cycle	25	75	12.37	297.84
Second curing cycle	75	110	8.66	289.49
Third curing cycle	110	160	12.37	297.84
Hold time	-	-	360	810
Cooling	160	25	67.50	151.87

4.5.5 Heat Requirements for SBC Production

The heat required for mixing and preheating of structural electrolyte constituents as well as curing of SBC produced in the later stages was determined using the equation mentioned below.

$$Q = mc_p \left(T_{\text{end}} - T_{\text{start}}\right) \tag{4.8}$$

where m is the mass, C_p is the specific heat capacity, T_{end} is the temperature at which the specific process takes place or ends and T_{start} is the temperature at which the process starts.

A weighted average of mass and specific heat capacity values of individual structural electrolyte constituents (excluding use of D-400 curing agent as it is used in later stages of structural electrolyte production) was calculated as the specific heat capacity of the resultant structural electrolyte for different electrolyte to epoxy content scenarios. This value in addition to total mass of structural electrolyte corresponding to different electrolyte to epoxy resin content scenarios and difference between ambient and process temperatures were used to determine the heat required for electrolyte-epoxy blend preheating in each scenario.

A weighted average of mass and specific heat capacity values of carbon fibers and structural electrolyte corresponding to different electrolyte to epoxy resin content scenarios was calculated as the specific heat capacity of SBC produced. This value in addition to total mass of SBC produced and difference between start and end temperatures for each curing cycle were used to determine the heat requirements for the curing processes in each scenario.

The heat requirements for electrolyte-epoxy blend preheating and individual SBC curing cycles are mentioned in Table 4.14 and Table 4.15. These values apply for the laboratory and pilot scale production of structural battery composites respectively. The tables represent values of heat requirements prior to normalization using performance scaling factors determined in section 4.5.3 of the report.

Table 4.14: Heat requirements for 1 m^2 of SBC Production

Parameter	Lower electrolyte content scenario (kJ)	Baseline electrolyte content scenario (kJ)	Higher electrolyte content scenario (kJ)
Heat required for preheating	69.84	46.59	11.03
Heat required for curing cycles:			
First cycle	262.30	101.27	38.79
Second cycle	183.61	70.89	27.15
Third cycle	262.30	101.27	38.79

Table 4.15: Heat requirements for 1 kg of SBC Production

Parameter	Lower electrolyte content scenario (kJ)	Baseline electrolyte content scenario (kJ)	Higher electrolyte content scenario (kJ)
Heat required for preheating	38.77	15.53	5.81
Heat required for curing cycles:			
First cycle	158.58	61.24	48.19
Second cycle	111.00	42.87	33.73
Third cycle	158.58	61.24	48.19

In short, the equipment for individual SBE and SBC production processes was selected based on alignment with process specifications such as duration and operation of equipment. The power rating of equipment was determined from the equipment specifications mentioned in online resources.

4.6 Modeling of Scenarios using OpenLCA

The normalized values of structural electrolyte constituent and carbon fiber masses, electricity and heat requirements for each step of SBC production were used to model scenarios in relation to different electrolyte-epoxy resin composition ratios and SBC production at laboratory and pilot scales. The modelling was performed separately for 1 m^2 and 1 kg of SBC production. The supply chain providers for each material and energy input are provided in Table 4.16.

Table 4.16: Providers and sources for material and energy inputs obtained from EcoInvent 3.11 database

Constituent	Provider	Function
AG-80	epoxy resin production, liquid | epoxy resin, liquid | Cutoff, U-RER	Additional epoxy resin - improves flexibility and toughness of structural matrix
E-51	market for bisphenol A, powder | bisphenol A, powder | Cutoff, U-RER	Primary Structural matrix resin - provides mechanical strength
D-400	Polyether Polyols Production, Short Chain Polyether Polyols, Short Chain Cutoff, U-RoW	Curing agent-mixed with epoxy resins to create crosslinked matrix
Propylene carbonate	ethylene carbonate production | Cutoff, U	Solvent to improve lithium-ion mobility
EMIM-Tf2N	pyridine production, Chichibabin process | hydrogen, gaseous, low pressure | Cutoff, U	Ionic liquid – enhances ionic conductivity in the polymer matrix
Li-Tf2N	LiTf2N production	Lithium salt-provides lithium ions for intercalation
Carbon fibers	Carbon fiber production	Serves a dual purpose as the mechanical reinforcement to provide structural integrity and as the active electrode material that stores energy through lithium insertion and extraction.
Electricity	market for electricity, medium voltage | Cutoff, U	Used in preheating and mixing of structural electrolyte constituents as well as generating heat for curing of SBC
Heat	market for heat, district or industrial, other than natural gas | Cutoff, U	Preheating of electrolyte-epoxy blends and curing of SBC

Separate product flows were created for all the structural electrolyte constituents as these materials were not directly available in the Ecoinvent database and then linked to relevant production processes in OpenLCA software.

Carbon fiber flows modelled in the study were produced using acrylonitrile. The information on input and output materials along with energy requirements, emissions and supply chain providers for each input material for carbon fiber production process is provided in Table 4.17.

Table 4.17: LCI for Carbon Fiber Production.

Flow	Amount	Unit	Provider
Inputs			
Acrylonitrile	2.00	kg	Acrylonitrile production, Sohio process | acrylonitrile | Cutoff, U
Electricity (medium voltage)	35.00	kWh	market for electricity, medium voltage | Cutoff, U
Heat, district or industrial, other than natural gas	20.00	MJ	market for heat, district or industrial, other than natural gas | Cutoff, U
Water (deionised)	1.00	kg	market for water, deionised | Cutoff, U
Outputs			
Carbon fibers	1.00	kg	
Carbon dioxide (fossil)	0.50	kg	Emissions to air

$LiTf_2N$ modelled was produced by the synthesis of bis (trifluoromethanesulfonyl)imide (HTFSI) and lithium carbonate. The information on input and output materials along with energy requirements, emissions and supply chain providers for $LiTf_2N$ production process is provided in Table 4.18.

Table 4.18: LCI for $LiTf_2N$ Production.

Flow	Amount	Unit	Provider
Inputs			
HTFSI	0.98	kg	chemical production, organic | Cutoff, U
Electricity (medium voltage)	2.00	kWh	market for electricity, medium voltage | Cutoff, U
Lithium carbonate	0.13	kg	market for lithium carbonate | Cutoff, U
Outputs			
LiTf2N	1.00	kg	
Carbon dioxide (non-fossil)	0.08	kg	Emission to air
Water	0.03	m^3	Emission to water

4.7 Life Cycle Impact Assessment

Five major impact categories were selected as these impact categories were commonly assessed in screening LCA studies in literature reviewed (Zackrisson et al. (2019), Chordia et al. (2021)) and significant changes in results in the laboratory and pilot scale structural battery composite (SBC) production were observed with respect to these impact categories. The impact categories chosen for this study are listed below.

- Climate change (GWP)
- Terrestrial Ecotoxicity Potential (TETP)
- Ozone Depletion Potential (ODP)
- Ionising Radiation
- Water Use

5

Results and Discussion

5.1 Interpretation of Results

The values of impact categories obtained after modelling of scenarios were assessed and interpreted in this step of the LCA study. This is the last step of the LCA. The impact assessment method used for analyzing the modelling results across all impact categories was ReCiPe 2016 v1.03, midpoint(H).

5.2 1 m^2 of SBC Production

The interpretation of results obtained due to modelling of scenarios in relation to 1 m^2 of SBC production has been provided below. The change in results across impact categories due to production scaling are mentioned first followed by the contribution of individual production process to environmental impacts. A summary of result interpretation is provided in section 5.4 of the report.

5.2.1 Global Warming Potential

The variation in climate change impacts obtained from modelling of each scenario at laboratory and pilot production scales is shown in Figure 5.1.

The contributions to climate change impacts due to individual SBC production steps at laboratory and pilot scales are mentioned in Table 5.1.

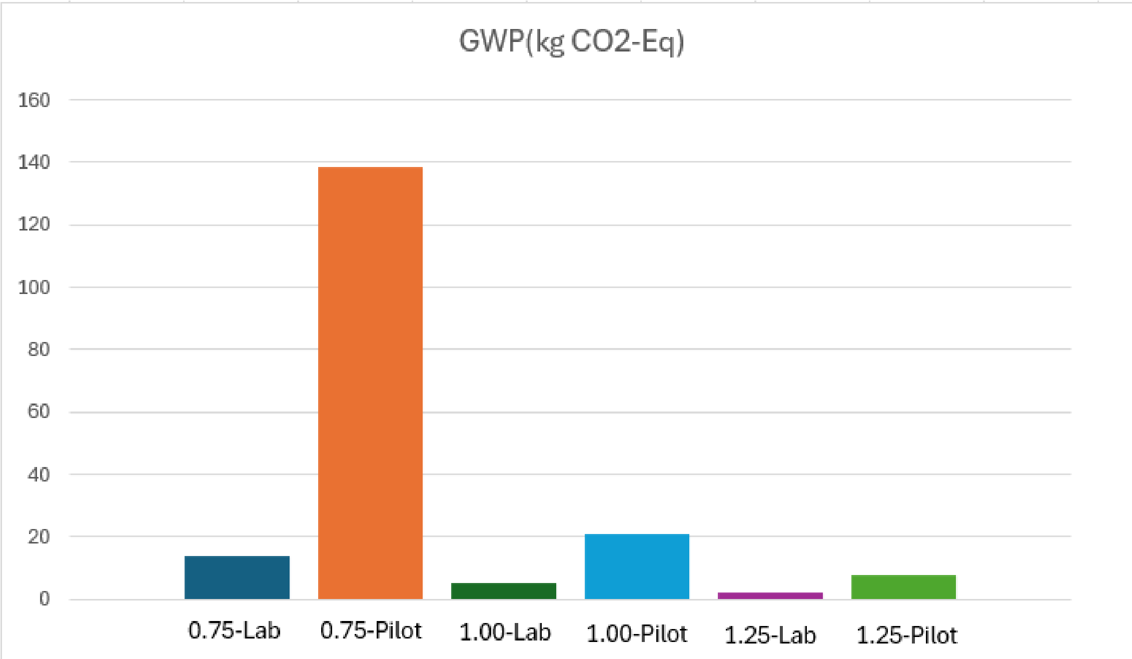


Figure 5.1: Climate Change Impacts due to 1 m^2 of SBC Production

Table 5.1: Contribution to Climate Change Impacts (%) from Different Production Processes and Scenarios: 1 m^2 of SBC Production.

