Beyond Industrial Energy Assessments: The Life Cycle Design Perspective

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ABSTRACT

Industry is increasingly challenged with moving toward sustainable production. Industrial energy assessments can identify some improvements in existing manufacturing processes of current products. However, a more comprehensive approach that considers the entire product lifecycle from raw material extraction through the manufacturing process, use phase, and the end-of-life management offers much greater potential for overall resource efficiency. In fact, a systematic lifecycle approach is critical for driving innovative, sustainable product and process design. In this paper, we propose a methodology for considering industrial energy efficiency from the lifecycle perspective and investigate how it could be integrated into existing methods of improving energy efficiency. A general methodology is posed and a case-study approach is employed to demonstrate the efficacy of the methodology. There are four methods to be examined. We begin by analyzing the baseline energy consumption of an existing industrial facility. Second, we consider how energy efficiency can be improved from current production by a traditional energy assessment. Third, in an enhanced energy assessment, we explore the energy efficiency potential of alternative production technologies and/or the entire elimination of unnecessary processes. Finally, the total energy consumption over the entire product lifecycle is considered. Comparing energy use from these scenarios provides critical insights about the potential for radical improvements in sustainable manufacturing.

Introduction

Industry is a large energy consumer, and new energy standards such as ISO 50001 require industries to strongly commit to the efficient energy use on the production process and the supply chain while meeting the emission abatement goals [1]. The United States Federal Government provides free energy audits to small- and medium-sized companies through the Department of Energy's Industrial Assessment Centers programs located at 24 universities around the country. These centers identify opportunities for increasing energy efficiency and typically reduce energy use by about 5% [2]

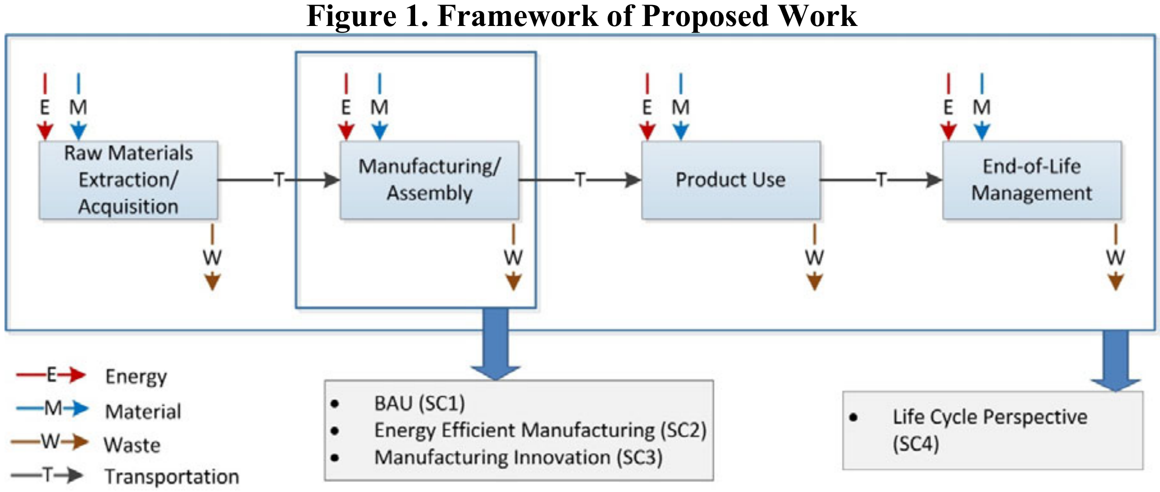
Industrial energy use is diverse and numerous changes are needed to yield large energy reduction. The methods available for improving energy efficiency are as varied as the ways industry uses energy but can be grouped into following categories: i) operational changes – maintenance, housekeeping, and accounting; ii) equipment changes – equipment improvement, equipment sizing, fuel switching, and energy management systems; iii) process refinements, and changes – equipment integration, general automation, quality control, waste minimization and utilization, recycling, raw material substitution; iv) product shifts- product refinement, materials substitution, product quality and performance [3]. The reason for these changes may or may not be related to energy, but energy use is affected nonetheless. Larger gains are obtained from retrofitting and optimizing existing facilities, while the biggest improvements come from major investments in new plants and processes. Most energy audits are focused on the first two categories with some attention to the third category. Typically, little attention is given to a holistic change of the production processes with innovative process planning. Even further, product life cycle energy consumption from cradle to grave (i.e. raw material extraction/acquisition, manufacturing/assembly, product use phase, and end-of-life phase) is almost never addressed in traditional energy audits.

