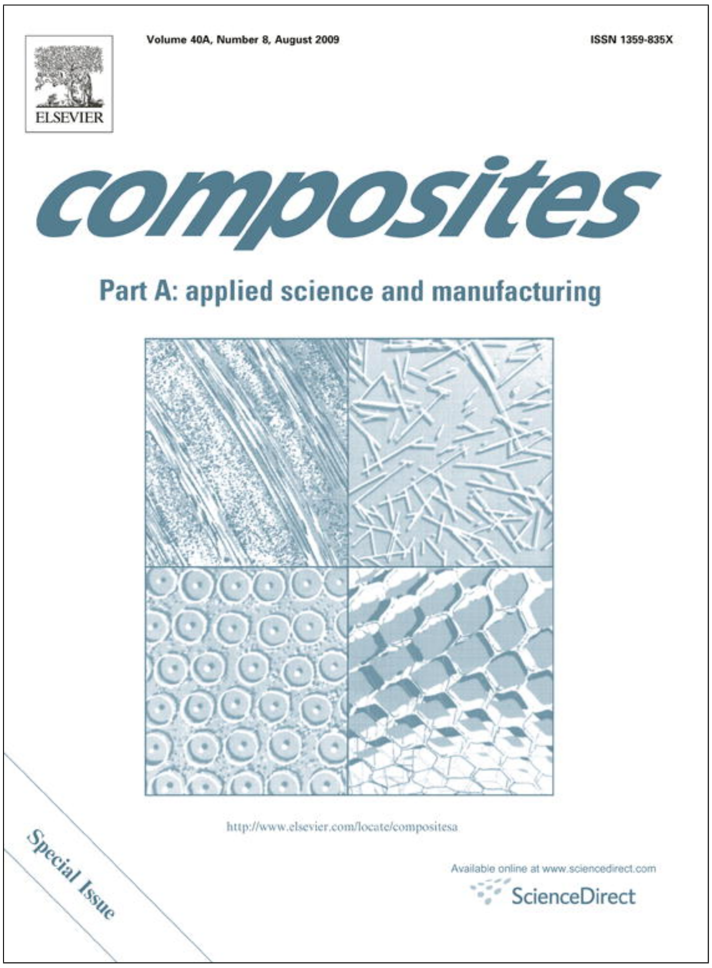
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Life cycle energy analysis of fiber-reinforced composites

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ABSTRACT

Life cycle assessment is a technique to assess environmental aspects associated with a product or process by identifying energy, materials, and emissions over its life cycle. The energy analysis includes four stages of a life cycle: material production phase, manufacturing phase, use phase, and end-of-life phase. In this study, the life cycle energy of fiber-reinforced composites manufactured by using the pultrusion process was analyzed. For more widespread use of composites, it is critical to estimate how much energy is consumed during the lifetime of the composites compared to other materials. In particular, we evaluated a potential for composite materials to save energy in automotive applications. A hybrid model, which combines 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.

1. Introduction

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 is growing interest in understanding these effects and the differences between products. Recently, producers and consumers are using life cycle assessment (LCA) to evaluate the life cycle of products, materials, and services [1,2]. Furthermore, when corporate and public decision is made, LCA increasingly serves as one of the key factors in environmental management.

Cost estimation models (CEMs) indicate that composite structures may be cost-effective in some applications because they can eliminate large assembly costs [3,4]. 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 phase.

Several LCA analyses for composite applications have been carried out and reported [5–11]. 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 [5]. Other interesting application areas are wind turbines and bridge decks [9–11]. Rankine et al. investigated the energy use and carbon emission of a rooftop wind turbine and showed that microgeneration may be a good means of lowering carbon emission by using small generators in the house [9]. Meiarashi et al. analyzed the life cycle cost of all-composite suspension bridge and compared conventional steel bridges with composite ones [10]. In recent years, composites made of bio-fiber and resin system have attracted lots of attention as a substitute for synthetic fiber and resin [12,13].

