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Life Cycle Energy Assesment of Advanced Fiber Reinforced Composite Design and Manufacturing Methodologies

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LIFE CYCLE ENERGY ASSESSMENT OF ADVANCED FIBER REINFORCED COMPOSITE DESIGN AND MANUFACTURING METHODOLOGIES

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ABSTRACT

Automotive industry at large is focused on vehicle light-weighting since a 6%-8% increase in fuel efficiency can be achieved with a 10% reduction in vehicle weight [1]. With the growing demand for cost-effective and sustainable light weighting of automobile structures, interest has increased in the application of fiber reinforced plastic (FRP) composites for use in the Body-in-White (BiW), which can account for up to 40% of the total vehicle weight. Traditional FRP composite manufacturing processes like vacuum assisted resin transfer molding, autoclave consolidation or use of automated fiber placement have been successfully used for marine and aerospace applications. However, these processes are not suitable for the automotive industry due to the low production rate, need for highly skilled labor for manufacturing and quality control, and poor joining with traditional structural materials like steel. This necessitates the use of higher throughput out-of-autoclave (OOA) processes like high pressure resin transfer molding (HP-RTM), wet compression molding (WCM) or even fiber reinforced thermoplastics (FR-TP) forming. The transition to these OOA processes face two major challenges: a) the time-consuming iterative design and thermal profiling process required for metal tools which increases cost; and b) the lack of a low-cost, scalable, and sustainable multi-material joining pathways that can enable integration of FRP composite parts with traditional metal structures. This is because existing composite joining methods necessitate significant redesign of existing OEM infrastructure, incur high capital costs, and produce weak joints between metal and composite components.

To address the first challenge, a new paradigm where additive manufacturing of thermoplastic filament reinforced with continuous fiber is used to develop a low-cost and sustainable composite tool, is investigated. Furthermore, additive manufacturing can enable faster tool design turn-around times and allows for designing of complex tool geometries with embedded sensors and conformal cooling channels. This opens greater avenues for process and design optimization and will enable manufacturers to gain a better understanding of the process based on sensor data gathered in real time from the embedded sensors. To address the later challenge, a highly integrated multi-material, FRP-intensive BiW design was developed using unique multi-material transition joints which retain existing OEM joining infrastructure [2]. It incorporates multi-material transition joints where continuous dry fibers are laid through machined looped channels in a metal substrate and additional metal layers are additively manufactured on top of the looped fiber and metal substrate to embed the fibers within the metal and create a strong metal – fiber mechanical interlocking bond. The fibers are then infused with a thermoset matrix that fills out the loops as well, forming a string FRP-metal transition [3]. Thus, the resulting CFRP component with metal tabs can be spot welded to other metal components without piercing, drilling, or punching holes - significantly increasing the mechanical performance of the multi-material joints.

To ascertain the advantages of these multi-material designs and the use of state-of-the-art additively manufactured smart tools, their life cycle impact must be investigated and compared with existing technology. The results from the LCA can provide vital understanding of the energy requirements of the new processes methodologies and can help quantify the benefits offered by transitioning to this new proposed paradigm of composite design and manufacturing from a sustainability and emission reduction standpoint. To best of the authors knowledge there have been no studies that address the LCA for each of the proposed solutions. Thus, this work, conducts two comparative life cycle analyses on the proposed additively manufactured smart composite tool for OOA processes and for the multi-material designs for automotive structural components. Different scenarios are studied for both the LCAs to consider the existing FRP production processes as well as the production process of traditional materials.

DEDICATION

To my parents, who always supported me and believed in me.

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CHAPTER ONE

1 INTRODUCTION

1.1 Motivation

Automobiles have become an integral part of modern society. Each year more than ten million vehicles [2] are sold in the USA, with US residents consuming about 135 billion gallons [3] of E10 petroleum to fuel their vehicle. Increasingly tighter government regulations and consumer awareness about sustainability of vehicles has led to growth in demand for more sustainable products. The automotive industry has been driven to produce more sustainable and less polluting vehicles and has responded by not only increasing the fuel efficiency of the conventional Internal Combustion Engine powertrains but also introducing alternative powertrains such as hybrids, plugin hybrids, fuel cell and fully electric powertrains. In addition, another avenue pursued by automotive industry for more sustainable vehicles has been the pursuance of light weighting technology as 6%-8% increase in fuel efficiency can be achieved with a 10% reduction in vehicle weight [1].

By replacing traditional materials like steel with advanced lightweight materials, designers can reduce the vehicle weight without sacrificing passenger comfort, safety, and performance. Light weighting also allows for inclusion of advanced emission control systems, safety devices and integrated electronics technology without making the vehicle overweight from a design standpoint. For vehicles with alternative power trains, light weighting also has secondary benefits of increased range without increasing the size of the battery pack, thus increasing the vehicle value for the consumer. Most importantly, light weighting of the vehicle reduces the operational energy demand of the vehicle. This is due to the fact that less energy is required to accelerate a lighter vehicle. This is expected to offset the higher energy consumed in the manufacturing phase, making light weighting a viable strategy for more sustainable vehicles.

The BiW (Figure 1-1) constitutes the biggest proportion of weight in an automobile (up to 40% of the total weight). As the industry focuses on light weighting, reduction in the weight of the BiW becomes an important design objective. BiWs have traditionally been manufactured from similar grades of steels, such as mild steels, and high strength steels. In the pursuit of light weighting and efficiency gains, aluminum has also been widely adopted for use in modern BiW construction. However, further reduction in weight requires the use of more novel materials that not only enable lightweighting through material substitution but also enable simplification of design and assembly through parts consolidation.

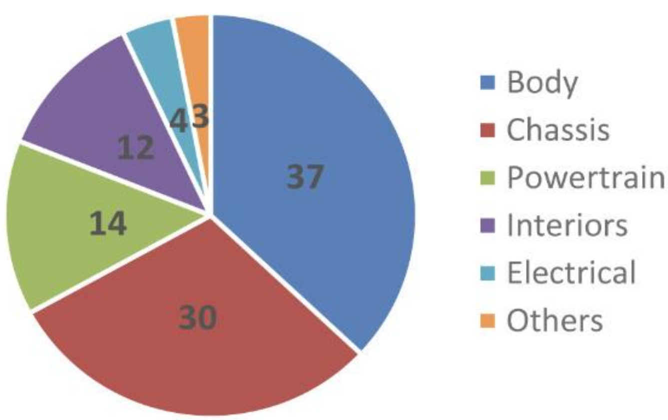


Figure 1-1 Curb weight distribution of typical automobile [4]

High strength steel, titanium alloys, aluminum alloys, magnesium alloys, fiber reinforced polymer (FRP) composites have all been proposed for adoption in Body in white components. Each of them has their advantages and disadvantages. Figure 1-2 represents the relative strengths of each of the major light weighting materials. In this paper, for reasons further explained we will consider the use of FRP composite in the light weighting of body in white.

1.2 FRP composites

FRP composites have very high strength-to-weight ratios compared to traditional materials. FRP composites also show lower fatigue and creep compared to steel and aluminum, allowing for lower safety factors to be built in in the designs [5], [6]. Furthermore, FRP composites provide enhanced safety due to their superior stiffness. . FRP composites also provide superior chemical properties as compared to metallic counterparts. FRP composites are corrosion-resistant over a wide range of operating temperatures and humidity scenarios. Various simulations and tests have achieved as much as 70% weight reduction per component [7], [4], [8]. These qualities have made FRP composites highly attractive for the automotive industry.

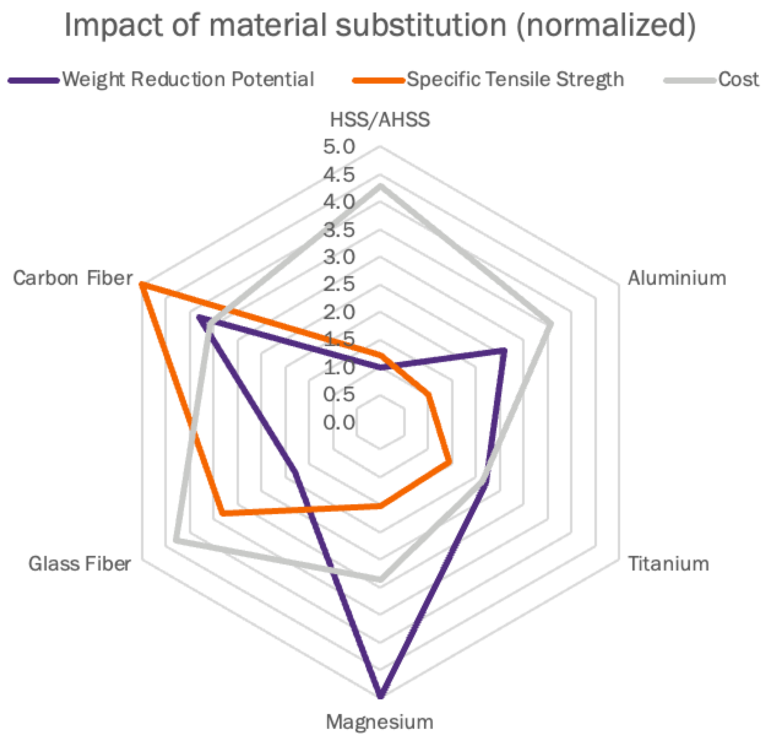


Figure 1-2 Comparison between options for light weighting materials.

However, FRP composites, especially continuous fiber reinforced composites, have traditionally come at a higher cost premium than other less lightweight material alternatives. This has limited the adoption of composites and composite components made exclusively from FRP composites. Thus, a multi-material approach is now being increasingly adopted by automotive OEMs. An additional challenge in this approach is the joining of dissimilar materials or multi-material joining. Automotive manufacturing is highly capital intensive. Original Equipment Manufacturers (OEMs) and their suppliers have large amounts of capital invested in the research, development, manufacturing infrastructure, and tooling of production processes for components made from legacy materials. Furthermore, the automotive industry is cautious with adoption of new materials and manufacturing technologies due to regulatory and safety concerns. The high production volumes and need to achieve and maintain high quality control in automotive manufacturing means that there is a tendency for a component-by-component adoption of FRP materials instead of an all-out redesign away from legacy materials and towards a multi-material structural design. Studies have also shown that a partial adoption is more sustainable than a complete replacement of traditional materials with FRP composites, at least until FRP composites material manufacturing is completely matured.

The fact that high investment has been made by manufacturers into legacy materials and their manufacturing techniques, combined with the fact that FRP composites are relatively immature means that components made from FRP composites need to be compatible with the legacy materials for manufacturers to adopt composites them [9]. FRP components must also be integrated with manufacturing processes involved in legacy materials to reduce the capital investment needed for the adoption of FRP composites. This inherently calls for multi material joining.

1.3 Multi material joining

Multi material joining can be categorized into three types of processes, namely thermal, chemical, and mechanical joining processes. Thermal joining processes are the most prevalent joining processes used in the assembly of components made from legacy metals. These processes are well researched, cost efficient, scalable and have comparatively low cycle times. Thermal joining processes include various welding processes such as electric arc welding, electron and laser beam welding, resistance spot welding, as well as additive processes, all of which are fundamentally designed to achieve a metallurgical bond. Of these, resistance spot welding (RSW) is the most widespread solution in automotive industries for joining of steel components in automotive body in white manufacturing. It is able to be highly automated, flexible, and allows for self-leveling of the joint, and often does not require use of filler materials, preventing additional weight and weld contamination. Despite their advantages thermal joining processes are not particularly suitable for FRP composite-metal multi-material joining [10]. The main cause of this is the vastly different thermal characteristics of FRP composites and metals which make any thermal joint between them infeasible [11].

Chemical joining processes mainly include adhesive joining and depend on the chemical bonds formed between the adherent or substrate, and the adhesive. These chemical bonds work on almost any combination of materials. Adhesive joining processes have been adapted in automobile manufacturing for non-structural parts and in noise, vibrations, and harshness applications.

However, adhesive joining has not been adopted widely for joining in automotive body in white structural joint manufacturing due to the attenuation of the bond strength over time [12]. Adhesive joints are also time consuming, due to the time needed for surface decontamination, preparation and curing, posing a challenge for high volume production [13]. Furthermore, adhesive joining requires well prepared surfaces and a larger area for bonding, of the joint face which adds further complexity and weight to the design, and time for the joining process. The presence of adhesive material also introduces challenges with the thermal compatibility of the joint materials [13].

Mechanical joining processes are thus preferred for FRP composite metal joining. Traditional joining methods such as riveting, screwing, sewing, filament winding require a puncture in the composite laminate [14]. This may lead to local high-stress concentrations and increases the chance of failure. Thus, these mechanical joining processes are not suitable for composite metal joints [15].

1.4 Ultrasonic Additive Manufacturing

A novel multi material joining technology is proposed by the research team at Honda and Ohio State University [16]. Ultrasonic additive manufacturing (UAM) is utilized to create a mechanical interlocking joint between the fiber weave and a metal matrix. UAM is a low temperature solid state welding process that uses friction between rough surfaces to disrupt the oxide layers and cause plastic deformation at the surface, which results in fusing without melting. The low welding temperatures of UAM allow for the fibers to be easily integrated in the matrix without causing thermal degradation of the fiber or the fiber sizing.

The UAM process has several advantages. As the preform is formed after the multi material joint, varying fiber orientation, layers and even the use of recycled discontinuous fiber is possible in the laminate. UAM allows for the elimination of the need to cut, drill or punch holes in the fiber which better preserves the mechanical properties of FRP composites. Furthermore, the strength of the bond can be modelled by FEA procedures which allows for better design control. The use of recycled fiber is especially attractive as the cost of recycled fiber is order of magnitude lower than virgin fiber. The recycling also reduces the increase in energy intensity associated with the manufacturing of FRP composite. However, the main benefit of the UAM technology is the ability to integrate the composite parts into the existing spot-welding joining infrastructure employed in almost all OEMs' BIW manufacturing methodology.

1.5 Additively Manufactured composite tooling

As more composite components are incorporated into the automobile industry, traditional composite manufacturing methods, such as vacuum infusion using machined molds have become less feasible. This is due to their limited scalability for medium to large scale manufacturing and larger size of components. Thus, newer techniques for composite manufacturing, such as thermoforming, wet compression molding and resin transfer molding are required. The adoption of these new molding processes, however, is hindered due to the significant limitations of present, metal tooling technology.

Current molds used in composite manufacturing are made through subtractive machining of metals and have a thermal heating element located centrally in the tool. The cooling channel geometry is also limited to capabilities of subtractive manufacturing. This creates zones of uneven heating and cooling of the composite components. This may lead to shrinkage of the component, warping, or improper curing of the composite component.

To avoid these phenomena, physical manufacturing trials and thermal profiling of the tool surface during trial runs is required. Results from these trials may, in certain cases, require the re-tooling of the entire mold. This is a time-consuming and costly process. Furthermore, to ensure real-time monitoring of the process, data from embedded sensors in the tool is needed. With traditionally manufactured tools it may be impossible to create desired locations for these sensors through machining.

Additively manufactured tools are proposed as an innovative solution to the challenge of retooling the mold. This allows for the design of complex cooling channels, as well as geometries to incorporate in situ centers that allow real time monitoring of the component curing. Furthermore, additive manufactured tools can also incorporate selectively hollow molds optimized for reducing the material required for the tool manufacture.

One novel solution to address the challenge of enabling uniform tool surface heating is carbon nano tube (CNT) coated continuous carbon fiber (CCF) reinforced composite tool designs [17]. Use of CNT coated CCF reinforcements on the continuous fiber reinforced composites are used to additively manufacture composite tools, the tool strength and stiffness is significantly increased. This is achieved by CNTs aiding in mechanical interlocking between the 3-D printed layers. Carbon fiber composite and carbon nanotubes are also susceptible to heating via microwave radiation. Microwave annealing causes local heating of the tool which creates uniform tool surface temperature distribution, allowing the minimization of warping, shrinkage, and other defects. This is advantageous as the mold can be annealed to improve the fiber-matrix adhesion, and the components can be cured uniformly and rapidly using microwave heating of the tool surface. A key benefit of microwave heating is that it is an order of magnitude lower in energy consumption, compared to conventional oven annealing and autoclave annealing. This is further beneficial as it will reduce the overall energy required for the manufacturing of composite components.

1.6 Literature review

Several studies have performed LCA on light weighting of vehicles resulting in numerous publications. Table 1-1 list some of the LCA studies available in the literature which has been visually represented in Figure 1-3 that shows the energy demand reduction (the energy savings) over the vehicle's lifetime is linearly dependent on the weight reduction achieved. Additionally, most LCAs focused on light weighting do not consider FRP composites due to the high cycle times and labor requirements of FRP autoclave molding processes. LCA studies that have included FRP composites, have rarely used out-of-autoclave processes for molding of FRP composite components. Without out-of-autoclave processes such as RTM, HPRTM and WCM, that enable lower cycle times, the adaption of FRP composites is unlikely to be successful at medium to high production scale. Also shown in the table is the lack of multi-material joining processes investigated in the LCA studies.

Sullivan and Hu [18] performed LCA for Aluminum, CFRP and GFRP component based light weighting. They were able to show 13% weight reduction resulting in 8% energy saving over the life cycle. However, the molding process used for FRP component manufacturing is not specified in the study and has not been investigated in detail. Similarly, Overly et al [19] light weighted closure panels by 60% and showed 50% reduction in lifecycle energy while ignoring the molding process from the LCA. Meanwhile, Moon et al [20] performed full vehicle light weighting with FRP composites but left the molding process unspecified in the paper. Suzuki [21] used CFRP components made with RTM to achieve 40% weight reduction that resulted in 25% energy saving in the vehicle life cycle. In another paper Suzuki et al [22] used preform match die (PMD) forming to show 18% life cycle energy reduction through 36% weight reduction of the full vehicle. Mayyas et al [23] used SMC composite to achieve 53% life cycle energy saving by light weighting the BiW by 55%. Kelly et al [24] and Templeman et al [25] reduced the weight of chassis door system and BiW respectively with use of thermoformed FRP composite. They were able to achieve 24% and 10% energy reduction over life cycle respectively. Witik et al [26] light weighted the bulkhead with structural reaction injection molding by 61% resulting in energy savings of 52% over life cycle. Stodolsky et al [27] used aluminum to achieve 31% weight reduction in full vehicle light weighting resulting in 21% energy saving over lifetime. Du et al [28] and Hakamada et al [29] used Magnesium for full vehicle light weighting and demonstrated potential for life cycle energy saving. Saur et al [30] and Stasinopoulos et al [31] showed that BiW weight reduction using aluminum reduced life cycle energy consumption. Hayashi et al [32] also employed aluminum for 20% reduction in weight and showed 2% reduction in GHG emissions.

Similar results were achieved by Kim et al [33] and Birat et al [34] but with varying degree of results.