Process	**0.75 Scenario (%)**		**1.00 Scenario (%)**		**1.25 Scenario (%)**	
	Lab	**Pilot**	**Lab**	**Pilot**	**Lab**	**Pilot**
Blend preheating	0.97	2.89	1.03	0.26	1.20	0.29
Shear mixing	0.20	0.61	0.20	0.77	0.20	0.77
Power mixing	0.15	15.37	0.15	1.90	0.15	1.90
Electrolyte infusion	96.29	23.09	96.23	24.22	98.07	24.23
Curing Cycles						
First cycle curing	0.81	19.53	0.81	24.51	0.14	24.50
Second cycle curing	0.77	18.98	0.77	23.83	0.10	23.81
Third cycle curing	0.81	19.53	0.81	24.51	0.14	24.50
Total	100.0	100.0	100.0	100.0	100.0	100.0

Lower electrolyte content scenario:

A significant increase in climate change impacts from 13.52 kg CO_2-eq to 138.49 kg CO_2-eq was observed due to physical scaling of SBC production in this scenario. The highest contribution to climate change impacts of 96.29 % and 23.09 % resulted from structural electrolyte infusion process at laboratory and pilot scale SBC production cases respectively.

Baseline scenario:

A significant increase in climate change impacts from 5.19 kg CO_2-eq to 20.79 kg CO_2-eq due to physical scaling of SBC production was observed in this scenario. The highest contribution to climate change impacts of 96.23 % and roughly 49 % resulted from structural electrolyte infusion process and curing processes at laboratory and pilot scale SBC production respectively.

Higher electrolyte content scenario:

A significant increase in climate change impacts 1.93 kg CO_2-eq to 7.88 kg CO_2-eq was observed due to physical scaling of SBC production in this scenario. The highest contribution to climate change impacts of 98.07 % and roughly 49 % resulted from structural electrolyte infusion process and curing processes at laboratory and pilot scale SBC production respectively.

Important Results:

The highest share of impacts resulted from structural electrolyte infusion process at laboratory scale production (at pilot scale production in the case of lower electrolyte use) while curing processes contributed to highest share of impacts at pilot scale SBC production. The production of acrylonitrile, followed by generation and consumption of heat and electricity, were found to contribute to significant impacts due to carbon fiber production, hence making electrolyte infusion process contributing to major share of impacts. The generation of electricity and heat by treatment of blast furnace gas as well as combustion of hard coal and heavy fuel oil were found to contribute to significant impacts from majority of processes. The production of lithium salt, pyridine (required for the production of ionic liquid) and Bisphenol-A were found to contribute to major share of impacts due to blend preheating process at both production scales. The consumption of electricity in all processes was found to substantially increase the impacts due to pilot scale SBC production.

5.2.2 Terrestrial Ecotoxicity Potential (TETP)

The variation in terrestrial ecotoxicity impacts obtained in each scenario at laboratory and pilot production scales is shown in Figure 5.2.

The contributions to terrestrial ecotoxicity potential impacts due to individual SBC production steps in all scenarios are provided in Table 5.2.

Lower electrolyte content scenario:

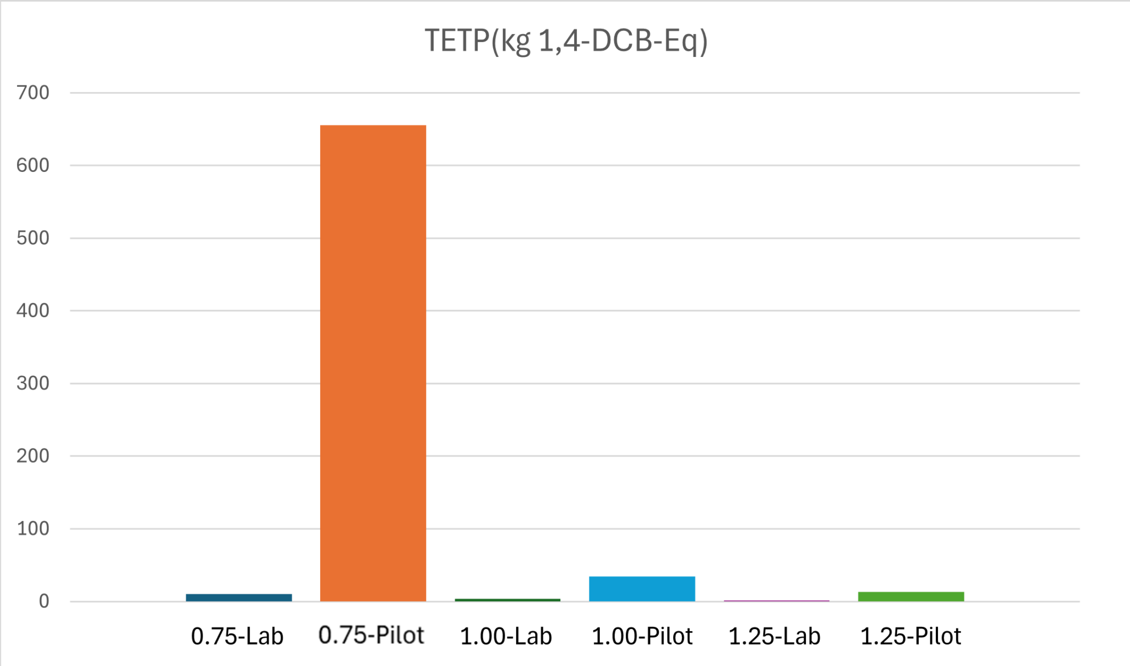


Figure 5.2: Ecotoxicity (terrestrial) Impacts due to 1 m^2 of SBC Production

A drastic increase in ecotoxicity (terrestrial) impacts from 10.16 kg 1,4-DCB-eq to 655.52 kg 1,4-DCB-eq due to physical scaling of SBC production was observed in this scenario.

Baseline scenario:

A significant increase in ecotoxicity (terrestrial) impacts from 3.89 kg 1,4-DCB-eq to 34.18 kg kg 1,4-DCB-eq was observed due to physical scaling of SBC production in this scenario.

Higher electrolyte content scenario:

A notable increase in ecotoxicity (terrestrial) impacts from 1.39 kg 1,4-DCB-eq to 12.95 kg 1,4-DCB-eq due to physical scaling of SBC production was observed in this scenario.

Important Results:

The combustion of wood chips to produce heat and electricity majorly contributed to ecotoxicity impacts. The import of electricity from Denmark was also found to contribute significantly to impacts. The highest share of impacts due to carbon fiber production resulted from the production and consumption of heat, followed by electricity consumption and acrylonitrile production, at laboratory and pilot production scales respectively. The production of propylene from dehydrogenation of

Table 5.2: Contribution to Ecotoxicity (terrestrial) impacts (%) from Different Production Processes and Scenarios:1 m^2 of SBC Production.

Process	**0.75 Scenario (%)**		**1.00 Scenario (%)**		**1.25 Scenario (%)**	
	Lab	**Pilot**	**Lab**	**Pilot**	**Lab**	**Pilot**
Blend preheating	0.20	1.47	0.05	0.01	0.22	0.03
Shear mixing	0.53	0.90	0.53	0.91	0.56	0.91
Power mixing	0.39	3.63	0.40	2.25	0.42	2.25
Electrolyte infusion	92.42	8.71	92.56	10.61	97.72	10.61
Curing Cycles						
First cycle curing	2.19	28.70	2.19	29.01	0.40	29.01
Second cycle curing	2.08	27.89	2.08	28.20	0.28	28.18
Third cycle curing	2.19	28.70	2.19	29.01	0.40	29.01
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

propane and production of light olefins was found to contribute to a major share of impacts due to acrylonitrile production. The impacts due to establishing a transmission network for medium voltage electricity majorly contributed to impacts. The consumption of electricity in all processes was found to substantially increase the impacts due to pilot scale SBC production. The production of pyridine, required for the production of ionic liquid, as well as production of lithium salt and Bisphenol-A, were found to contribute to major impacts due to blend preheating process at both SBC production scales. Structural electrolyte infusion and curing processes were found to constitute the highest share of impacts at laboratory and pilot scale SBC production respectively.

5.2.3 Ozone Depletion Impacts

The variation in ozone depletion impacts obtained in each scenario at laboratory and pilot production scales is illustrated in Figure 5.3.

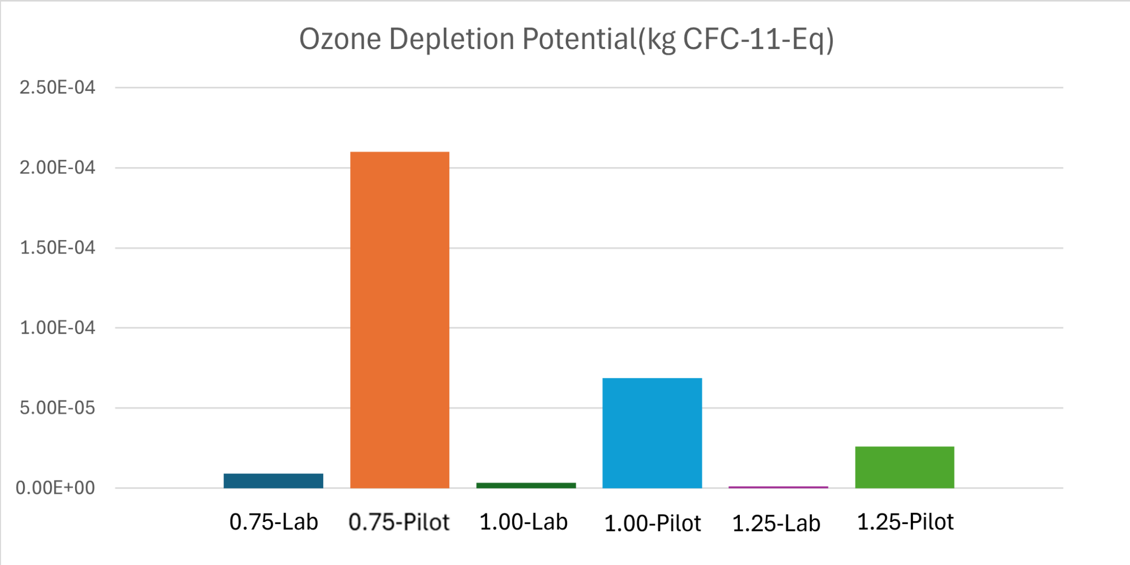


Figure 5.3: Ozone Depletion Impacts due to 1 m^2 of SBC Production

The contributions to ozone depletion impacts due to individual SBC production steps in all scenarios are provided in Table 5.3.

Table 5.3: Contribution to Ozone Depletion Impacts (%) from Different Production Processes and Scenarios:1 m^2 of SBC Production.

Process	0.75 Scenario (%)		1.00 Scenario (%)		1.25 Scenario (%)	
	Lab	Pilot	Lab	Pilot	Lab	Pilot
Blend preheating	0.09	0.44	0.01	0.02	0.44	0.02
Shear mixing	1.28	0.93	1.27	0.95	1.47	0.97
Power mixing	0.95	4.81	0.96	2.41	1.11	2.41
Electrolyte infusion	82.16	5.34	82.18	4.22	94.17	4.22
Curing Cycles						
First cycle curing	5.26	29.77	5.28	31.09	1.04	31.08
Second cycle curing	5.00	28.94	5.02	30.22	0.73	30.22
Third cycle curing	5.26	29.77	5.28	31.09	1.04	31.08
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Structural electrolyte infusion and curing processes were found to constitute the highest share of impacts at laboratory and pilot scale SBC production respectively in all scenarios. The treatment of blast furnace gas to produce high voltage electricity and import of electricity from Norway were found to contribute to major impacts. The consumption of electricity, followed by consumption of heat and acrylonitrile production, were found to constitute significant impacts due to carbon fiber production, responsible for increased share of impacts from electrolyte infusion process. The production of pyridine, required for the production of ionic liquid, as well as production of lithium salt and Bisphenol-A, were found to contribute to major impacts due to blend preheating process at both SBC production scales. The consumption of electricity in all processes was found to substantially increase the impacts due to pilot scale SBC production.