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 carry out a life cycle assessment in order to look into energy flows throughout the lifetime of pultruded composites, i.e., cradle to grave as shown in Fig. 1. The current study is organized as follows: firstly we review the LCA methods, especially hybrid analysis. Two typical analysis methods, process-level analysis and economic input–output model analysis, are covered and their strength and weakness are described. Secondly, a variety of materials and composite manufacturing methods are reviewed and compared in terms of energy intensities. Then, hybrid analysis for the pultrusion process is conducted, in which automotive application is taken into account for the use phase. In this analysis, we show the feasibility of replacing steel with advanced composite structures or aluminum. We end 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

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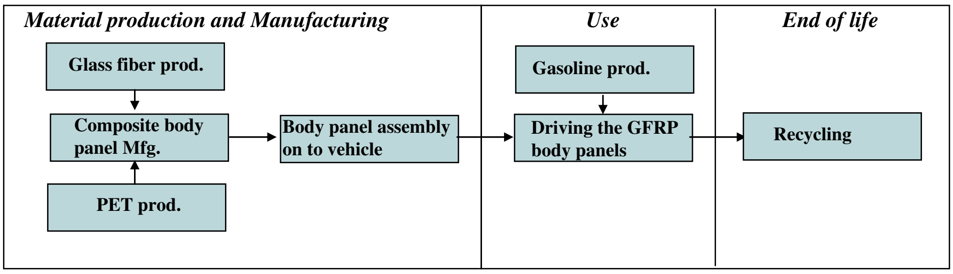

Fig. 1. Life cycles of pultruded composites considered in this study.

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 [14–16]. 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 [17]. 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 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) [18].

The framework of LCA includes the following four stages: first, the goal and scope of a study investigated are defined. Then, a model is prepared for the product life cycle with all the energy and materials inflows and outflows, referred to as LCI. Third, the environmental impact assessment is done based on the understanding of the environmental relevance of all the inflows and outflows during a life cycle. Finally, the entire results are interpreted. A system boundary for LCA, through which inputs such as energy and materials and outputs including goods and activities come and go, is defined. Considering material flows starting with extraction of raw materials and ending with disposal of waste products, the stages of a product life cycle consist 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 is estimated and their environmental burdens are 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 are used to assess the life cycle of products, materials, or processes: process-level analysis and economic input–output analysis. Most LCAs have been performed based on process analysis where the resource uses, environmental releases from the main production processes, and some important contributions from suppliers are assessed in detail. With use of facility-level data, the system is 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 [19] 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 will show 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 [20]. 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 analyses combining 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.

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 [21–23]. Hybrid analysis which blends process analysis with input–output analysis makes up for the weak points of both analysis. The current study adopts the hybrid life cycle analysis introduced by Williams [24].

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 analyses of others have indicated, can be quite substantial [24]. Furthermore, the hybrid approach can be further modified to try to accommodate the previously mentioned problems.

3. Life cycle stages

Prior to assessing the life cycle energy of fiber-reinforced composites, life cycle stages for composite structures, material production, manufacturing, use, and end-of-life stages are outlined in the following sections.

3.1. Material production

The first stage of the product life cycle is "material extraction" for plastics or similar materials, which involves pulling fossil fuels from the earth. These materials are then refined and separated before producing the input materials for manufacturing. The next step is to call for extraction and production of materials, called "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 [25]. 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. 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, OwensCorning, and Vetrotex [32]. OwenCorning 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 a 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, 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 et al. [38], 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 [39].

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 prepreg preparation are often required prior to integration of fibers and polymer resins. These 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

Table 1
Energy content of various materials.

Materials	Energy intensity (MJ/kg)	References
Polymers		
Polyester	63–78	[5,26–28]
Epoxy	76–80	[5,26]
LDPE	65–92	[28,29]
PP	72–112	[28,30]
PVC	53–80	[26–31]
PS	71–118	[26–28,30]
PC	80–115	[28,29]
Fibers		
Glass fiber	13–32	[30,32,33]
Carbon fiber	183–286	[5]
China reed fiber	3.6	[34]
Flax fiber	6.5	[35]
Metals		
Aluminum	196–257	[2,36,37]
Steel	30–60	[30,36,37]
Stainless steel	110–210	[2,30]
Copper	95–115	[30,37]
Zinc	67–73	[30,37]
Cast iron	60–260	[2,30,37]

Table 2
Energy intensities of manufacturing processes.

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

[a] Source: estimation in this study.
[b] Source: Ref. [5].
[c] Source: Ref. [40].
[d] Source: Ref. [32].
[e] Source: Ref. [41].

necessary for curing. As listed in the table, more automated processes such as the filament winding and pultrusion tend to spend lower energy. The pultrusion process considered in this study 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.

3.3. Use

Estimation of the use phase 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 Dreamliner, 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 order to fully appreciate the advantages of composite structures such as lightweight, long life time, high specific strength, and chemical inertness, a transportation application is selected in this study. 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 [42]. In most cases, composites are discarded to landfill. However, thinking over their extremely long life span, this option 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 feedstocks for petrochemicals [43]. Hydrolysis can retrieve monomers from specific composite materials such as polyester and polyamides [44]. Chemical recycling involves separation of the polymer matrix from reinforcing fibers, thereby allowing reuse of the fibers [45]. 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 phase acts as a major barrier to environmental friendly large scale applications of composite materials owing to no viable restorative recycling methods.

4. Case study: hybrid analysis for pultruded composite parts

The composite system considered in the current study is glass fiber/unsaturated polyester. As a composite manufacturing method, the pultrusion process is selected and automotive application of the composite materials is assumed in the use phase. In the material production and manufacturing stages, the major industrial activities associated with glass fiber/unsaturated polyester composites are glass fiber production, unsaturated polyester production, fabric manufacturing, and pultrusion. It is well-known that reinforcing fibers and polymer resins generally used in composites have relatively high energy input requirements, thus resulting in high energy intensities [32]. The weight fraction of glass fiber is assumed to be 50% and textile production of glass fabrics requiring 2.58 MJ/kg is also taken into account for sandwich structure with three layers [32].

The hybrid analysis proposed by William [24] is 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. Fig. 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, the three analyses are connected and contribute to the total energy required for making composites. The main concept of the hybrid life cycle assessment can be given by the following equations:

$$\textit{Total energy} = \textit{process sum result} + \textit{IO correction factor} \quad (1)$$

$$\textit{IO correction factor} = E_A + E_{RV} \quad (2)$$

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 efficeintly. Table 3 indicates that a process-level energy of 50.31 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 intensity from 3.1 MJ (for the pultrusion process in itself) to 50.31 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 [20]. In the additive input–output analysis, submaterial and equipment depreciation of the pultrusion process are employed as the additive factors. The submaterial includes chemicals and auxiliary materials for the pultrusion process not covered in the process-level analysis. The additive factor is written as

$$E_A = \sum Exp_j E_j^{SC} \quad (3)$$

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 submaterial and equipment are acquired from a combination of the literature, IO model, and consultation with pultrusion companies [46]. As presented in Table 3, an energy of 61.47 MJ arises from the additive factors, which is a significant amount of energy compared to the process-level energy.

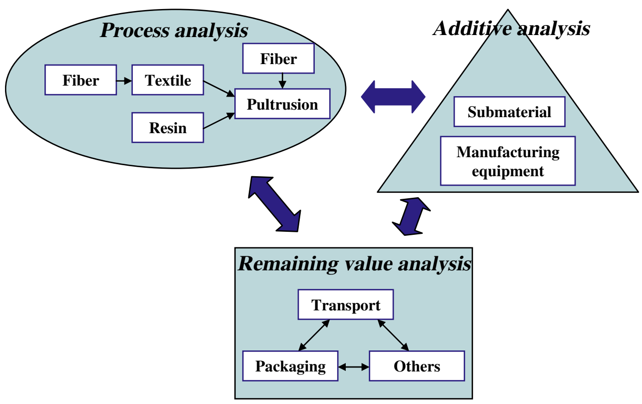

Fig. 2. Schematic description of the hybrid analysis model [24].

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

	Direct fossil (MJ/kg)	Electricity (kWh/kg)	Total energy (MJ/kg)
Process analysis			
Fiber production	9.86	0.66	12.24
Fabric production	0.056	0.199	0.772
Resin production	n/a	n/a	34.2
Pultrusion process	n/a	n/a	3.1
Sub-total			50.31
Additive analysis			
Submaterial	25.87	1.02	29.35
Equipment depreciation	26.10	1.67	32.12
Sub-total	51.97	2.69	61.47
Remaining value analysis			
Transport	16.94	0.052	17.13
Packaging and documentation	24.73	1.61	30.51
Other processes	7.64	0.73	10.26
Sub-total	49.31	2.39	57.91
Total			169.69

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

$$V_p = \sum Exp_k \cdot valuc\text{-}added\ share_k \tag{4}$$

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

$$Valuc\text{-}added = value\ added + energy - capital \tag{5}$$

The used data are based on the statistics from the US Annual Survey of Manufactures and typical producer prices [47].

The monetary value of the additive analysis is obtained by addition of the expenditure given in Eq. (3).

$$V_A = \sum Exp_j \tag{6}$$

The total remaining value (RV) is expressed as

$$RV = product\ price - V_p - V_A \tag{7}$$

Finally, the remaining value factor is cast as

$$E_{RV} = RV \sum (Value\ share_l) \cdot E_l^{SC} \tag{8}$$

As a result, the total economic value associated with the process analysis is USD $26.15: $0.86 for fiber, $2.23 for fabrics, $0.96 for resin, and $22.1 for the pultrusion process. When the producer price of pultruded composite of 1 kg is $50, the remaining value is $18.05 (= $50 (the total value) – $26.15 (the process value) – $1.65 (the submaterial value) – $4.15 (the equipment value)). The remaining value shares and related energy intensities are 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 are categorized into transportation, packaging and documentation, and other processes. Table 3 shows that

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

Sector #		RV share (%)	Fossil (MJ/$)	Elec. (kWh/$)	Fossil (MJ/kg)	Elec. (kWh/kg)	Total (MJ/kg)
	Transportation						
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 transportation and support activities for tr	0.95	0.038081	0.000539	0.68736	0.00973	0.72239
492000	Couriers and messengers	0.91	0.0521	0.000028	0.94041	0.00051	0.94222
491000	Postal service	0.52	0.001193	0.000214	0.02153	0.00386	0.03544
483000	Water transportation	0.23	0.056153	0.000019	1.01356	0.00034	1.01480
485000	Transit and ground passenger transportation	0.12	0.00684	0.000016	0.12346	0.00029	0.12450
	Packaging, Documentation						
3221A0	Paper and paperboard mills	19.60	1.363464	0.087727	24.61053	1.58347	30.31103
32311A	Commercial printing	1.08	0.003512	0.000913	0.06339	0.01648	0.12272
32222A	Coated and laminated paper and packaging materials	0.41	0.003172	0.00033	0.05725	0.00596	0.07870
	Other processes						
420000	Wholesale trade	25.86	0.172796	0.011805	3.11897	0.21308	3.88606
550000	Management of companies and enterprises	13.70	0.039672	0.011952	0.71608	0.21573	1.49272
531000	Real estate	3.91	0.020592	0.007094	0.37169	0.12805	0.83265
52A000	Monetary authorities and depository credit intermediation	3.06	0.002511	0.000087	0.04532	0.00157	0.05098
513300	Telecommunications	2.24	0.003696	0.00054	0.06671	0.00975	0.10180
5419A0	All other miscellaneous professional and technical services	2.16	0.003819	0.000571	0.06893	0.01031	0.10604
541300	Architectural and engineering services	1.93	0.002317	0.000497	0.04182	0.00897	0.07412
33441A	All other electronic component manufacturing	1.86	0.00405	0.001195	0.07310	0.02157	0.15075
541700	Scientific research and development services	1.73	0.000759	0.001033	0.01370	0.01865	0.08082
811300	Commercial machinery repair and maintenance	1.51	0.003293	0.000381	0.05944	0.00688	0.08420
561300	Employment services	1.14	0.000497	0.00002	0.00897	0.00036	0.01027
541800	Advertising and related services	1.14	0.001793	0.000257	0.03236	0.00464	0.04906
230320	Maintenance and repair of nonresidential buildings	1.11	0.00147	0.000358	0.02653	0.00646	0.04980
562000	Waste management and remediation services	1.10	0.085774	0.001318	1.54822	0.02379	1.63386
493000	Warehousing and storage	0.98	0.070153	0.002009	1.26626	0.03626	1.39681
4A0000	Retail trade	0.89	0.005438	0.001057	0.09816	0.01908	0.16684
561900	Other support services	0.54	0.004833	0.000166	0.08724	0.00300	0.09802
Total		100			49.31690	2.38607	57.90673

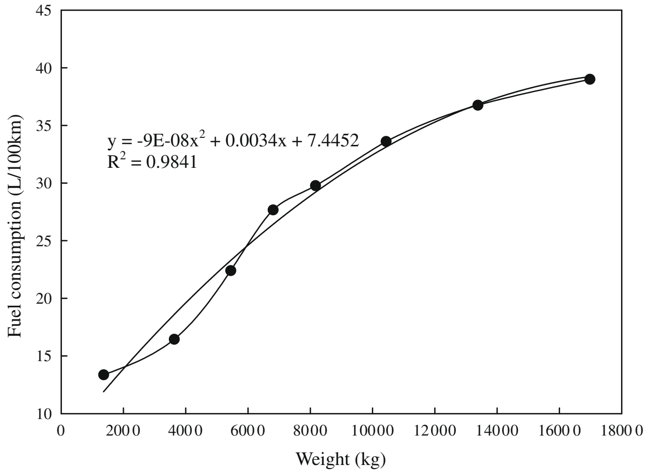

Fig. 3. Fuel efficiency with respect to curb weight for heavy vehicles [47].

the energy consumed by the economic activities related to the remaining sectors is 57.9 MJ. Overall, the total energy required for a 1 kg pultruded composite part is estimated to be 169.7 MJ. 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 phase 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 heavy vehicles including trucks and buses. As presented in Fig. 3, the quadratic regression equation was employed to evaluate the effect of fuel savings by weight reduction. We chose a middle sized Isuzu N-series with a total curb weight of 3600 kg as shown in Fig. 4a. 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) [48]. Additionally, this study considered a Provost Car XLII bus as demonstrated in Fig. 5b. Its total weight is 16,980 kg, and its exterior finish was selected to be lightened by substitution of composites. The weight of the exterior finish is 723 kg, which corresponds to 4.26% of the total bus weight [49].

In this study, aluminum was compared with composite materials as well as steel. In order to determine how much weight is saved through replacing steel parts with composites or aluminum, equivalent reinforcing mass was calculated by using the beam theory, i.e., $E^{1/3}/\rho$ based on a stiffness-controlled design [30]. 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 [50]. 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 phase, which accounts for the biggest amount of energy consumption in the automotive life cycle. The total traveling distance of the truck is assumed to be 190,000 km for ten years and that of the intercity bus is 3,200,000 km in 15 years [49,51]. Additionally, energy consumption for gasoline production was also considered in the use phase.

(a)

(b)

Fig. 4. Pictures of (a) the truck and (b) the bus selected in this study.

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 study, two options were considered for composites: (1) land fill and (2) pyrolysis. Fig. 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, 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 [52]. 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 phase.

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 [36]. 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 is adopted since hybrid analyses on steel and aluminum are not taken into account. The life cycle energy savings obtained from lightening vehicle weights are presented in Fig. 6a and b. Fig. 6a

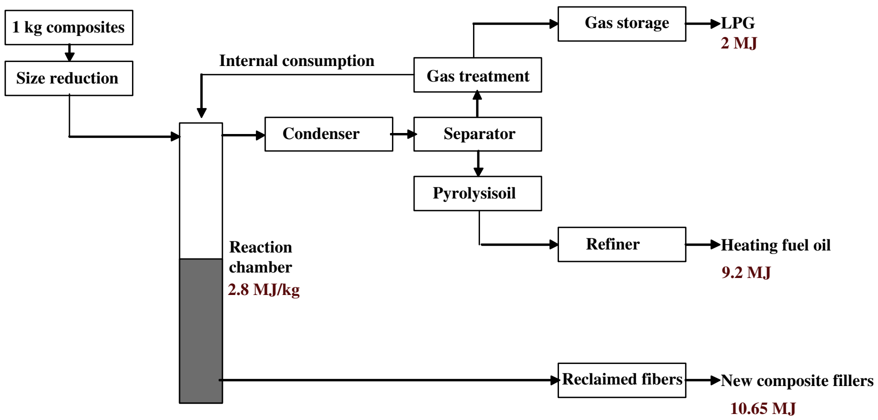

Fig. 5. Schematic diagram of pyrolysis for composites and energy credits [42].

