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SYNTHETIC GLASS FIBER-REINFORCED POLYESTER POLYMER COMPOSITE HYBRID LIFE CYCLE ENERGY ANALYSIS

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ABSTRACT
Life cycle analysis is a technique to analyze environmental aspects associated with products or processes to identify energies, materials, and emissions over its life cycle. The energy analysis concerned material production phase, manufacturing phase, use phase, and end-of-life phase. In this research, the synthetic glass fiber-reinforced polyester polymer composites manufactured by using the pultrusion process was analyzed. For wider spread use of composites, it became critical to estimate how much energy was consumed during the lifetime of the composites compared to other materials. In particular, we evaluated potentials for composite materials to save energy in auto industry applications. Hybrid model, that combined process analysis with economic input–output analysis, was used to capture both direct and indirect energy consumption of the pultrusion process in the material production and manufacturing stages.

Keywords: Polymer-matrix composites, Synthetic glass fiber, Pultrusion, Recycling

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INTRODUCTION

in recent times, producers and consumers are using life cycle assessment (LCA) to assess the life cycle of products, materials, and services (Gradel and Allenby, 2003; Fitch and Cooper, 2004). Furthermore, when corporate and public resolution is made, LCA increasingly serves as one of the key factors in environmental management. Environmental issues such as ozone depletion, global warming, acidification, and climate change have been drawing wide concern from the public as well as scientists and engineers. Products used in our ordinary life produce environmental damage during their life time. There are growing interest in understanding these effects and the differences between products.

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Cost estimation models (CEMs) indicate that composite structures may be cost-effective in some applications for the reason that they can eliminate large assembly costs (Gutowski, Henderson, and Shipp, 1991; Busch, and Poggiali, 1986). Such a cost reduction can lead to expanding application areas of composite structures. Additional motivations for composite use might come from its environmentally benign aspects, i.e., energy savings and emission reduction during the use periods.

In recent years, composites made of bio-fiber and resin system have attracted lots of attention as a substitute for synthetic fiber and resin (Pervaiz, and Sain, 2003). Several LCA analyses for composite applications have been carried out and reported (Suzuki, and Takahashi, 2005). For instance, Suzuki and Takahashi calculated the energy intensity of carbon fiber-reinforced composites for applications to passenger cars. It was shown that the high energy intensity and costs of carbon fibers used in the composites are obstacles to the composite application (Suzuki, and Takahashi, 2005). Other interesting application areas are wind turbines and bridge decks (Meiarashi, Nishizaki, and Kishima, 2002; Ehlen, 1999). Rankine, Chick, and Harrison (2006) investigated the energy use and carbon emission of a rooftop wind turbine and showed that micro-generation may be a good means of lowering carbon emission by using small generators in the house. Meiarashi, *et al*. (2002) analyzed the life cycle cost of all composite suspension bridge and compared conventional steel bridges with composite ones. Among many composite-manufacturing processes such as autoclave molding, liquid composite molding (LCM), spray-up, filament winding, and so on, the pultrusion process has been known to be the most cost-effective and energy-efficient due to its high automation and production rate. It is interesting to see how much environmental impact the pultruded composite parts have.

In this study, we carried out a life cycle assessment in order to look into energy flows throughout the lifetime of pultruded composites, as shown in Figure 1. The current study was organized as depicted: firstly, we reviewed the LCA methods, especially hybrid analysis. Two typical analysis methods, process-level analysis and economic input–output model analysis, were covered and their strengths and weaknesses were described. Secondly, varieties of materials and composite manufacturing methods were also reviewed and compared in terms of energy intensities. Then, hybrid analysis for the pultrusion process was conducted, in which automotive application was taken into account for the use period. In this analysis, we depicted the feasibilities of replacing steel or aluminum with advanced engineering composite material structures. We concluded with a critical assessment of the hybrid analysis.

2. Life cycle assessment (LCA)

Life cycle assessment is a useful technique for estimating the environmental performance of products, materials, and services from extraction of raw materials to final disposal, which encompasses extraction, materials processing, manufacturing, transport, use, re-use, maintenance, and recycling. Since net energy analysis was done in the 1970's, much effort has been made to construct the framework of the LCA methodology (Hannon, 1972; Azapagic, 1999; Hunkeler, and Rebitzer, 2005). Life cycle assessment aims at offering a systematic view of product and process evaluation by tracking down the major inputs and outputs of materials and energy, identifying and quantifying the energy and material uses, and assessing the environmental impact. Unlike site-specific methods such as environmental audit (EA), LCA can widen system boundaries to contain all the burdens and impacts on emissions and wastes (Maltby, 1995). Given specific amounts of inputs used or outputs emitted, this kind of analysis is called a life cycle inventory (LCI). LCA contains LCI connecting the loads generated with harm caused. Even though LCA is conceptually simple, it is in reality quite complex and difficult due to the following reasons: there exist difficulties for establishing system

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boundaries, obtaining accurate data, and valuing the results properly. The LCA approach is extensively regarded as a useful framework to combine life cycles of products with related decisions. The framework of LCA is constructed through the series of environmental management standards (EMS) introduced by the International Standards Organization (ISO 14000) (International Standards Organization, 1998).

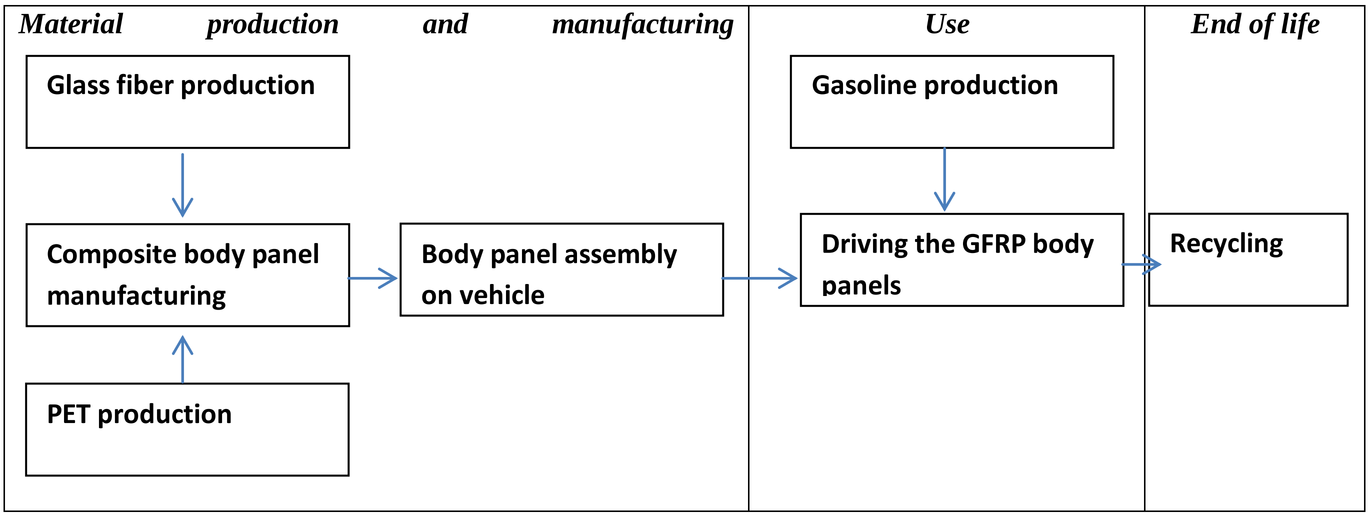

Figure 1: Life Cycles of Pultruded Composites Considered in the Work

The framework of LCA includes the following four stages: firstly, the definition of goal and scope of the investigation. Secondly, the preparation of a model for the product life cycle with all the energy and materials inflows and outflows, referred to as LCI. Thirdly, the study of environmental impact assessment based on the understanding of the environmental relevance of all the inflows and outflows during a life cycle. A system boundary for LCA, through which inputs such as energy and materials and outputs including goods and activities comes-in and goes, was defined. Considering material flows starting with extraction of raw materials and ending with disposal of waste products. The stages of a product life cycle consisted of material extraction, primary material production, manufacturing, use, and final disposal. Also there are cross flows and backflows such as product reuse, component remanufacturing, and material recycling. Materials and energy for functional units within the boundary were estimated and their environmental burdens were also assessed. System boundaries including all the sequence of the stages have a possibility of truncation error caused by boundary cutoff.