5.2.4 Ionising Radiation Impacts

The change in ionising radiation impacts obtained in each scenario at laboratory and pilot production scales is illustrated in Figure 5.4.

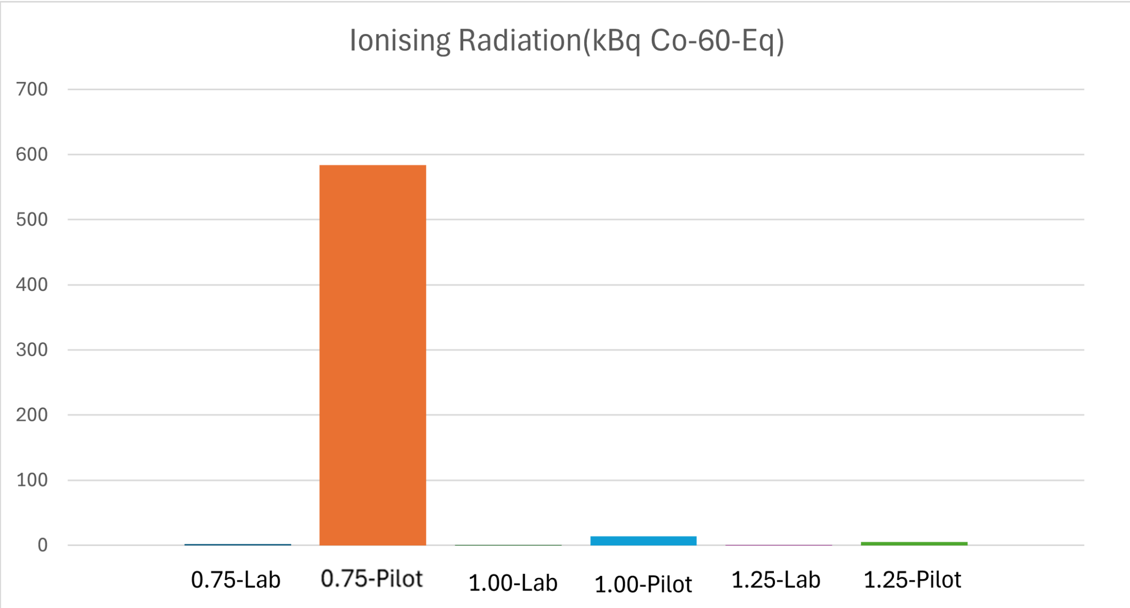


Figure 5.4: Ionising Radiation Impacts due to 1 m^2 of SBC Production

The contributions to ionising radiation impacts due to individual SBC production steps in all scenarios are provided in Table 5.4.

Lower electrolyte content scenario:

In the scenario where lower electrolyte content was used, a drastic increase in ionising radiation impacts from 1.62 kBq Co-60-Eq to 584.08 kBq Co-60-Eq when SBC production was physically scaled from laboratory to pilot scale was observed.

Baseline scenario:

In the baseline scenario where equal amounts of liquid electrolyte and epoxy resins were used, a considerable increase in ionising radiation impacts from 0.62 kBq Co-60-Eq to 13.50 kBq Co-60-Eq due to physical scaling of SBC production from laboratory to pilot scale was observed.

Table 5.4: Contribution to Ionising radiation(%) from Different Production Processes and Scenarios:1 m^2 of SBC Production.

Process	**0.75 Scenario (%)**		**1.00 Scenario (%)**		**1.25 Scenario (%)**	
	Lab	**Pilot**	**Lab**	**Pilot**	**Lab**	**Pilot**
Blend preheating	0.03	0.12	0.02	0.02	0.50	0.02
Shear mixing	1.60	0.98	1.40	0.96	1.66	0.98
Power mixing	1.27	2.11	1.06	2.43	1.24	2.43
Electrolyte infusion	79.91	3.77	80.25	3.74	93.41	3.75
Curing Cycles						
First cycle curing	5.83	31.30	5.85	31.24	1.18	31.23
Second cycle curing	5.53	30.42	5.57	30.37	0.83	30.36
Third cycle curing	5.83	31.30	5.85	31.24	1.18	31.23
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Higher electrolyte content scenario:

In the scenario where higher electrolyte to epoxy resin content was used, a notable increase in ionising radiation impacts from 0.202 kBq Co-60-Eq to 5.11 kBq Co-60-Eq due to physical scaling of SBC production from laboratory to pilot scale was observed.

Important Results:

Structural electrolyte infusion process contributed the highest to ionising radiation impacts at laboratory scale while curing processes contributed the highest to ionising radiation impacts at pilot scale SBC production in all scenarios. The generation of electricity using nuclear power based boiling water reactor and pressure water reactor was found to contribute significantly to ionising radiation impacts at both SBC production scales. The production of pyridine, required for the production of ionic liquid, as well as production of lithium salt and Bisphenol-A, were found to contribute to major impacts due to blend preheating process at both SBC production scales. The consumption of electricity in all processes was found to substantially increase the impacts due to pilot scale SBC production.

5.2.5 Water Use Impacts

The change in water use impacts obtained in each scenario at laboratory and pilot production scales is illustrated in Figure 5.5.

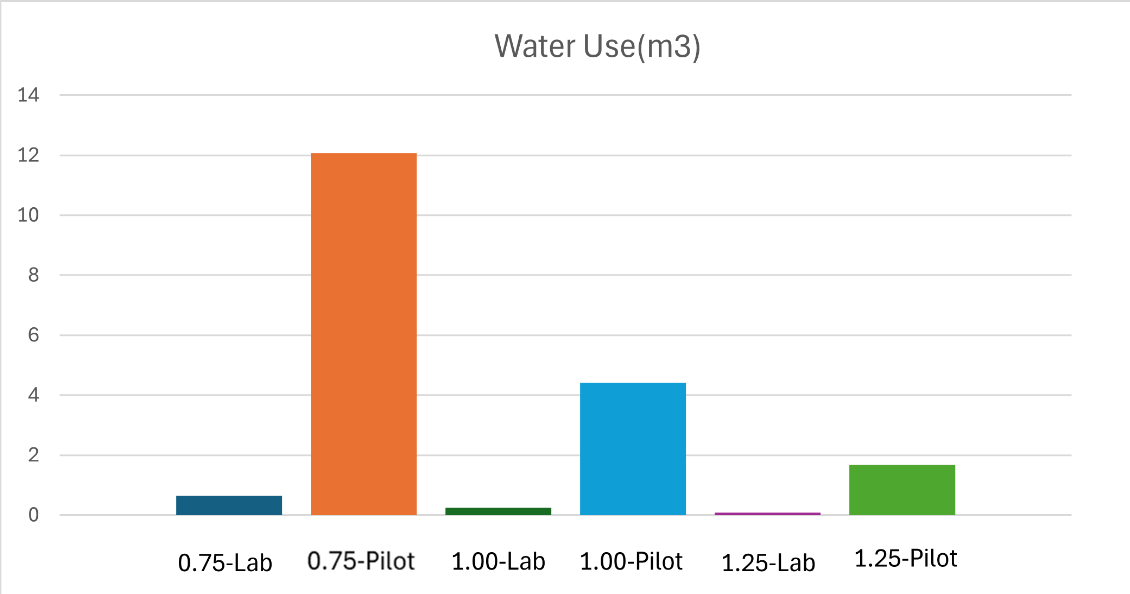


Figure 5.5: Water Use Impacts due to 1 m^2 of SBC Production

The contributions to water use impacts due to individual SBC production steps in all scenarios are provided in Table 5.5.

Table 5.5: Contribution to Water use impacts(%) from Different Production Processes and Scenarios:1 m^2 of SBC Production.

Process	**0.75 Scenario (%)**		**1.00 Scenario (%)**		**1.25 Scenario (%)**	
	Lab	**Pilot**	**Lab**	**Pilot**	**Lab**	**Pilot**
Blend preheating	0.61	0.35	0.31	0.02	0.44	0.04
Shear mixing	1.15	0.96	1.16	0.97	1.47	0.97
Power mixing	0.86	2.41	0.86	2.40	1.10	2.40
Electrolyte infusion	83.37	5.52	83.63	4.72	94.17	4.73
Curing Cycles						
First cycle curing	4.75	30.54	4.76	30.92	1.04	30.91
Second cycle curing	4.51	29.68	4.52	30.05	0.74	30.04
Third cycle curing	4.75	30.54	4.76	30.92	1.04	30.91
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Lower electrolyte content scenario:

In the scenario where lower electrolyte content was used, a significant increase in water use impacts from 0.641 m^3 to 12.07 m^3 was observed when SBC production was physically scaled from laboratory to pilot scale.

Baseline scenario:

In the baseline scenario where equal amounts of electrolyte and epoxy resins were used, a notable increase in water use impacts from 0.245 m^3 to 4.419 m^3 due to physical scaling of SBC production from laboratory to pilot scale was observed.

Higher electrolyte content scenario:

In the scenario where higher electrolyte to epoxy resin content was used, a surge in water use impacts from 0.082 m^3 to 1.674 m^3 was observed due to physical scaling of SBC production from laboratory to pilot scale.

Important Results:

Structural electrolyte infusion and curing processes were found to constitute the highest share of impacts at laboratory and pilot scale SBC production respectively in all scenarios. The generation of electricity from hydropower plant in non-alpine regions and nuclear power based pressure water and boiling water reactors along with import of electricity from Norway were found to contribute to significantly high water use impacts. The generation of heat and electricity from combustion of lignite was also found to contribute to greater water use impacts at both SBC production scales. The production of pyridine, required for the production of ionic liquid, as well as production of lithium salt and Bisphenol-A, were found to contribute to major impacts due to blend preheating process at both SBC production scales. The consumption of electricity in all processes was found to substantially increase the impacts due to pilot scale SBC production.

5.3 1 kg of SBC Production

The impact categories discussed in the previous section of the report were chosen for analyzing environmental impacts due to 1 kg of SBC production to maintain uniformity of result interpretation. The change in results across impact categories due to production scaling are mentioned first followed by the contribution of individual production process to environmental impacts. A summary of result interpretation is provided in section 5.4 of the report.

The interpretation of results based on 1 kg of SBC production is provided below.

5.3.1 Global Warming Potential

The change in climate change impacts across the electrolyte based scenarios modelled in the study is illustrated in Figure 5.6.