Several studies have been done on improvement of the tooling technology of composite manufacturing. Gouveia et al [35] have performed LCA of additive manufacturing repair processes for molds. The paper showed reduced cost and environmental impact of additive manufacturing on tooling. Ma et al [36] showed the benefit fits of composite tools on reducing the environmental impact. Vita et al [37] compared composite and metal mold in autoclave and PBM processes. The paper demonstrated lower costs of composite mold compared to metal molds due to lower material requirements of composite molds. On contrary, Forcellese et al [38] performed similar experiment but showed that autoclave process with metal mold was less environmentally impactful compared to composite mold. Li et al [39] created a computer system for lifecycle cost estimation of composite manufacture and included composite tools in the system. The paper also performed a case study and demonstrated the cost effectiveness of composite tools. Hodor et al [40] demonstrated 75% tool cost reduction and 50% lead time reduction with the use of additive manufacturing for mold construction. Kim G[41] et al demonstrated the viability of using additively manufactured composite tool along with coating for composite manufacture.

Table 1-1 Light weighting LCA review

REFERENCE	COMPONE-NT	COMPOSITE MATERIAL USED?	MOLDING PROCESS	MULTIMATERIAL JOINING	WEIGHT REDUCTION	ENERGY SAVING ACHIEVED
[18]	Vehicle	Yes	unspecified	No	13%	8%
[27]	Vehicle	No	NA	NA	31%	21%
[30]	BIW	No	NA	No	22%	29%
[32]	Vehicle	No	NA	NA	20%	2%*
[19]	Closures	Yes	Ignored	NA	60%	50%
[34]	Vehicle	No	NA	NA	35%	0%*
[22]	Vehicle	Yes	RTM	No	40%	25%
[21]	Vehicle	Yes	PMD	No	36%	18%
[20]	Vehicle	Yes	unspecified	No	30%	17%
[29]	Vehicle	No	NA	NA	10%	6%
[33]	Vehicle	No	NA	NA	24%	22%*
[28]	Vehicle	No	NA	NA	6%	2%
[25]	BiW	Yes	Thermoforming	No	24%	10%
[31]	BiW	No	NA	No	31%	18%
[26]	Bulkhead	Yes	Structural RIM	NA	61%	52%
[23]	BiW	Yes	SMC	No	55%	53%
[24]	Door	Yes	Thermoforming	No	40%	24%

*GHG in ton CO_2 equivalent

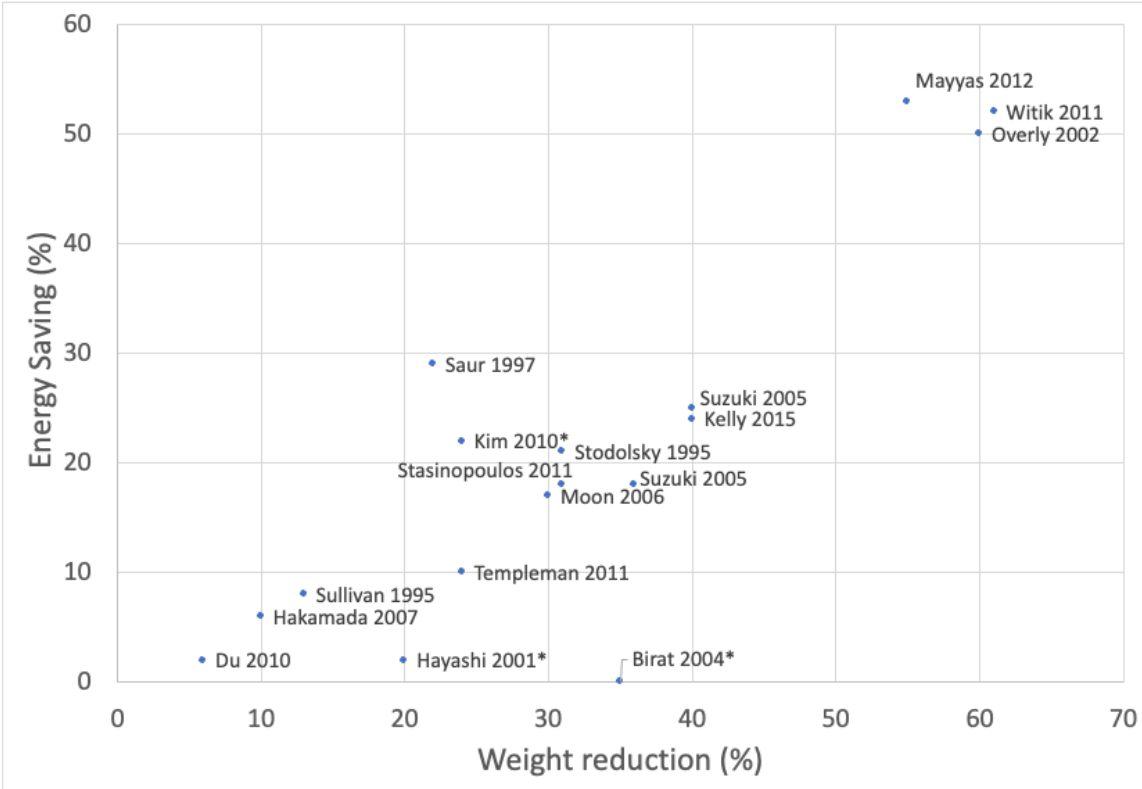


Figure 1-3 Weight reduction vs Energy Saving in prior automobile light weighting LCAs.

Table 1-2 Additive Manufacturing of composite tools literature review

	Additive manufactured tool	Composite tool	LCA of tool
Gouveia 2021 [35]	✓	✗	✓
Kim 2023[42]	✓	✓	✗
Jayasree 2020 [43]	✗	✓	✗
Kim 2021 [41]	✓	✓	✗
Yurtdas 2016 [44]	✗	✓	✗
Hodor 2013 [40]	✓	✓	✗
Li 1997 [39]	✗	✓	✓
Forcellese 2020 [38]	✗	✓	✓
Vita 2019 [37]	✗	✓	✓
Ma 2021 [36]	✗	✓	✓

1.7 Research Gaps

1.7.1 Research Gap 1:

While many studies have shown the benefits of light weighting in reducing energy demand, none of the studies have addressed multi-material joining and corresponding multi-material lightweight designs specifically in case of FRP composite. In addition, there have not been any comparative studies on the life cycle analysis of different joining methodologies in automobiles. This is to be expected as relative to the vehicle life cycle, joining processes require far lower energy and material inputs. In addition, most joining processes do not contribute any major emissions to air, water, or soil. However advanced multi-material joining technologies such as UAM require greater amount of energy input compared to traditional joining technologies and therefore merit to be included in life cycle analysis. Furthermore, most previous LCAs on automobile light weighting do not specify the exact molding process used to manufacture FRP composite components and derive their manufacturing inventory for FRP composites from adjacent industries such as motor sports, aerospace, or sport goods. However, for adoption of FRP in medium-to-high production of automobile structures utilizing low cycle time out-of-autoclave processes like HPRTM will need to be addressed in a comprehensive LCA study. **No study to date has been performed on LCA of FRP composite manufactured in Out of autoclave process and combined it with multimaterial joining for use in BiW**. The comparative LCA performed between a baseline steel BIW and a composite-intensive multi-material BiW in this thesis intends to fill this research gap.

1.7.2 Research Gap 2:

Many advances have been made to improve cycle times, achieve better quality control, reduce labor cost, and increase automation in composite manufacturing. However less attention has been spent on improving the tool design and material used in manufacturing of composite materials. With composite materials production requiring iterative design of tools, additive manufacturing of the tool allows rapid tool evolution and deployment. In addition, by using thermoplastic composite materials for the tool, the thermal expansion of the tool material and the composite part can be reduced. Furthermore, uneven heating of the tool surface can be reduced by using uniform microwave heating to aid in the curing of the composite component. However, As shown in Table 1-2 and Figure 1-5, while standalone studies have been done on additively manufactured of tools, LCA of tools, and use of composite materials for tools, **no study, according to the author's knowledge, has been done on comparative LCA of additively manufactured composite tools**. This is a huge omission in literature as composite materials are highly energy intensive to manufacture due to higher embedded energy of the raw materials but can enable significant energy savings downstream. Therefore, LCA of the composite tools must be performed to determine the energy saving of the additive manufactured composite tools relative to traditional metal tools and hand laid composite tools.

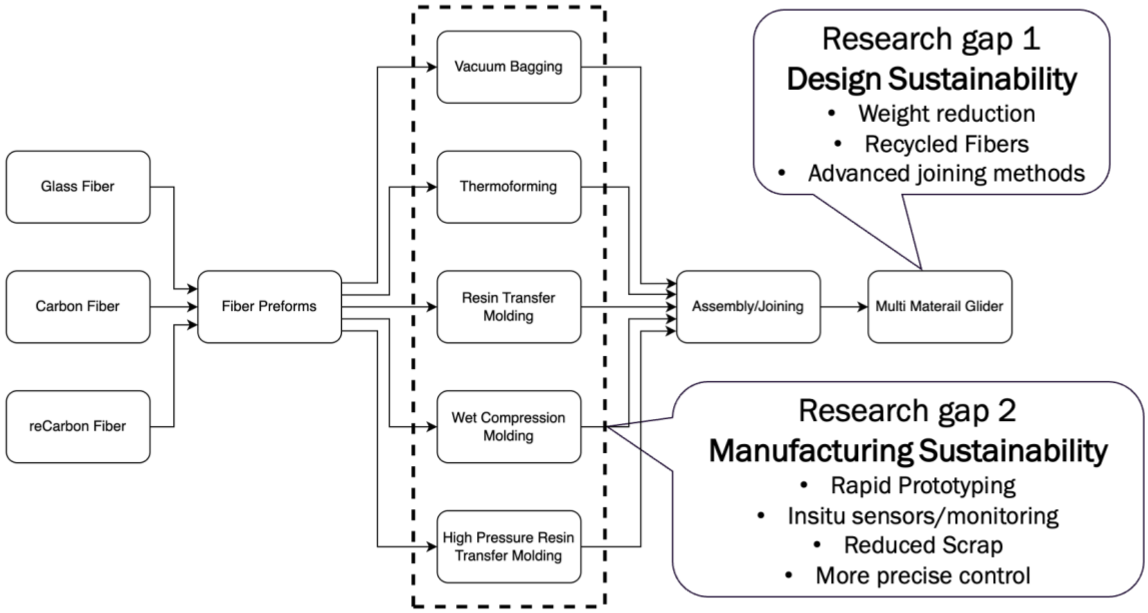


Figure 1-4 Research gaps addressed in the report.

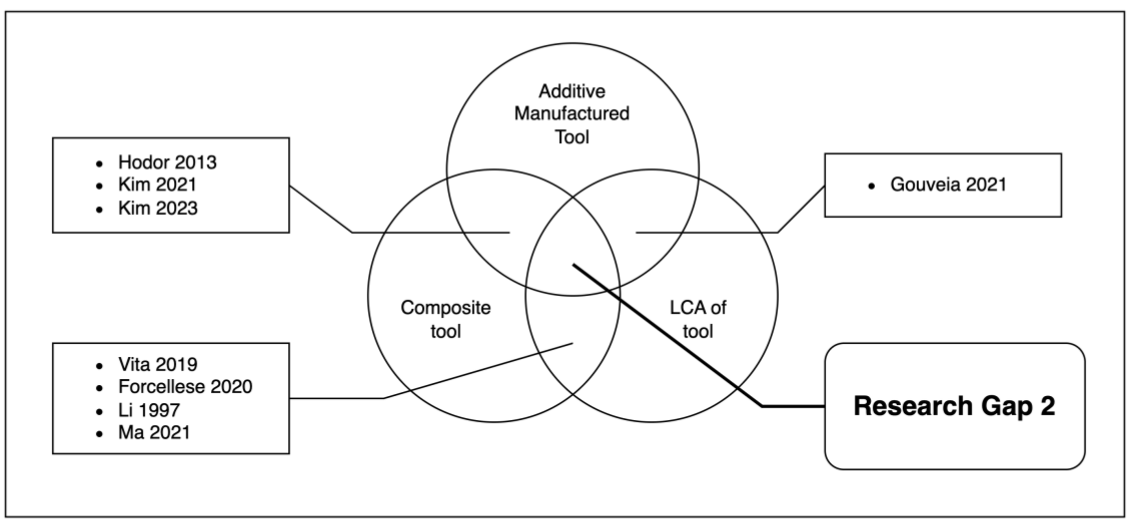


Figure 1-5 Illustration of the research gap in the LCA of additive manufactured composite tooling

1.8 Outline of the Chapters

The thesis has been divided into five chapters, which are as follows.

Chapter 1 discusses the brief overview of importance of light weighting of automobile Body-in-White for sustainability and energy efficiency, along with the literature review, the motivations, and objectives of the work.

Chapter 2 reviews the concept of Life Cycle Assessment, its methodology, its history, its applications, and limitations.

Chapter 3 discusses, in detail, the current manufacturing technologies and tools used in the production of baseline steel BIWs and proposed multi-material composite body in white, and novel multi-material joining technologies.

Chapter 4 discusses the comparative LCA for the multi-material body in white concept and discusses the results and implication of the LCA on the design approach and provides a guideline for material selection used for sustainable light weighting.

Chapter 5 discusses the Comparative LCA for the smart 3-D printed tool concept proposed for use for composites manufacturing, as well as the results and the implication of the life cycle assessment on the tool material selection, and the product development cycle of a production-ready tool.

Chapter 6 concludes the results of the two LCAs and discusses future work.

CHAPTER TWO

2 Life Cycle Assessment

In order to understand the use of life cycle assessment, we must first understand the concepts of LCA, and how they work to provide a holistic picture of the environmental impact of any product or process on which the life cycle assessment is conducted. In this section, we will discuss the theory of LCA, its shortcomings, definition, limitations, methodology, and assumptions that are required to perform an accurate LCA.

The earliest Life Cycle Study was conducted in the 1960s by the Coca-Cola company along with the US Midwest research institute to determine the use of cans instead of glass bottles for the distribution of beverages. The early LCS were primarily focused on energy consumption and did not consider other environmental impacts such as emissions or impact to the local ecology. Following this lifecycle assessment standardization occurred in the 1990s with international organization for standardization creating standard methodologies for performing lifecycle assessment [45].

This LCA study is conducted according to the ISO 14040:2006 [46] and ISO 14044:2006 [47] standards. ISO 14040:2006 [46] and ISO 14044:2006 are internationally recognized standards that provide guidelines and principles for conducting Life Cycle Assessment (LCA) used to evaluate the environmental impacts of a product, process, or system throughout its entire life cycle.

ISO 14040:2006 outlines the general principles and framework for conducting an LCA. It emphasizes the need for a holistic and comprehensive analysis that considers all life cycle stages, including raw material extraction, manufacturing, distribution, use, and end-of-life treatment. The standard highlights the importance of defining the goal and scope of the assessment, setting clear boundaries, selecting appropriate methodologies, and ensuring transparency and consistency in data collection and interpretation.

ISO 14044:2006 provides detailed guidelines for conducting the four phases of an LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation. It specifies the requirements for data collection, allocation procedures, system boundaries, and selection of impact categories. The standard also emphasizes the need to evaluate uncertainties and limitations associated with the assessment and communicate the results effectively.

These ISO standards promote a consistent and standardized approach to LCA, ensuring the reliability, credibility, and transparency of their LCA studies. LCA consists of four distinct phases, each serving a specific purpose in evaluating the environmental impact of a product, process, or system. Figure 2-1 represents the relation between the four phases of the LCA.

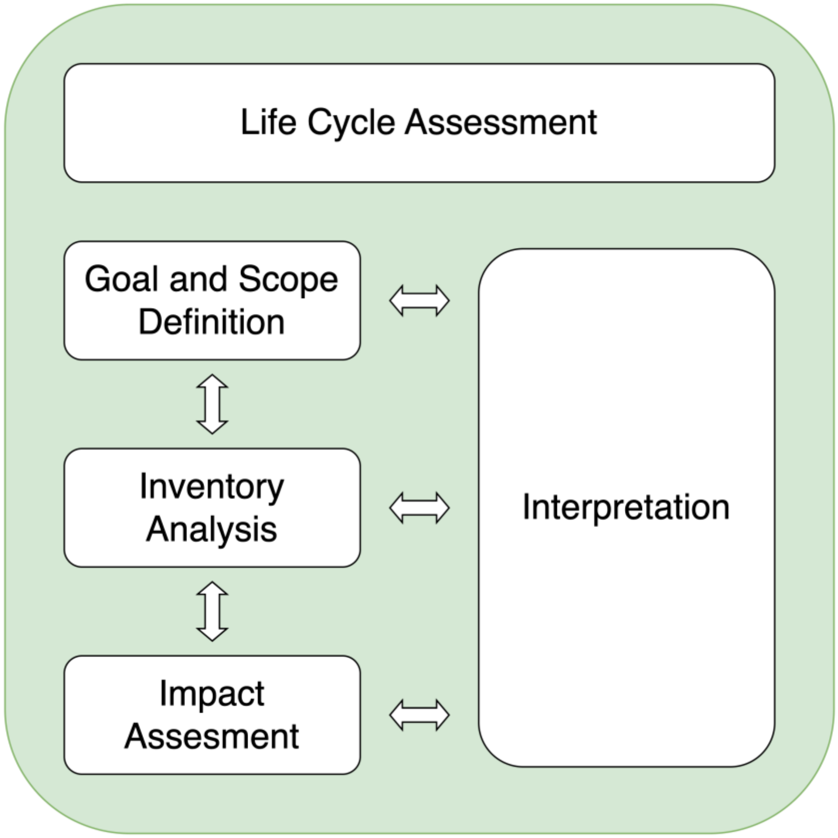


Figure 2-1 Phases of LCA

2.1 Phases of LCA

2.1.1 Goal and Scope Definition:

This initial phase involves clearly defining the objectives, boundaries, and intended applications of the LCA study. It establishes the purpose of the assessment and identifies the key stakeholders. The scope of the study is determined by defining the system boundaries, considering the life cycle stages to be included, and specifying the functional unit for comparison. This phase sets the foundation for the entire LCA study, guiding subsequent data collection and analysis.

2.1.2 Inventory Analysis:

The inventory analysis phase focuses on gathering data on the inputs (e.g., raw materials, energy, water) and outputs (e.g., emissions, waste, co-products) associated with the life cycle of the product or system under assessment. It involves compiling a comprehensive inventory of all relevant material and energy flows throughout each life cycle stage. The collected data is organized into a life cycle inventory (LCI), which quantifies the environmental inputs and outputs at each stage.

2.1.3 Impact Assessment:

In the impact assessment phase, the collected inventory data from the previous phase is evaluated to determine the potential environmental impacts associated with the assessed product or system. Various impact assessment methods can be employed, which categorize and quantify the potential effects on specific environmental indicators or impact categories. These impact categories can include global warming potential, acidification potential, ozone depletion potential, and others. The goal is to understand the magnitude and significance of the identified impacts and their contributions across the life cycle stages.