In general, two basic methods for LCA were used to assess the lifecycle of products, materials, or processes: process-level analysis and economic input–output analysis. Most LCAs had been performed based on process analysis where the resource uses, environmental releases from the main production processes, and some important contributions from suppliers were assessed in detail. With use of facility-level data, the system was described in terms of the inputs of energy and materials and the outputs of products and emissions. On the other hand, the economic input–out model (EIO) proposed by Leontief (1987) tracks down various economic transactions, resource requirements, and environmental emissions and uses input–output tables which model the whole economy with financial transactions between approximately 500 aggregated economic sectors.

Even though LCA serves as a consistent tool providing insight into environmental loads of products, materials, and processes, both methods have several shortcomings: first, while process analysis is more specific than input–output analysis, it is also a labor and time-intensive method. Furthermore, the process level LCA can describe technologies more precisely but important contributions including capital and service are left behind in the analysis. In other words, process-level analysis has a high spatial and temporal resolution, yet the lack of consideration of effects outside a rather close boundary may lead to a significant underestimation. Because of setting a system boundary and omitting contributions outside the boundary, process analysis contains a systematic truncation error. In what follows, we showed how input–output analysis can be used in order to assess the order of magnitude of the truncated parts. On the other hand, input–output analysis contains an aggregation problem that a single sector stands for different kinds of processes or materials. For example, polyester, epoxy, PVC, PE, and so on must have different energy, raw materials, and activities associated with production, but only a single plastic material and resin manufacturing sector (#325211) represents the production of all of them in the input–output analysis (Green Design Institute, 2007). But economic input–output analysis does not have cut-off errors because the entire domestic system is included in the analysis.

For the purpose of keeping the strengths and reducing the weaknesses of each method, hybrid analysis combined process analysis with input–output analysis have been promising. To figure out the features of hybrid analysis, a brief explanation on it is given in the next section below.

2.1. Hybrid analysis

A great deal of work on LCA has been reported over the past several decades since the 1970’s. The two main methodologies are process-level analysis and input–output analysis. As stated above, process-level analysis can describe a target process or activity more in detail, yet it has a truncation error. Input–output analysis adopting wider system boundaries also possesses an aggregation problem. There are several methods to overcome these limitations of life cycle assessment, such as extension of LCA, use of toolbox, and hybrid analysis (Udo de Haes, Heijungs, Suh, and Huppes,2004; Suh, and Huppes, 2005; Suh, 2006). Hybrid analysis which blends process analysis with input–output analysis makes up for the weak points of both analysis. The current work adopted the hybrid life cycle analysis introduced by Williams (2004).

In a hybrid LCA, ‘‘background” and infrastructure components beyond a target process or activity, which can be specified easily, are dealt with via an input–output analysis methodology. On the other hand, process-level analysis and economic input–output analysis used in the hybrid LCA are not perfectly matched: there exist some differences such as base year, level of resolution, inclusion of capital goods, treatment of import, and applied allocation principles. In spite of these distinctions, hybrid analysis provides a reasonable analysis framework to handle the truncation or cut-off errors effectively, which as this analysis and the analysis of others have indicated, can be quite substantial (Williams, 2004). Furthermore, the hybrid approach can be further modified to try to accommodate the previously mentioned problems.

3. Life cycle stages

Prior to the synthetic glass fiber-reinforced epoxy polymer composites life cycle energy assessments, life cycle stages for composite structures, material production, manufacturing, use, and end-of-life stages were outlined in the following sections.

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3.1. Material production

The first stage of the product life cycle was ‘‘material extraction” for plastics or similar materials, which involves pulling fossil fuels from the earth. These materials were then refined and separated before producing the input materials for manufacturing. The next step was to call for extraction and production of materials, known as “material production”. Materials used in manifold fields have different energy intensities for extraction and production as listed in Table 1. Polymer matrices such as thermosetting and thermoplastic polymers are created through energy intensive chemical processing. The plastic material and resin sector of the chemical industry alone accounted for 414 million GJ of energy consumption in the USA in 1998, which amounts to 2.2% of the total energy consumed by USA (US Chemical industry statistical handbook (1998). Among polymer resins, thermosets including polyester and epoxy resins used in fiber-reinforced composites possess relatively low energy intensities. Since the energy intensities of materials vary depending on technology, methods, and infrastructure, they are in a wide range as shown in the Table 1. For example, glass fibers which are one of the most common basic materials to reinforce plastics, have broadly varying production energy intensities. Stiller compared and analyzed several manufactures of glass fibers, PPG, Owens Corning, and Vetrotex (Stiller, 1999). Owen Corning consumed the lowest intensity of 12.58 MJ/kg, whereas Vetrotex had the largest intensity of 32.0 MJ/kg. Besides, even at one manufacturer energy intensities change significantly: Vetrotex plants in Germany consume 32.0 MJ/kg, while Vetrotex International plants use 25.3 MJ/kg. This can be explained in part by economies of scale. That is, such low energy consumption results from large-sized plants, thus allowing energy savings of about 20%. On the other hand, energy consumption is roughly independent of the filament diameter of the glass fibers produced. As seen in the Table 1, the natural fibers including China reed and flax fibers have relatively low energy intensities in that they come from natural sources. However, there are other environmental impacts related to their cultivation, especially the use of land, water, fertilizers, and pesticides. According to Wotzel, Wirth, and Flake (1999), natural fibers use 45% less energy but result in higher water emissions due to fertilizer application in cultivation. Carbon fibers, which are typical reinforcing materials in polymer-based composites, have a very high energy content compared to other fibers. The high energy intensity of carbon fibers causes high costs. This may be a barrier to a widespread use of carbon fiber-reinforced composites even though carbon fibers show outstanding physical properties compared to other engineering materials such as metals and ceramics. Fiber-reinforced composites (FRC) have been employed in broad applications since they are lightweight, strong, and chemically inert. Weight saving arising from the use of FRC might lead to a significant reduction of energy waste, especially in the transportation sector in comparison to heavy metals like steel even if their energy intensities are higher than those of steel. It was reported that replacing steel components with carbon fiber-reinforced composite ones can save as much as 60–80% in the component weight (Mazumdar, 2002).

3.2. Manufacturing

While fiber-reinforced composites have showed potential for automobile parts in the past several decades, the application has yet to be realized on a mass production scale due to several drawbacks including low production, automation rates, and significant costs. Table 2 presents the energy intensities of various manufacturing processes. Note that the energy intensities represent energies associated only with processes but not relevant materials. Since the composite materials in general involve two or more different materials, processing techniques for composites are quite different from those for metal or polymer processing. After reinforcing fibers and polymer matrices are made, additional processes such as textile manufacturing and proper preparation are often required prior to integration of fibers and polymer resins. These

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processes also need additional energy, although not as much as in the primary processing. In addition to energy, many materials use solvents and additives. In general during fabrication processes, a significant amount of energy is used to provide heat and pressure necessary for curing.

Table1: Energy content of various materials

Materials	Energy intensity (MJ/kg)	References
Polymers		
Polyester	63-78	
Epoxy	76-892	
LDPE	65-92	
PP	72-112	
PVC	53-80	
PS	71-118	
PC	80-115	
Fibers		
Glass fiber	13-32	
Carbon fiber	183-286	
China reed fiber	3.6	
Flax fiber	6.5	
Metals		
Aluminum	196-257	
Steel	30-60	
Stainless steel	110-210	
Copper	95-115	
Zinc	67-73	
Cast iron	60-260	

As listed in the Table 2, more automated processes such as the filament winding and pultrusion tend to spend lower energy. The pultrusion process considered in this research has an energy intensity of about 3.1 MJ/kg. Other highly automated processes including the filament winding, SMC molding, and perform matched die employed in the auto industry have similar low values.