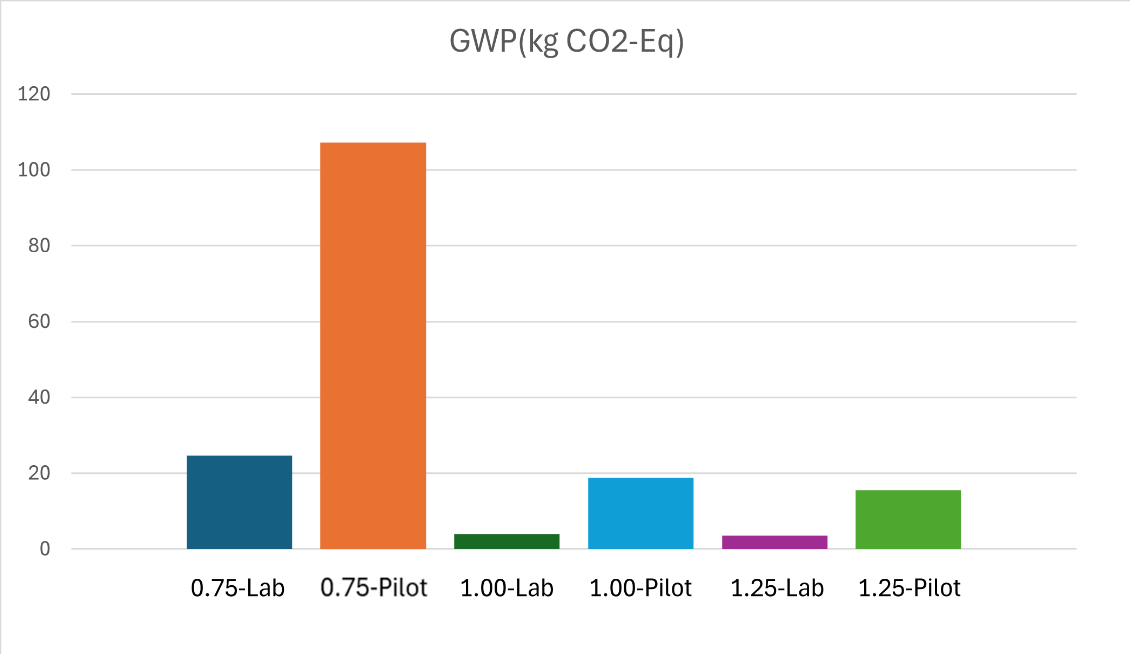


Figure 5.6: Climate change impacts due to 1 kg of SBC Production

The contributions to climate change impacts due to individual SBC production steps in all scenarios are provided in Table 5.6.

Table 5.6: Contribution to Climate change impacts(%) from Different Production Processes and Scenarios:1 kg of SBC Production.

Process	0.75 Scenario (%)		1.00 Scenario (%)		1.25 Scenario (%)	
	Lab	Pilot	Lab	Pilot	Lab	Pilot
Blend preheating	9.00	2.10	0.84	0.20	9.04	2.12
Shear mixing	0.23	0.79	0.26	0.81	0.23	0.79
Power mixing	2.03	2.39	0.20	2.01	1.91	2.36
Electrolyte infusion	85.77	19.74	95.52	19.89	85.75	19.68
Curing Cycles						
First cycle curing	1.00	25.23	1.08	25.94	1.05	25.25
Second cycle curing	0.97	24.52	1.02	25.21	0.97	24.55
Third cycle curing	1.00	25.23	1.08	25.94	1.05	25.25
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Lower electrolyte content scenario:

A considerable increase in climate change impacts from 24.63 kg CO_2-eq to 107.18 kg CO_2-eq due to physical scaling of SBC production was observed in this scenario.

Baseline scenario:

A notable increase in climate change impacts from 3.90 kg CO_2 to 18.77 kg CO_2 due to physical scaling of SBC production was observed in this scenario.

Higher electrolyte content scenario:

A surge in climate change impacts from 3.56 kg CO_2-eq to 15.57 kg CO_2-eq was observed due to physical scaling of SBC production in this scenario.

Important Results:

Structural electrolyte infusion process and curing processes were found to contribute to the highest share of impacts at laboratory and pilot scale SBC production respectively. Significant contributions to impacts due to generation of electricity and heat by treatment of blast furnace gas as well as combustion of heavy fuel oil and hard coal was observed in all scenarios. The production of acrylonitrile, followed by consumption of heat and electricity, were primary reasons for increase in impacts due to electrolyte infusion process. The production of pyridine, required for the production of ionic liquid, was found to contribute to major impacts due to blend preheating process at both SBC production scales. The consumption of electricity in all processes was found to substantially increase the impacts due to pilot scale SBC production.

5.3.2 Terrestrial Ecotoxicity Potential (TETP)

The change in terrestrial ecotoxicity potential impacts across the electrolyte based scenarios modelled in the study is illustrated in Figure 5.7.

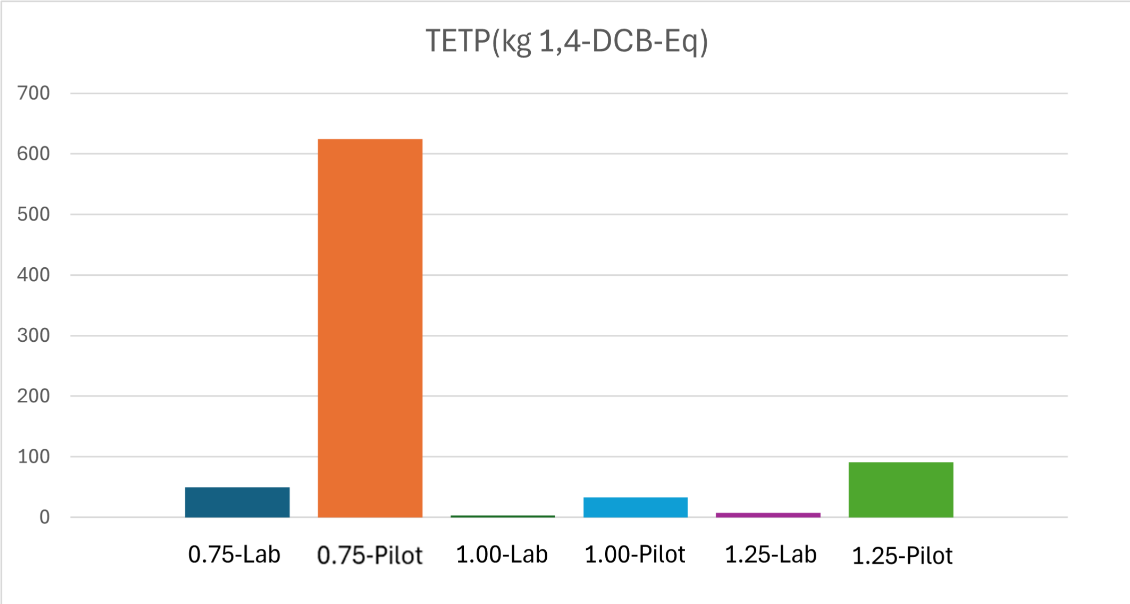


Figure 5.7: Ecotoxicity (terrestrial) impacts due to 1 kg of SBC Production

The contributions to ecotoxicity impacts due to individual SBC production steps in all scenarios are provided in Table 5.7.

Table 5.7: Contribution to Ecotoxicity impacts(%) from Different Production Processes and Scenarios:1 kg of SBC Production.

Process	**0.75 Scenario (%)**		**1.00 Scenario (%)**		**1.25 Scenario (%)**	
	Lab	**Pilot**	**Lab**	**Pilot**	**Lab**	**Pilot**
Blend preheating	10.63	0.89	0.26	0.07	10.53	0.89
Shear mixing	0.79	0.94	0.74	0.94	0.80	0.94
Power mixing	2.79	2.51	0.55	2.32	2.66	2.50
Electrolyte infusion	75.87	6.09	89.51	7.67	76.09	6.06
Curing Cycles						
First cycle curing	3.31	30.14	3.03	29.95	3.37	30.15
Second cycle curing	3.30	29.29	2.88	29.10	3.18	29.31
Third cycle curing	3.31	30.14	3.03	29.95	3.37	30.15
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Lower electrolyte content scenario:

A substantial increase in terrestrial ecotoxicity impacts from 49.67 kg 1,4-DCB-eq to 624.25 kg 1,4-DCB-eq was observed due to physical scaling of SBC production in this scenario. The highest change in impacts was observed in this scenario.

Baseline scenario:

A large increase in terrestrial ecotoxicity impacts from 2.81 kg 1,4-DCB-eq to 33.06 kg 1,4-DCB-eq was observed due to physical scaling of SBC production in this scenario.

Higher electrolyte content scenario:

A considerable increase in terrestrial ecotoxicity impacts 7.17 kg 1,4-DCB-eq to 90.76 kg 1,4-DCB-eq was observed due to physical scaling of SBC production in this scenario.

Important Results:

Structural electrolyte infusion process and curing processes were found to contribute to the highest share of impacts at laboratory and pilot scale SBC production respectively. Significant contributions to impacts due to generation of electricity and heat using nuclear power based boiling water and pressure water reactors as well as combustion of heavy fuel oil and hard coal was observed in all scenarios. The production of acrylonitrile, followed by consumption of heat and electricity, were primary reasons for increase in impacts due to electrolyte infusion process. The production of pyridine, required for the production of ionic liquid, as well as production of lithium salt and Bisphenol-A, were found to contribute to major impacts due to blend preheating process at both SBC production scales. The consumption of electricity in all processes was found to substantially increase the impacts due to pilot scale SBC production.

5.3.3 Ozone Depletion Potential

The change in ozone depletion impacts across the electrolyte based scenarios modelled in the study is illustrated in Figure 5.8.

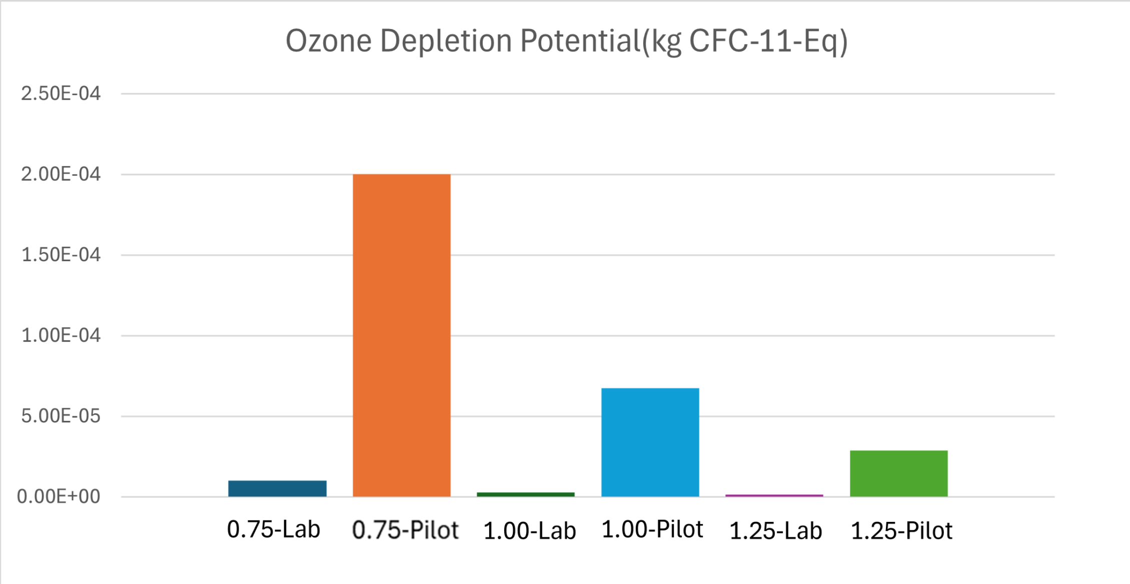


Figure 5.8: Ozone Depletion Impacts due to 1 kg of SBC Production

The contributions to ozone depletion impacts due to individual SBC production steps in all scenarios are provided in Table 5.8.