2.1.4 Interpretation:

The interpretation phase involves analyzing and evaluating the results of the impact assessment, drawing conclusions, and communicating the findings. It aims to provide a comprehensive understanding of the environmental implications and trade-offs associated with the assessed product or system. The interpretation phase may include sensitivity analyses, uncertainty assessments, and identification of areas for improvement. It also considers the intended audience and facilitates the effective communication of the LCA results, enabling informed decision-making and guiding environmental improvement strategies.

These four phases of LCA work together to provide a systematic and comprehensive assessment of the environmental impacts throughout a product or system's life cycle. They allow for the identification of hotspots, evaluation of alternatives, and development of strategies for environmental performance improvement.

For this study we have conducted two comparative LCAs to understand the energy saving benefits of light weighting through use of FRP composites, multi-material joining of those FRP components with steel structures and use of the 3D printed composite tools employed for composites manufacturing, over the various stages of their lifecycle.

2.2 Impact assessment method:

Various impact assessment methods are used in Life Cycle Assessment (LCA) to evaluate and quantify the potential environmental impacts associated with a product, process, or system. These methods aim to categorize and assess the effects on specific environmental indicators or impact categories. Some common methods are ReCiPe, IMPACT 2002+, Eco-indicator 99, Ecological footprint, Global warming potential etc. Other methods exist that focus on specific impact categories, such as water scarcity, toxicity, or biodiversity. The choice of impact assessment method depends on the goals and scope of the LCA study, the availability of data, and the specific environmental concerns relevant to the assessed product or system.

Mid-points are defined as points in the cause effect chain (environmental mechanism) of a particular impact category, prior to the endpoint, at which the relative importance of the emissions or extraction of the inventory can be calculated. E.g., Assessing the human health impact (Endpoint) that may occur due to the depletion of the ozone layer (Mid-point). While end point impact assessment categories can provide informed weighting and science-based aggregation across categories in terms of common parameters, sufficiently robust models remain too limited to support endpoint modeling. This reduces comprehensiveness of the LCA model and may result in extreme uncertainty in the analysis. On the contrary Midpoint impact assessments are more robust and have greater certainty but lack the relevance to decision making as end point impact assessment. However, despite this limitation midpoint impact assessments are preferred due to its higher certainty [48]

For this study we are primarily concerned with life cycle energy saving. As elaborated in introduction, the premise of the study is to determine the light weighting required for breakeven or payback of the Body in White in terms of fuel savings. Thus, Cumulative Energy Demand, which is an impact assessment method used in LCA to evaluate the energy-related environmental impacts of a product, process, or system throughout its life cycle, is used. CED assesses the cumulative energy consumption associated with the production, use, and disposal of the assessed entity.

Figure 2-2 Cumulative Energy Demand energy consumption in relation to the various stages of product life [49]

CED considers both direct energy consumption, such as the energy used in manufacturing and operation, and indirect energy consumption, which includes the energy embodied in the raw materials, transportation, and infrastructure required for the life cycle stages. It provides a comprehensive assessment of the energy demands associated with the entire life cycle, from the extraction of resources to the final disposal.

CED can be used alongside other impact assessment methods to provide a more comprehensive understanding of the environmental performance of a product or system. It allows for the comparison of different alternatives based on their energy demands, facilitating informed decision-making and the development of energy-efficient strategies. It's important to note that CED focuses solely on energy consumption and does not directly assess other environmental impacts, such as greenhouse gas emissions or resource depletion. However, energy consumption is a crucial aspect of environmental sustainability, and CED provides valuable insights into the energy-related impacts of a product or system. Thus, even though this study does not consider other environmental impacts, CED impact assessments can provide reasonable estimations of the impact the products have on the environment [50].

CHAPTER THREE

3 Description and Methodology

3.1 Process description:

3.1.1 Steel body in white production:

The initial stage of steel production involves the extraction of iron ore, typically taconite in the United States. This extraction process entails mining the ore through blasting, followed by additional processing to concentrate the ore to a minimum purity level of 66% before it can be utilized in steelmaking. Initially, the ore is crushed into a fine powder, and subsequently, the metal is separated from the waste rock using magnetic properties. The powder is then moistened and rolled with clay inside a large rotating cylinder. Afterward, it undergoes heating and cooling to form iron ore pellets [51].

Another intermediate product in steelmaking is sinter, produced by igniting a mixture of fine iron ore powder, coke, limestone ($CaCO_3$), dolomite, and flue dust in a gas-fired furnace. This fusion process forms a porous cake-like substance. Both the iron ore pellets, and sinter serve as inputs for blast furnaces, where pig iron is produced. Pig iron represents a crude and high-carbon form of iron that is brittle and necessitates further processing.

Coking involves the heat treatment of metallurgical coal in the absence of oxygen, resulting in the release of 25% to 30% of its mass as volatiles. This process yields a carbonaceous product known as coke, which serves as both a fuel and a reducing agent in blast furnaces. Additionally, the coking process produces coke oven gas (COG), a high-quality fuel utilized in blast furnaces. Two major by-products, coal tar and chemicals obtained from the gas, are also generated. Coal tar finds applications as pitch, road tar, and in the production of various basic chemicals. Condensed coal gas provides light oil, anhydrous ammonia, and sulfur through gas desulfurization.

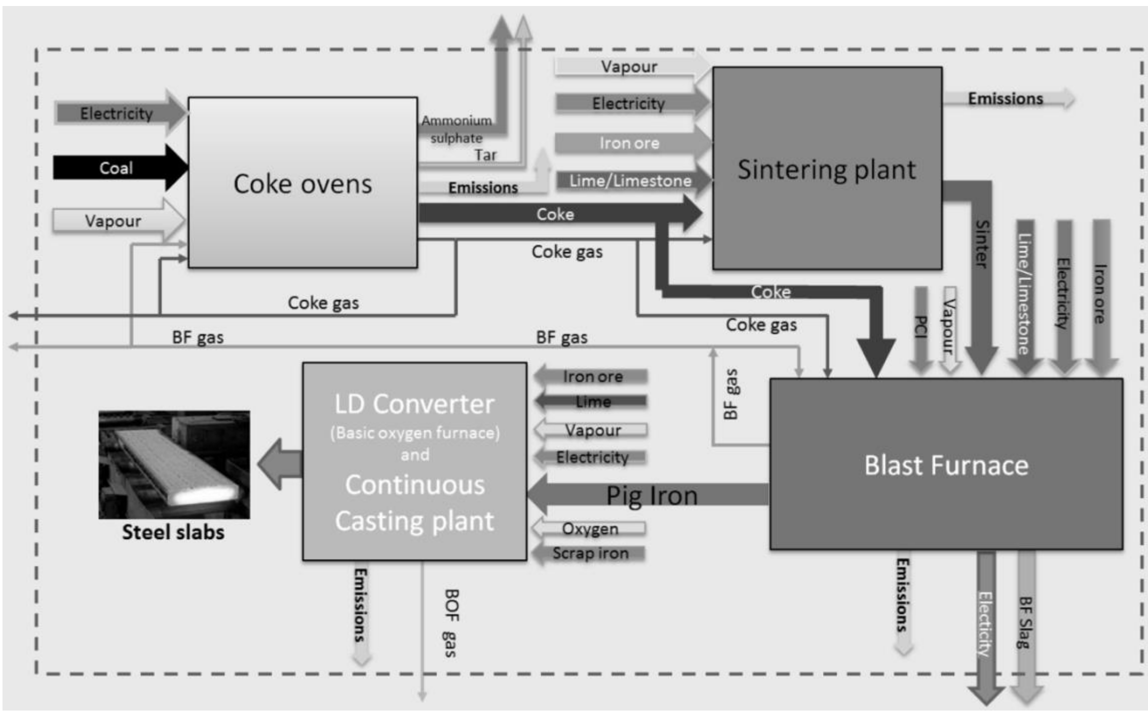


Figure 3-1 Illustration of the steel making process [52].

In the blast furnace, iron ore pellets, sinter, and coke are introduced from the top of a tall chimney-like furnace, while pre-heated air is blown into the middle, referred to as the "blast." The furnace operates at temperatures ranging from 1,200 °C to 1,500 °C, facilitating the reduction of iron ore into molten pig iron. A layer of limestone, known as slag floats on top of the molten iron, absorbing impurities. Initially, the slag is removed from the furnace, followed by the drainage of pig iron from the bottom. The process also generates BFG, a fuel that can be utilized for coke production or electricity generation. Direct iron reduction, a potential alternative technology for pig iron production that does not require coke, has the potential to reduce overall energy requirements and associated emissions in steelmaking. However, significant cost and technological challenges must be addressed before direct iron reduction can be widely adopted.

In the subsequent stage of the steelmaking process, the molten iron is transformed into steel through the utilization of the basic oxygen process (BOP). Initially, the molten iron is transferred to a large ladle, where the addition of magnesium helps reduce sulfur impurities. It is then poured into a vessel, where 99% pure oxygen is blown onto the iron, elevating the temperature to approximately 1,700 °C. Subsequently, burnt limestone is introduced into the vessel to create slag, which absorbs additional impurities. The iron is subsequently transferred to a furnace, where various alloying materials are added based on the intended application. The remaining slag is removed, and the resulting steel is poured into an ingot mold and allowed to cool. Figure 3-1 illustrates the steel making process.

The produced ingots are then conveyed to a hot-rolling mill, where the steel undergoes reheating in a furnace to reach temperatures of around 1,200 °C. The hot rolling process is then employed to decrease the thickness of the steel from an initial range of 100-250 mm to a final thickness of 2-3 mm. Due to the high temperature involved in hot rolling, a thin layer of iron oxide, known as scale, forms on the surface of the steel. To eliminate the scale, the steel undergoes a pickling process, involving the passage through tanks containing hydrochloric acid (HCl). Subsequently, the thinner slab is coiled and transported to a cold-rolling mill for further processing, tailored to meet specific requirements. For the production of automotive products, sheet steel with a thickness of approximately 0.5 mm is generated.

Steel is highly corrosive, and catches rust quickly, especially in presence of moisture. Thus, to extend the life of steel it is made to undergo galvanization. Many galvanization processes are available at industrial scale including hot-dip galvanizing (HDG), electroplating, metallizing (zinc spraying), mechanical plating and zinc-rich painting. However, the most common process used in automobile industry is HDG method as it provides the optimal combination of functionality and cost [53]. HDG is a five-step process. First, the steel is degreased in acid to remove organic matter and other impurities. Second, the steel undergoes pickling process to remove any preexisting zinc from recycled material. Third, the steel undergoes fluxing in hydrogen peroxide to reduce iron (II) from steel. Fourth, the steel is dried using natural gas combustion to remove moisture and passed through molten zinc bath at 450 °C. Fifth, excess zinc is removed by centrifugation process. Figure 3-2 represents the process flow created for modeling hot dip galvanization in LCA.

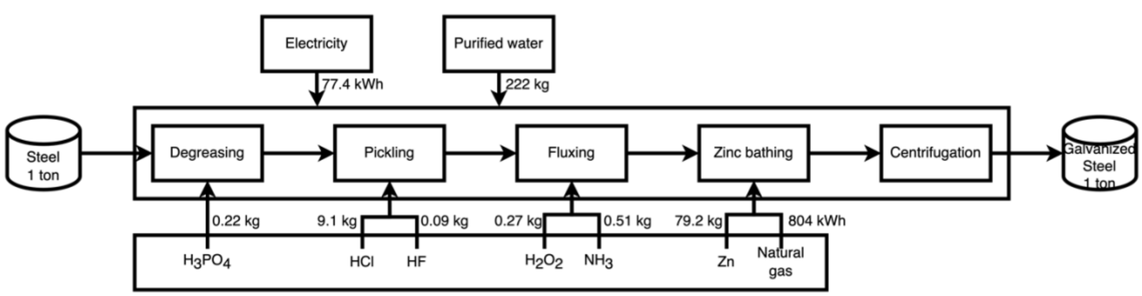


Figure 3-2 Hot dip galvanization process flow

The cold-rolling process results in the hardening of the steel, rendering it more brittle and challenging to shape. To restore the steel's formability, it undergoes an annealing heat treatment process. The steel sheet is then stamped using multiple dies to shape it into automotive parts, such as body panels and BIW structures. The stamped parts are then trimmed to remove excess metal and the designed component is achieved. For assembly Resistance spot welding is used to join the various subcomponents into the vehicle body in white assembly. Figure 4-6 illustrates the entire steel BiW production process.

3.1.2 FRP multimaterial body in white production:

Carbon Fiber production starts with precursor which are of three main types: Polyacrylonitrile (PAN), Pitch and Cellulose. Of the three, PAN is the most common industrial precursor as it provides the highest strength fibers and therefore for this report we have considered CF made from PAN precursors. PAN fibers are first spun in one of three processes: wet spinning, dry spinning, and dry jet wet spinning. Of the three dry spinning provides fibers with least surface defects and better mechanical properties. In dry spinning DMF is used as solvent and highly concentrated polymer solution is extruded through 2500 holed spinneret into a two-stage vertical tower where the upper part is at 400 °C and inert gas is blown from bottom. The solvent is removed by gas and recovered by distillation and PAN fibers are solidified by cool air.

The fibers freshly spun are then subjected to post processing where they are washed, surface treated and drawn. Drawing is critical in reducing the fiber diameter, eliminating defects, and improving fiber quality. Post drawn fibers are then stabilized at about 300 °C. After stabilization the fibers undergo a process known as carbonization, where the fiber is heated to 1500 °C temperature in nitrogen rich environment. In the process hydrogen is removed from fiber and carbon percentage increases. This is followed by another high temperature process at 3000 °C known as graphitization in which the remaining non carbon atoms in the fiber are released to form pure carbon fibers. The resulting fibers have extremely high specific strength and are prime candidate for light weighting application. Figure 3-3 represents the CF production process.

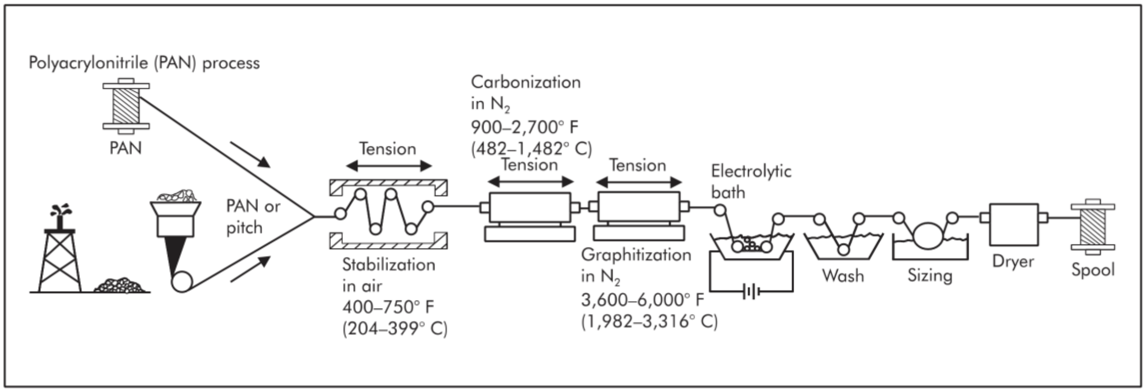


Figure 3-3 Carbon Fiber production from PAN fibers

Glass fiber production is comparatively much simpler and less energy intensive. Glass fiber originates as silica derived from sand. In glass fiber production silica particles are feed into a continuous flow furnace. The temperature inside the is above 1500 °C which results in the silica particles melting. The molten silica is then passed through a refiner and is entered into the forehead. On the end of forehead is a platinum plate with tine holes called bushings. The molten glass is forced through the bushings due to hydrostatic pressure and emerges out as molten fiber. The molten fiber is immediately sprayed with water to cool down and solidify. Filament is the passed through applicator and stretched by a gathering shoe. Various additives can be added to the fibers in the furnace to modify the properties of the fiber.

For recycling carbon fiber, there are number of methods such as Pyrolysis, solvolysis, fluidized bed, and incineration. However, the most mature technology is mechanical recycling. In mechanical recycling the waste CFRP components are first chorused by a powerful hammer which separates the resin powder and broken fibers. The resulting mixture is then separated using water bath to remove the resin power and the broken fibers are graded to different lengths. The various length fiber mats are then recycled for use in composites.

Traditional FRP composite manufacturing which involve the use of autoclave for curing of resin matrix have been successfully incorporated in aerospace industries and motorsport and have demonstrated their high performance and reliable quality. However, the production volume in these industries is several orders of magnitudes lower than production volumes of automotive industries. While autoclave processes are capable of producing high quality parts in low volume production, the high capital costs and the slow cycle time of autoclaves makes them unsuited for high volume production. Furthermore, autoclave production processes need relatively large skilled labor which further exasperates the cost of production. Thus, alternative out of autoclave processes are needed for adoption of FRP composites in the automotive industries.

HPRTM is one such out of autoclave process for the infusion and curing of resin matrix in preformed fiber to produce FRP composites. HPRTM is similar to RTM process, but the resin injection pressure is higher, on the magnitude of 150 bars compared to 15 bars in RTM [54].

In HPRTM processes the fiber laminates layers are cut into the component shape to form the fiber preform. The mold is cleaned and coated with release solvent and the fiber preform is positioned in the mold for resin infusion. The mold is then closed, and resin mix is injected into the mold through an impingement mixer at a pressure of 150 bars. The mold is heated to curing temperature and the resin is cured at high pressure to form the FRP composites. After the composite is fully cured the mold is opened and the component is released from the mold. The cycle is then repeated.

HPRTM process has a number of advantages that make it attractive for high volume production. HPRTM allows for lower cycle times of about 5-10 minutes depending on the part size and geometry which compares favorably to other out of autoclaves such as Resin transfer molding which have a cycle time in hours [54]. HPRTM allows for greater automation as many of the processes such as layup of the preform, release agent coating and the release of the components can be automated. HPRTM also provides greater surface quality finish due to the high pressure in the mold.

The proposed multi material joining technology involves a four-stage UAM process [55]. In stage 1 the fiber is weaved into the desired weave pattern, but the joining edge has additional loops to be interlocked with the metal matrix. In stage 2 the metal matrix is machined to create channels for the fiber loops. Stage 3 involves the alignment of the fiber loops with the machined channels through the use of a piston-guide alignment device. In stage 4, UAM process is used to add metal matrix layer sealing the channels and completing the interlocking of the continuous fiber loops and metal matrix. The process can be further repeated to create multi layered interlocking of fiber and matrix. The interlocked weave is then preformed into the desired shape and is cured in out-of-autoclave HPRTM process discussed above. Figure 3-4 shows an illustration of the UAM joining processes. The metal matrix tab then can be used to form traditional metal-metal joining using RSW or any other joining method preferred by the OEM. Figure 4-7, Figure 4-8 and Figure 4-9 illustrate the lightweight multi-material BiW production process.