Table 2: Energy intensities of manufacturing processes

Manufacturing methods	Energy intensity (MJ/kg)
Autoclave molding	21.9
Spray up	14.9[b]
Resin transfer molding	12.8[b]
(RTM)	10.2[b]
Vacuum assisted resin	11.8[b]
infusion (VARI)	10.1[b]
Cold press	3.5[b]
Preform matched die	2.7[b]
Sheet molding compound	3.1[b]
(SMC)	40.0[b]
Filament winding	19.0[c]
Pultrusion	2.6[d]
Prepreg production	13.6[c]
Injection molding	
(hydraulic)	
Glass fabric manufacturing	
Iron casting (Cuola)	

3.3. Use

Estimation of the use period of composite structures is determined by what application is considered. Composite materials are currently being used in the following industry areas: aerospace, automobile, construction, marine, consumer products, and appliance equipment. In particular, advanced composite structures have been adopted in the aerospace application where their benefits are well known. For instance, The Boeing 787 Dream - liner, a mid-sized jet airplane, currently in production by Boeing, consists of around 80% composite materials by volume (50% composites by weight), which is known as a breakthrough in the aerospace field.

Even though the pultrusion process has a low energy intensity and high production rate, it has limitation in making products with complex shapes. As a result, the pultrusion process is used for making parts with simple cross-sections such as railings, ladders, poles, and pipes. In

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order to fully appreciate the advantages of composite structures such as lightweight, long life time, high specific strength, and chemical inertness, a transportation application was selected in this research. Furthermore, the transportation sector can significantly affect our society from a perspective of energy savings.

3.4. End-of-life

There are several potential recycling and end-of-life methods for polymeric composites including pyrolysis, hydrolysis, chemical recycling, regrinding, and incineration. However, the actual recycling level for composites is currently quite low (Scheirs, 1998). In most cases, composites are discarded to landfill which is not ideal. It is necessary to extract and reuse the energy still embodied in the composite parts. On the other hand, pyrolysis can yield products that can be used as fuels or feed-stocks for petrochemicals (Ganan, Gonzalez, Gonzalez-Garcia, Cuerda-Correa, and Macias-Garcia, 2006). Hydrolysis can retrieve monomers from specific composite materials such as polyester and polyamides (Khalil, Elsamahy, and Elanany, 2002). Chemical recycling involves separation of the polymer matrix from reinforcing fibers, thereby allowing reuse of the fibers (Allred, 1996). In the regrinding method, composite materials are broken down into small pieces that are used as fillers in other molded composite parts. While both chemical recycling and regrinding methods allow materials to be reused, both require considerable processing steps before reuse. Also, particularly in the case of the regrinding method, most recovered scraps cannot be substituted for virgin materials, so the majority is down cycled into much less demanding applications. Overall, the end-of-life period acts as a major barrier to environmental friendly large scale applications of composite materials owing to no viable restorative recycling methods.

4. Pultruded composite parts hybrid analysis

The composite system considered in the current research was glass fiber/unsaturated polyester. As a composite manufacturing method, the pultrusion process was selected and automotive application of the composite materials was assumed in the use period. In the material production and manufacturing stages, the major industrial activities associated with glass fiber/unsaturated polyester composites were glass fiber production, unsaturated polyester production, fabric manufacturing, and pultrusion. It was well-known that reinforcing fibers and polymer resins generally used in composites have relatively high energy input requirements, thus resulting in high energy intensities. The weight fraction of glass fiber was assumed to be 30% and textile production of glass fabrics requiring 3.58 MJ/kg was also taken into account for sandwich structure with three layers (Stiller, 1999).

The hybrid analysis proposed by William (2004) was adopted in a bid to avoid the truncation error and to present a complete assessment of the energy consumed in the materials production and manufacturing stages of pultruded composites. Figure 2 illustrates the hybrid method schematically, in which more generalized system boundary contains three different analysis sections; process level analysis, additive analysis, and remaining value analysis. As seen in the figure 2, the three analyses were connected and contributed to the total energy required for making composites. The main concepts of the hybrid life cycle assessment were given by the following equations:

$$Total\ energy = process\ sum\ result + IO\ correction\ factor \quad (4.1)$$

$$IO\ correction\ factor = E_A + E_{RV} \quad (4.2)$$

where E_A is the additive factor and E_{RV} is the remaining value factor. The total energy is a sum of the process-level analysis and the input– output analysis as illustrated in Fig. 2. This separate consideration enables us to deal with data and results more efficiently. Table 3 indicated that a process level energy of 47.91 MJ is needed to prepare a 1 kg pultruded glass fiber/unsaturated polyester composite. It is interesting to see that consideration of composite materials leads to a dramatic increase in the energy

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intensity from 2.5 MJ (for the pultrusion process in itself) to 47.91 MJ.

As system boundaries are enlarged, we consider energies for other activities associated with the pultrusion process. The Carnegie Mellon University input–output model using the 1997 US benchmark table is employed to estimate these contributions (Green Design Institute, 2007). In the additive input–output analysis, sub-material and equipment depreciation of the pultrusion process are employed as the additive factors. The sub-material includes chemicals and auxiliary materials for the pultrusion process not covered in the process-level analysis. The additive factor is written as

$$E_A = \sum Exp_j E_j^{SC} (4.3)$$

in which Exp_j is the expenditure regarding activity j per unit product and E_j^{SC} is the supply chain energy intensity (MJ/$). These monetary values and energy intensities of the sub-material and equipment were acquired from a combination of the literature, IO model, and consultation with pultrusion companies (Meiarashi, Nishizaki, and Kishima, 2002). As presented in Table 3, energy of 58.54 MJ arises from the additive factors, which is a significant amount of energy compared to the process-level energy.

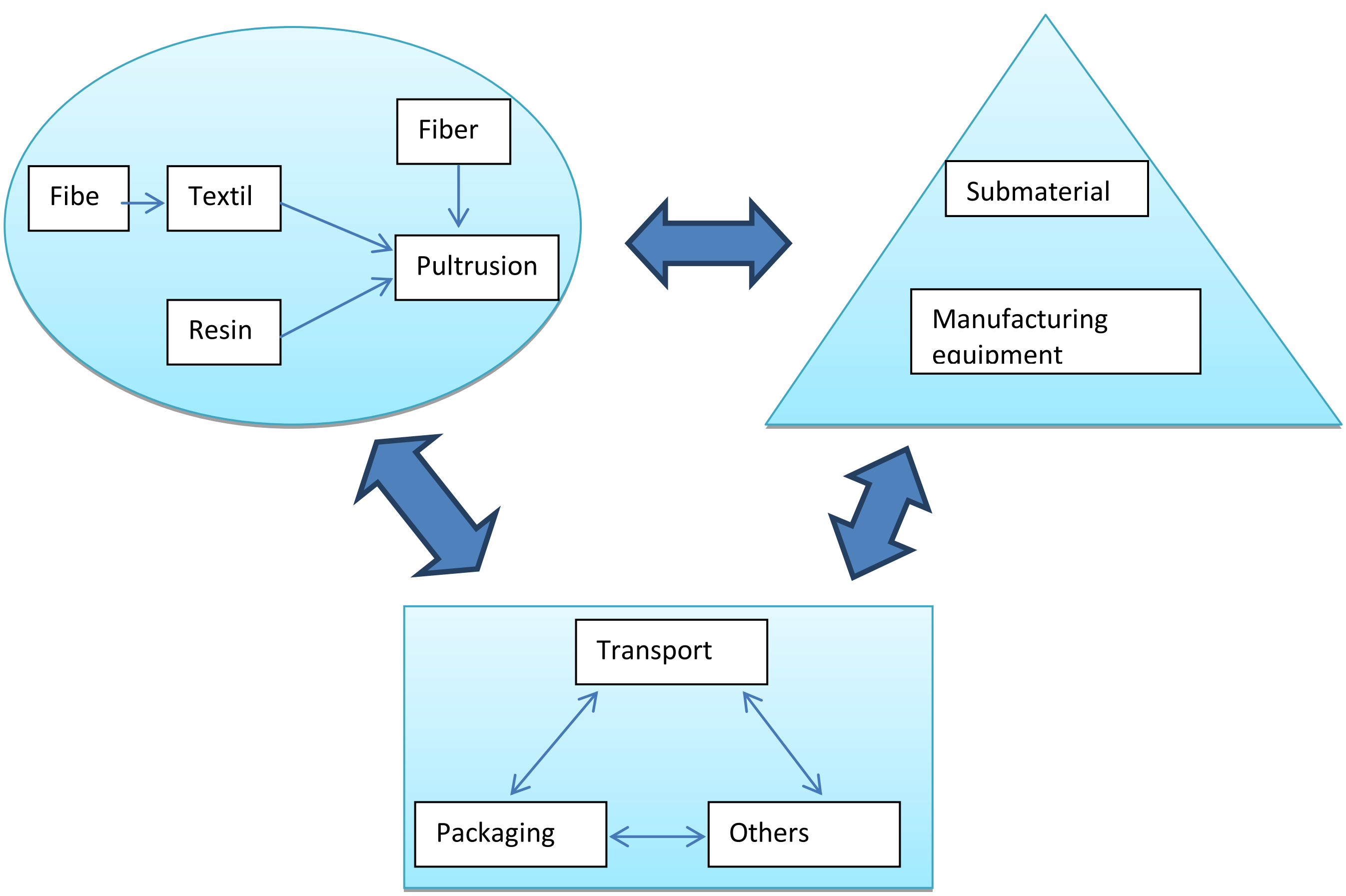

Figure 2: Schematic Description of the Hybrid Analysis Model Source: William (2004)

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Table 3: Energy consumption for composite materials estimated by hybrid analysis

	Direct fossil(MJ/kg)	Electricity(kWh/kg)	Total energy(MJ/kg)
Process analysis	8.76	0.55	11.24
Fiber production	0.045	0.177	0.672
Fabric production	n/a	n/a	33.50
Resin production	n/a	n/a	2.50
Pultrusion process			47.91
Sub-total			
Additive analysis			
Sub-material	24.76	1.00	28.24
Equipment depreciation	25.09	1.56	31.51
Sub-total	49.85	2.56	59.75
Remaining value			
analysis	15.72	0.051	16.12
Transport	23.52	1.51	29.50
Package and	6.52	0.53	09.25
documentation	45.76	2.091	54.87
Other processes			
Sub-total			162.53
Total			

The remaining activities, the so-called background processes such as transport and packaging which were not covered in either the process-level analysis or the additive one, were dealt with in the remaining value analysis. The selected remaining sectors were composed of economic activities related to transport, packaging, and other services. The remaining value analysis was carried out as follows:

$$V_P = \sum Exp_k \ .\ valuc - added\ share_k$$
(4.4)

where the $valuc - added$ similar to a value-added concept is defined as

$$valuc - added = value - added + energy - capital$$
(4.5)

The used data were based on the statistics from the US Annual Survey of Manufactures and typical producer prices (US Census Bureau, 2004 & 2005).

The monetary value of the additive analysis was obtained by addition of the expenditure given in Equ (4.3).

$$V_A = \sum Exp_j$$
(4.6)

The total remaining value (RV) was expressed as

$$RV = product\ price - V_P - V_A$$
(4.7)

Finally, the remaining value factor was cast as

$$E_{RV} = RV \sum (Value\ share_l \ .\ E_l^{SC}$$
(4.8)

As a result, the total economic value associated with the process analysis is USD $25.55: $0.86 for fiber,

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$2.23 for fabrics, $0.96 for resin, and $21.5 for the pultrusion process. When the producer price of pultruded composite of 1 kg is $60, the remaining value is $29.40 (= $60 (the total value) – $25.55 (the process value) – $1.55 (the sub-material value) – $3.50 (the equipment value)). The remaining value shares and related energy intensities were listed in Table 4. The sector of laminated plastic plates and sheets in the input–output model was employed. Total 28 sectors accounting for meaningful values were selected in the remaining value analysis and they were categorized into transportation, packaging and documentation, and other processes. Table 3 shows that the energy consumed by the economic activities related to the remaining sectors is 54.87 MJ. Overall, the total energy required for a 1 kg pultruded composite part was estimated to be 162.53MJ.

Table 4.Remaining value shares and related values for IO sectors [53]

Sector #		RV share (%)	Fossil (MJ/$)	Elec. (kWh/$)	Fossil (MJ/kg)	Elec. (kWh/kg)	Total (MJ/kg)
	Transport						
484000	**Truck transportation**	**8.18**	**0.49285**	**0.001558**	**8.89594**	**0.02812**	**8.99718**
482000	**Rail transportation**	**1.76**	**0.136577**	**0.000168**	**2.46521**	**0.00303**	**2.47613**
481000	**Air transportation**	**1.38**	**0.154833**	**0.00034**	**2.79474**	**0.00614**	**2.81683**
48A000	**Scenic and sightseeing**	**0.95**	**0.038081**	**0.000539**	**0.68736**	**0.00973**	**0.72239**
492000	**transportation and**	**0.91**	**0.0521**	**0.000028**	**0.94041**	**0.00051**	**0.94222**
491000	**support activities for tr**	**0.52**	**0.001193**	**0.000214**	**0.02153**	**0.00386**	**0.03544**
483000	**Couriers and**	**0.23**	**0.056153**	**0.000019**	**1.01356**	**0.00034**	**1.01480**
485000	**messengers**	**0.12**	**0.00684**	**0.000016**	**0.12346**	**0.00029**	**0.12450**
	Postal service						
	Water transportation						
3221A0	**Transit and ground**	**19.60**	**1.363464**	**0.087727**	**24.61053**	**1.58347**	**30.31103**
32311A	**passenger**	**1.08**	**0.003512**	**0.000913**	**0.06339**	**0.01648**	**0.12272**
32222A	**transportation**	**0.41**	**0.003172**	**0.00033**	**0.05725**	**0.00596**	**0.07870**
	Packaging,						
420000	**Documentation**	**25.86**	**0.172796**	**0.011805**	**3.11897**	**0.21308**	**3.88606**
550000	**Paper and paperboard**	**13.70**	**0.039672**	**0.011952**	**0.71608**	**0.21573**	**1.49272**
531000	**mills**	**3.91**	**0.020592**	**0.007094**	**0.37169**	**0.12805**	**0.83265**
52A000	**Commercial printing**	**3.06**	**0.002511**	**0.000087**	**0.04532**	**0.00157**	**0.05098**
513300	**Coated and laminated**	**2.24**	**0.003696**	**0.00054**	**0.06671**	**0.00975**	**0.10180**
5419A0	**paper and packaging**	**2.16**	**0.003819**	**0.000571**	**0.06893**	**0.01031**	**0.10604**
541300	**materials**	**1.93**	**0.002317**	**0.000497**	**0.04182**	**0.00897**	**0.07412**
33441A		**1.86**	**0.00405**	**0.001195**	**0.07310**	**0.02157**	**0.15075**
541700	**Other processes**	**1.73**	**0.000759**	**0.001033**	**0.01370**	**0.01865**	**0.08082**
811300	**Wholesale trade**	**1.51**	**0.003293**	**0.000381**	**0.05944**	**0.00688**	**0.08420**

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561300 541800 230320 562000 493000 4A0000 561900	Management of companies and enterprises Rea estate Monetary authorities and depository credit intermediation Telecommunications	1.14 1.14 1.11 1.10 0.98 0.89 0.54	0.000497 0.001793 0.00147 0.085774 0.070153 0.005438 0.004833	0.00002 0.000257 0.000358 0.001318 0.002009 0.001057 0.000166	0.00897 0.03236 0.02653 1.54822 1.26626 0.09816 0.08724	0.00036 0.00464 0.00646 0.02379 0.03626 0.01908 0.00300	0.01027 0.04906 0.04980 1.63386 1.39681 0.16684 0.09802
Total	All other miscellaneous professional and technical services Architectural and engineering services All other electronic component manufacturing Scientific research and development services Commercial machinery repair and maintenance Employment services Adverting and related services Maintenance and repair of nonresidential buildings Waste management and remediation services Warehousing and storage Retail trade Other support services	100			49.31690	2.38607	57.90673

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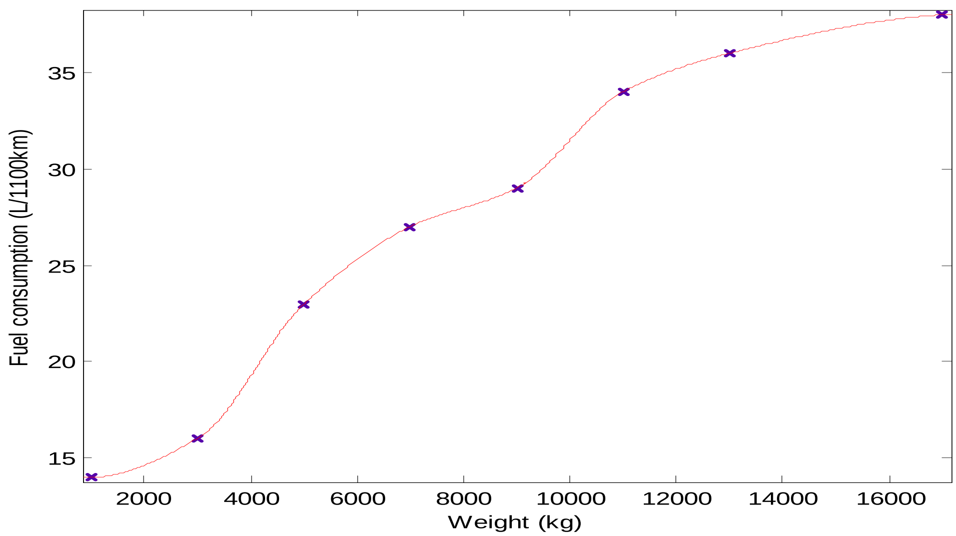

Figure 3i: Fuel efficiency with respect to curb weight for heavy vehicles [47]

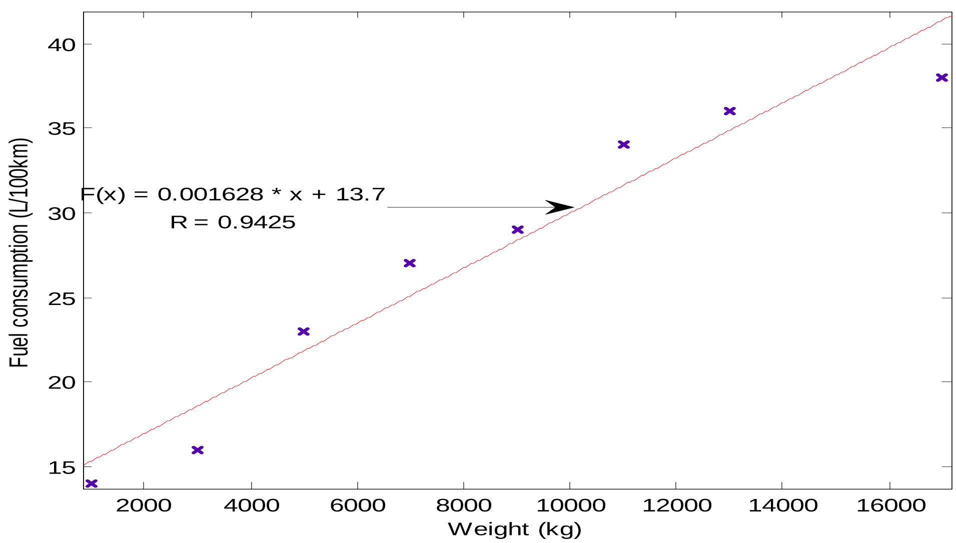

Figure 3ii: Linearized fuel efficiency with respect to curb weight for heavy vehicles [47]

These findings show that besides the process-level analysis, the additive and remaining value analyses make significant contributions to the total energy intensity of composites.

For the use period of pultruded composites, trucks and buses were selected because of the shape limitation of the pultrusion process. Although the average weight of vehicles has been increased since the late 1980's, weight reduction by means of substitution of lightweight materials is a viable strategy to reduce energy use. Before investigating mass reductions, it is necessary to determine the relationship between fuel efficiency and curb weight of

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heavy vehicles including trucks and buses. As presented in Figure 3, the quadratic regression equation was employed to evaluate the effect of fuel savings by weight reduction. We chose a middle sized truck with a total curb weight of 3600 kg. Among its steel parts, the rear body with fairly simple structure was assumed to be replaceable with pultruded composites. The rear body possesses a weight of 643 kg (17.9% of the total truck weight) (Suzuki, Hukuyama, Zushi, Origuchi, and Takahashi, 2003). Additionally, this research considered a bus with its total weight of16,980 kg, and its exterior finish was selected to be lightened by substitution of composites. The weight of the exterior finish was723 kg, which corresponds to 4.26% of the total bus weight (Martec Limited Prevost Car and Virtural Prototyping Technology Inc., 2000).

In this research, aluminum was compared with composite materials as well as steel. In order to determine how much weight was saved through replacing steel parts with composites or aluminum, equivalent reinforcing mass was calculated by using the beam theory, i.e., E1/3/q based on a stiffness-controlled design (Ashby, 1992). Consequently, glass/unsaturated polyester composites of 1.0 kg have the same stiffness as 1.8 kg steel and 0.9 kg aluminum. In the total weight reduction calculation, the secondary weight reduction caused by the use of lighter and smaller structures was considered as well as the primary weight savings. The secondary mass reduction was reported to be approximately half the primary one (Hawken, Lovins, and Lovins, 1999). Compared to a steel truck of around 3600 kg, composites and aluminum can provide 429 kg and 482 kg weight savings, respectively. Such weight reductions offer considerable energy savings in the use period, which accounts for the biggest amount of energy consumption in the automotive life cycle. The total traveling distance of the truck was assumed to be 190,000 km for ten years and that of the intercity bus was 3,200,000 km in 15 years (Martec Limited Prevost Car and Virtural Prototyping Technology Inc., 2000; Sullivan, William, Yester, Cobas-Flores, Chubbs, Hentges, and Pomper, 1998). Additionally, energy consumption for gasoline production was also considered in the use period.

Fiber-reinforced composites have a low caloric value due to their high fiber content. Therefore, in many cases, incineration is not suitable for energy recovery of composites. An ideal way of maximizing the energy recovery of the recycling stage is not down cycling but closed-loop recycling, in which recycled fibers can be used in the production of other polymeric composites such as short fiber-reinforced composites and SMC without losing their performance characteristics. In the present research, two options were considered for composites: (1) land fill and (2) pyrolysis. Figure 5 demonstrates the pyrolysis method schematically. Pyrolysis decomposes organic materials into gas and liquid which can be reused as fuels or chemical. As shown in the figure 5, 1 kg composites need 2.8 MJ for the pyrolysis reaction but can provide useful energies in the different forms of LPG, fuel oil and composite fillers (Henshaw, Han, and Owens, 1996). Consequently, the energy recovery of composite structures ideally obtainable through the pyrolysis method is 19 MJ/kg. Presuming landfill as an end-of-life scenario for composites, we cannot obtain any recovery energy from composites. Therefore, the energy savings of the composite truck will be reduced by 19 MJ/kg in the end-of-life period.

We can understand the effect of replacement with composites in the automotive application from comparison of the life cycle energy of composites with those of steel and aluminum. Considering the primary and secondary production energies of steel and aluminum and assuming a 100% recycling rate, energy credits of steel and aluminum are 21.9 MJ/kg and 172 MJ/kg, respectively (Das, 2000). It is noted that very high production energy of aluminum gives rise to its high energy credit. For fair comparison between composites, steel, and aluminum, the process-level energy intensity of composites was adopted since hybrid analyses on steel and aluminum were not taken into account. The life cycle energy savings obtained from lightening vehicle weights are presented in Figure 6a and

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b. Figure 6a. shows the energy savings throughout the life cycle for trucks when assuming that steel parts are replaced with composites or aluminum. The comparison between the steel and composite trucks indicates that a great part of the energy savings is achieved in the use phase and that the composite structure is more environmentally friendly than the steel part. On the other hand, the aluminum truck can save more energy than the composite truck although aluminum requires more manufacturing energy.