Table 5.8: Contribution to Ozone Depletion Impacts(%) from Different Production Processes and Scenarios:1 kg of SBC Production.

Process	**0.75 Scenario (%)**		**1.00 Scenario (%)**		**1.25 Scenario (%)**	
	Lab	**Pilot**	**Lab**	**Pilot**	**Lab**	**Pilot**
Blend preheating	4.76	0.28	0.53	0.07	4.51	0.29
Shear mixing	1.30	0.97	1.75	0.99	1.32	0.97
Power mixing	4.45	2.58	1.31	2.45	4.26	2.58
Electrolyte infusion	73.33	3.72	75.14	2.88	73.80	3.71
Curing Cycles						
First cycle curing	5.39	31.10	7.21	31.50	5.46	31.11
Second cycle curing	5.38	30.25	6.85	30.61	5.19	30.23
Third cycle curing	5.39	31.10	7.21	31.50	5.46	31.11
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

An increase in ozone depletion impacts due to scaling up SBC production was observed in all scenarios. Structural electrolyte infusion process and curing processes were found to contribute to the highest share of impacts at laboratory and pilot scale SBC production respectively. Significant contributions to impacts due to generation of electricity and heat using nuclear power based boiling water and pressure water reactors as well as combustion of heavy fuel oil, hard coal and wood chips was observed in all scenarios. The production of acrylonitrile, followed by consumption of heat and electricity, were primary reasons for increase in impacts due to electrolyte infusion process. The production of pyridine, required for the production of ionic liquid, as well as production of lithium salt and Bisphenol-A, were found to contribute to major impacts due to blend preheating process at both SBC production scales. The consumption of electricity in all processes was found to substantially increase the impacts due to pilot scale SBC production.

5.3.4 Ionising Radiation Impacts

The change in ionising radiation impacts across the electrolyte based scenarios modelled in the study is illustrated in Figure 5.9.

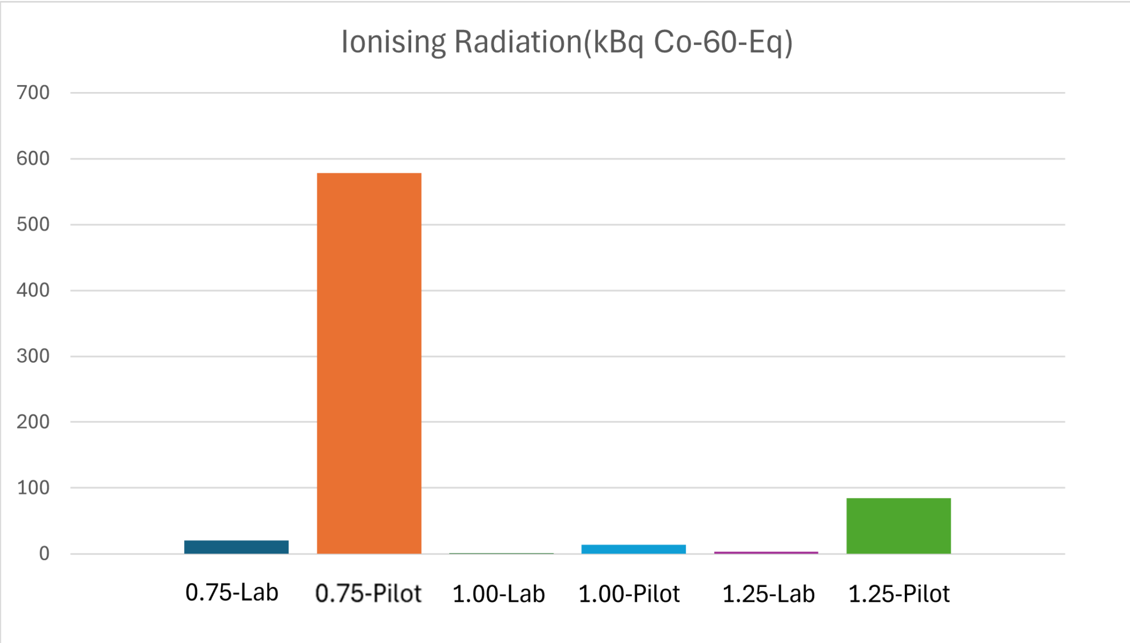


Figure 5.9: Ionising radiation impacts due to 1 kg of SBC Production

The contributions to ionising radiation impacts due to individual SBC production steps in all scenarios are provided in Table 5.9.

Lower electrolyte content scenario:

A considerable increase in ionising radiation impacts from 20.25 kBq Co-60-Eq to 578.59 kBq Co-60-Eq due to physical scaling of SBC production was observed in this scenario.

Baseline scenario:

A significant increase in ionising radiation impacts from 0.45 kBq Co-60-Eq to 13.34 kBq Co-60-Eq was observed due to physical scaling of SBC production in this scenario.

Table 5.9: Contribution to Ionizing radiation impacts(%) from Different Production Processes and Scenarios:1 kg of SBC Production.

Process	0.75 Scenario (%)		1.00 Scenario (%)		1.25 Scenario (%)	
	Lab	Pilot	Lab	Pilot	Lab	Pilot
Blend preheating	1.38	0.09	0.58	0.07	0.90	0.10
Shear mixing	1.89	0.99	1.94	0.99	1.92	0.99
Power mixing	1.52	2.45	1.45	2.45	1.54	2.45
Electrolyte infusion	71.84	2.58	72.51	2.53	72.40	2.55
Curing Cycles						
First cycle curing	7.79	31.59	7.98	31.61	7.88	31.60
Second cycle curing	7.79	30.71	7.56	30.74	7.48	30.71
Third cycle curing	7.79	31.59	7.98	31.61	7.88	31.60
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Higher electrolyte content scenario:

A drastic increase in ionising radiation impacts from 2.91 kBq Co-60-Eq to 84.13 kBq Co-60-Eq was observed due to physical scaling of SBC production in this scenario.

Important Results:

Structural electrolyte infusion process and curing processes were found to contribute to the highest share of impacts at laboratory and pilot scale SBC production respectively. Significant contributions to impacts due to generation of electricity and heat using nuclear power based boiling water and pressure water reactors as well as combustion of heavy fuel oil, hard coal and wood chips was observed in all scenarios. The production of electricity, followed by production and consumption of heat and acrylonitrile, were primary reasons for increase in impacts due to electrolyte infusion process. The production of pyridine, required for the production of ionic liquid, as well as production of lithium salt and Bisphenol-A, were found to contribute to major impacts due to blend preheating process at both SBC production scales. The consumption of electricity in all processes was found to substantially increase the impacts due to pilot scale SBC production.

5.3.5 Water Use Impacts

The change in water use impacts across the electrolyte based scenarios modelled in the study is illustrated in Figure 5.10.

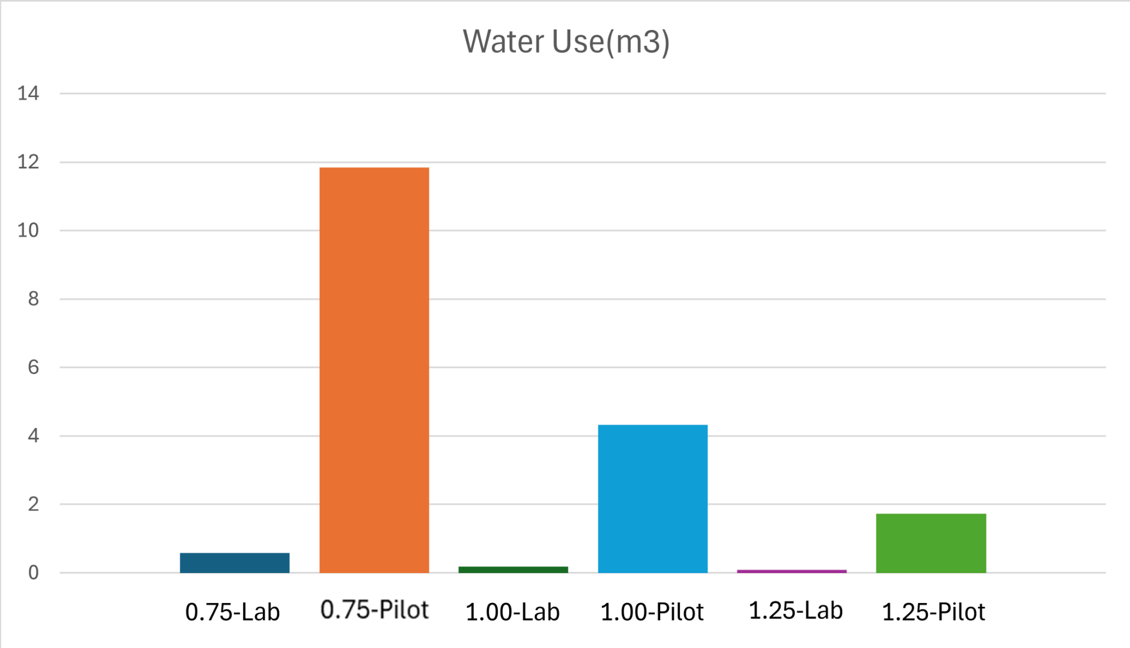


Figure 5.10: Water Use Impacts due to 1 kg of SBC Production

The contributions to water use impacts due to individual SBC production steps in all scenarios are provided in Table 5.10.

Table 5.10: Contribution to Water Use Impacts(%) from Different Production Processes and Scenarios:1 kg of SBC Production.