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. The recycling phase

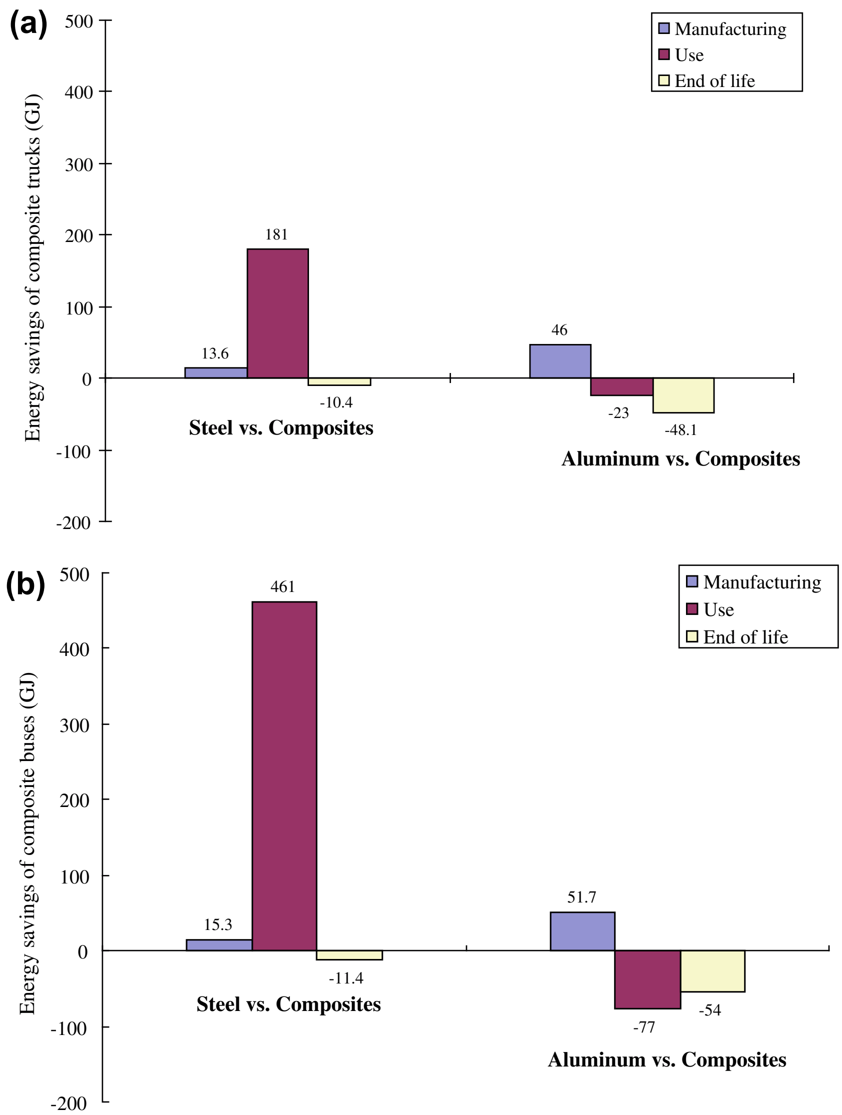

Fig. 6. Life cycle energy savings from replacement of steel with aluminum and composites for (a) trucks and (b) buses.

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 case study for the bus are presented in Fig. 6b. The overall trend is quite similar to the results of the truck. The longer traveling distance of the bus makes the use phase more significant 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 study, life cycle 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 indicate 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 phases, 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 study show that pultruded composite parts can save more energy in the application to trucks and buses than steel but not aluminum.

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