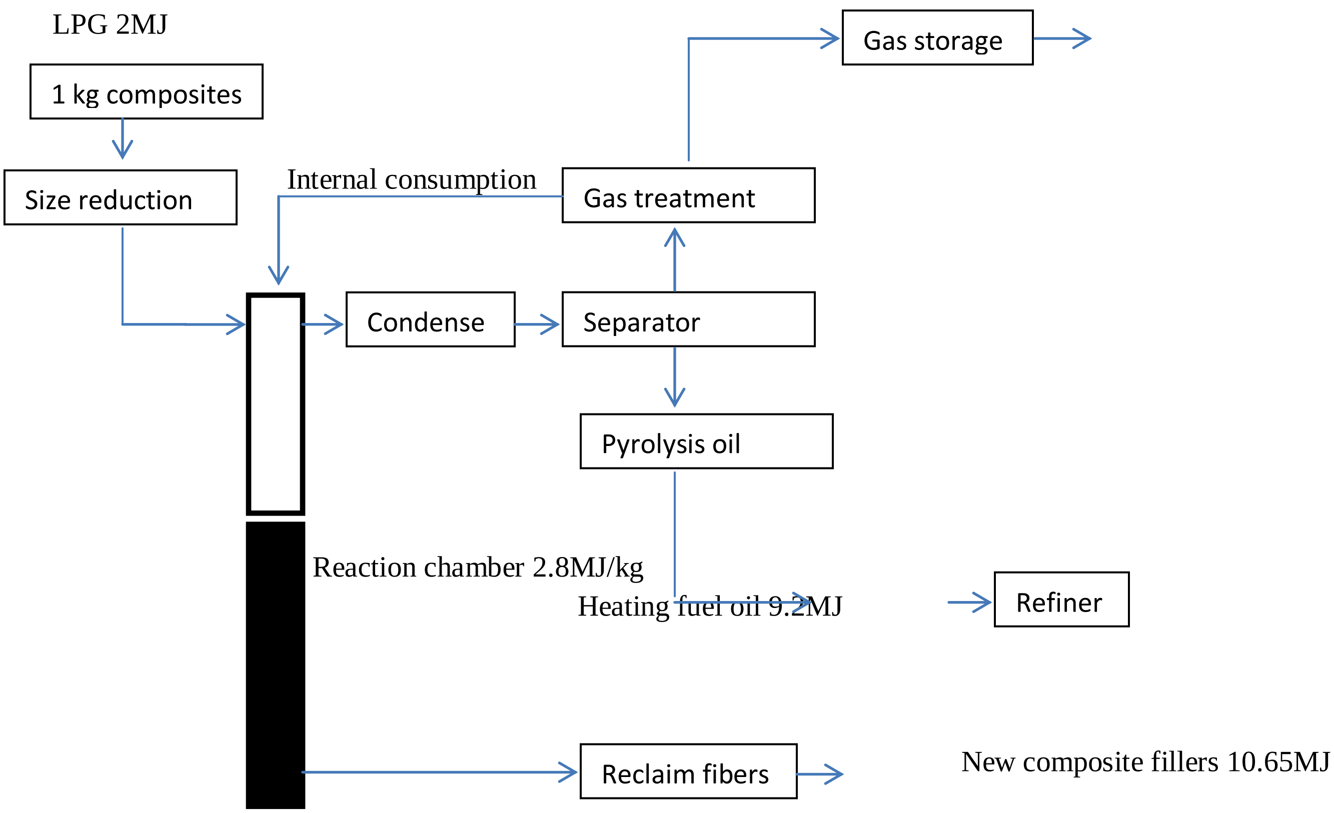

Figure 5: Schematic diagram of pyrolysis for composites and energy credits. Source: Scheir (1998)

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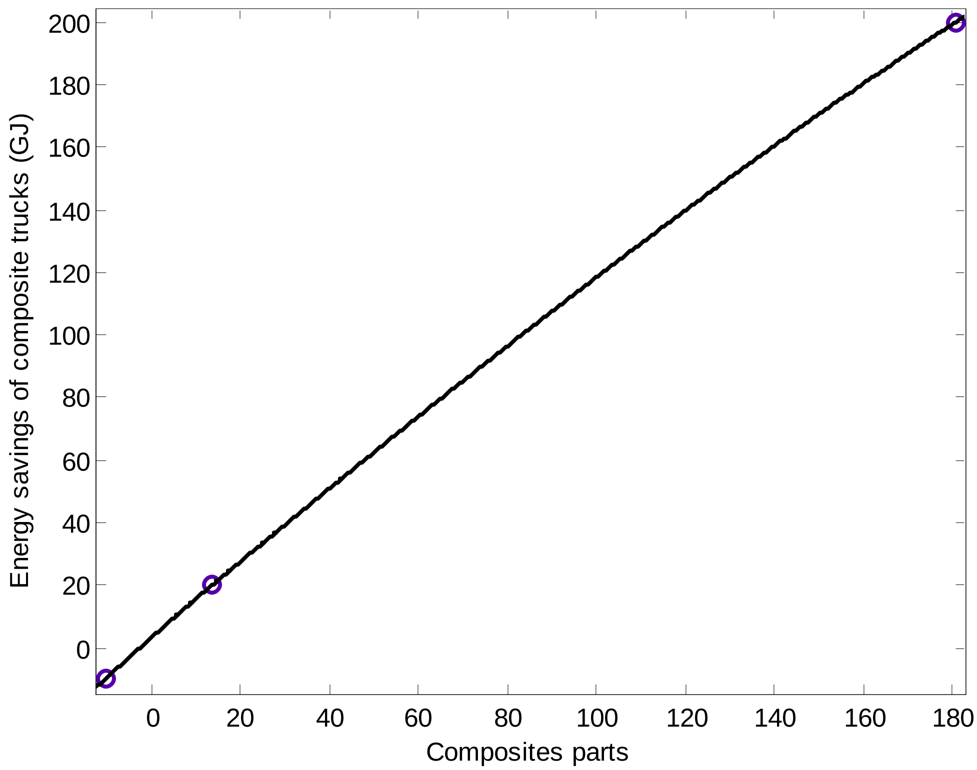

Figure 6ai: Life cycle energy savings from replacement of steel vs. composites for trucks

Table 6ai: Analysis table of life cycle energy savings from replacement of steel vs. composites for trucks

Xi	f(Xi)	df(Xi)/dX	$d^2f(Xi)/dX^2$	Integral f(Xi)
-10.4	-10	1.27191	0.00233338	0
8.74	14.1642	1.22134	-0.00761752	41.3951
27.88	36.7547	1.16805	-0.00078582	529.899
47.02	58.9547	1.15105	-0.000990358	1446.36
66.16	80.7919	1.13014	-0.0011949	2784.37
85.3	102.191	1.10531	-0.00139943	4536.28
104.44	123.078	1.07657	-0/00160397	6692.98
123.58	143.377	1.04391	-0.00180851	9243.96
142.72	163.014	1.00734	-0.00201305	12177.2
161.86	181.913	0.96685	-0.00221759	15479.4
181	200	0.96685	-0.00242212	19135.7

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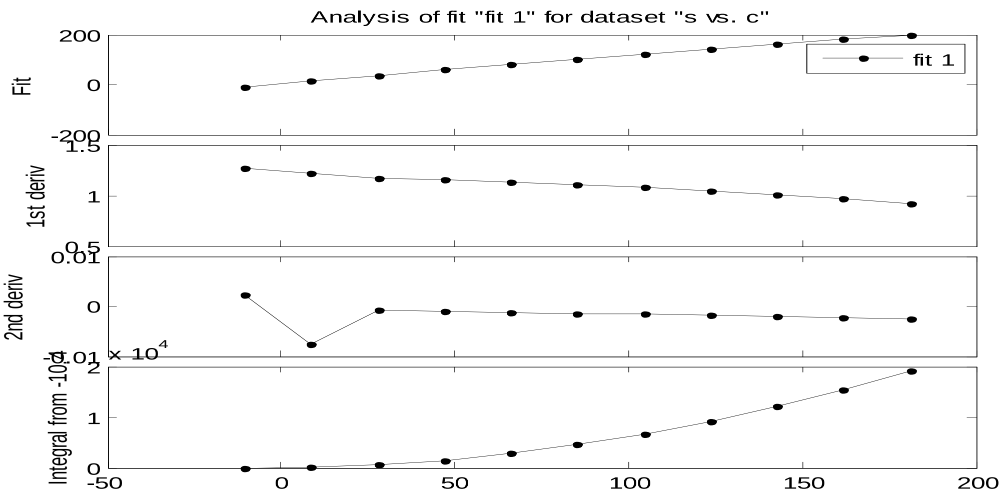