Process	**0.75 Scenario (%)**		**1.00 Scenario (%)**		**1.25 Scenario (%)**	
	Lab	**Pilot**	**Lab**	**Pilot**	**Lab**	**Pilot**
Blend preheating	3.69	0.23	0.70	0.08	3.50	0.23
Shear mixing	1.34	0.98	1.56	0.98	1.35	0.98
Power mixing	2.07	2.45	1.16	2.43	2.02	2.46
Electrolyte infusion	76.37	3.77	77.68	3.34	76.71	3.75
Curing Cycles						
First cycle curing	5.51	31.15	6.41	31.35	5.57	31.15
Second cycle curing	5.51	30.27	6.08	30.47	5.28	30.28
Third cycle curing	5.51	31.15	6.41	31.35	5.57	31.15
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Lower electrolyte content scenario:

A significant increase in water use impacts from 0.57 m^3 to 11.83 m^3 due to physical scaling of SBC production was observed in this scenario.

Baseline scenario:

A notable increase in water use impacts from 0.182 m^3 to 4.33 m^3 was observed due to physical scaling of SBC production in this scenario.

Higher electrolyte content scenario:

A surge in water use impacts from 0.083 m^3 to 1.721 m^3 due to physical scaling of SBC production was observed in this scenario.

Important Results:

Structural electrolyte infusion process and curing processes were found to contribute to the highest share of impacts at laboratory and pilot scale SBC production respectively. Significant contributions to impacts due to generation of electricity and heat using nuclear power based boiling water and pressure water reactors and hydropower plant as well as combustion of heavy fuel oil, hard coal and lignite was observed in all scenarios. The production of electricity, followed by production and consumption of heat and acrylonitrile, were primary reasons for increase in impacts due to electrolyte infusion process. The production of pyridine, required for the production of ionic liquid, as well as production of lithium salt and Bisphenol-A, were found to contribute to major impacts due to blend preheating process at both SBC production scales. The consumption of electricity in all processes was found to substantially increase the impacts due to pilot scale SBC production.

5.4 Summary of Result Interpretation

An impact analysis and contribution analysis of product and process flows to impact categories was performed after obtaining results from modelling on OpenLCA software. An increase in impacts due to scaling up SBC production from laboratory to pilot scale was observed in all scenarios. This trend of results was observed in the case of 1 m^2 and 1 kilogram of SBC production. The greatest change in impacts was observed when lower quantities of structural electrolyte were used for SBC production.

Structural electrolyte infusion process was found to contribute the highest to impacts at laboratory scale. This was majorly due to aspects associated with carbon fiber production such as production of carbon fiber precursor material, acrylonitrile, along with production and consumption of heat and electricity. The contribution analysis of processes and materials to impacts implied significant use of heat and electricity in carbon fiber production. In the case of producing 1 m^2 of SBC, a higher amount of SBC was produced (4.191 kg) in the lower electrolyte content scenario as opposed to the baseline scenario (1.608 kg) and higher electrolyte content scenario (0.61 kg). The production of 1 kilogram of SBC was scaled based on values of scaling factors. Hence, a greater amount of SBC by mass was produced in the case of lower electrolyte content scenario. A major fraction of SBC by mass is constituted by carbon fibers. Carbon fiber production, being a highly energy intensive process, as well as production of greater amounts of SBC to meet desired values of electrochemical properties caused significantly higher environmental impacts resulting from the lower electrolyte use scenario.

Curing processes were found to contribute the highest share of impacts at pilot scale SBC production. This is due to significant share of impacts resulting from generation and consumption of heat and electricity and greater energy requirements due to higher duration of curing processes. The production of E-51 epoxy resin, pyridine (required for producing ionic compound EMIM-Tf_2N) and lithium salt ($LiTf_2N$) were the main factors contributing to impacts due to blend preheating process. A major contribution to impacts due to power mixing process resulted from polyether polyols production, required for production of the curing agent. A reduction in contribution to impacts due to electrolyte infusion process was compensated by increase in contribution to impacts from mixing and curing processes during scaling up of SBC production. The **generation and consumption of electricity** in these processes caused increase in impacts at pilot scale SBC production. The impacts due to background processes such as production of ethylene carbonate for preparation of electrolyte-epoxy resin blends, transport of structural electrolyte constituents produced at different sites, use of deionised water in carbon fiber production and production of sulphur hexafluoride for transmission of electricity were found to be minimum in all scenarios.

Detailed information on the processes contributing to significant environmental impacts as observed in all scenarios has been mentioned in Table 5.11 below.

5.4.1 Impact Analysis of Energy Flows and Emissions

An impact analysis of product and process flows to environmental impacts was analyzed using OpenLCA software. This helped to provide more information on the environmental impacts associated with production and consumption of heat and electricity in SBC production.

Global Warming Potential: The impact analysis performed post scenario modelling showed majority of carbon emissions resulted from the combustion of fossil fuels such as coal and oil for the generation of electricity required for laboratory and pilot scale SBC production. The conversion of electricity from high to medium voltage also resulted in considerable impacts. A small share of impacts due to electricity use resulted from import of electricity from neighboring countries Norway and Denmark. Heat used in blend preheating, curing and carbon fiber production processes was generated by combustion of heavy fuel oil and hard coal. The production of propylene and production of ammonia by steam reforming and partial oxidation methods resulted in major impacts due to acrylonitrile production. The emissions of methane to air, resulting from mining of hard coal and combustion of natural gas for electricity production, was observed with increase in electrolyte content.

Table 5.11: Causes and Sources of Major Environmental Impacts due to SBC Production

Process	**Cause of major impacts**	**Source of impacts**	**Specific Process / Method**
Blend preheating	Production of E-51 epoxy resin	Production of Bisphenol-A	Production of phenol and acetone
	Production of EMIM-Tf2N (via Pyridine)	Production of ammonia	Steam reforming
		Production of formaldehyde	Methanol oxidation
		Production of acetaldehyde	Wacker process (ethylene oxidation)
	Production of LiTf2N	Production of lithium carbonate	Production of lithium carbonate from spodumene
Power mixing	Production of curing agent	Production of polyether polyols	Production of propylene oxide
Structural electrolyte infusion (carbon fiber production)	Production of acrylonitrile (Sohio process)	Production of propylene	• Steam cracking • Production of light olefins • Dehydrogenation of propane • Production of naphtha and butane
		Production of ammonia	Steam reforming

Terrestrial Ecotoxicity Potential: The impact analysis performed post scenario modelling implied the generation of electricity by combustion of wood chips and production of heat from the combustion of hard coal, heavy and light fuel oils caused significant emissions of copper, nickel and zinc to air due to SBC production at laboratory scale. A significant share of terrestrial ecotoxicity impacts resulted from generation of electricity by uranium tailing process at pilot scale SBC production. This in addition to generation of electricity by smelting of copper ore and production of heat due to combustion of wood chips and combustion of heavy and light fuel oil resulted in major contribution to terrestrial ecotoxicity impacts at pilot scale production.

Ozone Depletion Impacts: The impact analysis performed post scenario modelling implied the consumption of heat and electricity in SBC production obtained from the combustion of wood chips and hard coal as well as combustion of lignite (to produce high voltage electricity) resulted in production of dinitrogen monoxide, causing significant ozone depletion impacts at laboratory and pilot scale SBC production cases respectively. The probability of increased risks due to emission of dinitrogen monoxide (having high values of characterization factor), in spite of lower emission values, could be significant in the future.

Ionising Radiation: Impact analysis showed major share of impacts resulted from generation of electricity using nuclear energy based boiling water reactor and uranium tailing process at laboratory and pilot SBC production cases respectively. Significant amounts of radioactive materials such as Carbon-14 and Radon-222 are emitted to air in all scenarios.

Water Use: The impact analysis of individual processes to water use impacts implied the generation of electricity from hydropower plant in non-alpine regions resulted in major impacts at laboratory and pilot scale SBC production cases. Electricity required for SBC production was also generated using nuclear power based boiling water reactor and pressure water reactor at both production scales.

The above mentioned information has been summarized in Table 5.12.

Table 5.12: Sources of Heat and Electricity used in SBC Production

Energy	**Environmental impact**	**Source of energy**
Electricity	Global Warming Potential (GWP)	• Treatment of blast furnace gas • Establishment of transmission network for medium voltage electricity
	Terrestrial Ecotoxicity Potential (TETP)	• Combustion of lignite and wood chips
	Ozone Depletion	• Treatment of blast furnace gas
	Ionising Radiation	• Nuclear power (pressure water and boiling water reactors) • Uranium tailing (extraction of uranium from ore)
	Water Use	• Hydropower plant in non-alpine regions
Heat	Impact categories discussed in the study	• Combustion of lignite • Combustion of heavy and light fuel oils • Combustion of hard coal • Combustion of wood chips

5.5 Discussion

5.5.1 1 m^2 and 1 kg of SBC Production

An increase across all impact categories was observed when SBC production was scaled up from laboratory to pilot scale. **Structural electrolyte infusion process** was found to contribute the highest share of impacts at laboratory scale SBC production, the primary reason being production of carbon fibers. The production of carbon fibers was found to be not only energy intensive, but also contribute to increased environmental impacts. **Curing processes** were found to contribute the highest share of impacts at pilot scale SBC production. The significant consumption of energy for longer durations in curing processes primarily contributed to significantly high impacts resulting from curing processes. The production of structural electrolyte constituents (Bisphenol-A, ionic liquid and lithium salt) were found to contribute to substantial impacts due to blend preheating process. A major contribution to impacts due to power mixing process resulted from polyether polyols production, required for production of the curing agent. A reduction in impacts due to structural electrolyte infusion and blend preheating processes was observed while a significant increase in impacts from mixing and curing processes was observed with pilot scale SBC production. **Electricity use** was found to be the major driver of increase in impacts due to SBC production upscaling. The generation of electricity and heat majorly by combustion of fossil fuels and transformation from high to medium voltage electricity resulted in significantly high impacts at laboratory and pilot SBC production scales.

The environmental impacts due to producing 1 m^2 of SBC was found to be higher than the impacts due to producing 1 kg of SBC although the trend in results across scenarios and environmental hotspots remains same. This is due to producing SBC of greater mass. The mass equivalent of producing 1 m^2 of SBC corresponding to increasing electrolyte content was found to be greater than 1 kg in all the scenarios. This in turn led to higher material and energy requirements to produce 1 m^2 of SBC as opposed to producing 1 kg of SBC.

5.5.2 Influence of Electrolyte Composition on the Environmental Impacts due to SBC Production

The significantly high impacts due to SBC production when lower amount of electrolyte was used was due to production of greater quantity of SBC in order to manufacture structural batteries with desired electrochemical properties. This in turn would require greater heat and electricity requirements, causing greater environmental impacts. The lowest environmental impacts were found to result from the scenario where higher electrolyte content was used. A higher value of scaling factor used to normalize inventory data corresponding to the scenario of lower electrolyte use and lower value of scaling factor used to normalize inventory data corresponding to the scenario of higher electrolyte use also resulted in higher impacts in the lower electrolyte scenario as opposed to the scenario of higher electrolyte scenario. In short, the environmental performance of structural batteries is majorly influenced by the electrolyte composition.