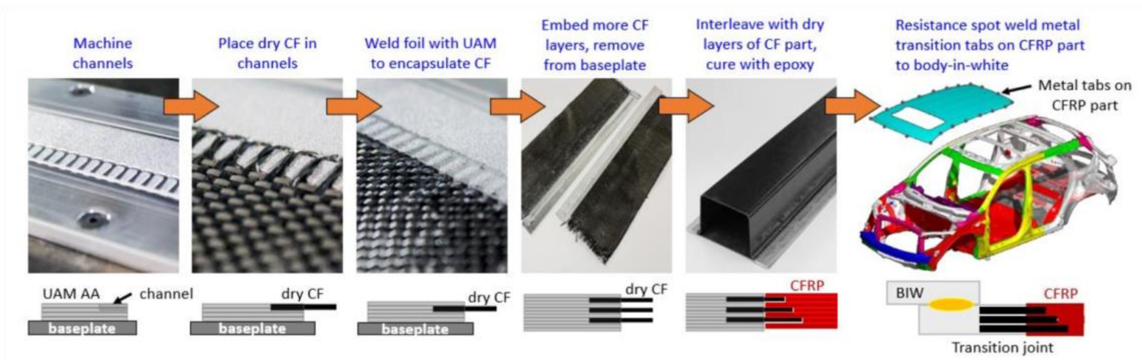


Figure 3-4 Multi-material joining of FRP composite with metal using UAM technology [56].

3.1.3 Additive manufacturing of composite tool

Savanah River National Laboratory has developed a novel additive manufacturing technology for 3D printing CF-nylon tool. The continuous CFs are first treated in acetic acid bath which contains Carbon Nano Tubes (CNT). The CNT coated tubes are then cleaned in water bath [17]. The CNT coated CF is then shown to be highly suspectable to microwave radiation, with the fibers reaching temperatures above 200 °C. These fibers are then extruded together with nylon 6 to form a composite additively manufactured tool. To undergo further increase in strength the tool is annealed in microwave oven. SRNL performed microwave annealing on test pucks and showed that the microwave annealing was an order of magnitude lower in energy intensity than conventional annealing [57].

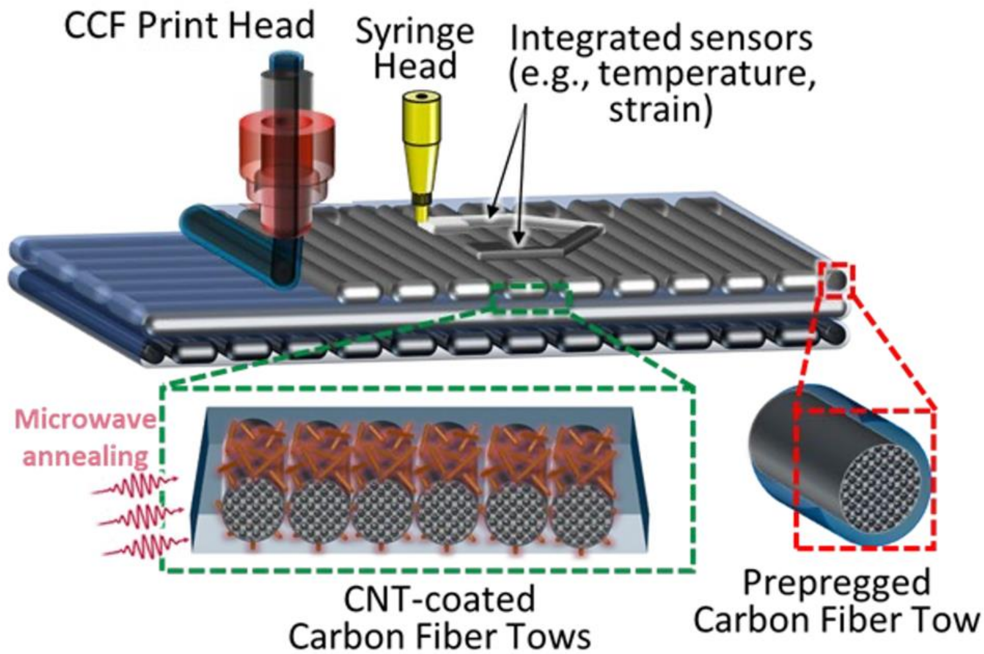


Figure 3-5 Illustration of additive manufacture of composite tool [58]

3.2 Use stage calculation methodology:

For calculating the use case energy consumptions of the body in white the US06 Supplemental Federal Test Procedure (SFTP). The US06 Supplemental Federal Test Procedure (SFTP) was developed to address the shortcomings with the FTP-75 test cycle in the representation of aggressive, high speed and/or high acceleration driving behavior, rapid speed fluctuations, and driving behavior following startup.

From the US06 data, the acceleration was calculated by the difference between instantaneous speeds at each second interval. The distance was calculated as the direct magnitude of the velocity. The acceleration term in the kinematics equations for distance traveled was ignored as the initial and final velocity of the vehicle is zero miles per hour in US06 data. Thus, the net acceleration over the drive cycle of the vehicle has zero magnitude and the effect of the acceleration term in the kinematic equation will be cancelled out over the full cycle. Hence the energy required from the power train in the full drive cycle for the body in white was calculated as

$$E = \text{S}\,(M_{BiW} - m_C) * a * d \tag{1}$$

Where,

E = Energy required from the powertrain for the body in white per drive cycle

M_{BiW} = Mass of baseline BiW

m_c = Compounded Mass of the body in white

a = instantaneous positive acceleration

d = instantaneous distance covered

For the instants where instantaneous acceleration was negative, the energy required was not considered in the total energy. This is considering the fact that negative acceleration is caused by braking of the vehicle, which does not require energy input from the power train.

For the use case scenario, the effect of the secondary weight savings was considered. This is because the secondary weight saving will represent significant reduction in energy demand during use phase of the vehicle and can be calculated without the need to expand the scope of the study to rest of the vehicle [59].

To calculate the secondary weight saving the mass compounding model was used [60]. Formula for compounded mass reduction:

$$m_c = m_p(1 + S) \tag{2}$$

Where,

m_c = Compounded mass saving

m_p = Primary mass saving

S = The Secondary mass coefficient for the vehicle = 1.28 [61]

Unlike secondary mass savings the mass of the rest of the vehicle is not necessary for consideration in the use case energy consumption calculation as the rest of the vehicle mass excluding the secondary weight savings remains constant in our analysis.

$$M_{use(scenario2)} = {}^{BiW}M_2 + {}^{RoV}M_2 \tag{3}$$

$$M_{use(scenario2)} = {}^{BiW}M_2 - m_{pwr2} + {}^{RoV}M_2 - m_{swr2} \tag{4}$$

$$M_{use(scenario2)} = {}^{BiW}M_1 - m_{c2} + {}^{RoV}M_1 \tag{5}$$

$$M_{use(scenario1)} = {}^{BiW}M_1 + {}^{RoV}M_1 \tag{6}$$

Thus, all scenarios have ${}^{RoW}M_1$ term. As we are not considering the RoW in the production stage, we should ignore it in use case scenario as well to maintain consistency and clarity. And importantly it will not affect the comparative LCA.

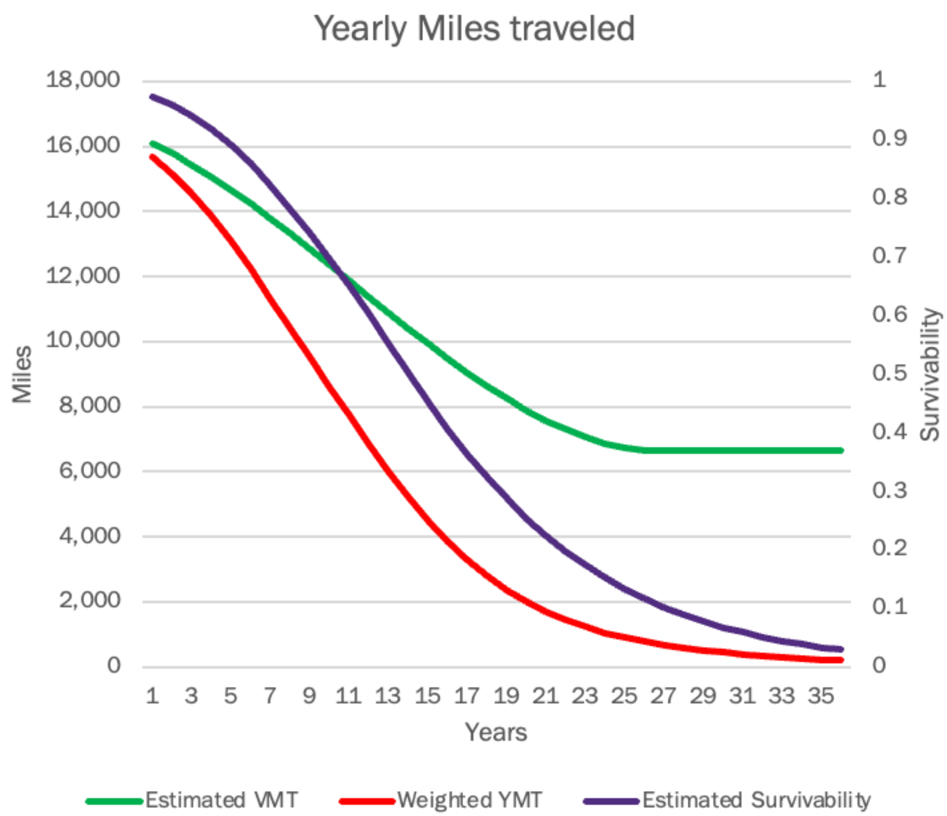


Figure 3-6 Yearly miles travelled data from National Highway Traffic Safety Administration [62].

Once the energy supplied by the power train was calculated, the mass of fuel consumed was calculated by assuming a 33% thermal efficiency of the powertrain. The fuel considered was E10 gasoline mix. To calculate the vehicles miles driven per year the data from 2006 report of National Highway Traffic Safety Administration [63] was used. The report includes the weighted yearly miles travelled data which is calculated as the product of the estimated yearly miles travelled of each vehicle in that year and the estimated survivability of the vehicle to that year. Thus, the weighted yearly miles travelled data captures the probability that any given vehicle will be decommissioned before its life span is complete due to accident or malfunction of the vehicle.

CHAPTER FOUR

4 Multimaterial Body-in-White comparative LCA

In this chapter, the comparative LCA of BiW system is presented. First, the chapter will discuss the Goal and Scope of the LCA. Second, the chapter will detail the inventory analysis of the LCA. Third, the chapter will discuss the results of the comparative analysis. And fourth, the chapter discusses the implications of the LCA results.

4.1 Goal and Scope:

4.1.1 Goal:

The goal of the competitive lifecycle assessment is to assess the environmental benefits of light weighting the body in white of large scale, production, midsize SUV Body in white system. The reason for conducting the study is to address the research gap that exist in the lifecycle assessment of the use of multi material body in white scenarios where no extensive modification of existing vehicle production assembly line is required. This is achieved using multi-material joining. The intended audience for the study is original equipment manufacturers, tier 1 suppliers, design engineers, regulatory bodies, and researchers. The results are intended to be used to make comparative assertions that are intended to be disclosed to the public.

4.1.2 Scope:

Scope of the comparative LCA involves the 2019 mid-size SUV weight reduced Body-in-White designed in [56]. The function of the body in white is to satisfies all the static and dynamic load cases and does not exceed the design constraints defined in Four scenarios are considered for the comparative analysis and the Figure 4-1 represent the relation between each of the scenarios:

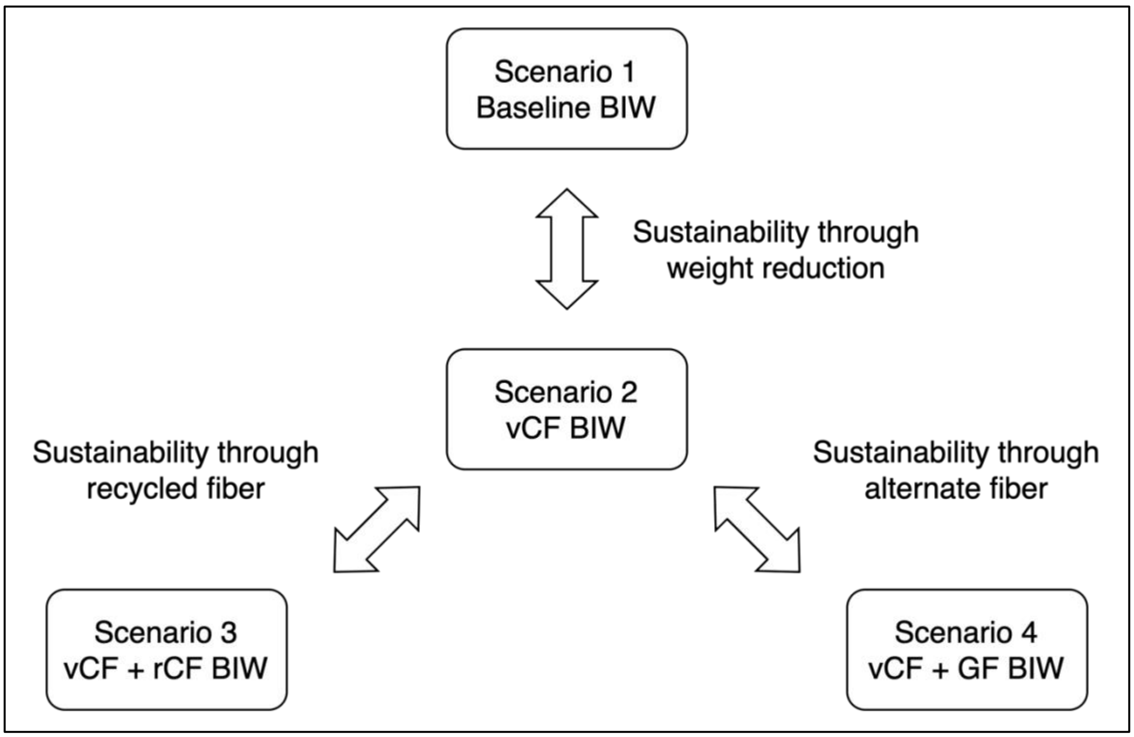


Figure 4-1 Comparison between the Scenarios for BiW LCA

Scenario 1: The baseline metal intensive Body-in-white system of the mid-size SUV weighting 408 kg.

Scenario 2: A multi-material light-weight Body-in-white system of a mid-size SUV using virgin carbon fiber reinforce polymer joined with UAM multi material joining weighting 320 kg.

Scenario 3: A multi-material light-weight Body-in-white system of a mid-size SUV with use of 50% virgin and 50% recycled carbon fiber in fiber reinforce polymer joined with UAM multi material joining weighting 340 kg.

Scenario 4: A multi-material light-weight Body-in-white system of a mid-size SUV with use of 50% virgin and 50% glass fiber in fiber reinforce polymer joined with UAM multi material joining weighting 340 kg.

Table 4-1 Weight reduction data for scenarios in LCA

	Scenario 1 (Baseline)	**Scenario 2 (vCF)**	**Scenario 3 (50% rCF)**	**Scenario 4 (50% GF)**
Baseline BIW weight	408 kg	408 kg	408 kg	408 kg
FRP composite weight	0 kg	50 kg	70 kg	70 kg
Steel Weight reduced	0 kg	138 kg	138 kg	138 kg
Final BiW weight	408 kg	320 kg	340 kg	340 kg
Primary Weight reduction	0 kg	88 kg	68 kg	68 kg
Coefficient of secondary weight reduction	1.28	1.28	1.28	1.28
Secondary Weight reduction	0 kg	112 kg	87 kg	87 kg
Compounded Weight reduction	0 kg	200 kg	155 kg	155 kg
Total weight used for Use stage calculation	408 kg	208 kg	253 kg	253 kg

In addition to the primary weight saving achieved by the BiW, secondary weight saving is achieved via light weighting the rest of the vehicle mass as result of primary weight saving for the BiW.

This secondary weight reduction along with primary weight reduction forms compounded weight reduction of the vehicle, which is the weight reduction value considered during calculation of energy demand during use stage. The secondary weight reduction for the production stage analysis is ignored. This is to reduce the complexity of the LCA. If the secondary weight reduction is considered in the production stage, then the scope of the LCA must be expanded to the manufacture and assembly of the whole vehicle and not just limited to the BiW, which is the focus of the study. While this causes some error in the production stage energy requirements of the vehicle, the results will still be accurate and provide a reliable picture of the overall energy consumption of the life cycle of the BiW. The primary, secondary, and compounded weight reductions are presented in the Table 4-1 Weight reduction data for scenarios in LCA. Further, Figure 4-2 illustrates the BiW weights and formula used to calculate them for each of the scenario.