Figure 6aii: Fits of analysis of life cycle energy savings from replacement of steel vs. composites for trucks

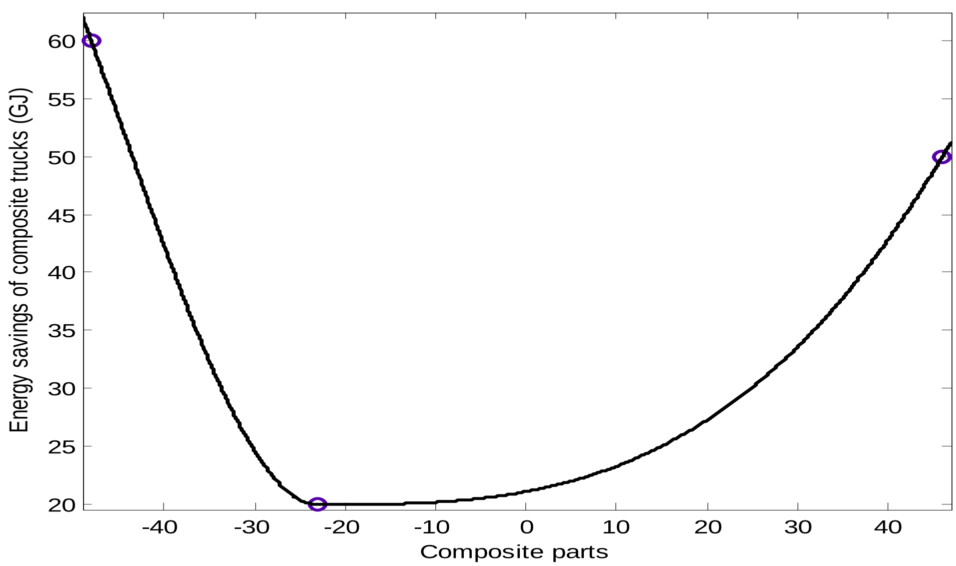

Figure 6aiii: Life cycle energy savings from replacement of aluminum vs. composites for trucks

Table 6aii: Analysis table of life cycle energy savings from replacement of aluminum vs. composites for trucks

Xi	f(Xi)	df(Xi)/dX	$d^2f(Xi)/dX^2$	Integral f(Xi)
-48.1	60	-2.13468	-0.0407586	0
-38.69	39.5002	-2.0744	0.0535705	467.704
-29.28	23.744	-1.12648	0.1479	758.274
-19.87	20.0028	0.00268401	0.00171502	954.53

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-10.46	20.1801	0.0430814	0.00687104	1143.29
-1.05	20.9658	0.131997	0.0120271	1336.23
8.36	22.8165	0.269431	0.0171831	1541.21
17.77	26.1887	0.455383	0.0223391	1770.41
27.18	31.5389	0.689853	0.0274951	2040.28
36.59	39.3239	0.972841	0.0326512	2371.6
46	50	1.30435	0.0378072	2789.43

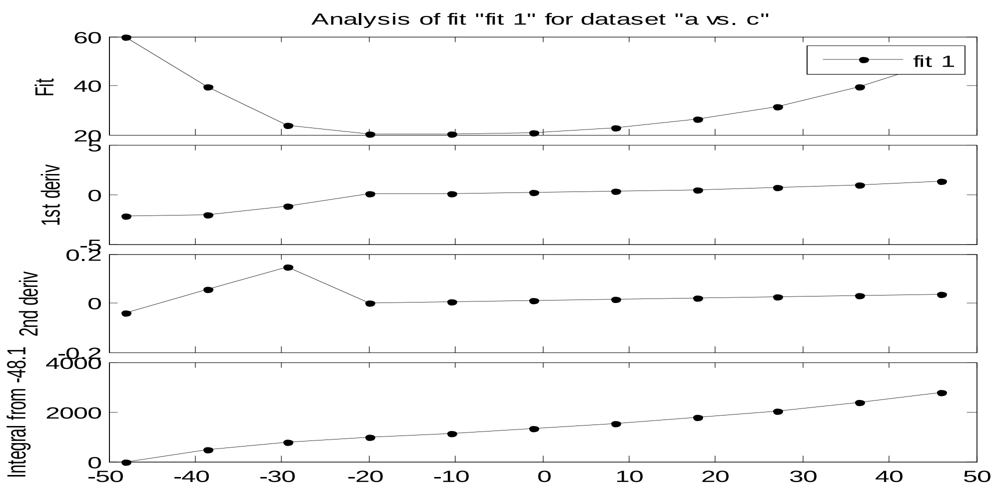

Figure 6aiv: Fits of analysis of life cycle energy savings from replacement of aluminum vs. composites for trucks

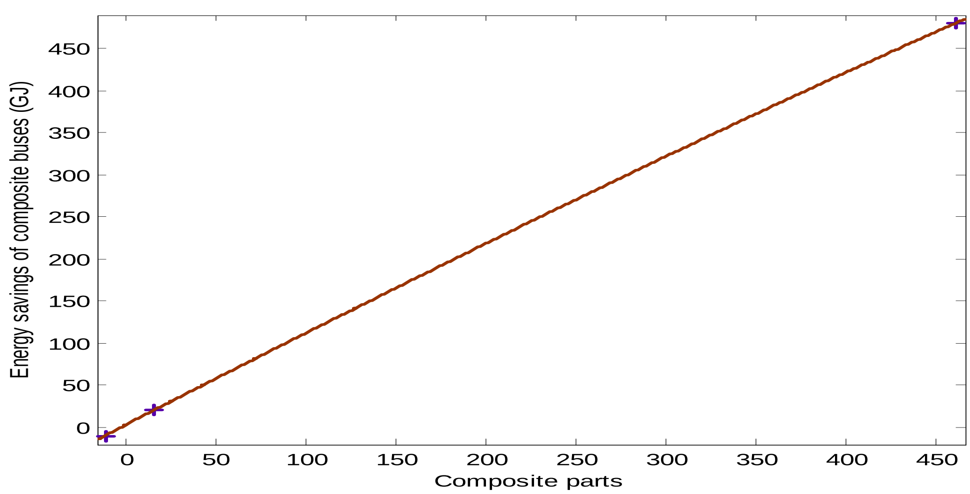

Figure 6bi: Life cycle energy savings from replacement of steel vs. composites for buses

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Table 6bi: Analysis table of life cycle energy savings from replacement of steel vs. composites for buses

Xi	f(Xi)	df(Xi)/dX	$d^2f(Xi)/dX^2$	Integral f(Xi)
-11.4	-10	1.12877	0.00177367	0
35.84	42.3515	1.08675	-0.000146405	776.277
83.08	93.5108	1.07886	-0.00018757	3986.81
130.32	144.252	1.06903	-0.000228735	9604.59
177.56	194.482	1.05725	-0.000269901	17607.7
224.8	244.11	1.04353	-0.000311066	27969.8
272.04	293.044	1.02786	-0.000352232	40660.2
319.28	341.192	1.01025	-0.000393397	55644.2
366.52	388.461	0.990692	-0.0004345462	72882.2
413.76	434.762	0.969191	-0.000475728	92330.7
461	480	0.945745	-0.000516893	113942