5.5.3 Trade-off between Mechanical and Electrochemical Properties

With the increase in electrolyte content, there was a significant decrease in mechanical stiffness observed. This is due to increase in porosity of the co-continuous structure between the liquid electrolyte and the epoxy resins. This not only results in the formation of cracks in the microstructure but also hinders the transfer of loads between carbon fibers and epoxy matrix. However, an increase in ionic conductivity with increase in electrolyte content was observed due to greater flow of lithium ions across the structural electrolyte. The values of battery capacity fluctuated with increase in electrolyte content. In short, a trade-off between mechanical and electrochemical properties of SBC was observed with an increase in the electrolyte content.

5.5.4 Comparison of Study Results with Existing Literature

The results from this study align with certain observations noted from literature. Carbon fiber production was found to be highly energy intensive and contributed significantly to environmental impacts based on modelling of electrolyte based scenarios. This aligns with the results mentioned in Prenzel et al. (2023) wherein the production of precursor material acrylonitrile was found to contribute majorly to environmental impacts and Zackrisson et al. (2019) which explains carbon fiber production contributing to significant amounts of total carbon emissions due to structural battery production. The energy consumption due to SBC production using higher electrolyte to epoxy resin content (corresponding to battery cells with greater capacity) was found to be lower. This aligns with information in Knehr et al. (2024) which explains the need for manufacturing of battery cells with higher capacity to reduce the energy consumption. A fairly low contribution to impacts resulted from the production and use of propylene carbonate in SBE production, aligning with results studied in Zackrisson et al. (2019).

A major contrast to the information extracted from literature was the increase in environmental impacts observed when scaling up SBC production from laboratory to pilot scale. The duration of SBC production processes was kept constant for laboratory and pilot scale cases. The production of equal amounts of SBC for a definite duration using equipment of different specifications at laboratory and pilot scales was found to be the primary reason for increase in impacts at pilot scale. This is contrary to the real world case and has been addressed earlier in section 4.1.4.7 of the report. The reduction of environmental impacts when battery cell production is scaled up from laboratory to industrial scale was observed in studies Chordia et al. (2021), Liu et al. (2024) and Erakca et al. (2023).

6
Conclusion

This study focuses on assessing the environmental impacts associated with the physical scaling of structural battery composite (SBC) production from laboratory to pilot scale using screening life cycle assessment (LCA).

The modelling of scenarios and analyzing the contribution to impacts due to individual SBC production steps implied the significant **increase in impacts** across all impact categories due to physical scaling from laboratory to pilot scale. The largest change in absolute values of impacts was observed when electrolyte composition used in SBC production was lower. The environmental impacts were found to be the highest when lower amount of electrolyte was used and the environmental impacts were found to be the lowest when higher amount of electrolyte as opposed to epoxy resin content was used in SBC production. The environmental impacts due to producing 1 m^2 of SBC was found to be higher than the impacts due to producing 1 kg of SBC due to greater material and energy requirements to produce SBC with desired electrochemical properties in the former case.

A substantial rise in environmental impacts due to production scaling implies higher energy consumption and utilization of constituent materials by mass. The material inputs (production of acrylonitrile and epoxy resin E-51) as well as energy (heat and electricity) requirements were found to contribute to significant environmental impacts due to SBC production at laboratory and pilot scale. This raises a challenge of tackling **high energy consumption** especially when producing SBC at pilot scale. A **trade-off between mechanical and electrochemical properties** due to increase in electrolyte content was observed. The **production of carbon fibers** required to produce SBC was found to be not only energy intensive but also contribute to significant environmental impacts. The generation of electricity and heat was primarily from combustion of **fossil fuel based sources** such as coal, oil and natural gas in addition to utilization of nuclear power and hydropower energy sources. This in turn led to significant emissions to air and water from individual SBC production processes.

Energy efficient pilot scale equipment must be selected for performing mixing, electrolyte infusion and curing processes. This would not only reduce environmental impacts due to pilot scale SBC production but also lead to large scale implementation of structural battery technology. The **reliance on more renewable sources**

rather than fossil fuels for generating heat and electricity which are required for mixing of structural electrolyte and curing of SBC would help to significantly minimize environmental impacts due to SBC production. The multi-functional performance of structural batteries, influence by variation in electrolyte content, must be enhanced. This would help to produce SBC of lower mass, lead to lower environmental impacts and make structural battery technology competitive with other battery technologies. **Alternate materials or renewably sourced carbon fibers and epoxy resins** must be used as the electrolyte infusion process is critical to the production of SBC from technological and environmental perspective. A solution to reducing environmental impacts due to carbon fiber production would be to **re-use carbon fibers** obtained from the end-of-life management of SBC. While Raugei and Winfield (2019) proves hydrometallurgical recycling to be less energy intensive and contributes to lesser GHG emissions as opposed to pyrometallurgical recycling, Wickerts et al. (2023) considers hydrometallurgical recycling process to be fairly energy intensive in spite of recovering lithium. The information on different methods for recycling of composite materials extracted from Gunnarsson and Kasliwal (2024) and other literature sources are explained in the Appendix section of the report. These recycling methods could be studied and implemented in future research to recover carbon fibers from composite materials. This would help to tackle high energy consumption and reduce environmental impacts as opposed to producing virgin carbon fibers. The implementation of these recommendations in the long run would result in structural battery technology being a reliable and environment friendly battery technology.

Bibliography

Admix, Inc. Rotosolver® hygienic high shear industrial mixer. Web Page, 2025. URL https://admix.com/hygienic-sanitary-industrial-mixing-equipment/rotosolver-hygienic-high-shear-industrial-mixing. Accessed on 2025-09-02.

Salem M Aldosari, Bandar M AlOtaibi, Khalid S Alblalaihid, Saad A Aldoihi, Khaled A AlOgab, Sami S Alsaleh, Dham O Alshamary, Thaar H Alanazi, Sami D Aldrees, and Basheer A Alshammari. Mechanical recycling of carbon fiber-reinforced polymer in a circular economy. *Polymers*, 16(10):1363, 2024.

Eylem Asmatulu, Janet Twomey, and Michael Overcash. Recycling of fiber-reinforced composites and direct structural composite recycling concept. *Journal of Composite Materials*, 48(5):593–608, 2014.

Carbolite Gero. *Laboratory & Industrial Ovens & Furnaces*. Carbolite Gero Ltd., 2018. URL https://www.carbolite-gero.com/. Product Catalog. Document ID: E-12-2018.

Richa Chaudhary, Johanna Xu, Zhenyuan Xia, and Leif E Asp. Unveiling the multifunctional carbon fiber structural battery. *Advanced Materials*, 36(48):2409725, 2024.

ChemicalBook. Bis(trifluoromethane)sulfonimide lithium salt. Web Page, 2025a. URL https://www.chemicalbook.com/ChemicalProductProperty_EN_CB6311504.htm. CAS 90076-65-6. Accessed on 2025-09-12.

ChemicalBook. Poly(oxy-1,2-ethanediyl), .alpha.-[4-(1,1,3,3-tetramethylbutyl)phenyl]-.omega.-hydroxy-. Web Page, 2025b. URL https://m.chemicalbook.com/ProductDetail_EN_900940.htm. CAS 9002-93-1. Accessed on 2025-09-12.

Mudit Chordia, Anders Nordelöf, and Linda Ager-Wick Ellingsen. Environmental life cycle implications of upscaling lithium-ion battery production. *The International Journal of Life Cycle Assessment*, 26(10):2024–2039, 2021.

Mixers. Cole-Parmer, 2003. URL https://www.coleparmer.com/Mixers. Product Catalog.

Despatch. Large truck-in/walk-in ovens tad3-48/tad3-96 and tfd3-48/tfd3-96. Product Data Sheet TAD 3-48/96 04-28-20, ITW EAE, April 2020. URL https://www.despatch.com.

Easy Composites Ltd. Industrial vacuum pump ec20. Technical datasheet, Easy Composites Ltd, Stoke on Trent, United Kingdom, 2022. URL https://www.easycomposites.com. Version 1.1.

Merve Erakca, Sebastián Pinto Bautista, Samineh Moghaddas, Manuel Baumann, Werner Bauer, Lea Leuthner, and Marcel Weil. Closing gaps in lca of lithium-ion batteries: Lca of lab-scale cell production with new primary data. *Journal of cleaner production*, 384:135510, 2023.

GlobalGilson. Quincy forced-air lab oven, 0.6 cubic feet. Web Page, 2025. URL https://www.globalgilson.com/quincy-forced-air-lab-oven-0-point-6-cubic-feet. Accessed on 2025-08-19.

Erik Gunnarsson and Suvidhi Kasliwal. Connecting impact and quality-prospective life cycle assessment of recycling carbon fibre composites. 2024.

Jack Howarth, Sada SR Mareddy, and Paul T Mativenga. Energy intensity and environmental analysis of mechanical recycling of carbon fibre composite. *Journal of Cleaner Production*, 81:46–50, 2014.

IOLITEC GmbH. 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide. Web Page, 2025. URL https://iolitec.de/en/node/455. CAS 174899-82-2. Accessed on 2025-09-12.

Tianwei Jin, Gerald Singer, Keyue Liang, and Yuan Yang. Structural batteries: Advances, challenges and perspectives. *Materials today*, 62:151–167, 2023.

Kevin W Knehr, Joseph J Kubal, SeungRyeol Yoon, HyeongRyul Jeon, Whan Jin Roh, and Shabbir Ahmed. Energy consumption of lithium-ion pouch cell manufacturing plants. *Journal of Cleaner Production*, 468:143050, 2024.

LAKIDIS SA. Frozen meat blocks flaker lm1500l. Web Page, 2025. URL https://lakidis.gr/en/products/lm1500l/. Accessed on 2025-08-19.

Huiting Liu, Manuel Baumann, Hyein Moon, Xiang Zhang, Xinwei Dou, Maider Zarrabeitia, Eleonora Crenna, Roland Hischier, Stefano Passerini, Niklas von der Assen, et al. Life cycle assessment of bio-based hard carbon for sodium-ion batteries across different production scales. *Chemical Engineering Journal*, 495:153410, 2024.

Harsha Medicharla and Sanjeev Rao. A Critical Review on Structural Battery Composites: Current State, Challenges, and Future Prospects. *Polymer Sci peer Rev J.*, 5(5), 2024. doi: 10.31031/PSPRJ.2024.05.000624. PSPRJ. 000624.

Polyestershoppen. Biltec vacuümpomp standaard, 2025. URL `https://polyestershoppen.com/vacuummaterialen/biltec-vacuumpomp-standaard-333.html`.

Tobias Manuel Prenzel, Andrea Hohmann, Tim Prescher, Kerstin Angerer, Daniel Wehner, Robert Ilg, Tjark von Reden, Klaus Drechsler, and Stefan Albrecht. Bringing light into the dark—overview of environmental impacts of carbon fiber production and potential levers for reduction. *Polymers*, 16(1):12, 2023.

Marco Raugei and Patricia Winfield. Prospective lca of the production and eol recycling of a novel type of li-ion battery for electric vehicles. *Journal of cleaner production*, 213:926–932, 2019.