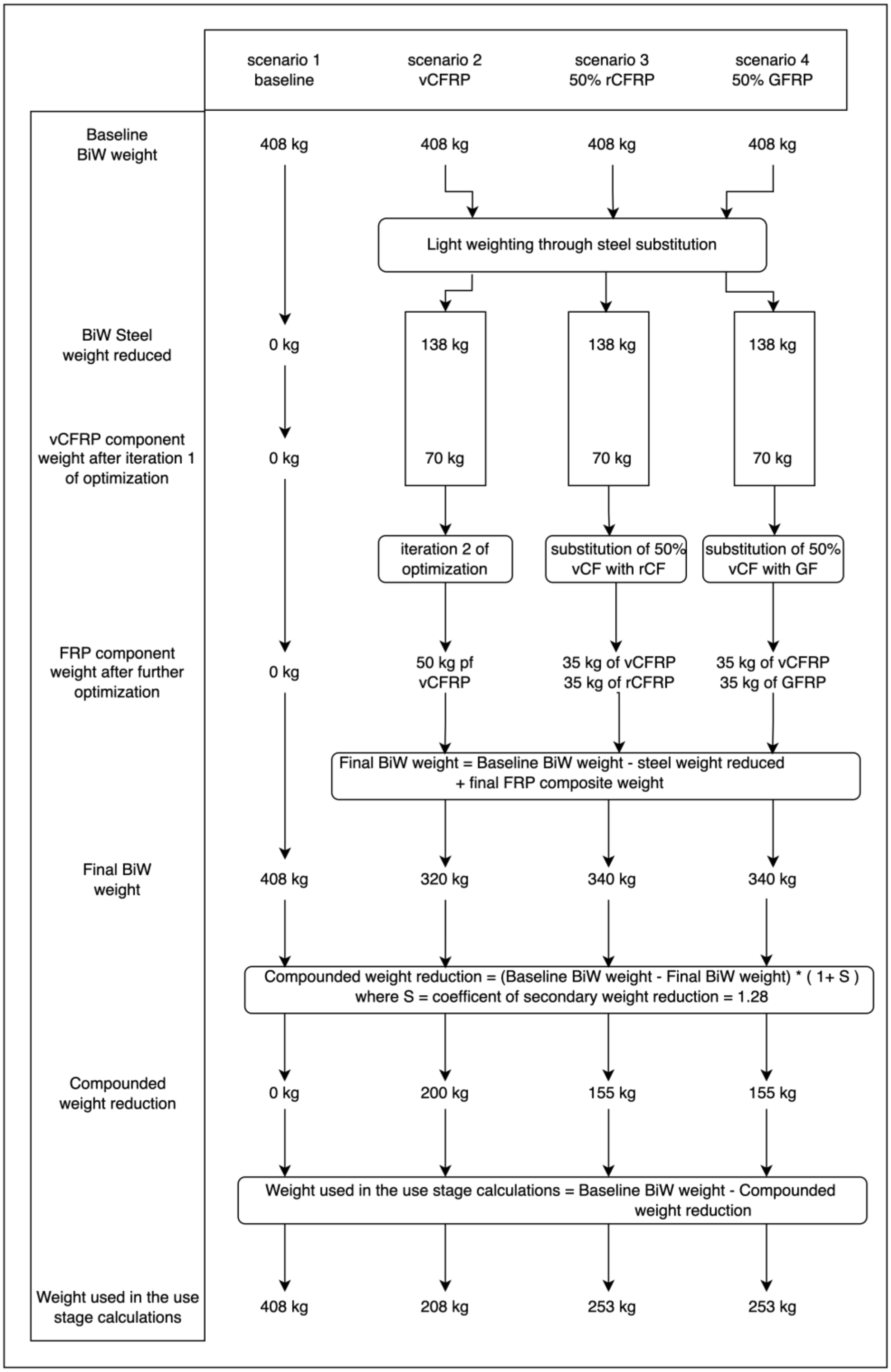


Figure 4-2 BiW weight calculations and formula in each scenario

4.1.3 Functional Unit:

The functional unit for this study is one complete Body-in-white system that meets all the Body-in-white functions defined by the manufacturer [56]. The selection of the functional unit is justified as the main purpose of the LCA is to demonstrate the energy saved by the application of UAM multi-material joining technology. Thus, by limiting the functional unit to a single Body-in-white the variables to be considered such as the scalability of the UAM technology, the quality control of the CFRP manufacturing processes and the tool life for the processes are reduced. While this limits the applicability of the LCA to the prototype stage of the lightweight Body-in-white concept, it presents a fairer LCA of the UAM and CFRP manufacturing technologies as these are rapidly evolving and thus will have significant variations in the manufacturing properties. This also simplifies the inventory collections on these process as reliable data for these processes is extremely limited.

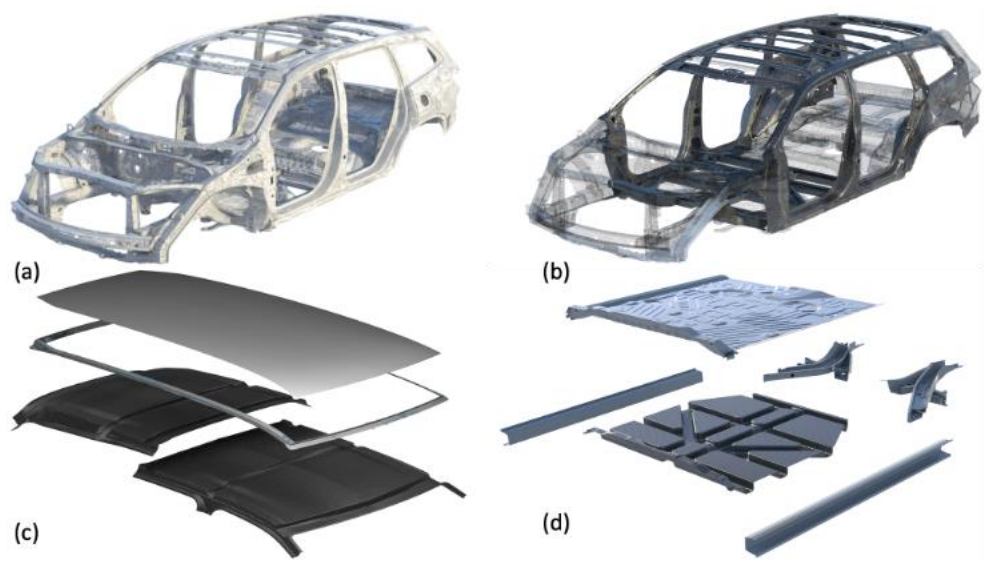


Figure 4-3 (a) Baseline Steel BiW (b) FRP composite light weight BIW (c) Multi-material roof section (d) Multi-material floor section

4.1.4 Systems boundaries:

System boundaries of the Comparative LCA includes the raw material extraction, material synthesis, Body-in-white manufacturing, use phase and end-of-life phase which includes 100% recycling of virgin material and landfill for recycled material. Thus, the LCA is cradle-to-grave LCA. In processes where emissions to air, water and soil are relatively minute are ignored for simplifying process flows. The geographical location for all process is considered to be in the USA market and thus all inputs are from USA region. For all electricity consumption the US medium voltage electric supply is used. For process with large capital goods requirements such as furnaces, large molds, presses etc. are ignored .The allocation procedure used is the (APOS unit) for reasons stated in Chapter 3. The impact category chosen for the analysis is Cumulative Energy Demand (CED) as it provides a good benchmark for the environmental impact of an activity.

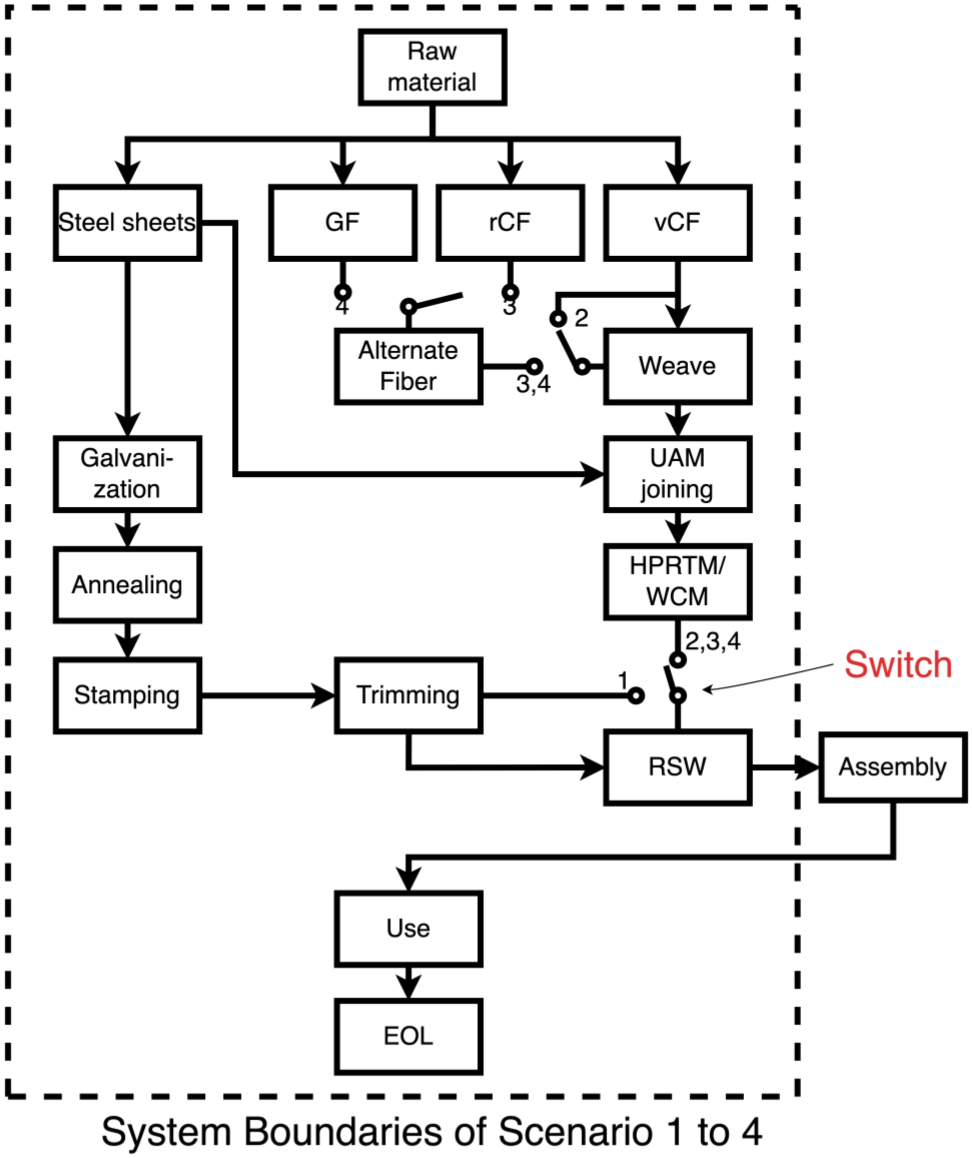


Figure 4-4 System Boundary for BiW LCA (dashed line)

The life cycle inventory, and environmental impact analysis for the BIW LCA was compiled in the professional LCA software Simapro. The Ecoinvent 3.0 database [64] was used for lifecycle inventory as well as data from literature was used for the creation of process flows for the process not available in Ecoinvent database.

4.1.5 Limitations:

The limitation of the comparative LCA is mainly in terms of two considerations: 1) The multi-material joining, and out-of-autoclave composite manufacturing processes used in the LCA are not mature and thus cannot reliably reflect the true CED for the various process. This includes the ignoring of the major capital tools that are used for millions of components such as dies, presses, furnaces etc. As the technology matures more accurate data for life cycle inventory will be available and the comparatively LCA can be upgraded. 2) The comparative LCA considers that after first optimization iteration is performed on 100% virgin unidirectional carbon fiber, the components are further optimized by varying the thicknesses of the fiber panels or the virgin fiber is substituted with recycled or alternate fibers (refer to Figure 4-2). While all three approaches are theoretically sound, there are practical limitations to each of the approach. For the approach in which the virgin fiber components are further optimized with variable thickness, the variable thickness may be impossible to manufacture with good quality control with out-of-autoclave molding processes for example. Or, in case of alternate or recycled fiber substitution approach, further analysis will need to be conducted on the performance of the components in meeting the manufacturer provided constraints (refer to section). In addition, in EoL stage it is considered that steel and vCF are 100% recyclable. This is an unrealistic assumption made for simplification of EoL stage CED calculation. Thus, any results from the LCA should be used after consideration of these factors.

4.2 Inventory:

The data used for life cycle inventory analysis was obtained from primary and secondary sources. The primary source for the data was the equipment database included in the Simapro software. Various literature sources were used for the processes for which Ecoinvent data was not available.

For the material inputs of steel, glass fiber and epoxy available Simapro process flows were used. For the material inputs of Carbon fiber and recycled carbon fiber the input/output data was obtained via literature. Gopalraj et al [65] provide the most comprehensive data for the carbon fiber production. The Table 4-3 shows the data obtained for the carbon fiber production which was used to create the process flow in Simapro.

For the production of recycled carbon fiber, the data from [66] was used. While there are number of recycling methods available for recovering recycled CF from virgin CF the most mature technology mechanical recycling of CF is chosen to create the process flow. For galvanizing, trimming/finishing, annealing, Resistance Spot welding and HPRTM the data from [53], [67], [68], [69], [70] was used. All the literature data sources have been listed in the Table 4-2. The EoL energy saving by 100% recycling of steel was calculated from [71]. Meanwhile CF was considered to also be 100% recycled.

For the inventory data for UAM machine the energy consumption was measured by calculating the average power consumption of the UAM machine and multiplied by the feed rate of the Machine. The average power consumption of the UAM machine was determined to be 3 kW with a feed rate of 5.08 m/hr. Thus, the electric energy consumption for a 0.2 kg tab of UAM joint is calculated as 2.13 MJ/kg. The lubricant required for machine operation is ignored as the data for it is not readily available.

Table 4-2 Energy data for material and process flow of BiW LCA.

Material/Process	Remarks	Reference
Steel	Steel, low alloyed, hot rolled {GLO}| market for| APOS, U	[64]
CF	Table 4-3	[65]
rCF	36 MJ/kg of electricity for chopping of waste CFRP	[66]
GF	Glass fiber {GLO}| market for| APOS, U	[64]
Epoxy	Epoxy resin, liquid {ROW}| market for epoxy resin, liquid| APOS, U	[64]
Galvanizing	Figure 3-2	[53]
Annealing	449.3 kg of hard coal	[68]
Stamping	5.1 MJ/kg of Electricity for Heating, Blanking and Forming	[72]
Trimming/Finishing	2.015 MJ/kg of electricity for use of machine operation	[67]
RSW	0.344 MJ/m of electricity for machine operation	[69]
UAM	2.13 MJ/m of electricity for machine operation	Calculated
HPRTM	26.28 MJ/kg of Electricity for Preforming, Metering, Molding, Curing	[70]

Table 4-3 Inventory for the unit process flow of Carbon Fiber production

Inputs	Amount	unit	Outputs	Amount	unit
Ammonium bicarbonate	0.02	kg	Carbon fibers	1	kg
Epoxy resin	0.01	kg	Carbon dioxide	0.63	kg
Polyacrylonitrile fibers	1.89	kg	Nitrogen monoxide	0.33	kg
Polydimethylsiloxane	0.01	kg	Nitrogen dioxide	0.66	kg
Potassium permanganate	0.1	kg			
Sulphuric acid	0.02	kg			
Water	2.77	l			
Electricity	20.2	kWh			
Heat	98.4	MJ			

4.3 Results:

The first step in calculating the CED for each scenario was to calculate the CED of the individual processes involved in the manufacturing of the Body in white. The result of the LCA is presented in Figure 4-5. We can see that CF has the highest energy intensity of 619 MJ/kg. In manufacturing process HPRTM is the most energy intensive process at 80.3 MJ/kg. The high energy demand for HPRTM is due to the need for heating the large thermal molds during the curing of composite materials. This is one of the challenges being addressed in the smart 3D printed tool comparative LCA in the next chapter.

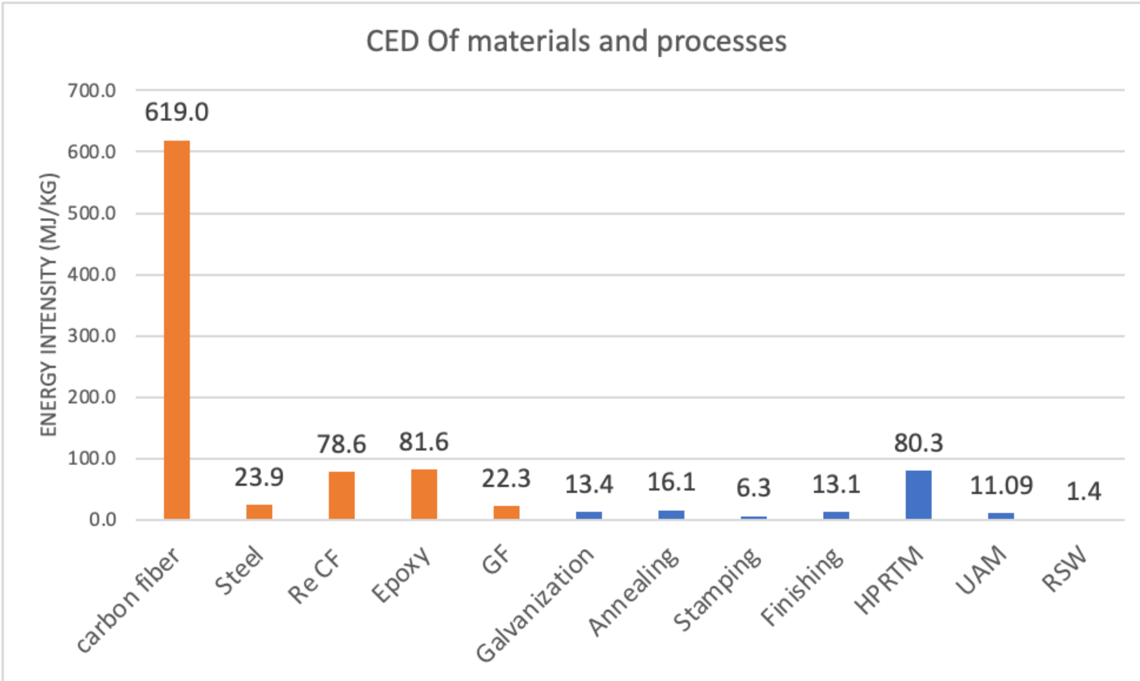


Figure 4-5 Cumulative Energy Demand for the materials and production processes

The material and production stage CED are presented in the Figure 4-10 and Figure 4-11 respectively. We can see that CF production is the single largest contributor to the energy demand of the composite Body in white. The other significant contributor is the HPRTM manufacturing process. Relative to the other processes the UAM multimaterial joining process does not contribute highly to the body in white production stage CED. Overall light weighting Body in white results in increase in energy demand during production stage even with the use of alternate fibers in composites.

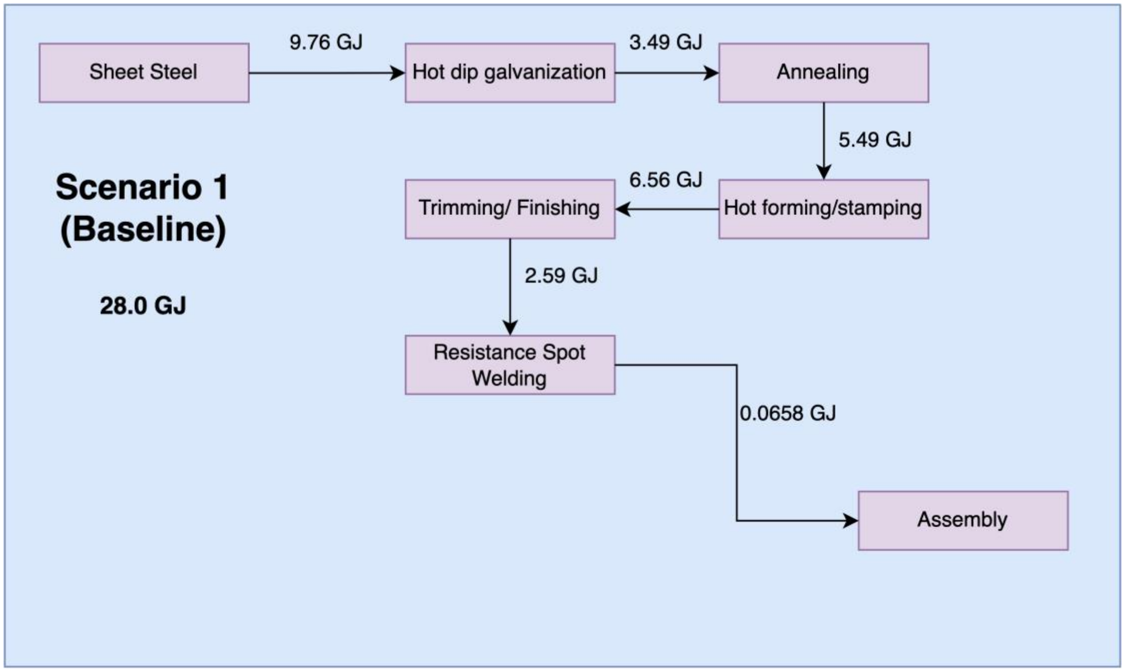


Figure 4-6 BiW production flow chart for scenario 1

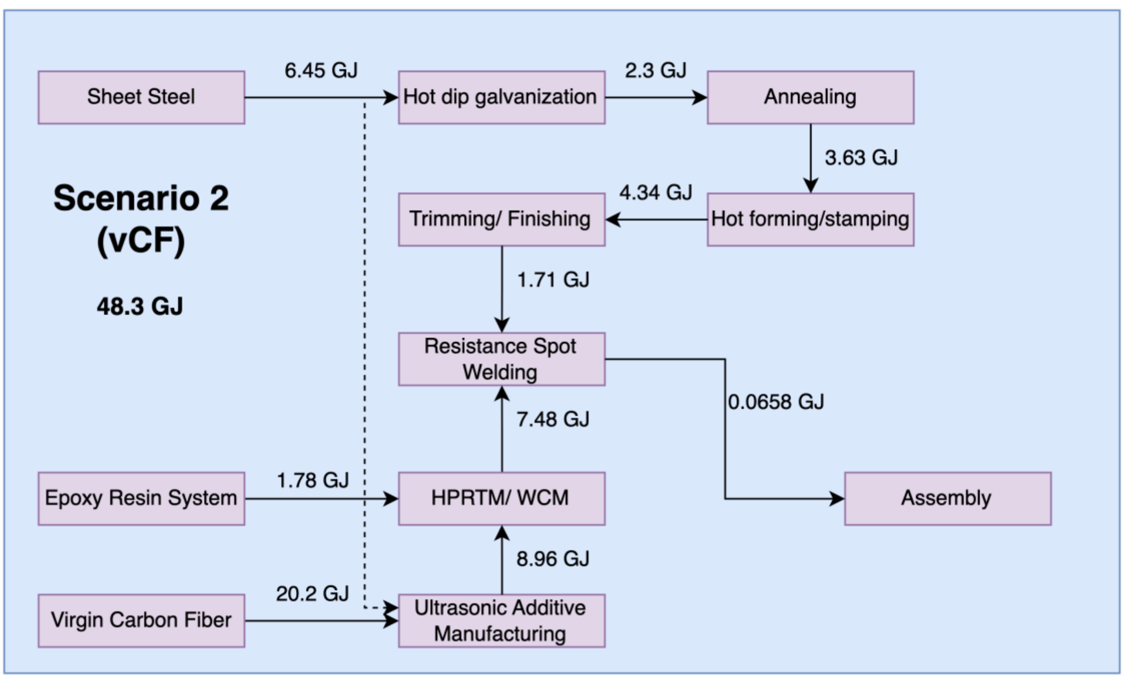


Figure 4-7 BiW production flow chart for scenario 2

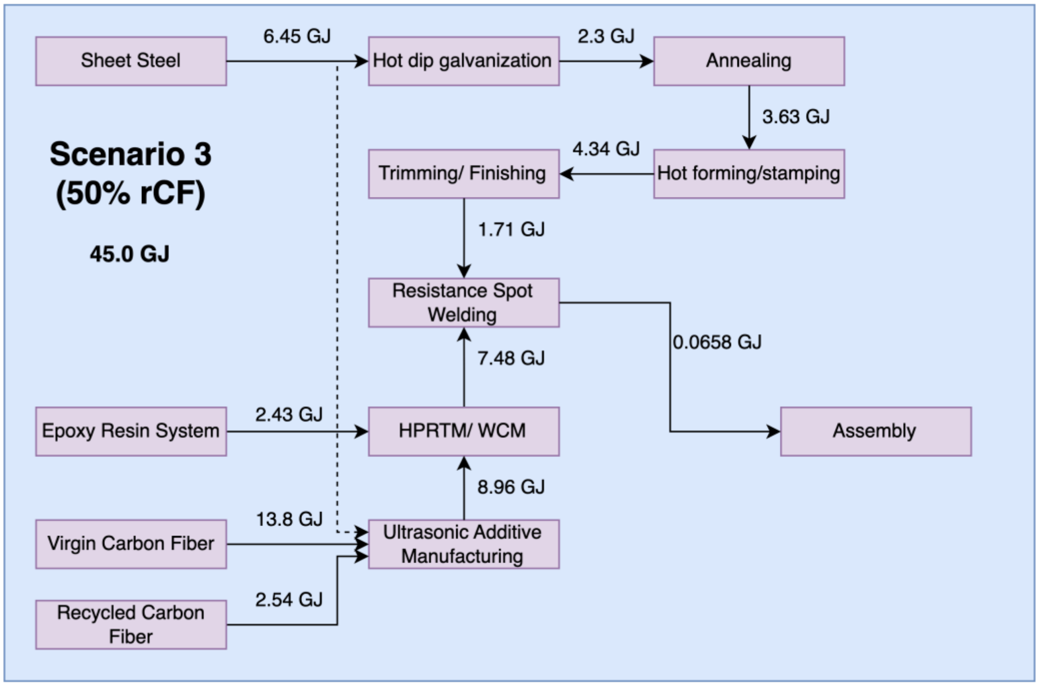


Figure 4-8 BiW production flow chart for scenario 3

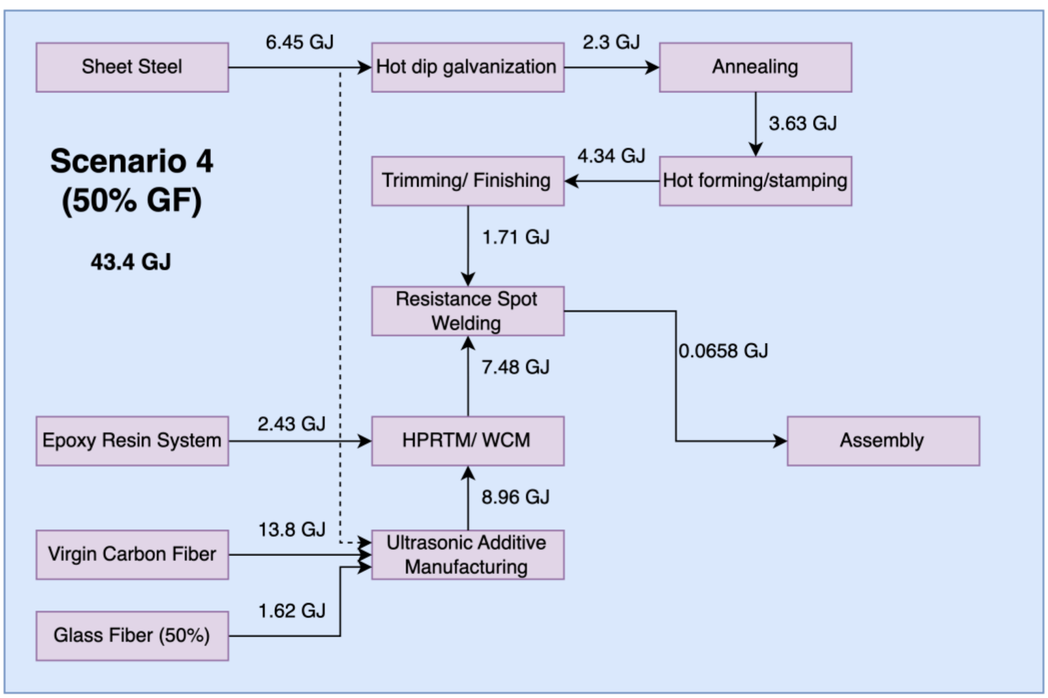


Figure 4-9 BiW production flow chart for scenario 4

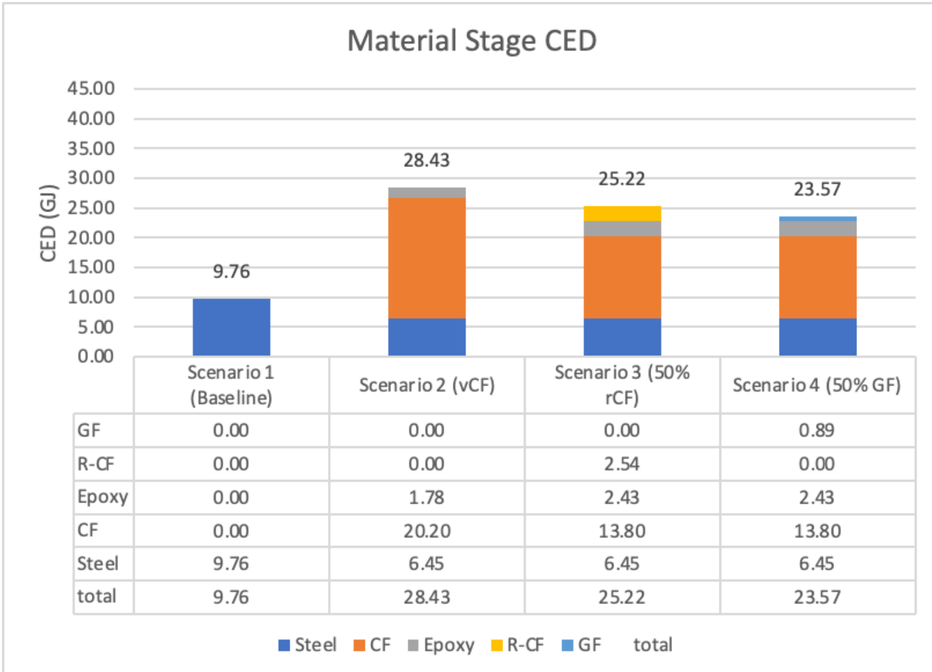


Figure 4-10 Materials stage CED for BiW LCA

Figure 4-11 Production stage CED for BiW LCA

When the use case energy demand is incorporated into the analysis we can see the life cycle benefits of light weighting of in terms of reduced overall demand. The results are presented in the Figure 4-12. We can observe that the baseline BiW in scenario 1 is least energy intensive in the first five years of vehicle use. However, by the seventh-year baseline BiW has the highest energy intensity. Comparing the three multimaterial BiWs we can see that 100% virgin carbon fiber BiWs have the least CED. This is due to optimization of the composite structures in the BiW. With the optimization of the structures, we get greater secondary weight saving for virgin CF which result in lower life cycle.

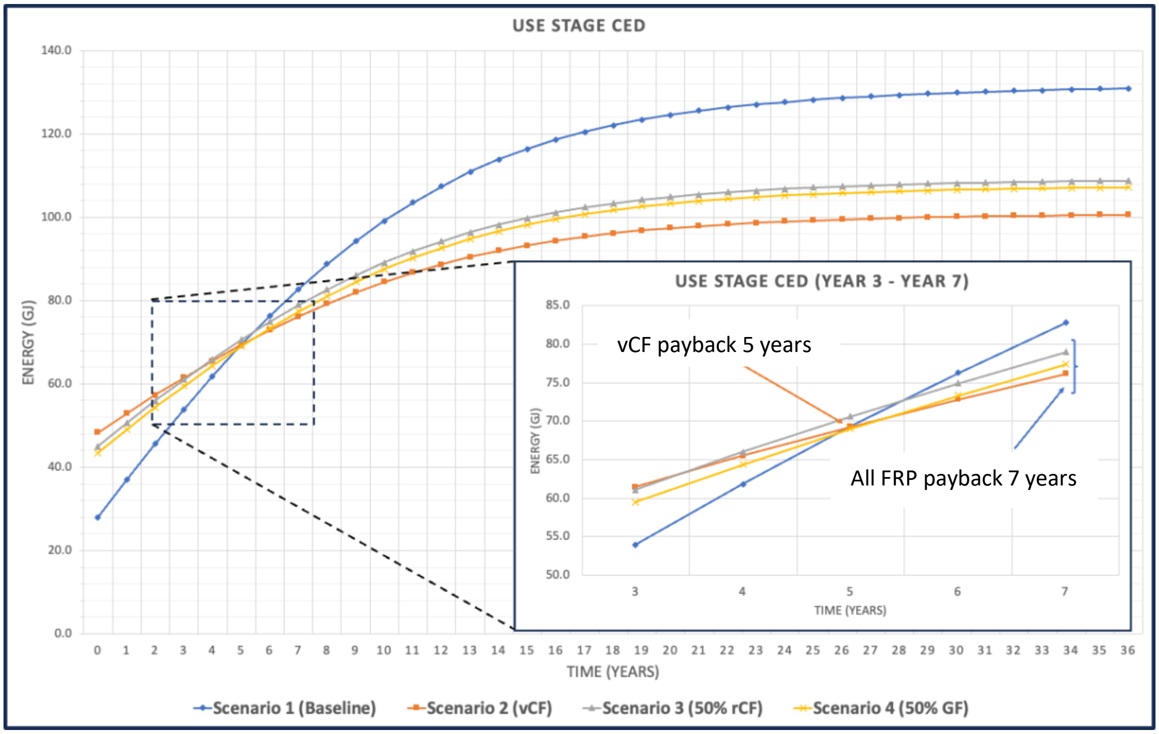


Figure 4-12 Use stage CED for BiW LCA

Analysis of the fuel consumption over the lifetime of the vehicle shows that due to compounded light weighting of the vehicle 734.9 kg of E10 gasoline fuel is saved by the vehicle. Figure 4-13 shows the life cycle CED after the consideration of EoL stage for each scenario.

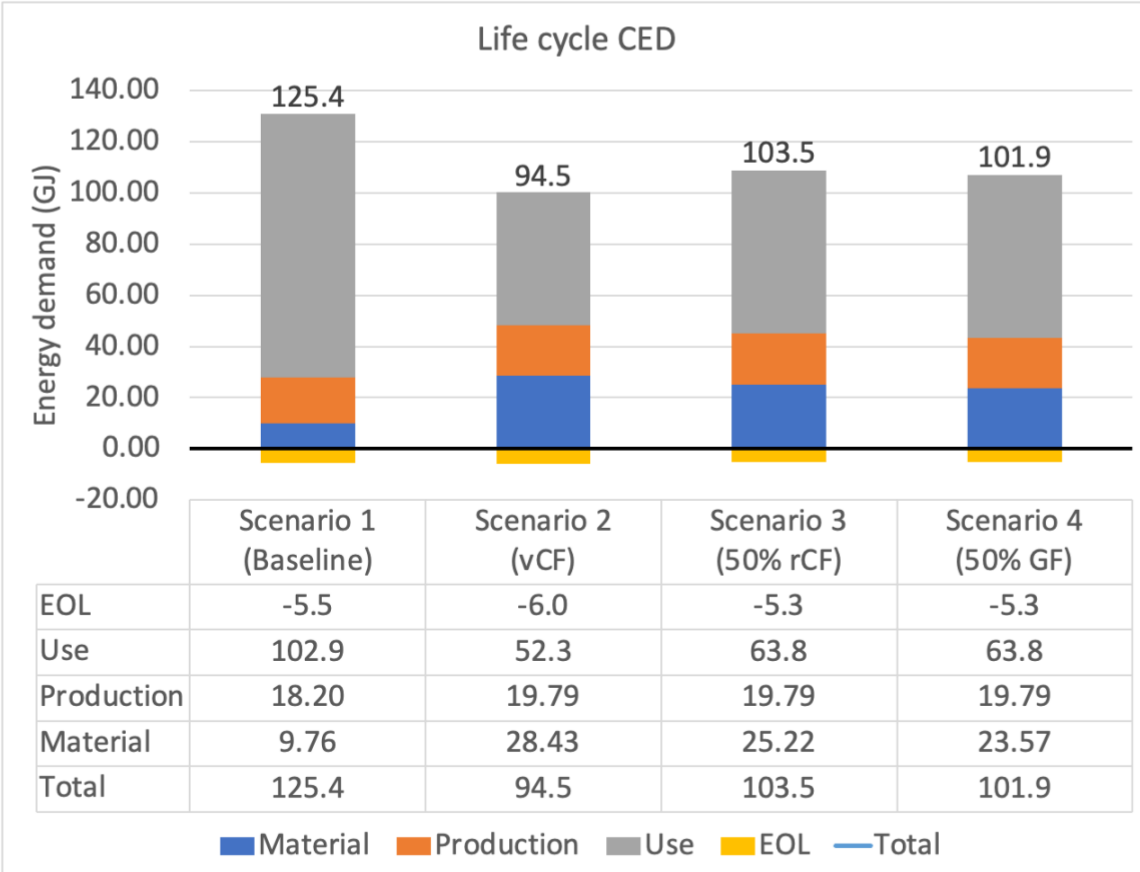


Figure 4-13 Life cycle CED for BiW LCA

4.4 Implication:

The results of the comparative LCA show that multi-material composite lightweight BiW design with transition joints reduces the life cycle CED. The CED for FRP composite light weight BiW increases during the production stage when compared to baseline BiW. However, the effect of light weighting combined with the secondary weight reduction reduce the fuel consumption of the vehicle. This results in FRP composites becoming less energy demanding within 6 years of vehicle operations. The use of alternate or recycled fibers shows that production stage energy demand for composite BiWs can be further reduced. This is however at slightly higher use stage energy demand. Overall, 100% vCFRP composite is the most optimal fiber configuration. Thus, the UAM transition joining combined with use of HPRTM to produce composite parts is a viable energy reduction strategy.

CHAPTER FIVE

5 Additive manufactured composite tool comparative LCA

5.1 Goal and Scope:

5.1.1 Goal and Scope:

The objective of the Life Cycle Assessment (LCA) is to quantify the energy savings achieved in the manufacturing process of a typical structural CFRP (carbon fiber reinforced polymer) component by utilizing a proposed additive manufactured CFRP composite tool. Additionally, the study aims to evaluate and quantify the benefits of using microwave annealing instead of traditional oven annealing for the 3D printed tool.

To facilitate an objective comparison of the manufacturing advantages provided by the innovative 3D printing technology, three scenarios are considered in the study:

Scenario 1: The additive manufactured CFRP thermoplastic composite tool.

Scenario 2: The baseline machined steel tool.

Scenario 3: The baseline hand laid CFRP thermoset composite tool.

Scenario 1 and Scenario 2 share the similar tool geometry and tool usage. Figure 5-2 represents the geometry of the tool considered in the two scenarios. However, scenario 3 does not have the same geometry. Vacuum infusion of resin requires a shell-like geometry of the mold. Thus, a shell-like tool that is quarter the volume of the solid tool is created. The shell-like tool will be limited in applicability in most the study omits the use and end-of-life phase for all three scenarios since the primary focus is to objectively assess the manufacturing stage advantages offered by the smart, 3D printed concept.