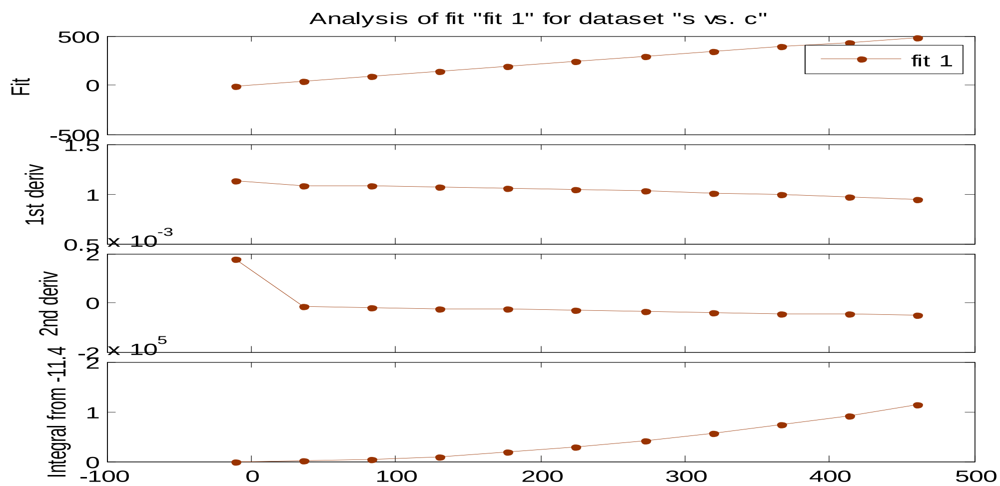

Figure 6bii: Fits of analysis of life cycle energy savings from replacement of steel vs. composites for buses

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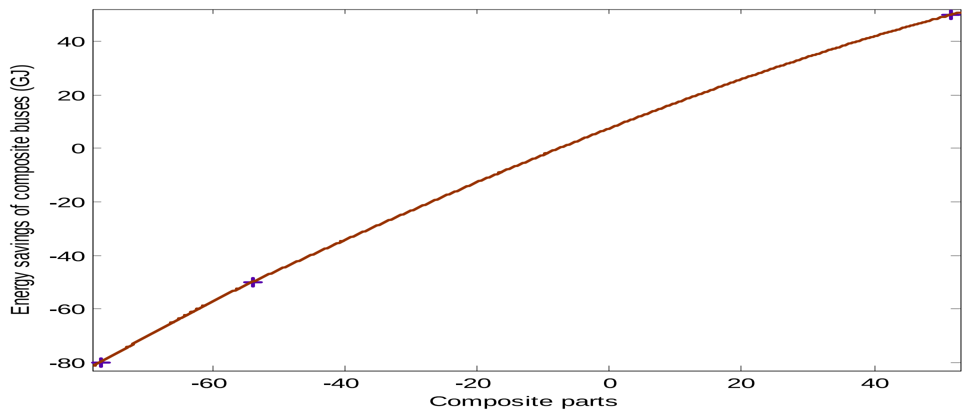

Figure 6biii: Life cycle energy savings from replacement of aluminum vs. composites for buses

Table 6bii: Analysis table of life cycle energy savings from replacement of aluminum vs. composites for buses

Xi	f(Xi)	df(Xi)/dX	$d^2f(Xi)/dX^2$	Integral f(Xi)
-77	-80	1.36838	0.00355513	0
-64.13	-62.5174	1.31558	-0.0117591	-916.37
-51.26	-46.8952	1.13082	-0.00175181	-1617.47
-38.39	-32.5066	1.10361	-0.00247691	-2128.05
-25.52	-18.5283	1.06707	-0.00320202	-2455.95
-12.65	-5.08038	1.02119	-0.00392713	-2607.24
0.22	7.71707	0.965981	-0.00465223	-2589.51
13.09	19.7439	0.901441	-0.00537734	-2411.91
25.96	30.8801	0.827568	-0.00610245	-2085.13
38.83	41.0055	0.744364	-0.00682755	-1621.39
51.7	50	0.651827	-0.00755266	-1034.5

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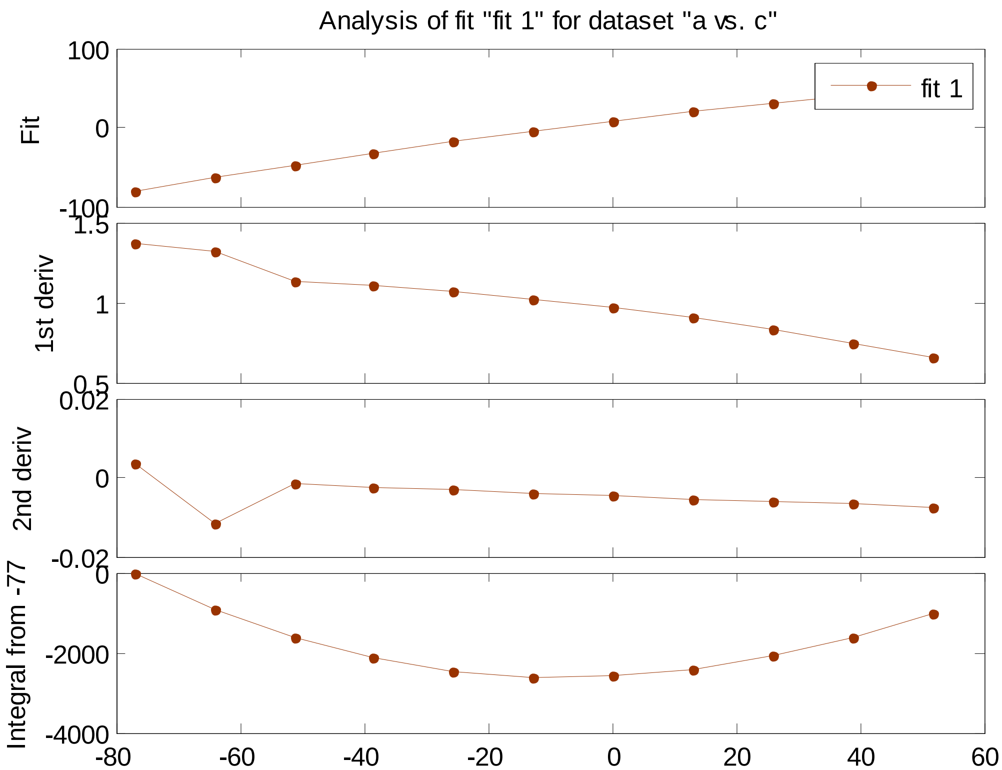

Figure 6biv: Fits of analysis of life cycle energy savings from replacement of aluminum vs. composites for buses

The recycling phase makes the biggest contribution to the energy savings of aluminum over composites. On the other hand, if the hybrid analysis of composites is considered in the manufacturing phase in lieu of the process- level energy intensity of composites, the energy savings from substitution for steel and aluminum are estimated to be -29.1 GJ and 3.33 GJ, respectively. These results are preliminary estimations due to the difference of energy analysis levels among steel, aluminum, and composites, yet similar conclusions still hold. The results of the research for the bus are presented in Figure 6b. The overall trend is quite similar to the results of the truck presented in Figure 6a. The longer the traveling distance of the bus, the more significant the use period makes in estimating the life cycle energy savings. Given the energy consumption of composites estimated through hybrid analysis, the energy savings of the composite bus in the manufacturing stage become -32.8 GJ and 3.66 GJ in the case of steel and aluminum, respectively. In summary, replacing steel with composites in automotive applications results in a positive effect on the energy savings, which is environmentally benign. However, looking into the composite and aluminum vehicles, composite materials turn out to consume more energy over their life time, which seems to be a significant barrier to overcome for expanding the use of composites in the auto industry.

5. Conclusions

In the current research, synthetic glass fiber-reinforced polyester polymer composite hybrid life cycle energy analysis was carried out to estimate energy for producing pultruded composite structure. The environmental impact of pultruded composite structures over the entire life cycles was investigated by calculating energy use. The results of the hybrid analysis indicated that economic input–output sectors associated with the pultrusion process have significant contribution to the total energy use compared to the energy consumption obtained from process-level analysis. All of the life cycle stages, i.e., material production, manufacturing, use, and end-of life periods, were taken into account in an effort to look into a possibility of using pultruded composites in the auto industry, especially for trucks and buses. Three cases of steel, composites, and aluminum vehicles were analyzed and compared in the entire life cycle. Since energy consumption of the use stage dominates the life cycle energy use of automobiles, lighter materials are more favorable for saving the life cycle energy. The findings of this research depicted that pultruded composite parts saves more energy in the application to trucks and buses than steel but in opposite to aluminum.

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