Mohammad Siam Siraj, Samia Tasneem, David Carlstedt, Shanghong Duan, Marcus Johansen, Carl Larsson, Johanna Xu, Fang Liu, Fredrik Edgren, and Leif E Asp. Advancing structural battery composites: robust manufacturing for enhanced and consistent multifunctional performance. *Advanced Energy and Sustainability Research*, 4(11):2300109, 2023.

Toray Composite Materials America, Inc. T700g standard modulus carbon fiber. Technical data sheet, Toray Composite Materials America, Inc., April 2018. URL `https://www.toraycma.com/`. Revision 5.

Xiao-Tong Wang, Zhen-Yi Gu, Edison Huixiang Ang, Xin-Xin Zhao, Xing-Long Wu, and Yichun Liu. Prospects for managing end-of-life lithium-ion batteries: present and future. *Interdisciplinary Materials*, 1(3):417–433, 2022.

Weiss Technik GmbH. Industrial laboratory ovens vötschoven lab. Technical Report WT-IndLabOfen/01.3 E/2022-07, Weiss Technik GmbH, Reiskirchen, Germany, July 2022. URL `https://www.weiss-technik.com/voetschoven`.

Sanna Wickerts, Rickard Arvidsson, Anders Nordelof, Magdalena Svanstrom, and Patrik Johansson. Prospective life cycle assessment of lithium-sulfur batteries for stationary energy storage. *ACS Sustainable Chemistry & Engineering*, 11(26): 9553–9563, 2023.

Yalin Yu, Boming Zhang, Mengjie Feng, Guocheng Qi, Fangyu Tian, Qihang Feng, Jiping Yang, and Shubin Wang. Multifunctional structural lithium ion batteries based on carbon fiber reinforced plastic composites. *Composites Science and Technology*, 147:62–70, 2017.

Mats Zackrisson, Christina Jönsson, Wilhelm Johannisson, Kristin Fransson, Stefan Posner, Dan Zenkert, and Göran Lindbergh. Prospective life cycle assessment of a structural battery. *Sustainability*, 11(20):5679, 2019.

A

Appendix

A.1 Composite Recycling Methods

Structural battery composites (SBC) produced during the manufacturing phase of structural batteries is recycled to recover carbon fibers which could be re-used for subsequent SBC production processes. The different categories for composite material recycling have been explained below.

A.1.1 Mechanical Recycling

Mechanical recycling includes grinding or cutting of materials into smaller particles followed by magnetic field separation, yielding coarse and fine fiber fractions, and re-use of output materials. The energy consumption in this process is fairly low (consumes about 0.15-0.30 MJ of electricity per kg of input material). Electricity is the major input of the process for grinding purposes. Mechanical recycling of composite materials yields carbon fibers of shorter lengths and lower tensile strength (reduction in tensile strength of about 18-30%) along with resin dust and filler as outputs from the process (Asmatulu et al. (2014)). The process is simple and less energy intensive while the significant change in the properties of fibers retained post recycling limit the application of the retained fibers. Aldosari et al. (2024) explains the limitations associated with mechanical recycling such as reduction in values of material properties due to increased material degradation and poor interfacial adhesion between carbon fibers and polymer matrix. Plasma treatment, chemical grafting and use of coupling agents like silane compounds and incorporation of nanomaterials like carbon nanotubes (CNT) can improve interfacial bonding between the recycled carbon fibers and the polymer matrix. Howarth et al. (2014) explains the reduction in energy consumption per kilogram of carbon fiber due to increase in processing rates of SBC. The study also explains the energy required for recycling carbon fibers was found to be substantially lower (0.27-2.03 MJ/kg of carbon fibers) as opposed to energy required for producing virgin carbon fibers (183-286 MJ/kg of carbon fibers). Mechanical recycling was found to increase risks of health impacts due to generation of dust in this study.

A.1.2 Chemical Recycling

In chemical recycling, fibers are treated with solvents or acids to ensure separation of carbon fibers from resin after the composite materials are grounded. This is followed by washing and drying of the retained fibers. The process requires higher operating temperatures compared to mechanical recycling process (about 200 °C to 450 °C). Fibers of high purity and maximum retention of properties are obtained in this process. The process also faces challenges such as increased risks due to chemical handling and higher operating costs (Asmatulu et al. (2014)). This recycling method consumes about 19.2-90 MJ of electricity per kg of input material (Aldosari et al. (2024)).

A.1.3 Thermal Recycling

This recycling method utilizes heat for recycling of carbon fibers. The method consumes about 3-30 MJ of electricity per kg of input material (Aldosari et al. (2024)). Asmatulu et al. (2014) explains three methods for thermal recycling of carbon fibers.

In **combustion**, composite materials are burned at higher temperatures and carbon fibers are recycled. The organic matrix present in composite materials is incinerated while the inorganic matrix remains as ash or residues. A significant reduction in properties of recycled carbon fibers is observed in this case.

In **fluidized bed combustion** (FBC) process, composite materials are broken down and fed into a fluidized sand bed. This leads to separation of carbon fibers and fillers. A drop in strength and stiffness of recycled carbon fibers is observed in this method. The process is said to operate at a temperature range of 450 °C to 550 °C.

The **pyrolysis** method utilizes even higher temperatures in the range of 400 °C to 700 °C. The composite materials are heated in an oxygen deficit environment to obtain recycled carbon fibers. Clean fibers and fibers of higher strength are obtained in this method.

A.1.4 Other Battery Recycling Methods

A non destructive form of composite recycling, direct recycling, being a new form of recycling method, was discussed in Wang et al. (2022). The active materials of batteries are restored without dismantling of battery components in this method. Although the method offers merits such as minimum energy consumption for material recycling and re-use of intact battery materials, the method is currently being implemented at laboratory scale and is challenged by difficulty in separating binders and the process being labor intensive as manual disassembly of components is required in this method of recycling.

Wang et al. (2022) also explains end-of-life management of spent lithium ion batteries (LIB). The challenges associated with LIB recycling were found to be difficulty in recycling due to different shapes and designs of LIB and requirement of manual disassembly of battery components which would be time and cost intensive. The article compares two battery recycling methods: pyrometallurgical and hydrometallurgical recycling. In **pyrometallurgical** recycling, LIB components are shredded and incinerated at high temperatures in furnaces. Valuable metals like cobalt, nickel, iron and copper are recovered in the form of alloys while lithium and aluminum often remain in the slag. This is a mature technology and can apply to wide range of battery chemistries. The shortcomings of this method include low recovery of lithium, increased risk due to significant carbon emissions and the process being highly energy intensive. Reduction roasting and modified sulphide recovery methods i.e. reduction of cathode materials to to liberate lithium and conversion of metal oxides to metal sulphates to easily extract heavy metals could be considered as solutions for improving this recycling process. The **hydrometallurgical recycling** process involves mechanical pre-treatment of batteries followed by chemical leaching using acids, bases and reducing agents. Valuable metals are recovered by precipitation, solvent extraction or other electro-chemical methods. The merits of this process include obtain of high purity valuable metals, use of lower temperatures and contribution to lower environmental impacts. However, the requirement of proper handling of chemicals and generation of large amounts of waste are the shortcomings of this method of recycling. The use of green solvents like deep eutectic solvents (DES) could be used as alternative materials for recovery of valuable metals.

The energy requirements for producing and recycling of composite materials and carbon fibers extracted from Asmatulu et al. (2014) have been mentioned in the tables below.

Table A.1: Energy Requirements for Composite Manufacturing.

Material	**Energy requirement (MJ/kg)**
Virgin CFRTP (Carbon Fiber Reinforced Thermoplastic)	155
Virgin CFRTS (Carbon Fiber Reinforced Thermoset)	234
Recycled CFRTP	15
Recycled CFRTS	33

Table A.2: Energy Requirements for Carbon Fiber Manufacturing.

Material	**Energy requirement (MJ/kg)**
Virgin CF (carbon fibers)	198–594
Recycled CF	10.8–36

A.2 Specifications of Laboratory Scale Equipment

The specifications of equipment used in different stages of SBE and SBC production at laboratory scale have been mentioned below.

Table A.3: Specifications for Blend Preheating Oven

Parameters	**Value**	**Unit**
Dimensions (capacity of oven)	$408 \times 380 \times 340$	mm^3
Input volume of structural electrolyte	280-365	cm^3
Rated output	**1.8**	**kW**
Rated voltage	230	V
Frequency	50/60	Hz
Rated temperature	300	°C
Process duration	**5**	**mins**
Electricity use	**0.1875**	**kWh**

Table A.4: Specifications for High Shear Mixer

Parameter	**Value**	**Unit**
Maximum capacity of equipment	2	L
Input volume of structural electrolyte	280-365	cm^3
Motor power	**500**	**W**
Highest speed	8000	rpm
Duration of process	**1**	**hour**
Electricity consumption	**0.625**	**kWh**

Table A.5: Specifications for Heavy Duty Mixer

Parameter	Value	Unit
Motor power rating	**373**	**W**
Process duration	**1**	**hour**
Electricity consumption	**0.46625**	**kWh**

Table A.6: Specifications of Vacuum Pump

Parameter	**Value**	**Unit**
Voltage	230	V
Current draw	0.8	A
Frequency	50	Hz
Rotational speed	3000	rpm
Flow rate	2.5	m^3h
Power consumption	**180**	**W**
Process duration	**1**	**hour**
Electricity consumption	**0.225**	**kWh**

Table A.7: Specifications of Curing Oven

Capacity	17	L
Maximum operating temperature	232	^0C
Voltage	230	V
Frequency	50	Hz
Current draw	3.7	A
Power consumption	**0.851**	**kW**

A.3 Specifications of Pilot Scale Equipment

The specifications of equipment used in different stages of SBE and SBC production at pilot scale have been mentioned below.

Table A.8: Specifications of Pilot Scale Preheating Oven

Capacity	450	L
Mixer power rating	6	kW
Process duration	5	mins
Electricity consumption	0.625	kWh

Table A.9: Specifications of High Shear Mixer at Pilot Scale

Power consumption (in horse-power)	10	hp
Power consumption	**7.46**	**kW**
Duration of process	**1**	**hour**
Electricity consumption	**9.325**	**kWh**

Table A.10: Specifications of Power Mixer at Pilot Scale

Maximum capacity	1500	L
Motor power rating	**18.5**	**kW**
Process duration	**1**	**hour**
Electricity consumption	**23.12**	**kWh**

Table A.11: Specifications of Pilot Scale Vacuum Pump

Motor power rating	**0.55**	**kW**
Process duration	**1**	**hour**
Electricity consumption	**0.6875**	**kWh**

Table A.12: Specifications of Pilot Scale Curing Oven

Maximum capacity	476	L
Voltage	480	V
Frequency	60	Hz
Power consumption	**108**	**kW**
Minimum operating temperature	34	°C
Maximum operating temperature	343	°C
Time taken for temperature rise from 40 to 343 degrees Celsius	75	mins
Heating rate	**4.04**	**°C per min**
Cooling rate	**2**	**°C per min**

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY