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A LIFE CYCLE ASSESSMENT OF A DIESEL GENERATOR SET

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by

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Abstract

Today, nearly every industry needs a continuous power supply, as data loss can be more expensive than the capital expenditure for the backup power equipment. The demand for emergency standby power (ESP) generator sets is on the rise because of increasing industrialization. With increased industrialization comes a societal concern about the issue of natural resource depletion and environmental degradation. In response, manufacturing companies are providing more sustainable solutions in their products and processes. In this work, the life cycle assessment (LCA) methodology has been applied to quantify the energy demands of each life cycle stage of an ESP generator set and identify areas of possible energy reductions in order to improve product sustainability. The energy demands were calculated using an Excel spreadsheet and data from Ecoinvent and the Inventory of Carbon and Energy (ICE) database. The life cycle inventory (LCI) was completed using data obtained from the manufacturing company and its suppliers. The results revealed that the use phase had the largest energy demand at nearly 95% of the total demand, followed by materials at 4%, transportation at 1%, and then manufacturing at less than 1%. Recommendations for potential energy reductions were made to the manufacturer. Because the use phase dominates the overall energy demand, increasing fuel efficiency will have the largest impact; however, the energy demands of the other stages should not be overlooked. In order for the generator set to have the most sustainable life, the goal should be to reduce energy demands wherever possible. Such reductions can be made by increasing remanufacturing rates and using materials with a higher recycled content.

Keywords: Life cycle assessment, sustainability, standby generator set, embodied energy, end of life, recycle, remanufacture

Dedication

I would like to dedicate this thesis to my family, friends, and teachers. My family was by my side since day one, and they stayed there through all of years, encouraging me through the last leg of this thesis. Friends have come and gone during my educational journey, but the good ones have stuck around and gave me tremendous moral support through the physical and mental challenges that have presented themselves over the years. I am lucky to have had such unique teachers - teachers of not only academia, but various extra-curricular activities as well. With each new activity came a new teacher and a new lesson. Over the course of my life, these individual lessons have collectively shaped me into who I am today. Perhaps the most influential lesson that has led me this far was that taught by Master Martin Martin. After each Tae kwon do class, he would say, “Repeat after me: patience--, humble--, respect--”; and we would (and I, to this day), echo him after each moral trait.

Acknowledgements

First, I would like to thank each and every one of the professors that taught me in the Environmental Engineering department at Montana Tech: Kumar Ganesan, Bill Drury, Holly Peterson, Jeanne Larson, Rod James, Raja Nagisetty, and the late Rick Appleman. They designed their courses to be challenging, which gave me no choice but to work hard and keep pushing forward, which has developed my academic and personal skills. I am grateful for their open office hours, during which I could ask them countless questions. It is their patience and openness that developed my confidence to question uncertainties, which is a skill that will be most useful in the work environment.

I would also like to thank Xufei Yang for serving as my committee chair and sharing his expertise in manuscript writing and providing guidance for this research project. I would also like to thank my other committee members Jeanne Larson and Jack Skinner for taking the time to be a part of this project.

Finally, I would like to thank Maddie Fogler for investing time in this project by meeting frequently with me, helping me collect data, and reading and editing this thesis in her “free” time. This project would not have been possible without her Design for Environment expertise.

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Glossary of Acronyms

Term	**Definition**
LCA	Life Cycle Assessment
SLCA	Streamlined Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
EPA	Environmental Protection Agency
DOE	Department of Energy
ISO	International Standards Organization
SETAC	Society of Environmental Toxicology and Chemistry
MIT	Massachusetts Institute of Technology
ICE	Inventory of Carbon & Energy
EE	Embodied Energy
NSPS	New Source Performance Standards
ESP	Emergency Standby Power
PCB	Printed Circuit Board
EoL	End of Life
MW	Megawatts
MJ	Megajoules
GJ	Gigajoules

Chapter 1

1. Literature Review

This section is a literature review on life cycle assessments (LCA) and diesel generator sets, which serves to provide background information and set the scene for the case study that will be presented in Chapter 2. Key components of LCA and the market demand for diesel generator sets are discussed.

1.1. Introduction to Life Cycle Assessments

This section presents the motivation behind LCA as well as its definition, life cycle stages, and applications.

1.1.1. Motivation

As environmental awareness increases, industries and businesses are evaluating how their operations affect the environment. Society has become concerned about the issue of natural resource depletion and environmental degradation. As a result, many businesses have responded by providing “greener”, or more sustainable, solutions (Environmental Protection Agency, 2006). Sustainability is based on a simple principle: Everything required for human survival and well-being depends, either directly or indirectly, on the natural environment. To pursue sustainability is to create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations (National Research Council, 2011). Businesses are now going above and beyond compliance by incorporating sustainability into their company values, which sends a message to the public that its employees are taking actions to protect the environment and conduct business in a sustainable manner. In response to the drive for sustainability, LCA was developed.

1.1.2. Definition

By definition, LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service over its entire life cycle by:

- compiling an inventory of relevant energy and material inputs and environmental releases,
- evaluating the potential environmental impacts associated with identified inputs and releases, and
- interpreting the results to help decision-makers make a more informed decision (EPA, 2006).

1.1.3. Life Cycle Stages

LCAs evaluate all stages of a product’s life, which provides an estimation of the cumulative environmental impact associated with the life cycle of the product (ISO 14040). The typical life cycle stages and relevant inputs and outputs are shown in Figure 1.

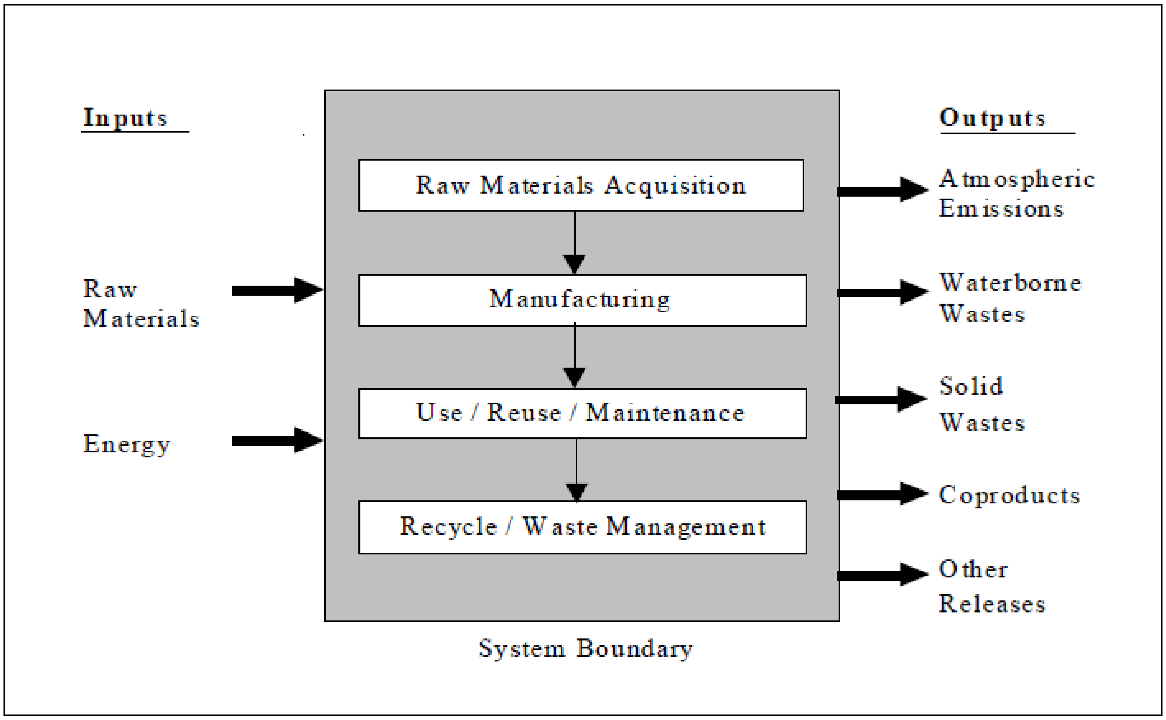

Figure 1: Typical life cycle stages (Adapted from: Environmental Protection Agency, 1993)

1.1.4. LCA Applications

Today, LCAs are used for research, industry, and policy. LCAs have come a long way since Harry E. Teasley, Jr. first developed the concept in order to decide whether or not the Coca-Cola Company should manufacture their own beverage cans (Hunt & Franklin, 1996). Initially, LCA was used for single products and issues, but is now used as a versatile tool to determine the impact of a product or process over several environmental metrics. LCA methodology also aids in the process of pollution prevention and even policy development (McManus & Taylor, 2015).

It is important to note that usually a LCA is only one piece of information used in a much more comprehensive decision-making process. Also, the results of different LCAs can only be compared when the assumptions and context of the studies are identical.

1.2. Conducting a LCA

This section provides general information on conducting a LCA, including LCA standards, software, data sources, fundamental methodology, and impact metrics.

1.2.1. LCA Standards

Because LCAs are being used in a variety of applications, standards have been developed in attempt to standardize the methodology and guide users in the process of conducting a LCA. However, the standards do not provide specific details and are therefore left to the interpretation of the LCA practitioner. The two standards listed below were developed by the International Standards Organization (ISO):

- *ISO 14040: 2006 Environmental management—Life cycle assessment: Principles and framework*
- *ISO 14044: 2006 Environmental management—Life cycle assessment: Requirements and Guidelines.*

1.2.2. LCA Software

A LCA practitioner may facilitate the process of conducting a LCA by using one of the many LCA software options available. The EPA identifies and describes 25 different software options. Two common names are GaBi and SimaPro. Each software has its own unique features, but the concept behind them is the same. The software uses a database with inventory data in a wide range of areas, from energy supply to biofuels, and calculates an environmental impact as a result of the model inputs. Most of the software is expensive, so it is important for the LCA practitioner to know the level of data analysis required. Software packages are desirable for simplifying very complex models but can be unnecessary if the LCA is a streamlined one. In the event of a streamlined LCA, an Excel spreadsheet is a simpler option that can be used to save time and resources. New users would have to invest time into learning LCA software but can quickly pick up the idea using an Excel spreadsheet. Another benefit of using an Excel spreadsheet is that the practitioner understands each of the calculations and the assumptions behind them. A risk of losing transparency exists when using commercial software because the computational methods and assumptions are not always stated (Environmental Protection Agency, 2006).

1.2.3. LCA Data Sources

A variety of data sources may be used for LCA. In addition to data supplied by the manufacturer, the sources of data in this study include the Ecoinvent database, the Inventory of Carbon & Energy (ICE), and Materials and the Environment: Eco-informed Material Choice. A brief description of each source is provided here:

- **Ecoinvent** – This database contains over 11,300 datasets in a variety of areas including energy supply, agriculture, transport, biofuels, biomaterials, bulk and specialty chemicals, construction materials, wood, and waste treatment. “Ecoinvent is the most comprehensive and transparent international life cycle inventory database” (About ecoinvent, 2016). A user license must be purchased in order to access this database.
- **ICE** – This database contains carbon and energy data for nearly 200 different materials associated with the construction industry. The data were extracted from peer-reviewed literature based on a set of specific criteria. Although mainly intended for construction in the UK, the material set included in the database applies to a wide variety of industries. The database is publicly available online

and has attracted interest from industry, academia, and government agencies (Hammond & Jones, 2008).

- **Materials and the Environment –** Ashby generated data sheets for embodied energy and basic recycling information in addition to other material data for 63 materials used in the greatest quantities. He also provides methods for calculating end of life credits and debits that are used in this study (Ashby, 2013).

1.2.4. LCA Methodology

The LCA framework consists of four phases:

- the goal and scope definition phase,
- the inventory analysis phase,
- the impact assessment phase, and
- the interpretation phase.

The scope of the study includes the system boundary and level of detail necessary for the intended use of the final LCA model. Each LCA has varying levels of detail because each goal is different. The life cycle inventory analysis phase (LCI) is an inventory of the input and output data relevant to the system being studied. It involves the collection of the data required to meet the goal of the LCA. The life cycle impact assessment phase (LCIA) is to provide additional information to assess the system's LCI results. Finally, the results of the LCI or LCIA, or both, are summarized and discussed as a basis for conclusions and recommendations (ISO 14040).

1.2.5. Impact Metrics

An agreement has not been made on a single environmental impact metric that is both workable and capable of guiding design. The Kyoto Protocol and subsequent treaties and protocols have established a degree of international agreement to reduce carbon emissions, usually presented as carbon dioxide (CO_2) or carbon dioxide equivalent ($CO_{2,eq}$), which is a value corrected for the global warming potential of gas emissions other than CO_2. On a national scale, the focus is to reduce energy consumption. Fortunately, energy consumption is closely related to CO_2 production, and the reduction of one usually results in the reduction of the other. Energy is a desirable impact metric because it is easiest to monitor, can be measured with relative precision, and can be used as a proxy for CO_2 if necessary (Ashby, 2013). Therefore, this study uses energy as the impact metric. Examples of other impact metrics include global warming, acidification, human toxicity, and ecotoxicity potential.

Different types of energy usage can be reported. This study will focus on embodied energy (EE), which is the total primary energy consumed from direct and indirect processes relevant to a product or service within the cradle-to-gate boundaries. This includes all activities from raw material extraction, manufacturing, transportation, and through fabrication until the product is ready to leave the factory gate (Hammond & Jones, 2008). Ashby describes this term in detail and explains that only part of the energy is “embodied”, meaning that it is in the material and could be theoretically be recovered. The remaining energy is lost to process inefficiencies (Ashby, 2013).

1.3. LCA Streamlining

This section describes the purpose behind LCA streamlining as well as different approaches to streamlining.

1.3.1. Purpose

LCA is meant to be a comprehensive assessment of the environmental impacts of products and processes on a “cradle-to-grave” basis. However, this definition has represented more of an ideal rather than a practical guide (Weitz & Sharma, 1998). Efforts to develop LCA methodologies date back to the 1970s. The Society of Environmental Toxicology and Chemistry (SETAC) in North America and the U.S. EPA have facilitated workshops to develop a framework for conducting LCAs. A major concern of the framework is the cost and time required. These concerns have led to LCA “streamlining” to make the assessment more feasible and more relevant without losing the key features of the life-cycle approach. A “streamlined” LCA (SLCA) and a “full-scale” LCA are said to be two points on a continuum, with the latter being at the top of the continuum. Most LCAs fall somewhere along the continuum, and as a result, the process of streamlining is considered to be an inherent part of the scope-and-goal definition process. The streamlining steps must be consistent with the study goals and anticipated uses, therefore, knowledge of what needs to be included to support the anticipated application is required (SETAC, 1999).

1.3.2. Streamlining Approaches

At an EPA conference on LCA streamlining, Weitz presented seven major techniques for on streamlining:

1) eliminating stages in the total life-cycle,
2) focusing the study on specific environmental impacts or issues from the outset,
3) analyzing for a limited list of inventory categories,
4) eliminating impact assessment,
5) using qualitative information,
6) using surrogate data from previous studies,
7) using “threshold” levels to curtail analysis at specific points.

The selection of a SLCA should be based on the inteded use of the results. Because not all data are available, every LCA that has been conducted to date has been streamlined (Curran & Young, 1996). A combination of the techniques listed above was used for this study.

1.4. Diesel Generator Sets

This section describes diesel generator sets and their applications as well as current market demand.

1.4.1. Product description

A diesel generator set, hereafter referred to as a genset, is a combination of a diesel engine with an alternator to convert mechanical energy to electrical energy. The diesel genset in this study is equipped with a heavy-duty 15 liter engine with a 500 kW rating for standby applications. It is rated at an EPA NSPS (New Source Performance Standards) Stationary Emergency Tier 2 emissions level. When the standby genset is running, it usually operates at 3/4 load and burns 25.7 gallons of diesel per hour. Its life expectancy is 20 years, and the operation limit is 200 hours per year based on warranty; however, a more realistic operation is 50-100 hours.

1.4.2. Applications

An emergency standby power (ESP) genset is used to supply power to a varying electrical load for the duration of power interruption of a reliable utility source. ESP is mandatory for any application that requires an uninterrupted power supply. Large data centers and healthcare facilities are two examples of large markets for ESP gensets.

1.4.3. Market Demand

Today, nearly every industry needs a continuous power supply, as data loss can be more expensive than the capital expenditure for the backup power equipment (India Diesel Genset

Market Outlook, 2014). The genset market is driven by the rapidly expanding global population and urbanization of cities throughout the world (Generator Industry Outlook, 2016). Genset demand will continue to increase as industries such as oil and gas, electronics, semiconductors, textiles, food processing units, automotive, industrial machinery, shopping malls, and high-rise buildings such as data centers turn to diesel generators to deal with unexpected power outages (Sverdlik, 2013). This demand is especially prevalent in Asia-Pacific, where the data center industry is rapidly expanding, especially in Singapore, Malaysia, Philippines, Thailand, and Australia. Data centers require gensets with a capacity of up to 20 megawatts (MW) for ESP applications, and therefore, the demand for large diesel gensets with a power output capacity between 1MW and 3MW is on the rise (Frost & Sullivan, 2013).

Frost and Sullivan predict that the market for 1-3MW diesel gensets will grow from about $590 million to about $800 million (U.S. Dollars) in 2017 (Sverdlik, 2013). Another study found that the Indian diesel generator market grew 9.5 % between 2012 and 2013, and it was predicted that the market would grow at a compound average growth rate of around 11 % in value terms during 2014-2018 (India Diesel Genset Market Outlook, 2014). The global genset market will continue to be driven by the lack of grid infrastructure in remote locations and increasing industrialization in developing countries.

Chapter 2

2. Case Study: Life Cycle Assessment of a Diesel Generator Set

This chapter describes a case study in which a life cycle assessment was conducted for a standby diesel generator set. This section was written to be read as an independent publishable manuscript and therefore includes pertinent information first presented in Chapter 1.

2.1. Introduction

As environmental awareness increases, industries and businesses are evaluating how their operations affect the environment. Society has become concerned about the issue of natural resource depletion and environmental degradation. As a result, many businesses have responded by providing “greener”, or more sustainable solutions (Environmental Protection Agency, 2006). Businesses are now going above and beyond compliance by incorporating sustainability in the list of company values, which sends a message to the public that its employees are taking actions to protect the environment and conduct business in a sustainable manner. These actions are prompting environmental managers and decision makers to look at their products and services from cradle to grave. In response to this approach, the need for Life Cycle Assessment (LCA) arose.

LCA is a method of evaluating the cumulative environmental impacts resulting from all stages in the product life cycle (EPA, 2006). What started as a tool to evaluate individual products has now developed into a standardized method for providing a scientific basis for environmental sustainability in industry and government (Curran, 2013).

This study describes a LCA performed on a standby diesel generator set in cooperation with a large diesel engine manufacturing company, which also produces power generation products. A standby diesel generator set, hereafter referred to as a genset, is a combination of a diesel engine with an alternator to convert mechanical energy to electrical energy. Emergency standby power (ESP) gensets are used to supply power to a varying electrical load for the duration of the power interruption of the utility source. ESP gensets are essential for any application that requires an uninterrupted power supply.

Today, nearly every industry needs a continuous power supply, as data loss can be more expensive than the capital expenditure for the backup power equipment (India Diesel Genset Market Outlook, 2014). The genset market is driven by the rapidly expanding global population and urbanization of cities throughout the world (Generator Industry Outlook, 2016). Genset demand will continue to increase as industries such as oil and gas, electronics, semiconductors, textiles, food processing units, automotive, industrial machinery, shopping malls, and high-rise buildings such as data centers turn to diesel generators to deal with unexpected power outages (Sverdlik, 2013). This demand is especially prevalent in Asia-Pacific, where the data center industry is rapidly expanding, especially in Singapore, Malaysia, Philippines, Thailand, and Australia. Data centers require gensets with a capacity of up to 20 megawatts (MW) for ESP applications, and therefore, the demand for large diesel gensets with a power output capacity between 1MW and 3MW is on the rise (Frost & Sullivan, 2013).

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With their predicted increase in market demand in the upcoming years, gensets will become more prevalent, which makes them a good LCA subject. By performing a LCA, the environmental impact of the product can be understood, reported, and interpreted by decision makers in a manner that promotes sustainable product and/or process choices in the future.

2.2. Methodology

2.2.1. Goal and Scope Definition

The goal of this study is to perform a LCA on a standby genset in order to quantify the energy demand for each life cycle stage and identify which is the most energy intensive. Life cycle stages of this analysis include materials, manufacturing, use, transportation, and end of life, making the study a "cradle-to-grave" analysis. This LCA has been streamlined in order to align the results with the goal of the study, thereby making this study a streamlined LCA (SLCA). A combination of techniques mentioned by Keith Weitz at the EPA conference on SLCA was used to perform this study (Curran & Young, 1996).

In 2013, the manufacturer partnered with a master's student from the Massachusetts Institute of Technology (MIT) to perform a SLCA on a 15 L displacement engine used in the on-highway application (Bolin, 2013). The primary focus of the study was to understand the energy demands of the life cycle stages prior to the use stage because it was well understood that the use phase was the most energy intensive for the on-highway application. This genset study not only includes the MIT engine information but extends the analysis to the full life cycle of the engine as a part of the genset. This will allow the energy demands of the use phases of an engine in two different applications (i.e. on-highway and standby) to be compared to each other.

2.2.1.1. Functional Unit

The functional unit for this study is one standby diesel genset. This particular model is equipped with a heavy-duty 15 L engine with a 455 kW rating. To conduct the LCA, the generator was divided into five main components: (1) engine, (2) alternator, (3) radiator, (4) electronic controls, and (5) skid. Additional parts, such as the air filter and smaller connecting pieces, were not considered because of time and resource restraints.

2.2.1.2. Process Description and System Boundaries

Before the system boundaries are defined, the processes that are specific to the production of this genset will be described. The individual parts are made in their respective manufacturing facilities and then shipped to the assembly facility. Upon completion of assembly, the product is distributed to the customer, where it is used until it has reached its end of life (EoL). Then it can be recycled, remanufactured, or sent to a landfill. Most likely, the disposal route is a combination of these three options.

This study assesses the entire life cycle of a genset with varying level of detail for each stage. The materials stage includes the raw material extraction and processing required to make the raw material into a usable form. Further processing such as casting, milling, and forging is not included in the system boundary. This grouping is a result of the impact metric, which will be described in a later section. The manufacturing stage for this LCA is defined as the stage in which each of the five main parts of the genset is built in its respective manufacturing facility. This stage also includes the step in which the individual parts are assembled into a genset because of the impact metric and similarity in data type. The use phase is fairly straight-forward and will be a category of its own. EoL analysis, however, is more complicated because of the variety of disposal routes, which will be explained in detail in a later section. While transportation occurs between each of these stages, the only piece that will be considered is between the part manufacturing facilities and final assembly site. Downstream transportation that occurs after the product is built will not be considered.

This LCA considers the processes discussed above and the energy inputs associated with them, which can be seen in Figure 2. Each process has outputs such as air and water emissions that have an impact on the environment but are not considered in this SLCA because the goal of the study is to quantify the energy demand for each stage. The impact metric will be described in the next section.

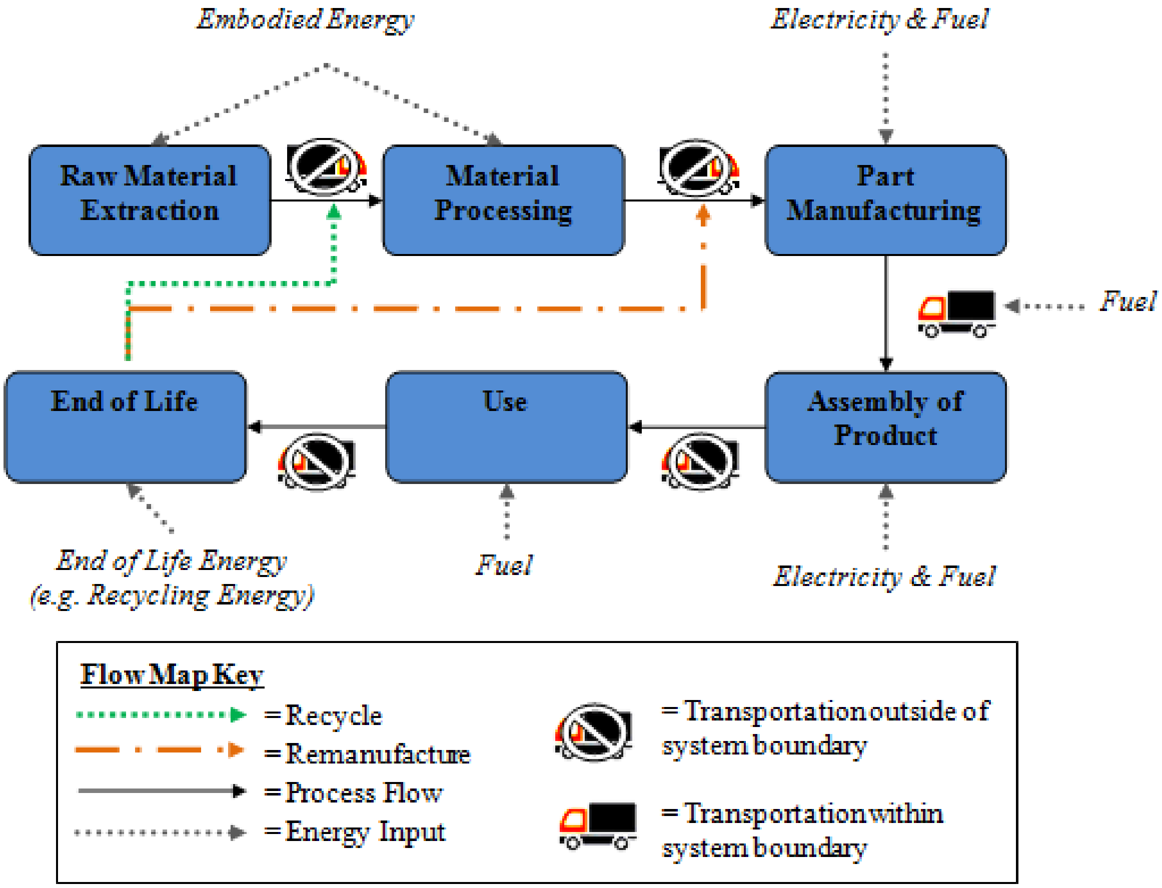

Figure 2: The system boundary of this study

2.2.1.3. Impact Metric

The impact metric used for this study is energy in units of megajoules (MJ). Energy will then serve as an indicator of the overall environmental impact. Energy is a simple metric and is generally understood by the public and can be used as a proxy for CO_2 if necessary (Ashby, 2013). The relationship between the two impact metrics for diesel engines was further validated by Bolin in the MIT study, in which a strong correlation between embodied energy (EE) and greenhouse gas emissions was presented. Also, energy is most closely related to production costs more than any other environmental metric (Bolin, 2013), so this metric has the benefit of relating to not only greenhouse gases, but cost as well.

The purpose of this method is to quantify the total energy use throughout the life cycle of the genset, including the direct and indirect energy usage during the extraction of raw materials, manufacturing, use, transportation, and waste disposal. Four different types of energy are considered in this study: (1) EE, primary production (2) EE, recycling (3) electricity, (4) fuel.

The EE is defined as the total primary energy consumed from direct and indirect processes relevant to the materials within the cradle-to-gate boundaries. This includes all activities from raw material extraction, manufacturing, transportation, and through fabrication until the product is ready to leave the factory gate (Hammond & Jones, 2008).

2.2.1.4. Data Requirements

The data required to conduct the LCA is presented in this section. The data collection methods will be described in a later section. The data requirements for each stage are listed in Table I.

Table I: Data requirements for each life cycle stage

Life Cycle Stage	Data Required	Units
Materials	Material composition of parts	-
	Material mass	kg
	Embodied energy, primary production values	MJ/kg
Manufacturing	Facility energy usage	MJ
	Production volume	-
Transportation	Travel mode	-
	Travel distance	km
	Weight of shipment	t
	Energy intensity of transportation mode	MJ/t•km
Use	Lifetime	yr
	Run time	hrs/yr
	Fuel type	-
	Fuel efficiency	gal/hr
	Calorific value of fuel	BTU/gal
End of Life	Disposal route	-
	Material type	-
	Material mass	kg
	Embodied energy, recycling values	MJ/kg

2.2.2. Life Cycle Inventory Analysis

The life cycle inventory analysis (LCI) phase includes the collection of the data and calculation procedures necessary to quantify the inputs and outputs, which will be described here.

2.2.2.1. Data Collection

Engineers and specialists from a variety of departments within the manufacturing company provided information for this study. The multi-disciplinary involvement required for this study speaks to the complexity and broad nature of LCAs. In addition to the manufacturer, a variety of data sources were used to complete this study. Table II summarizes the data type and source used for each life cycle stage. The most challenging stage to collect data for was the materials stage because the genset is made of over 15,000 parts. This expansive list consists of pieces as small as nuts and bolts. To make the part list manageable and realistic, the list was grouped into the five main parts described in the scope of this study.

A list of material types and masses for each part is not typically kept on record, so the level of accuracy was dependent on the data available. Part drawings, purchasing data, and general part knowledge shared by design engineers were all compiled to generate the data. It is important to note that these values are an estimate and are not exact.

The EE values for calculating primary production of materials were acquired from a combination of Ecoinvent, Materials and the Environment: Eco-informed Material Choice (Chapter 15), and the Inventory of Carbon and Energy (ICE) Version 2.0.

Manufacturing data was collected from plant records of the manufacturer and suppliers. The data included facility energy usage and production data for the year of 2014. Transportation data was simply acquired by identifying the manufacturing and assembly location and calculating a travel distance between the two locations. The transportation mode was identified by the manufacturer, and the transportation energy intensities were acquired from Ecoinvent.

Product warranty and life time data was collected from the manufacturer for the use phase. The EoL disposal route is difficult to identify. The product is in the customer's hands when it has reached its EoL, so they are at liberty of choosing the disposal route, which is not usually reported back to the original manufacturer. Therefore, it is difficult to acquire this data. In order to explore the energy demands of different disposal routes, four scenarios were used in which different combinations of disposal routes were used. The recycling EE used for these scenarios was acquired from Ashby. For the few materials that lacked recycling data, it was estimated that the recycling energy was one-fifth of the EE (Ashby, 2013).

Table II: Data sources

Life Cycle Stage	Data Required	Data Source
Materials	Material composition of parts	Manufacturer and suppliers
	Material mass	
	Embodied energy values	Ecoinvent, Ashby, and ICE
Manufacturing	Facility energy usage	Manufacturer and suppliers
	Production volume	
Transportation	Travel mode	Manufacturer
	Travel distance	
	Weight of shipment	
	Energy intensity of transportation mode	Ecoinvent
Use	Lifetime	Manufacturer
	Run time	
	Fuel type	
	Fuel efficiency	
	Calorific value of fuel	
End of Life	Disposal route	
	Material type	Manufacturer
	Material mass	
	Recycling embodied energy	Ashby

2.2.2.2. Data Calculation Procedures

Because each life cycle stage requires different types of data, the calculation procedures vary for each stage.

- **Materials**: The calculations for this stage are straightforward: the mass of material is multiplied by the EE value. The sum of each material's energy is then the total energy for the material stage, as shown in equation (1).

$$E_M = \sum_{i \in M} m_i * H_i \tag{1}$$

where M represents all of the materials in the genset and $i \in M$ represents the individual materials. E is energy (MJ), m is mass of material (kg), and H is effective EE of material (MJ/kg), which is defined in equation (7).

- **Manufacturing**: The energy for this stage was calculated by dividing the facility energy consumption by the number of parts produced. The sum of each facility's energy is then the total energy for the manufacturing stage, E_F, as shown in equation (2).

$$E_F = \sum_{j \in F} \left(\frac{f}{p}\right)_j \tag{2}$$

where F represents all of the manufacturing facilities and $j \in F$ represents the individual facilities. f is the energy of the manufacturing facility (MJ), and p is the number of parts produced at the facility.

- **Transportation:** The transportation stage is calculated by multiplying the transportation intensity by the shipment weight and the distance traveled. The energy for each part to be transported is then summed to acquire the total energy for the transportation stage, E_T, as shown in equation (3).

$$E_T = \sum_{k \in T} H_{t_k} * d_k * s_k \tag{3}$$

where T is all of the transportation modes and $k \in T$ represents the individual transportation modes. H_t is the transportation energy intensity (MJ/t•km), d is the distance traveled (km), and s is the shipment weight in metric tonnes (t).

- **Use:** The use phase is calculated by multiplying the life expectancy by operation time, fuel efficiency, and calorific value of the fuel. BTU units are then converted to

MJ, and the energy for the entire lifetime of the genset is calculated, as shown in equation (4).

$$E_U = LE * OT * e * CV \tag{4}$$

where *U* represents the use phase, *LE* is life expectancy (yrs), *OT* is operation time (hrs/yr), *e* is fuel efficiency (gal/hr), and *CV* is calorific value of fuel (BTU/gal). The calorific value used in the calculation was specified by the manufacturer as 130,000 BTU/gal.

- **End of Life:** The EoL stage is more complex than the others. Ashby describes the activities included in each of the three disposal routes considered for this study:
    1. **Landfill** – Collect and transport to landfill site.
    2. **Recycling** – Collect, sort by material family and class, recycle.
    3. **Remanufacturing** – Collect, dismantle, replace or upgrade components, re-assemble.

EoL credits can be assigned for recycling and remanufacturing, but the landfill disposal route receives an EoL debit. The credits are represented as a negative value because it is reducing the total energy demand, whereas the debits are expressed as positive values because it is adding to the total energy demand and has a negative impact on the environment. This is an effective method to present sustainable disposal routes as a benefit to the overall LCA. Ashby provides an equation for each disposal option. Equation (5) shows the energy debit of the landfill disposal route.

$$E_L \approx \sum_{i \in M} 0.1 * m_i * H_i \tag{5}$$

where *L* represents EoL debit for the landfill disposal route.

Equation (6) shows the energy credit for recycling.

$$E_{RC} = \sum_{i \in M} r * m_i * (H - H_{rc})_i \qquad (6)$$

where r is fraction recycled, H_{rc} is recycling EE, and H is defined by equation (7).

$$H = R \bullet H_{rc} + (1-R) \bullet H_m \qquad (7)$$

where H is effective EE (MJ/kg), R is recycle content of the material at start of life, and H_m is the EE (MJ/kg). R varies for each different material depending on the EE data source. To remanufacture a product, the potential EoL credit is described by equation (8).

$$E_{RM} = \sum_{i \in M} 0.9 * m_i * H_i \qquad (8)$$

Remanufacturing recovers almost all of the original EE.

The total energy for the production of a genset is then given in equation (9).

$$E_{Total} = E_M + E_F + E_T + E_U + E_L - E_{RC} - E_{RM} \qquad (9)$$

Table III shows the four different EoL scenarios analyzed in this study.

Table III: Four different scenarios analyzed for end of life

Scenario	Landfill	Recycle	Remanufacture
1	100%	0%	0%
2	34%	34%	32%
3	16%	34%	50%
4	5%	10%	85%

The methodology used to develop each of these scenarios is as follows:

Scenario 1: This scenario was modeled to show the negative impact of sending the entire product to the landfill. This is not realistic but provides a baseline for the other three scenarios.

Scenario 2: This scenario was based on the remanufacturing rates of the engine. The manufacturer knows that 85% of an engine can be remanufactured. Given the engine makes up about 38% of the entire genset and assuming that the engine is only part that could be remanufactured, that would mean that 32% (85%•38%) of the genset could be remanufactured.

The recycling rate for Scenario 2 came from an EPA report on waste generation, recycling, and disposal in the U.S. for 2012 (EPA, 2012), which listed the average recycling rate of metals as 34%. The remainder of the genset was then assumed to be sent to the landfill. Scenario 2 then serves as a baseline for Scenario 3 and Scenario 4 because realistically, more of the genset can be remanufactured.

Scenario 3: This scenario was generated with a remanufacturing rate in middle ground between scenario 2 and 4. The recycling rate was kept the same as scenario 2.

Scenario 4: This scenario was created to analyze what the EoL impacts would be if the remanufacturing rate of the entire genset was equal to that of the engine. The remaining 15% of the genset was divided into a recycling and landfill rate of 10% and 5%, respectively.

2.3. Results and Discussion

2.3.1. Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) evaluates the magnitude and significance of the potential environmental impacts of the life cycle of the product (ISO 14040). A variety of results were calculated based on the LCI. First, the overall results will be presented, and then the results for each stage will be presented. In order to protect propriety information, several results are presented in a scaled format. The energy demands of each process or material will remain proportional, so the relationship can be described as a relative energy demand.

2.3.1.1. Overall Results

The energy for each stage is shown in Figure 3. The EoL impact is not represented here since there are four different scenarios for this stage; rather, it will be explained in its designated results section. The use phase dominates the energy demand at nearly 95% of the total demand, which is consistent with other studies (Adalberth, Almgren, & Petersen, 2001; Asbhy, 2013; Li, Liu, Zhang, & Jiang, 2013). The next most energy intensive is the materials stage at 4% of the total energy demand, then transportation at 1%, and then manufacturing at less than 1% of the total energy demand.

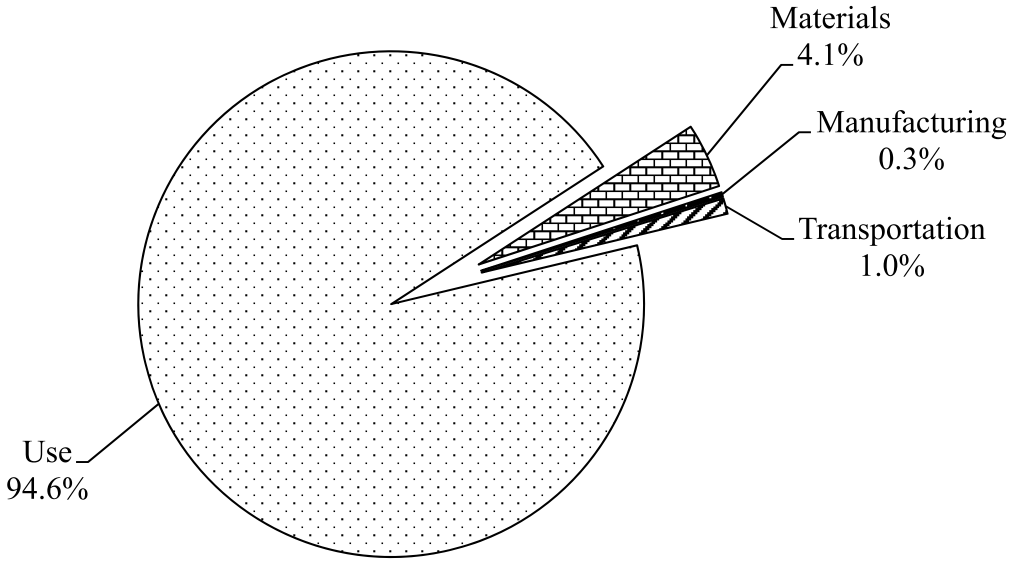

Figure 3: Energy demand per life cycle stage

2.3.1.2. Material Results

The original list of materials was simplified by grouping similar material types into categories defined by Ecoinvent, Ashby, and ICE. Eighteen material categories comprise the final list of materials.

- Aluminum Alloy
- Cast Aluminum
- Cast Iron
- Copper
- Epoxies
- Ferromanganese (Fe-Mn)
- Ferrosilicon (Fe-Si)
- Lead
- Low Alloy Steel
- Low Carbon Steel
- Molybdenum
- Nickel
- PCB
- Stainless Steel
- Steel, Bar, & Rod
- Tin
- Titanium Alloys
- Zinc

The primary production EE values and sources used to calculate the material energy can be found in Table A1 in the Appendix. For materials with a range of EE values, an average was used. This will be explained in more detail in the uncertainty analysis. Figure 4 shows the percentages of total mass and energy demand contributed by each material.

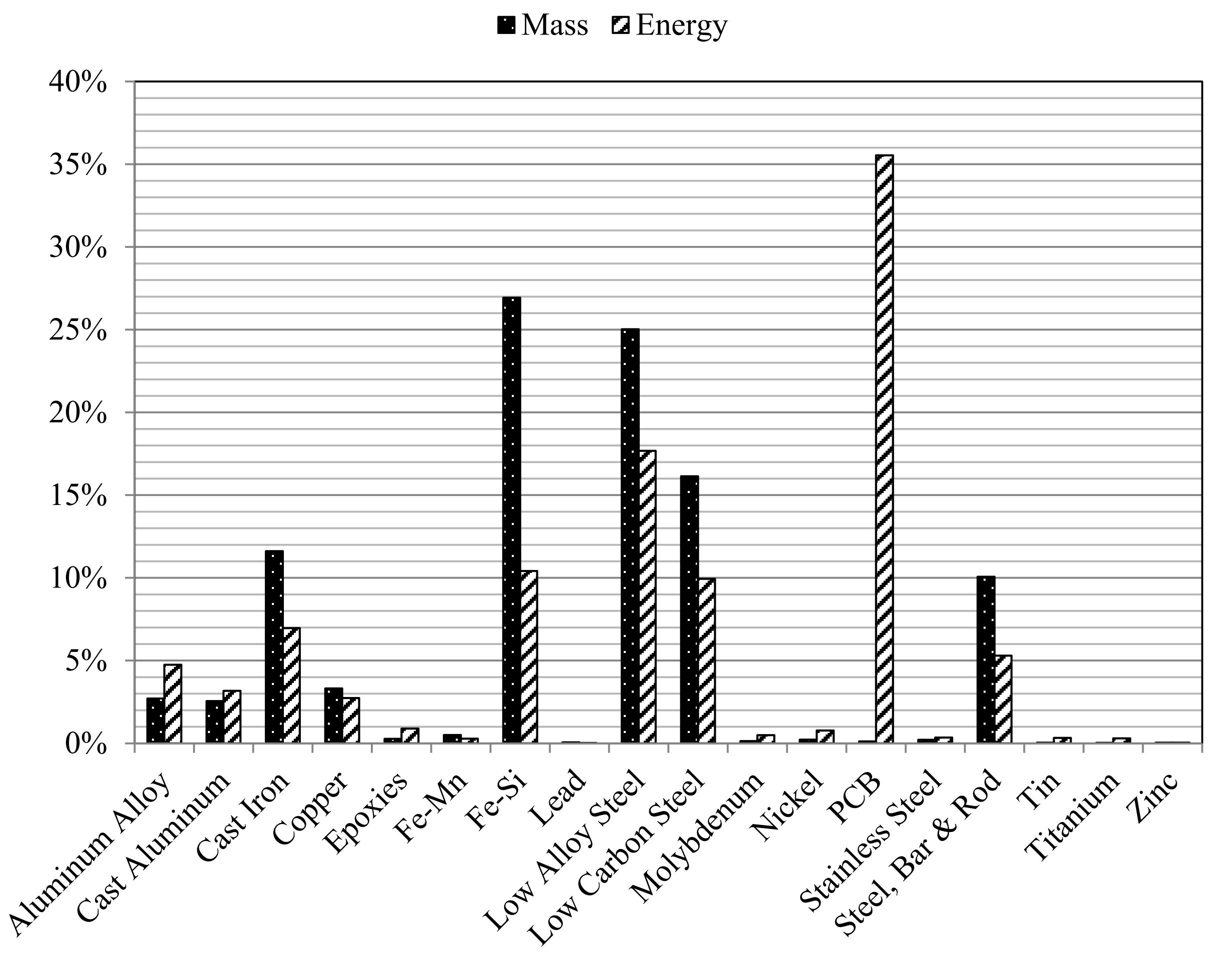

Figure 4: Mass and energy percentages of materials

It is clear that energy does not always have a proportional relationship to mass, which is further illustrated in Figure 5.

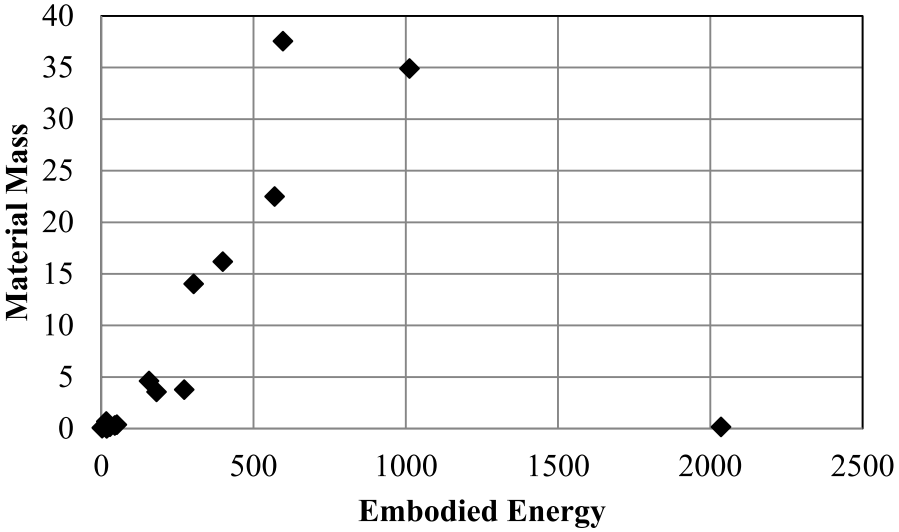

Figure 5: Relationship between mass and embodied energy (scaled)

The data point on the far right represents PCB (Printed Circuit Board) materials in the electronic control system. A PCB typically has a composition of over 70% non metals (i.e. plastic, resins, glass fibers, etc.), and about 16% copper, 4% solder, 3% iron, ferrite, 2% nickel, 0.05% silver, 0.03% gold, and 0.01% palladium (Zhou & Qui, 2010). The materials in a PCB are very energy intensive, which can be seen from Figure 6 and Figure 7, where the PCBs make up less than 1% of the mass, but make up 36% of the total EE of the genset.

In analyzing the results, it is helpful to understand the mass and energy breakdown of the individual parts of the genset as well. Figure 6 and Figure 7 show the allocation of mass and energy by parts. The heaviest components of the genset are the alternator and the engine, at a respective 44.7% and 37.8% of the total mass, and the most energy demanding part is the control system because of the energy intensive materials described earlier.

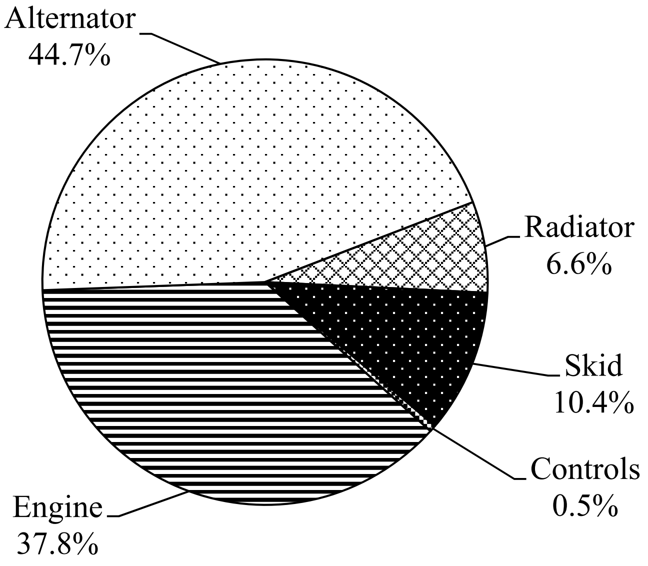

Figure 6: Mass allocation by part

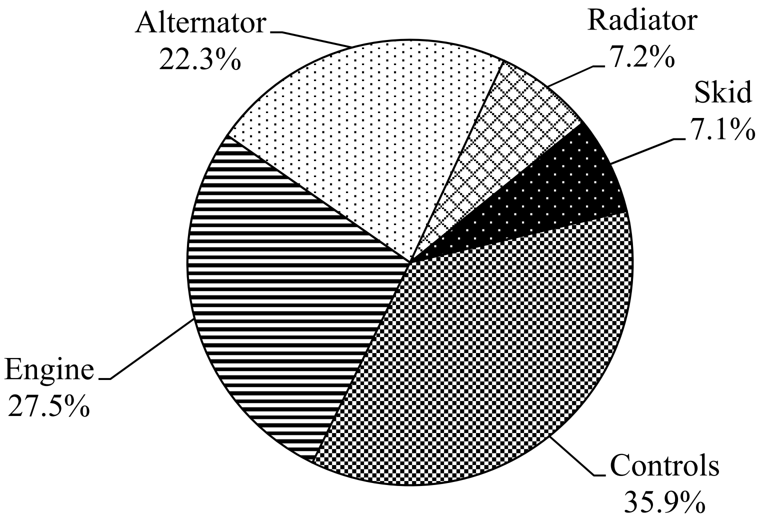

Figure 7: Energy allocation by part

2.3.1.3. Manufacturing Results

Figure 8 presents the relative energy requirements for each manufacturing facility. The 51% energy demand of the assembly & controls facility is representative of the large number of activities that occur at this site. In addition to the production of the controls and the assembly of the genset, other activities such as painting, testing, and validation also occur in the facility and contribute to the production of the genset. The skid production energy demand is higher than anticipated, most likely because of differences in data reporting methods. Suppliers' energy consumption reporting methods differ from those of the manufacturer. The skid and the radiator are produced by suppliers, whereas the engine, alternator, and controls are produced by the manufacturer. Manufacturing plant records contain information on the consumption of electricity, diesel, natural gas, and other fuels, namely propane, gasoline, ethanol, and biodiesel. Electricity usage reported by the manufacturer is electricity purchased from the grid. The United States Department of Energy (DOE) requires the manufacturer to include the source energy for electricity. To do this, the energy usage in kWh is multiplied by a factor of 3 to account for the generation and transmission losses from the utility. Since this level of detail is unknown for the supplier facilities, the most uncertainty lies in the skid and radiator facility energy usage.

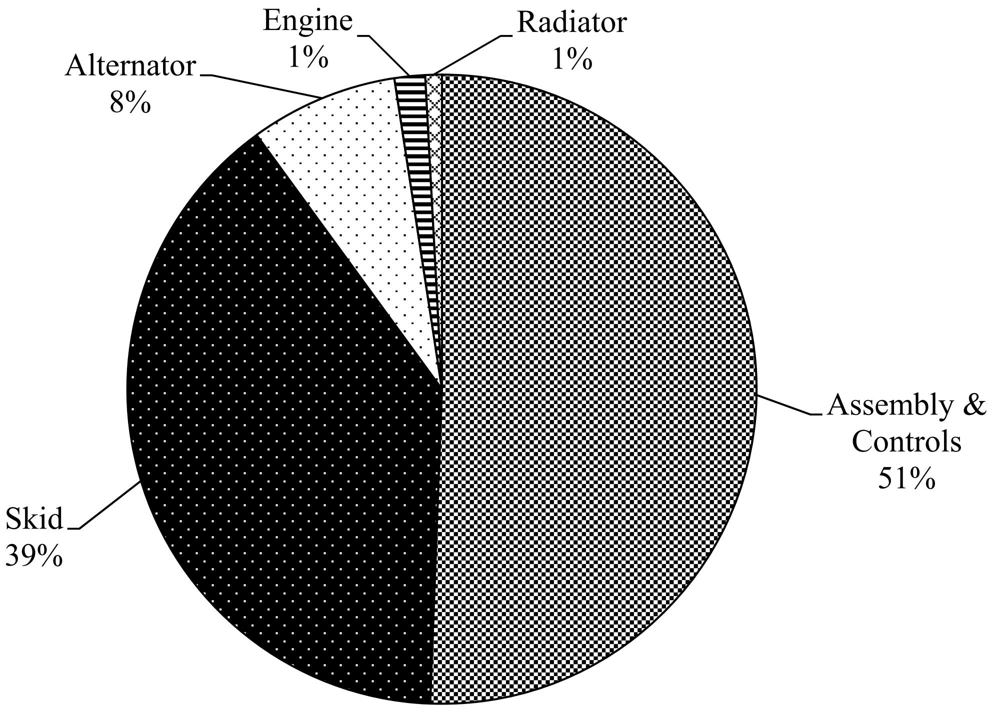

Figure 8: Manufacturing energy allocation

2.3.1.4. Transportation Results

Table IV contains the energy intensities for different transportation modes. Transportation by truck has the highest range of values and highest average energy intensity. Therefore, the products transported by truck have higher energy demands than other transportation methods. Except for the controls, each part is made at a manufacturing facility other than the genset assembly facility, which is located in the United States.

Table V shows the country of origin, transportation mode, transportation energy, and the percentage of overall energy contributed by the transportation for each part.

Table IV: Transportation energy intensities

Mode	Lower (MJ/t•km)	Upper (MJ/t•km)	Average (MJ/t•km)
Truck	1.70	7.30	4.50
Rail	0.49	0.70	0.56
Ship	0.15	0.61	0.38

Table V: Transportation information by part

Part	Country of Origin	Transportation Mode	Average Energy (MJ)	Energy (%)
Skid	United States	Truck	287	1
Controls[1]	United States	n/a		0
Radiator	China	Ship	877	2
		Truck	2,546	7
Engine	United States	Truck	10,291	28
Alternator	Mexico	Truck	23,172	62

[1] The controls are built at the genset assembly facility.

2.3.1.5. Use Results

As discussed in the overall results, the use phase has the highest energy demand of all of the life cycle stages. The energy demand for the use phase is a direct result of the hours of use. A graph showing the linear relationship between operation time and energy use is shown in Figure A1. The operation limit is 200 hours per year, which is based on the warranty. However, a more realistic option is in the range of 50-100 hours. This figure shows that even based on the lowest operation time of 50 hrs/yr, the use phase demands 3,500 GJ, which is 95% of the energy demand for all of the life cycle stages combined (see Figure 3). If the standby generator is operated at its maximum of 200 hrs/yr, the energy demand is 14,099 GJ, which is 99% of the total energy demand.

While it is common for the use phase to dominate the life cycle energy demand when the product uses fuel, it is surprising that this is still the case for a product that operates as an emergency power supply. In order to justify these results, a comparison of the use phase of an engine in an on-highway application was made, and the energy demand was calculated to account for 99.76% of the total energy demand, as shown in Table VI. While the use phase energy demand of the genset is large, it is not as large as that of an engine used in on-highway trucks. An on-highway engine has nearly 160,000 lifetime gallons, whereas a genset uses 28,000 gallons in a lifetime. Therefore, the energy demand is a result of the gallons of fuel burned.

Table VI: Comparison of engine and genset use phase

Life Cycle Stage	*Genset*	*Engine*
Materials	4.15%	0.19%
Manufacturing	0.29%	0.00%
Transportation	1.00%	0.05%
Use	94.57%	99.76%

2.3.1.6. End of Life Results

As previously mentioned, four different EoL disposal route scenarios were analyzed. Potential EoL credit and debit was calculated for each scenario and then added to the energy demand of the material stage in order to represent a potential increase or decrease in material energy demand as a result of the disposal route. The results are reported as positive and negative percent changes in the materials stage energy in order to communicate the positive effect recycling and remanufacturing has on the gensets as well as the negative effects of sending the product to a landfill. By remanufacturing the product, it is possible to reduce the initial energy consumption by nearly 83% (see Table VII), based on the assumptions mentioned in the calculation section. These results are similar to those of a study in which it was found that a remanufactured engine could be produced with 26% to 90% less raw material consumption than a brand new engine (Smith & Keoleian, 2004). Again, the specific disposal route of the genset was not determined, but these scenarios provide a good estimate of possible energy reductions that can be achieved by choosing sustainable disposal routes.

Table VII: Percent change in materials energy for each EoL scenario

Scenario	Percent Change in Materials Energy
1: Landfill 100%	+0.24%
2: Landfill 34%, Recycle 34%, Remanufacture 32%	-52.20%
3: Landfill 16%, Recycle 34%, Remanufacture 50%	-68.30%
4: Landfill 5%, Recycle 10%, Remanufacture 85%	-82.79%

2.3.1.7. Limitations

All LCAs contain inherent limitations but still provide valuable information. Estimates and assumptions have to be created for each life cycle stage. The assumptions used to perform this study were approved by the manufacturer and based on background information, previous studies, and logical thought. Regardless of the limitations of the study, the relative energy demands of each life cycle stage will remain about the same. Limitations specific to this study are described here:

- This LCA only addresses energy demand. Other impact metrics such as greenhouse gas emissions, eutrophication potential, and acidification potential are not presented in this study.
- Material inventory data gaps limit the accuracy of the results. However, 87% of the total genset mass was accounted for by using the data collection methods described earlier.

- The system boundary described in Figure 2 also limits the impact assessment because the transportation stage is more expansive than what is considered in this study. Also, the material processing stage only includes the initial material processing and not specific processing (e.g. machining, milling, forging) related to each part.
- The uncertainty of the EoL disposal route is also a limitation.

2.3.2. Sensitivity Analysis

A sensitivity analysis was conducted in order to test the extent to which overall energy demand is sensitive to a ±10% change in input parameters. Use, materials, transportation, and facility energy were the input parameters tested. Figure 9 presents the results in a tornado plot, where the centerline represents the baseline case, and the values to the left and right represent a 10% decrease and increase, respectively. The overall energy demand is most sensitive to the life cycle stages that account for the largest portion of overall energy. Since the use phase is most sensitive to change, this means that changes in the use parameters, such as fuel efficiency, will have a significant impact on the overall energy demand.

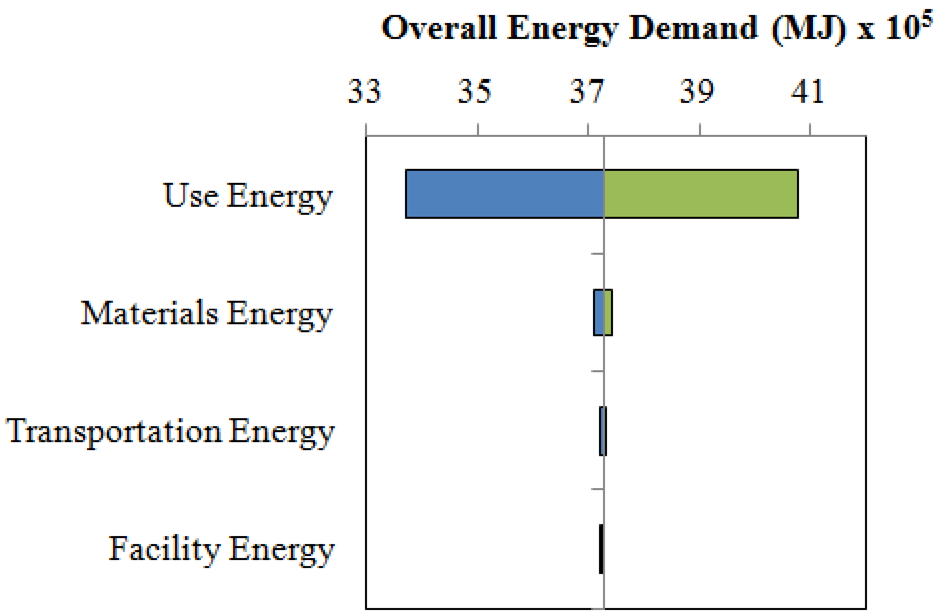

Figure 9: Tornado plot showing the sensitivity of overall energy demand to use, materials, transportation, and facility energy

An additional tornado plot was created for the materials energy in order to demonstrate the effect of changing the primary production EE values by ±10% for each. The top ten most sensitive EE values are shown in Figure 10. A combination of material mass and primary production EE values produce these results.

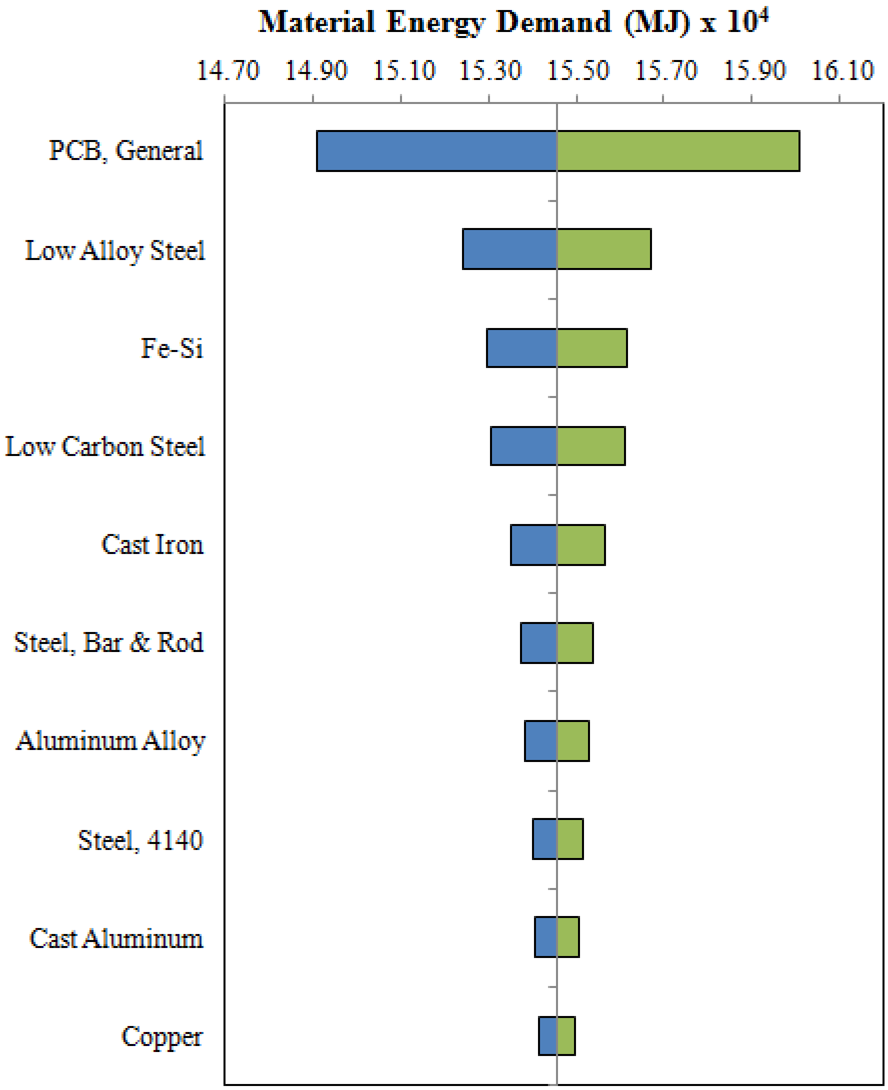

Figure 10: Tornado plot showing the sensitivity of material energy demand to primary production embodied energy values

2.3.3. Uncertainty Analysis

A Monte Carlo simulation was used for the uncertainty analysis. Twenty-one parameters used to calculate the overall energy demand were tested for uncertainty. To perform the simulation, transportation and material energy intensities were replaced with random numbers generated by Excel based on the specified distribution type. A lognormal distribution was used for material energy intensities with standard deviation and average data. In the case where a lower and upper energy intensity was provided, a triangular distribution was used. A complete list of the parameters varied and the corresponding distribution can be seen in Table A3 in Appendix A. The overall energy demand was calculated with a fixed manufacturing and usage energy value because there are no statistical data for these stages. For each parameter that was replaced with a random value, 1000 iterations were used, producing a total of 21,000 iterations.

Each iteration produces an overall energy demand value. After all of the iterations are complete, the results are represented by a histogram shown in Figure 11 with overall energy demand on the x-axis, and the corresponding frequency of occurrence on the y-axis. Also shown in Figure 11 is the actual overall energy demand of 3,727,318MJ, which lies within the bin frequency of 2581 and has a probability of 13.58%. The bin with the largest frequency is 3,708,000 MJ, which only has a percent difference of 1.0% from the calculated value. An additional materials energy demand uncertainty analysis was also performed. The histogram shown in Figure A2 in Appendix A reveals if the energy demand with the highest frequency was used for this study, the materials stage energy would account for 3.67% of the overall energy demand rather than the current 4.1%, which is a minor difference for this study.