In this paper, we compare various options for reducing industrial energy consumption using the traditional and enhanced life cycle perspectives, and discuss benefits and challenges associated with the proposed approach. A methodology is posed to illustrate the overall framework. A case study of a heavy duty truck production is presented to demonstrate the efficacy of the proposed framework. Finally, research challenges and future research are discussed.

Proposed Framework

Figure 1 illustrates the framework for the approach used here. Each box represents one stage in a product's life cycle; raw material extraction / acquisition, manufacturing / assembly, product use phase, and the end-of-life management. In each stage, energy and materials are consumed and the certain forms of effluents (wastes) are generated. Transportation is required to deliver the output of one stage to the next phase of a product lifecycle. Although not shown in this figure, there are also reverse flows of resources through activities such as reuse, remanufacturing, and recycling at the end-of-life stages to close material loops.

Figure 1. Framework of Proposed Work



In the sections that follow, four different energy consumption scenarios will be investigated: i) baseline energy consumption scenario, ii) energy consumption after a traditional energy assessment, iii) energy consumption after integration of a manufacturing innovation, and iv) lifecycle energy consumption of the product system. A primary goal of the study is to measure and compare the energy saving potentials of these scenarios.

Baseline Energy Consumption (SC1)

This first scenario identifies the base case energy consumption of an industry's current production system and sets a business as usual (BAU) case. This evaluation is usually based on utility billing data and detailed production process data gathered from an industry. When establishing the baseline, three approaches yield considerable insight; a utility cost analysis, a plant energy balance, and an investigation of why energy use changes over time. A utility cost analysis breaks utility costs into components that relate to plant activities, and yields information about energy cost saving opportunities such as reducing peak demand and adding capacitors to improve power factor. A plant energy balance is constructed by estimating or measuring the energy use of plant equipment and calibrating the sum to the total energy consumption reported on the utility billing data. The plant energy balance provides a starting point for prioritizing energy efficiency efforts and calibrating estimates of savings. Statistical models of energy use as a function of weather and production improve understanding of why energy use changes over time. This approach, called lean energy analysis (LEA), quantifies independent, weather-dependent and production-dependent energy use [4-6]. LEA analysis identifies energy saving opportunities and provides a statistical baseline model for measuring weather-normalized and production-normalized improvements in energy efficiency over time.

Implementation of Energy Assessment Recommendations (SC2)

The second scenario considers the energy use after a plant-wide energy assessment targeted at existing operations. Many organizations perform these types of assessments. For example, the U.S. Department of Energy (DOE) supports Industrial Assessment Centers (IACs) at 24 universities throughout the U.S. The IACs are managed by the Center for Advanced Energy System, Rutgers University under contract with the Advanced Manufacturing Partnership of the Energy Efficiency and Renewable Energy division of the U.S. Department of Energy [7]. The objective of the IAC program is to identify and evaluate, through visits to industrial facilities, opportunities for energy conservation. Each IAC is funded to perform 20 (or more) no-cost assessments per year for mid-sized manufacturers. As part of an assessment, the IAC teams perform a baseline analysis, and then visits a plant for one day to work directly with facility personnel to identify and quantify the industrial energy saving opportunities. The integrated systems plus principles approach (ISPA) has proven to be especially effective. ISPA applies seven principles of energy efficiency to relevant energy systems such as electrical, lighting, motors, fluid flow, compressed air, steam, process heating, process cooling, HVAC, CHP, and renewables [7]. Energy savings can be quantified using the public-domain open-source Energy Efficiency Guidebook (EEG) a spreadsheet based tool with energy system best practices, many specific energy saving examples, and software to calculate savings [8]. After the analysis, the IACs write a customized, independent report which documents the baseline analysis and contains specific energy saving recommendations. Nine months after the site visit, the IACs follow-up with the company personnel to determine what was implemented.

Integration of Innovation (SC3)

The third scenario seeks deeper energy saving opportunities through the innovation of product and process design. For example, in the case study about a truck assembly plant that follows, significant quantities of energy are directly and indirectly related to the painting operations. Energy using equipment associated with painting includes the paint booth, dipping tanks, pumps circulating waste water, fans moving exhaust air, e-coat systems and the industrial wet well.

When questioned about the motivation for painting, plant personnel reported that the main reason for painting is to provide aesthetic appeal for a client company's image. To do so, the plant offers about 2,000 different paint colors for the truck cabs. Another important reason for painting is protection against material disintegration such as rust and corrosion. This scenario considers a hypothetical case of process innovation through no-paint truck assembly options. Our main interest is to quantify the potential energy savings achieved from the removal of a major process, such as painting. However a trade-off analysis considering economics, environmental, and engineering perspectives of alternative options such as polishing instead of painting would be a necessary to fully evaluate the potential of this option.

Comparing with Life Cycle Energy Consumption (SC4)

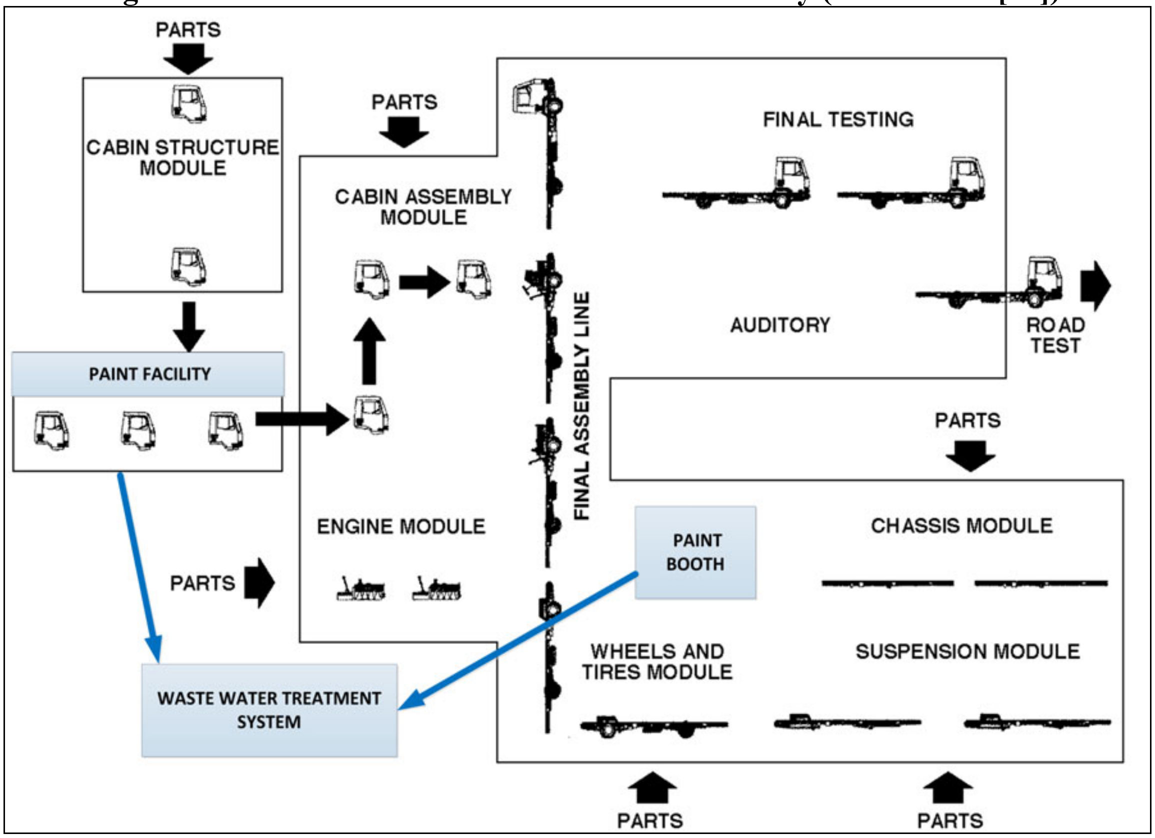
The last scenario takes a holistic approach which accounts for the energy and material use throughout the product life cycle. Life cycle assessment (LCA) is among the most important techniques for assessing environmental and energy aspects of industrial materials. LCA is a popular approach for analyzing the "cradle-to-grave" resource consumption and emissions of industrial products and processes [9, 10]. LCA aims to determine the inputs, outputs and impacts from the complex network of economic and industrial activities that constitute the life cycle of a product or process [11]. Data for LCA are available from a variety of different sources, which may be categorized according to their level of aggregation or spatial scale into manufacturing, value chain, and economy scales [12]. Among a variety of LCA methodologies, process LCA focuses on improving the design and operation of the manufacturing scale activities [13].

A primary reason for comparing the life cycle energy consumption with the three other manufacturing-focused scenarios is to identify the contribution of the energy efficiency measures in the manufacturing process to the complete life cycle energy consumption of a product. The lifecycle stage with the highest energy intensity (i.e. energy hotspot) varies with different products. High tech products such as semiconductor microchips have tremendous energy consumption in the fabrication stages where significant amounts of energy and chemicals are used to convert high-entropy (unorganized) raw materials to a low-entropy (highly organized) microchips [14]. For these types of products, the focus should be on improving the energy efficiency in the manufacturing process. However, in many other products, energy use is concentrated in the use phase. For example, in the use phase vehicles consume a significant amount of fuel; consequentially, it is crucial to integrate this energy consumption, including fuel extraction, refinery, and delivery to pump, into the life cycle assessment.

Case Study

Figure 2 shows the general process flow of a truck assembly operation. Primary processes include: frame assembly, axle assembly (wheels and tire module), engine assembly, chassis module (which includes a paint booth operation), cab painting, cab assembly, and final testing. In addition, waste water is cleaned in a treatment system. The plant receives 180 truckloads of materials per day and uses 400,000 gallons of fluids and 175,000 gallons of fuel per year. Over 600 suppliers provide over 85,000 different part numbers.

Figure 2. General Process Flow of a Truck Assembly (edited after [15])



Four different energy consumption scenarios for truck assembly are investigated here: i) baseline energy consumption, ii) energy consumption after a traditional energy assessment, iii) energy consumption after integration of a manufacturing innovation, and iv) the life cycle energy consumption of the product system.

Baseline Energy Consumption (SC1)

In the case study year, the plant consumed 59,086,908 kWh/year of electricity and 236,758 mmBtu/year of natural gas. The annual production volume was 20,807 units (trucks) that vary in size. Thus, about 22 GJ of site energy was used to produce 1 truck. In comparison, the energy required to assemble a mid-size passenger car is about 4.3 GJ/vehicle [16]. Thus the production of a heavy duty truck consumes about five times more energy than a passenger vehicle.

Implementation of Energy Assessment Recommendation (SC2)

A DOE compressed air energy expert and the University of Dayton IAC performed an energy audit of the plant and identified sixteen assessment recommendations (ARs) to improve plant energy efficiency (Table 1). The total estimated savings from all 16 ARs was 1,627 MJ/unit

(33,862 GJ/plant). Total estimated savings from ARs related to the painting options were 1,190 MJ/unit (24,761 GJ/plant). These results suggest that painting related energy consumption is large and significant saving opportunities exist in the painting line. Thus, painting energy savings comprise roughly 73% of the overall potential savings in the plant from a typical industrial assessment.

Table 1. Major Energy Assessment Recommendations

Utility	1	Repair failed capacitors to improve power factor
Motors	2	Replace rather than rewind failed motors with premium efficiency motors
Fluid flow	3	Replace smooth with notched V-belts on Motor drives
	4	Install VFD's on pump motors in the pre-treat area
	5	Install VFD's on agitator and pump motors and open throttling valves in waste water treatment plant
	6	Install non-return flaps on the 30hp sludge pumps in the sludge building
	7	Replace blower with mechanical agitator in waste water treatment
	8	Turn off one circulating pump for SAP heating loop during non-production hours
	9	Install a VFD on cooling water pump in the air compressor room
Process Heating	10	Install a heat exchanger to preheat combustion air for e-coat ovens
	11	Turn off boiler 2 and run boiler 1 in modulation mode
	12	Convert repair oven to establish counter flow heat exchanger
	13	Trim boiler excess air to 10%
Process Cooling	14	Use cooling tower instead of chiller to remove heat from e-coat dip-tank
HVAC	15	Install controls to stage cooling tower fans on/off
Compressed Air	16	Reducing off-shift compressed air demand (plant wise) + meet with nonproduction target

Energy Saving from the Implementation of Innovative Design (SC3)

The energy savings opportunities in Table 1 would reduce plant energy use by about 7.3%. However, achieving larger savings typically requires innovative design changes. Paints and other surface coatings provide protection to the truck and increase visual appeal. However, the painting operation comprises a significant portion of the total energy consumption in the production of a heavy duty truck. Steps in the painting process include: 1) substrate surface preparation, 2) application of the coating, and 3) drying of the coating. In this scenario, we assume a radical innovative design change: "what if the painting process was eliminated?" A "low bound" estimate of energy savings can be obtained from summing the energy use of the paint related equipment. An analysis of the entire painting operation reveals an annual energy expenditure of at least 5,560 MJ/unit (115,682 GJ/plant) per year (i.e., 25% of total energy consumption), significantly greater than the potential energy savings in the SC2 itself.

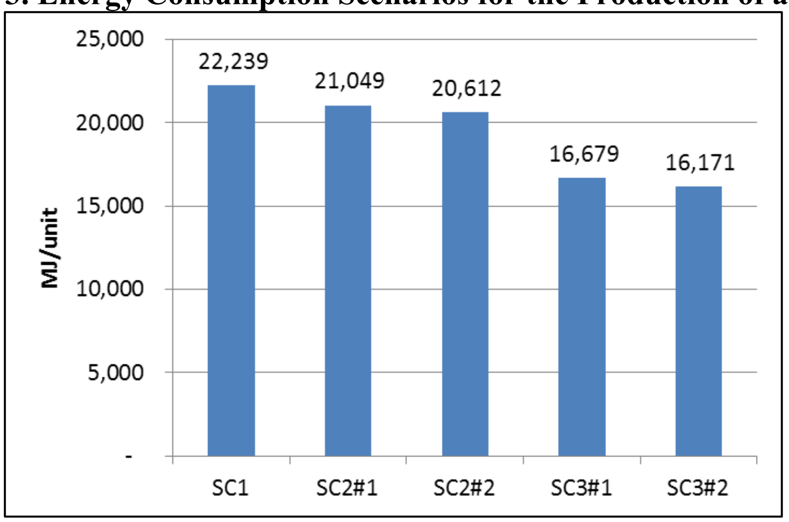
Comparison of Manufacturing Energy Consumption (SC1, SC2, SC3)

Table 2 shows five different energy consumption scenarios and Figure 3 shows the energy consumption associated with each scenario. Comparison of SC2#1 and SC2#2 reveals that energy savings from painting related recommendations are larger than for non-painting associated recommendations. SC3#1 shows energy use without painting and SC3#2 shows energy use without painting and with non-painting related ARs.

Table 2. Description of the Considered Truck Assembly Scenario

Scenario	Description
SC1	Baseline energy consumption scenario
SC2#1	After implementation of ARs associated with only painting operations
SC2#2	After implementation of all ARs
SC3#1	Innovation (i.e., no painting operation)
SC3#2	Innovation + ARs not associated with painting

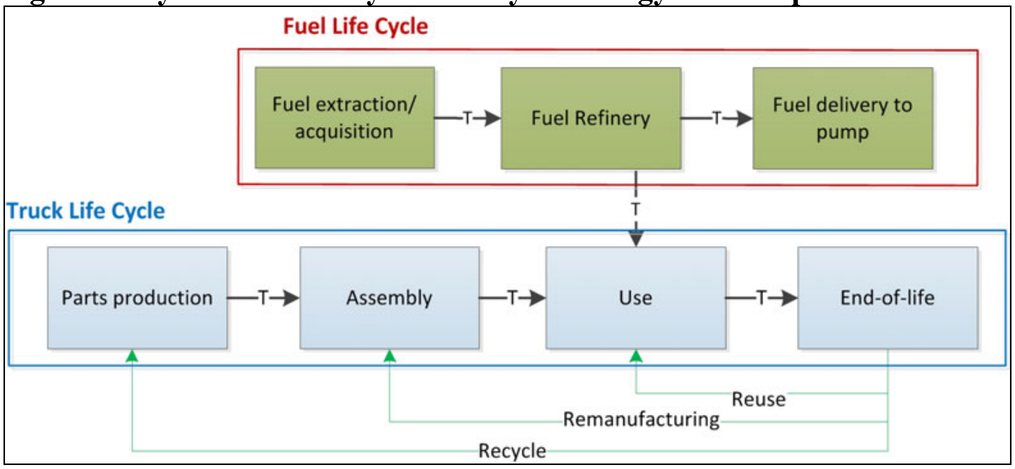
Figure 3. Energy Consumption Scenarios for the Production of a Truck



Comparison with Lifecycle Energy Consumption of a Truck

In order to evaluate the energy use of a truck in a lifecycle perspective, both the fuel cycle and the truck cycle should be considered as shown in Figure 4.

Figure 4. System Boundary for Lifecycle Energy Consumption of a Truck



The truck cycle includes the energy use associated with: 1) parts production (including raw material extraction), 2) assembly, 3) use, 4) fuel cycle and 5) end-of-life. Fuel consumption during the "use" stage makes up a significant fraction of total lifecycle energy. Further, the production of fuel requires energy in the extraction, refinery, and delivery stages of the fuel cycle. Therefore, energy consumption during the fuel cycle is also integrated into the total life cycle energy consumption.

Table 3 shows the five lifecycle stages and the source of data to compute the energy consumption during each stage. Base data for the parts production, fuel cycle and end-of-life stages were obtained from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by Argonne National Laboratory's Energy Systems Division [16]. Originally, GREET was developed to calculate emissions of five criteria pollutants and various fuels [17]. Thus, the original GREET model considered only the fuel-cycle. Recently, the model was extended to include the passenger vehicle-cycle. Data from the GREET model and literature [18] were utilized to modify passenger vehicle values to the heavy duty truck case.

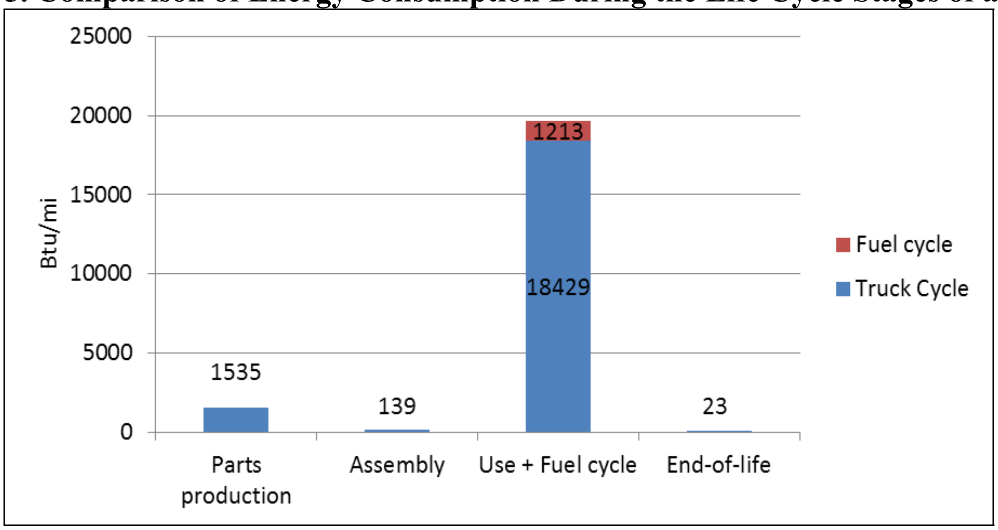
Table 3. Summary of Truck Lifecycle Scenarios

	Energy consumption	Data Source
Parts production	Production of material, batteries, fluids, and manufacturing of parts	GREET vehicle-cycle model [16] + Calibrated
Assembly	Assembly of truck	Baseline scenario (SC1) from case study
Use	Fuel consumption during the lifetime of truck operation	Literature[18-20]
Fuel Cycle	Lifecycle of diesel fuel production (i.e. extraction, refinery, deliveries)	GREET fuel-cycle model [17] + Calibrated
End-of- life	Dismantling	GREET vehicle-cycle model [16] + Calibrated

In the GREET model, the energy consumption during the use and fuel cycles depends on vehicle fuel type (i.e., biofuels, diesel, gasoline, electricity) and powertrain system (i.e., internal combustion, hybrid electric, fuel cells). In this study, we began with data from an internal combustion engine with diesel fuel and adapted it to a Class 8 heavy-duty truck. Fuel economy for Class 8 trucks ranges from 6 mpg to 7 mpg at a speed of 60~65 mph [19]. We assumed a truck drives 680,000 miles during its life time [20]. The unit of energy consumption used in the previous section and the GREET model is MJ/unit (truck). We converted the unit to Btu/miles to match units used in the use and fuel cycle data.

Figure 5 shows a comparison of energy consumption during the life cycle stages of a truck. About 92% of lifecycle energy is consumed in the combined use and fuel cycle stages; 86% is for fuel use and 6% percent for the fuel cycle. Energy consumptions in truck production and assembly account for 7% and 1% respectively.

Figure 5. Comparison of Energy Consumption During the Life Cycle Stages of a Truck



Conclusion

In this case study, energy efficiency improvements reduced energy use by 7.3%, and eliminating painting reduced energy by another 17.6%. Thus, both types of energy savings are significant. However, this work also showed that energy consumption in the parts production and use stages is much larger than the energy consumption in the assembly stage. In a total lifecycle context, the greatest gains in energy efficiency are probably from focusing on improving the energy efficiency of the product during the use phase by introducing technology innovations that improve fuel efficiency such as changes in vehicle materials, vehicle design, engine design and operation, and alternative fuel use.

Our intention is not to claim the insignificance of the manufacturing energy saving opportunities, but to show how life cycle assessment can be used to put energy saving opportunities into perspective. From a business perspective, some may question why manufacturers should consider energy consumption during the use and end-of-life stages which are outside of their business system boundary. The answer to this question is clear and straightforward; in the era of sustainability consumers may reject products with poor performance during the use and end-of-life stages.

We also acknowledge that for many products, energy use during the use stage is small compared to energy use during other stages. Thus, this result cannot be generalized indiscriminately. However, we suggest that in all cases, the proposed life cycle framework will always yield valuable information to focus efforts and gain perspective.

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