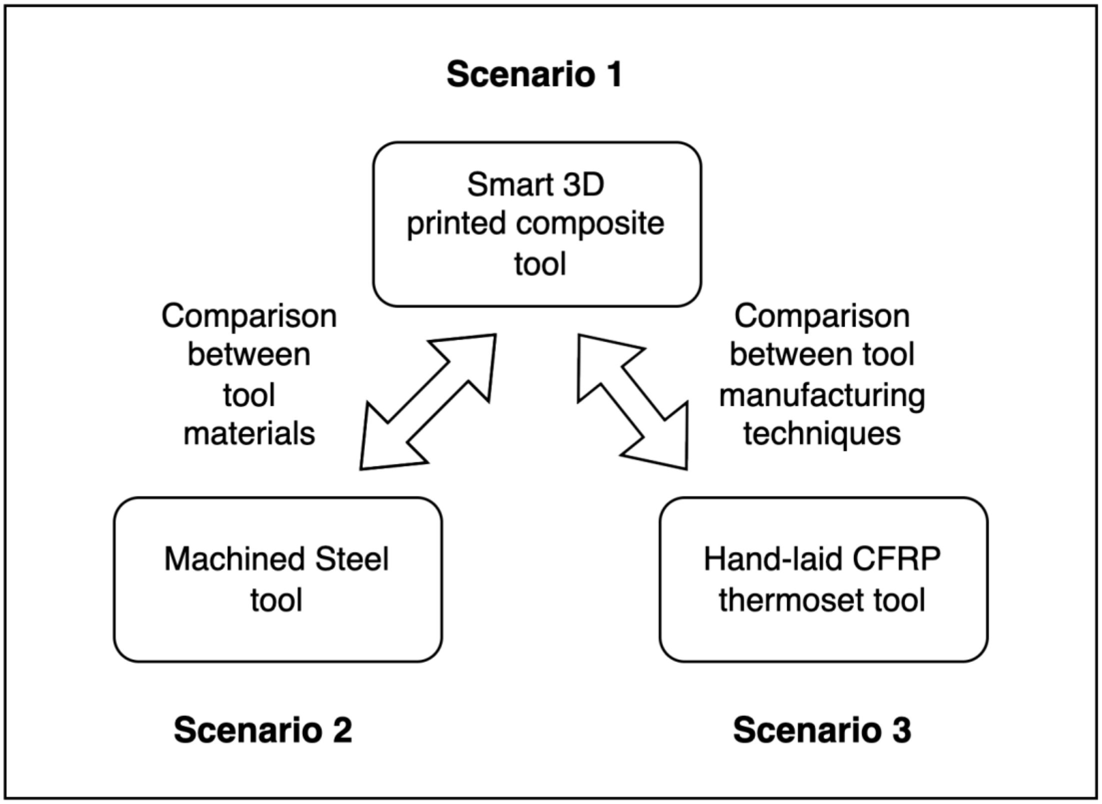


Figure 5-1 Comparison between the Scenarios for AM composite tool LCA

5.1.2 Functional Unit:

The proposed tool concept is intended for the production of automotive components that are typically manufactured using thermoforming molding process, with a moderate production scale. Consequently, the chosen functional unit for the LCA is "A single tool capable of producing 10,000 parts per year." This selection takes into consideration the influence of different material systems utilized for the tools on their durability, which, in turn, affects the number of CFRP components that can be manufactured using the tool.

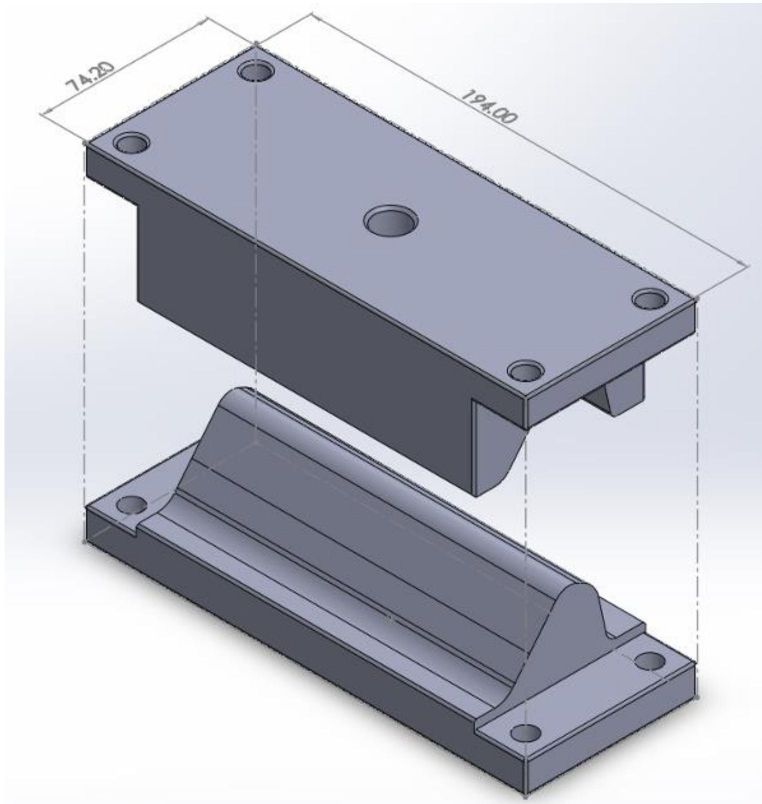


Figure 5-2 CAD drawing of solid tool for Scenario 1 and 2

Table 5-1 Volume and weight of tool in each scenario of tool LCA

Quantity	**Unit**	**Scenario 1 (AM composite tool)**	**Scenario 2 (Steel tool)**	**Scenario 3 (HL composite tool)**
Tool volume	cm3	427.79	427.79	112.00
Material density	g/cm3	1.67	7.85	1.58
Tool weight	grams	713.55	3358.12	177.41
Excess material	grams	0.00	2686.50	44.35

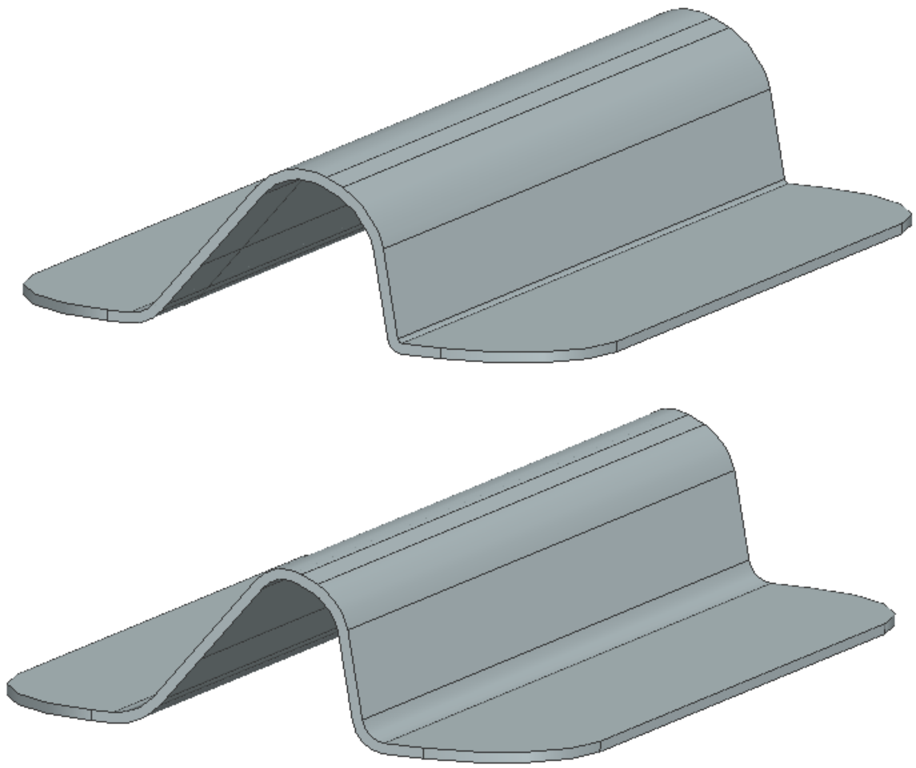


Figure 5-3 CAD drawing of the male and female mold of shell-like tool for Scenario 3

5.1.3 System Boundary:

In the study the LCA is carried on three stages: raw material extraction, material refining/synthesis, and manufacturing. In the investigated scenario for the SRNL-VTO concept the raw material extraction phase consist of the acquisition of CNT nanomaterial precursor, CF precursor polyacrylonitrile (PAN) and nylon 6 precursor. In the material refining/synthesis phase the raw materials were used to make CNT, CF, and nylon 6 respectively. In the manufacturing phase first the Carbon fibers were coated with CNT with novel continuous coating technique developed by SRNL VTO. The coasted CF were then mixed with Nylon 6 and 3-D printed using the Fused Deposition Modelling (FDM) method. The product is then microwave annealed at 120 °C. Figure 5-4 represent the process flow for manufacturing of additive manufactured composite tool.

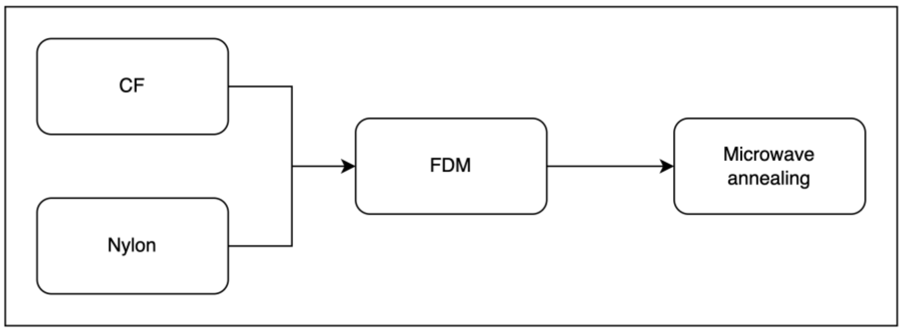


Figure 5-4 Process flow for Scenario 1 (AM composite tool)

In the Baseline Steel tool scenario, the raw material extraction phase includes the extraction of all the raw materials involved in steel production. The material refining/synthesis phase involves the alloying and the casting of the metal into machinable bocks. The manufacturing phase includes the machining of the cast metal into the tool geometry and the heat treatment of the tool in conventional oven for strength hardening. Figure 5-5 represents the process flow for manufacturing of hand laid composite tool.

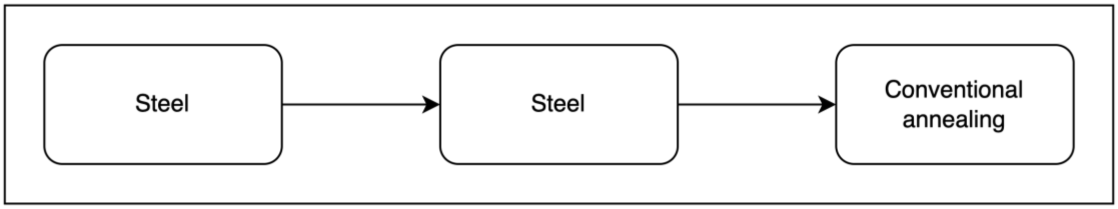


Figure 5-5 Process flow for Scenario 2 (Machined metal tool)

In the Baseline Composite tool scenario, the raw material extraction phase includes the extraction of CF precursor, thermoset matrix precursor, and wood material. The material refining/synthesis phase involves the synthesis of CF, Preform woven CF manufacture, Resin manufacturing and MDF manufacturing. In the manufacturing phase, the woven CF fibers and epoxy resins are combined to from prepreg while MDF is machined to form the core for tool layup and curing. Figure 5-6 represents the process flow for manufacturing of hand laid composite tool.

The study as mentioned above does not consider the use and End-of-Life phase as the goal of the study is to demonstrate the advantages in manufacturing of the 3D printed smart tool as compared to the baseline steel or composite tool.

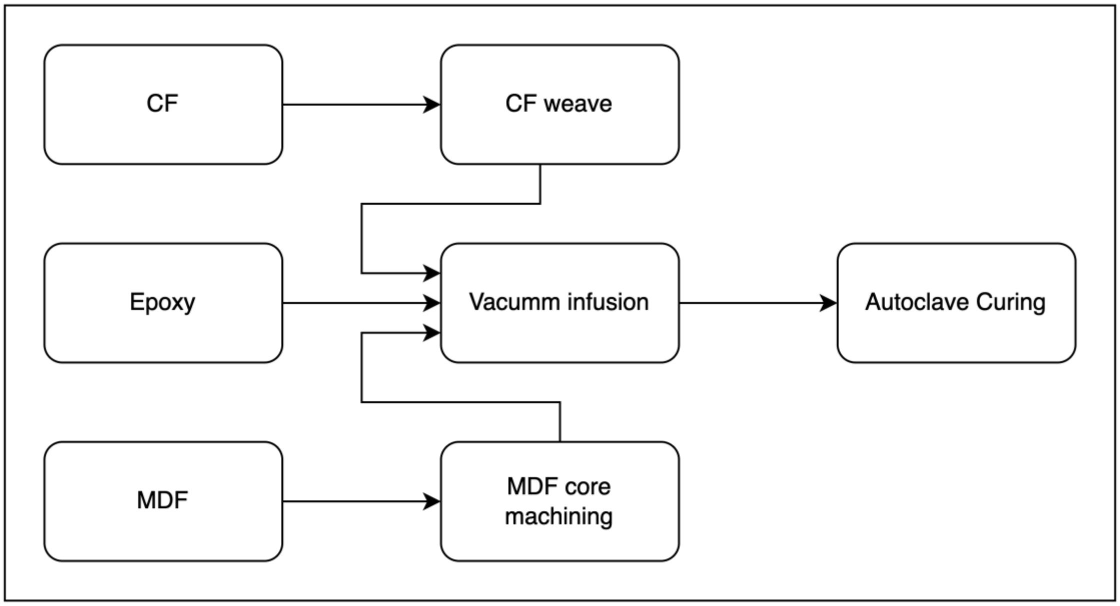


Figure 5-6 Process flow for Scenario 3 (HL composite tool)

5.1.4 Limitations:

The limitation of the comparative LCA is mainly in terms that the trials of the tools for production run 10,000 parts has not been conducted. Instead, initial static analysis was performed in a commercial FEA software to obtain the maximum stress (1.104 MPa) the tool is subject to. This maximum stress was then compared to the SN curve of the tool material [73] to determine whether the tool will undergo any significant local deformations. It was found all three tools should reach the 10,000-parts production run based on FEA result. While theoretically sound this is not a realistic representation of the tool life. Thus, any results from the LCA should be analyzed keeping the limitation in mind.

In addition, the result of the LCA will be skewed towards the scenario 3 hand laid composite tool. This is due to the fact that tool has different volume and geometry compared to the first two scenarios. The reason for the different geometry is the physical limitation of

5.2 Inventory

The data used for life cycle inventory analysis was obtained from primary and secondary sources. The primary source for the data was the equipment database included in the Simapro software. Various literature sources were used for the processes for which Ecoinvent data was not available. All the literature data sources have been listed in the Table 5-2

Table 5-2 Energy data for material and process flow of tool LCA

Material/Process	Notes	Reference
Steel	Steel, low alloyed, hot rolled {GLO}| market for| APOS, U	[64]
CF	Table 4-3	[65]
Epoxy	Epoxy resin, liquid {ROW}| market for epoxy resin, liquid| APOS, U	[64]
MDF	Medium density fiberboard {GLO}|market for| APOS, U	[64]
Nylon 6	Nylon 6 granulate (PA6), production mix, at plant RER| APOS, U	[64]
Steel Machining	Steel removed by milling, average {RoW}|steel milling, average|APOS, U	[64]
Prepreg	40 MJ/kg of electricity for prepregging	[74]
Vacuum infusion	Table 5-3	[37]
FDM of CF	2.014 MJ/kg of electricity for use of machine operation	[75]
Weaving of CF	Weaving, fiber {RoW}| processing| APOS, U	[64]
MDF machining	0.67 MJ/kg of electricity for use of machine operation	[76]
Autoclave curing	110.89 MJ/kg of electricity for use of autoclave	[77]
Conventional Annealing	150 MJ/tool of electricity for use of conventional oven	Calculated
Microwave Annealing	15 MJ/tool of electricity for use of microwave oven	Calculated

For the material inputs of steel, nylon 6, MDF and epoxy available Simapro process flows were used. For the material inputs of Carbon fiber, the input/output data was obtained via literature. Gopalraj et al [65] provide the most comprehensive data for the carbon fiber production. The Table 4-3 shows the data obtained for the carbon fiber production which was used to create the process flow in Simapro.

For process flows of steel machining, carbon fiber weaving available Simapro process flows were used. For the creation of process flows for MDF machining, FDM of CF-nylon composite and the vacuum infusion of epoxy the data from [76], [75], and [37] respectively. For the data for annealing of tool in conventional and microwave oven the data was obtained from Savanah River National Laboratory team who developed the additive manufactured tool technology. According to the test microwave annealing required a tenth of the energy for annealing the tool as compared to conventional annealing.

Table 5-3 Inventory for the unit process flow of Vacuum infusion process

Input	Value	Unit	Output	Value	Unit
Carbon Fiber	6.4	kg	CFRP	8	kg
Epoxy	3.6	kg	Scrap	2	kg
Electricity	11.582	kWh			
CFRP mold	0.15	kg			
PA66 (bag)	0.5	kg			
PET (breather)	0.375	kg			
TFE (film)	0.03	kg			

5.3 Results

The Figure 5-10 illustrates the result of the Additive manufacture tool LCA. The additive manufactured composite tool has a CED for production of 445.23 MJs while as machined metal tool has a CED for production of 673.56 MJ. The major contributing factor in lower energy demand for additive manufactured tool is the microwave annealing as compared to traditional annealing (Figure 5-9). Machining also creates a lot of scrap metal which also contributes to the higher CED for the metal tool (Figure 5-7). Compared to machined metal tool the shell-like hand laid composite tool has almost half the energy demand as the additively manufactured tool. This is however entire due to the lower volume of the tool which requires lower CF and lower autoclave curing energy. For the applications where shell-like tool is suitable, the hand laid composite tool is the most promising solution. However, such applications are limited and certainly come with limitation.

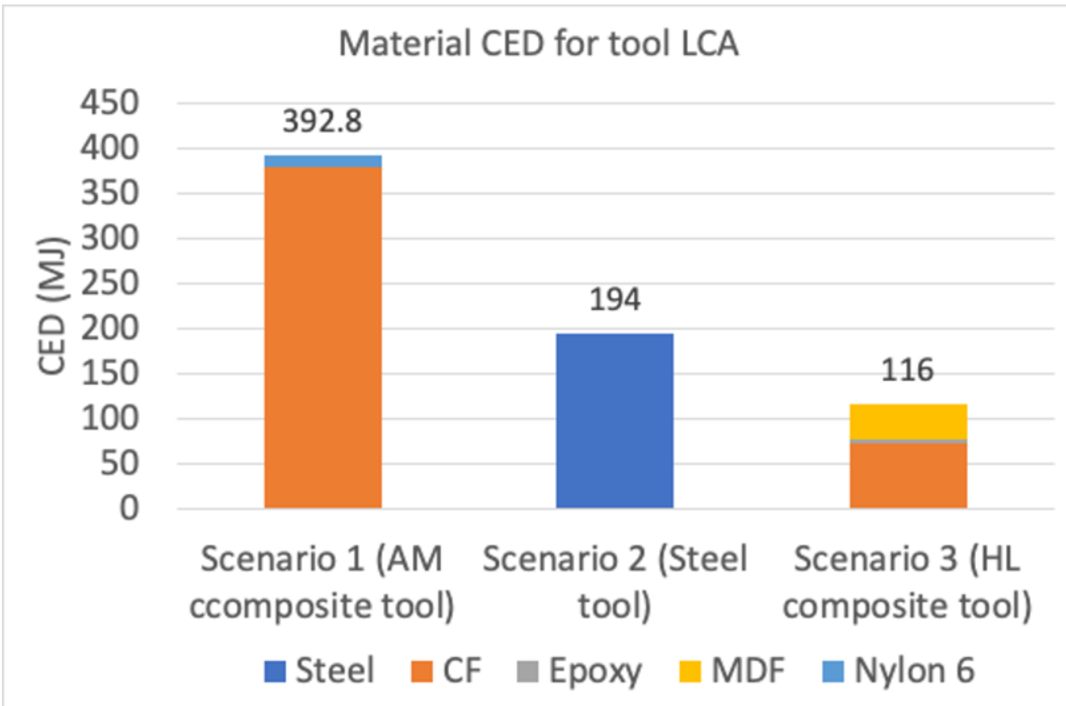


Figure 5-7 CED for materials for tool LCA

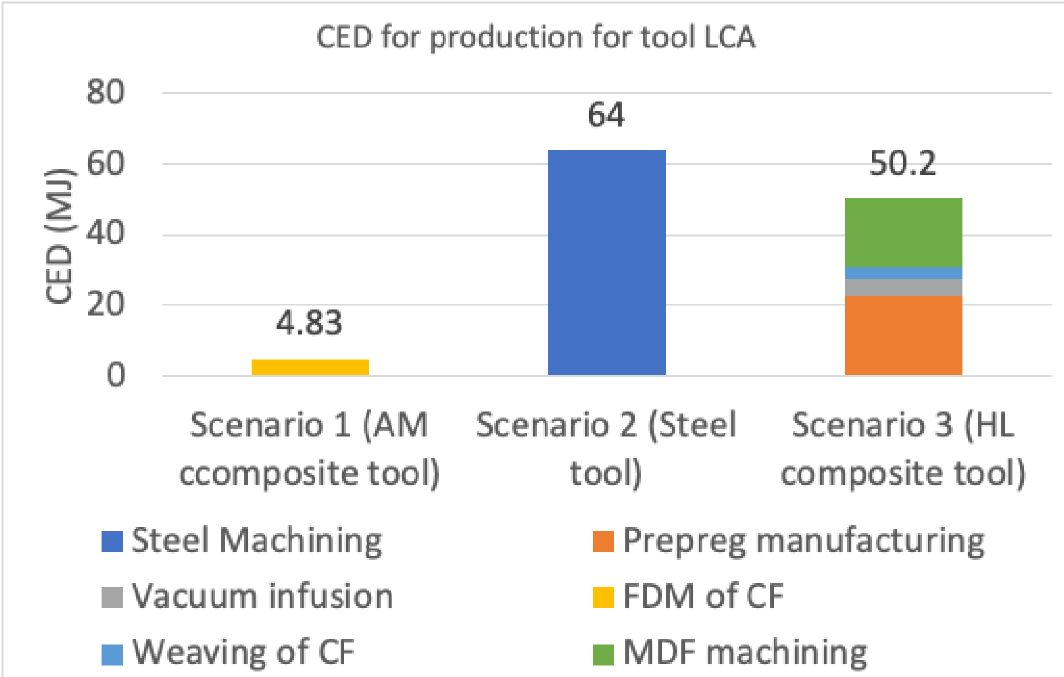


Figure 5-8 CED for production for tool LCA

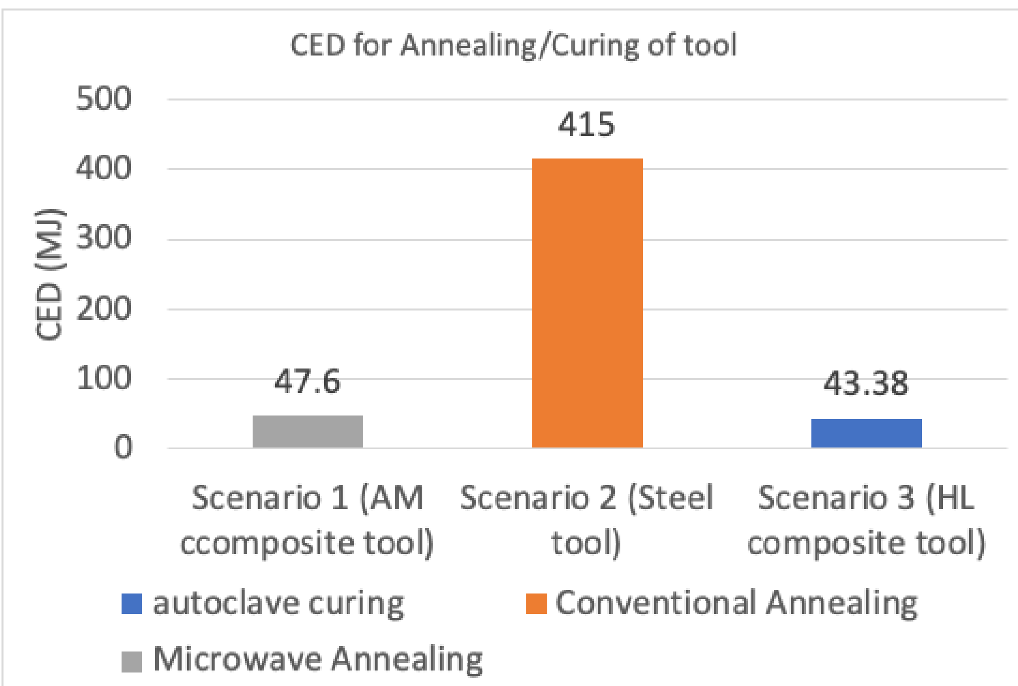
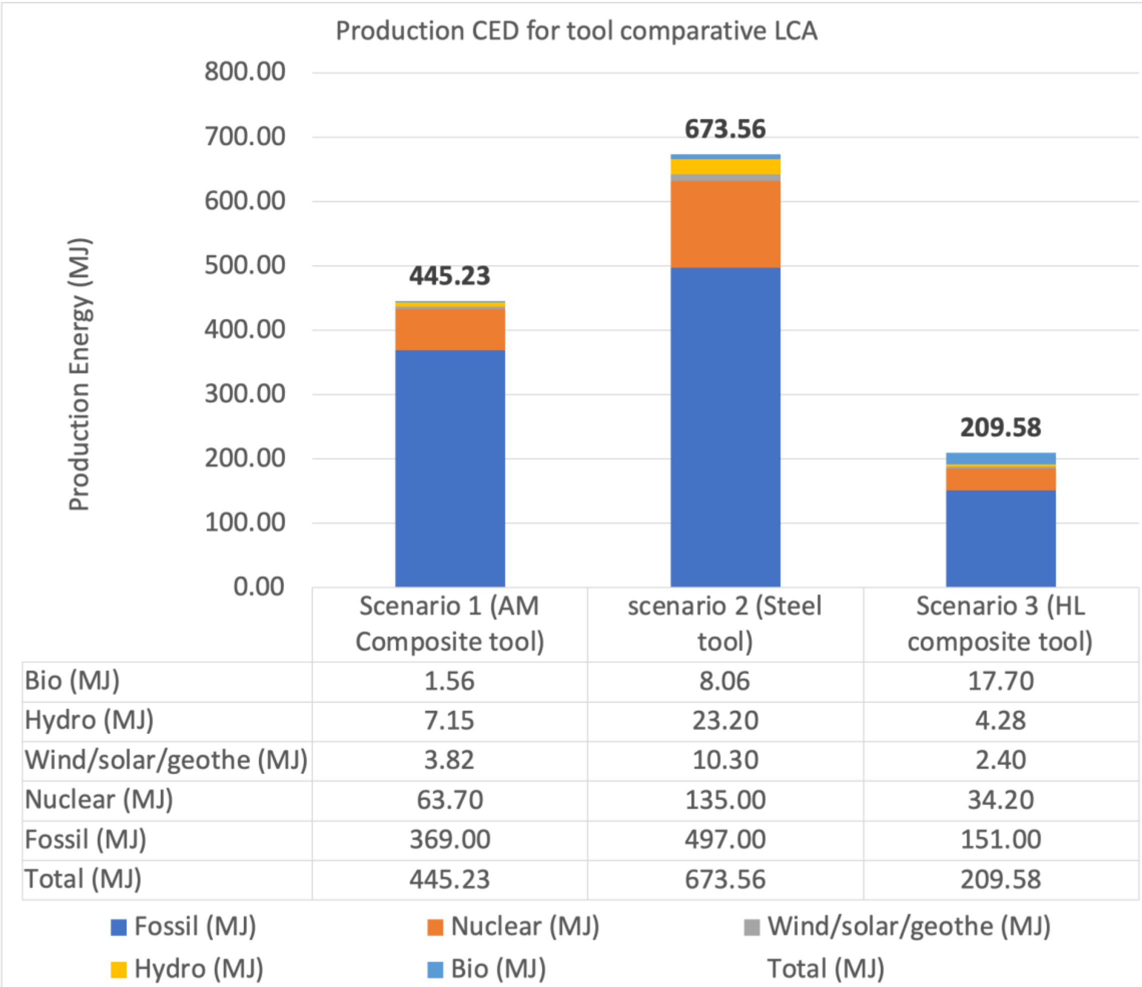


Figure 5-9 CED for Annealing/curing of tool LCA



	Scenario 1 (AM Composite tool)	scenario 2 (Steel tool)	Scenario 3 (HL composite tool)
Bio (MJ)	1.56	8.06	17.70
Hydro (MJ)	7.15	23.20	4.28
Wind/solar/geothe (MJ)	3.82	10.30	2.40
Nuclear (MJ)	63.70	135.00	34.20
Fossil (MJ)	369.00	497.00	151.00
Total (MJ)	445.23	673.56	209.58

Figure 5-10 CED for composite tool LCA

5.4 Implications

The result of the LCA shows the potential of additive manufactured composite tool for composite part production. The use of microwave annealing is highly effective in reducing the energy demand for the tool production. Alternatively, shell-like tool design as in scenario 3 can also significantly reduce the production energy demand, however with limited applicability. Overall, real tests on the durability of the tools are required to determine if the tool designed can indeed last 10,000 part per year production as shown on FEA result.

CHAPTER SIX

6 CONCLUSION

In this report two comparative LCAs were performed to address two research gaps existing in current literature on adoption of FRP composite materials in automobile application is conducted.

6.1 BiW LCA conclusion

The first comparative LCA address the research gap that exist in terms of the LCA of BiW that consider multi material joining technologies. This LCA also considers high production composite molding processes. The goal of the comparative LCA was to demonstrate the energy saving achieved over life cycle for FRP composite light weight BiW over conventional BiW. For the multi material joint novel Ultrasonic Additive Manufacturing technology developed at Ohio state university is used. For comparison a baseline metal BiW is considered and in order to find the optimal fiber configuration three scenarios are considered with 100% virgin CF, 50-50 blend of virgin and recycled CF and a 50-50 blend of CF-GF composite. For the molding process High pressure resin transfer molding process is used. Cumulative energy demand impact assessment was used to calculate the energy savings over life cycle in a cradle-to-grave LCA.

The production stage LCA results showed that FRP composite BiW was more energy consuming as compared to conventional BiW. The major contributor to the energy consumptions were the production of fibers and the molding process. Of the three fiber combinations studied the virgin CFRP composite was the most energy intensive. This result agrees with available literature.

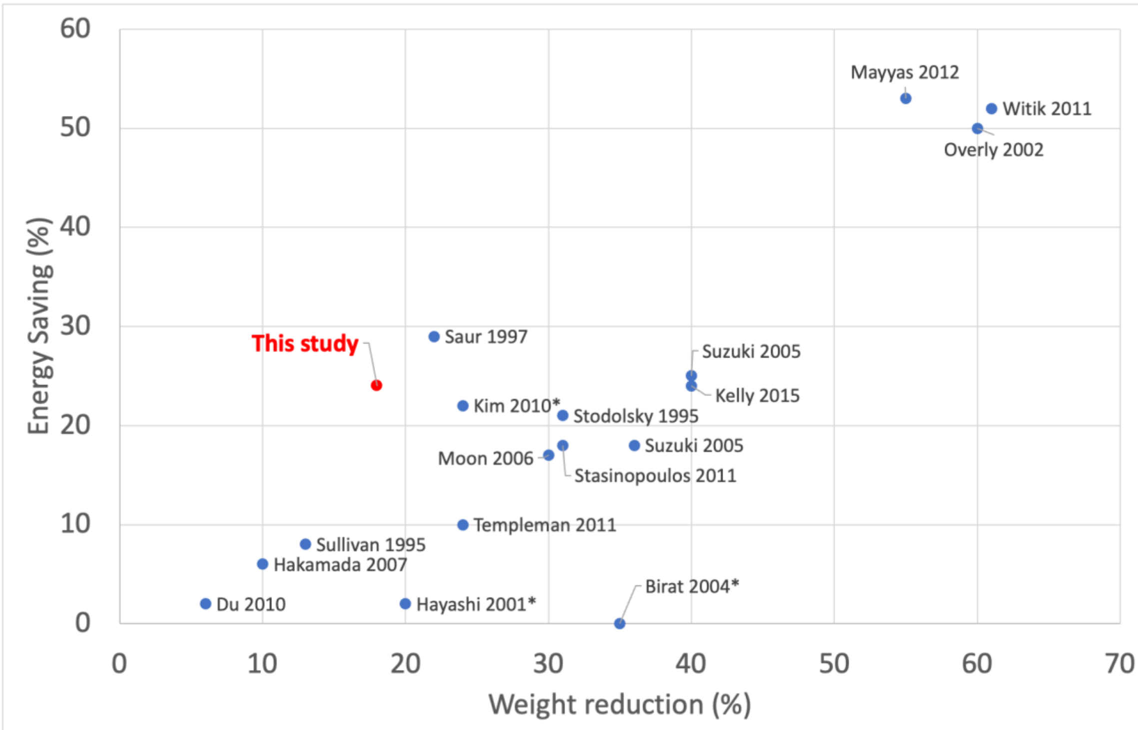


Figure 6-1 Comparison between the BiW LCA result in this study compaired with the literature

The use stage LCA result show the benefit of light weighting in terms of energy saving. The FRP composite light weight BiW is able to pay back the excess energy consumed during production stage within 6 years of vehicle operations for all the three FP light weighting scenarios. This is encouraging in the direction of adoptions the FRP composites for BiW application. Of the three fiber configurations the 100% virgin CF shows the least energy consumption over the lifetime of the BiW. This is due to the additional weight savings that virgin CFRP's superior mechanical properties can achieve over the other fiber configuration. The Figure 6-1 compares the result of this study to the previous literature data.

6.2 Tool LCA conclusion

The second comparative LCA address the research gap where no LCA has been performed on additively manufactured composite tooling. Composite tooling is desirable as they have the capability to be microwave annealed and heated while as additive manufacturing of the tool allows for rapid prototyping and complex geometries. LCA of the two technologies combined has not been performed. Thus, in the report the author performs a comparative LCA with two alternate tools, one made from metals via machining and the other made composites via hand laid vacuum infusion. The tool shape and size are same across all the first and second scenarios, but the volume of the tool in the third scenario is varied according to the manufacturing geometries allowed. The use and EoL stage were ignored for the LCA as it was considered that the tool use would be similar across the scenarios and the EoL for tools is difficult to predict.

For the production stage results showed that the additive manufactured tool was less energy intensive due to no scrap being generated by the additive manufacturing process in comparison to machining. Compared to AM tool, the machined tool required 42% material removal during machining. This results in higher material energy demand. Microwave annealing also allows for further reduction in energy demand for the AM tool.

When compared with the tool with hand laid composite geometry, the AM tool was more energy intensive, despite the hand laid tool being cured in autoclave. This can be clearly attributed to the size difference in the tool with the hand laid tool a fourth in the volume of AM tool.

6.3 Future work

The capital tools such as dies, presses and furnaces used in manufacturing of the BiW should be taken into consideration. Additionally, alternative molding processes other than HPRTM should be incorporated into the LCA. Scalability of the novel technologies involved in the BiW LCA needs to be studied and incorporated into the LCA. However, that development will not occur until UAM technology is begun to be adopted by the auto industry.

For the additive manufactured composite tool medium production run targeting the durability of the tool needs to be performed. Additionally, the difference between the tool use for metal and composite tool needs to be studied and incorporated into the LCA. For the hand laid tool process where the lack of cooling channels might hinder the production, effect of external heating cooling should be studied.

6.4 Acknowledgement

The author would like to acknowledge partial financial support from the Department of Energy, Project # DE-EE0009656 and industry partners including Siemens, Moldex3D, MSC Software (Hexagon), Zoltek and Carbon Conversions Inc.

7 APPENDIX A

Table A-1 FHTSA data for estimate miles travelled

Vehicle Age	Estimated Survivability	Estimated VMT	Weighted YMT
1	0.9741	16,085	15,668
2	0.9603	15,782	15,155
3	0.942	15,442	14,547
4	0.919	15,069	13,849
5	0.8913	14,667	13,072
6	0.859	14,239	12,230
7	0.8226	13,790	11,343
8	0.7827	13,323	10,428
9	0.7401	12,844	9,506
10	0.6956	12,356	8,595
11	0.6501	11,863	7,712
12	0.604	11,369	6,867
13	0.5517	10,879	6,002
14	0.5009	10,396	5,207
15	0.4522	9,924	4,488
16	0.4062	9,468	3,846
17	0.3633	9,032	3,281
18	0.3236	8,619	2,790
19	0.2873	8,234	2,366
20	0.2542	7,881	2,004
21	0.2244	7,565	1,697
22	0.1975	7,288	1,440
23	0.1735	7,055	1,224
24	0.1522	6,871	1,046
25	0.1332	6,739	898
26	0.1165	6,663	776
27	0.1017	6,648	676
28	0.0887	6,648	590
29	0.0773	6,648	514
30	0.0673	6,648	448
31	0.0586	6,648	389
32	0.0509	6,648	339
33	0.0443	6,648	294
34	0.0385	6,648	256

35	0.0334	6,648	222
36	0.029	6,648	193

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