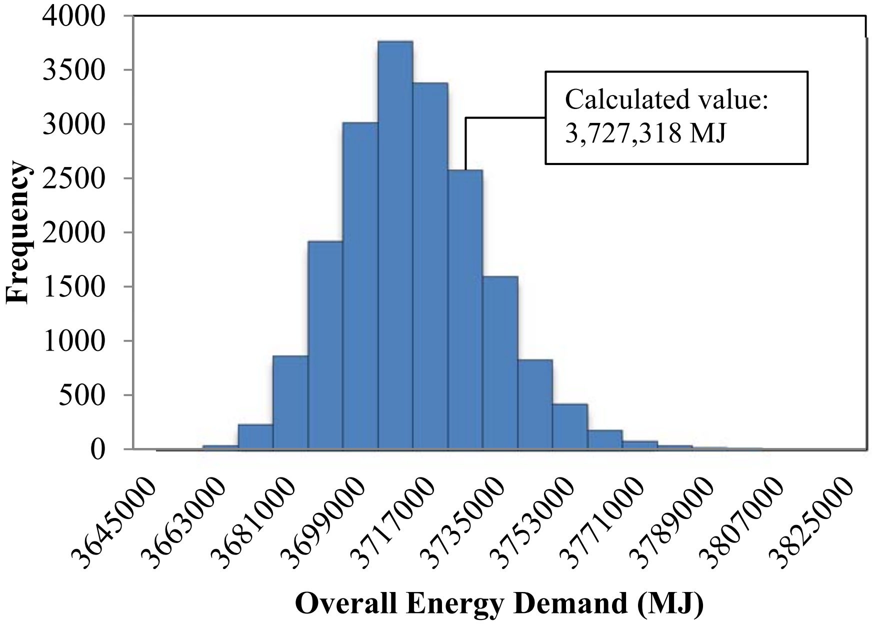

Figure 11: Monte Carlo simulation results for overall energy demand

2.4. Conclusion for Genset SLCA Case Study

A SLCA was conducted for a standby diesel genset. The use stage accounts for 94.6% of the overall energy demand using an operation time of 50 hrs/yr, which is on the lower range of operation time. These results were unexpected for an ESP genset but were put into perspective when the use phase of an on-highway application engine was calculated and found to account for 99.76% of the overall energy demand of engine production. While the use phase of the ESP genset is high, it is still lower than an engine in an on-highway application, which is expected. The sensitivity analysis shows that a 10% reduction in the use phase energy demand has the potential to reduce the overall energy demand by 3.56×10^5 MJ, or 9.5%.

The next most energy intensive stage is materials at 4.1%, transportation at 1.0%, and then manufacturing at 0.3%. A material energy analysis shows PCB has the highest energy demand at about 36% of the total because it is made of materials, like gold and palladium, that demand a significant amount of energy to be extracted from the earth. As a result, the controls consisting of several PCBs accounted for the largest energy demand out of all of the parts but only made up 0.5% of the overall mass of the genset. A more detailed analysis of the controls would most likely reveal that the controls account for more than 36% of the total material energy demand because of capacitors and resistors that could not be specifically accounted for in this analysis. The results may also be influenced by the 13% of the genset mass that was not included in the study.

The transportation that was considered only accounts for a portion of the transportation involved with the production of a genset. Therefore, this stage would most likely account for a larger percentage of the overall energy demand if a full analysis was conducted for transportation. The transportation of the alternator from Mexico to the United States accounts for 62% of the overall transportation energy because of the long distance traveled by truck.

The EoL results showed that if 85% of the genset is remanufactured, 10% is recycled and only 5% sent to a landfill, the materials energy could be reduced by 82%. In addition, the EoL analysis emphasizes the importance of recycling and remanufacturing in order to reduce energy intensive material extraction and processing.

Chapter 3

3. Overall Conclusion

This section concludes this study and provides a summary of this LCA case study, recommendations to the manufacturer, and suggestions for future work.

3.1. Summary

LCA is an effective technique to analyze the potential environmental impacts over the entire life cycle of a product. This SLCA of a genset was conducted in accordance with ISO standards. The goal of the study was to determine the overall energy demand for the life cycle of an ESP genset. Life cycle stages included in the analysis were materials, manufacturing, transportation, and EoL. Overall results showed that the use phase accounts for 94.6% of the overall energy demand. The materials, transportation, and manufacturing stages account 4.1%, 1.0%, and 0.3%, respectively. It is important to note that the use phase occurs over the entire life of the product and the other stages only occur once. As a result, the use phase has such a large energy demand that the other stages appear to be insignificant, but they are not. The other stages demand a significant amount of energy, but that may not be apparent by only looking at Figure 3, which shows the energy percentages of each life cycle stage relative to the overall energy demand.

The material results revealed that the control system is the most energy intensive part of the genset, accounting for 35.9% of the total genset energy but less than 1% of the genset mass. This is a result of the energy intensive materials within the controls. A more massive material does not necessarily correspond to a higher energy demand, as shown in Figure 5. The manufacturing results showed the facility in which the genset is assembled and the controls are built account for 51% of the total manufacturing energy. Next was the skid, at 39% and then the alternator, engine, and radiator at 8%, 1%, and 1%, respectively. This stage has the most uncertainty because some of the data comes from a supplier, and the level of detail and accuracy is unknown.

Transportation results showed that the alternator requires the most energy because it shipped from Mexico by truck. The radiator is shipped from China, but has a lower energy demand because a portion of the travel distance is by ship, which has a much lower energy intensity than a truck.

The use phase results showed that even at the lowest range of operation time, it accounted for 94.6% of the overall energy demand. If the upper range of operation time is used, the use phase accounts for 99% of the overall energy demand. Therefore, the use phase will always account for the largest portion of energy, but this also means that small changes in use parameters will have the largest impact on overall energy demand, as shown in the sensitivity results in Figure 9.

Simply because the use phase is the most energy intensive stage does not mean that the energy demands of the other stages are not important. In order for the genset to have the most sustainable life, the goal should be to reduce energy demands wherever possible. One such reduction can be achieved in the EoL stage. The results showed that varying remanufacturing rates have the potential to reduce the materials stage energy demand by nearly 83% (see Table VII).

Finally, to measure the uncertainty associated with the SLCA, a Monte Carlo simulation was performed in which twenty-one parameters were replaced with random numbers assigned by Excel according to the specified distribution shown in Appendix A. The results of the 21,000 iterations revealed that the uncertainties in the data have little effect on the overall energy demand and relative energy demands of each life cycle stage.

3.2. Recommendations

This section provides recommendations to the manufacturer based on the results of the SLCA that will improve the sustainability of the genset by making energy reductions where possible.

- In order to achieve the largest reduction in overall energy demand of the life of the genset, the focus should be on the use phase. Assuming that the life expectancy, operation time, and calorific value of diesel remain constant, the only influential parameter that remains is fuel efficiency. By improving fuel efficiency by 10%, the overall energy demand can be reduced by 9.5%, which may sound small but is actually 3.56 x 10^5 MJ.
- Energy reductions can also be achieved by increasing remanufacturing rates of gensets. A cost analysis should be performed if the manufacturer decides to implement a remanufacturing operation themselves. However, when thinking in broad terms of LCA, the goal is to improve sustainability on a global level; so, if the gensets are not being remanufactured by the original manufacturer but by a different company, the positive impact on the environment is still the same. Regardless of which company is remanufacturing the product, the raw material extraction phase is bypassed. The manufacturer’s role in environmental stewardship should then be to ensure that gensets are being disposed in a sustainable manner by contacting the customers and identifying EoL disposal routes. If results show that remanufacturing rates are lower than what is possible,

the manufacturer should encourage the customer to dispose of the product sustainably. By following these steps, the manufacturer will have committed to product sustainability from cradle-to-grave.

- Another possible method to reduce energy is to consider using materials with higher recycled content when possible. As the recycled content of a material increases, the EE value decreases.
- The transportation stage considered in this study accounts for 1% of the overall energy demand, but only considers one part of the transportation network. In order to ensure that goods are being transported in the most efficient method, more transportation data should be collected in order to get an idea of the overall transportation network. Focusing efforts on transportation for common parts that can be purchased from a variety of suppliers may be more productive than looking at specialty parts that are only available from one supplier at one location.

3.3. Future Suggestions

If future work on genset LCAs is performed by the genset manufacturing industry, the following suggestions may improve accuracy and facilitate the study:

- If multiple LCAs are going to be conducted, training personnel to be LCA subject matter experts would be a valuable use of time and resources so that the methodology remains consistent across all LCAs. This would facilitate the work and allow results to be compared across multiple studies.
- Future work should consider studying additional impact metrics such as water use or air emissions in order to ensure that environmental impacts are not trading off from one medium to another.

- Time should be invested into acquiring data from suppliers and learning about their reporting methods. This would allow manufacturing and supplier data to be more comparable and would improve data accuracy.
- Any industry that plans to conduct a LCA should keep product material inventory data easily on hand. This would speed up the data collection process, improve material data accuracy, and reduce uncertainties.

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Appendix A: Supporting Material

Table A1: Material primary production embodied energy values and corresponding sources

Material	Embodied Energy Value (MJ/kg)	Source
Aluminum Alloy	72	Ecoinvent, index #1045, aluminium alloy, AlMg3, at plant
Cast Aluminum	51	Ecoinvent, index #1057, aluminium, production mix, cast alloy, at plant
Cast Iron	25	ICE, Iron, General
Copper	34	Ecoinvent, index #1074, copper, at regional storage
Epoxies	133.5	Ashby, mean value, 127 and 140
Ferromanganese (Fe-Mn)	23	Ecoinvent, index #1097, ferromanganese, high-coal, 74.5% Mn, at regional storage
Ferrosilicon (Fe-Si)	15.88	Composite. 45% - Ecoinvent, index #321, silicon carbide, at plant. 55% - Ecoinvent, index #1132, pig iron, at plant.
Lead	16	Ecoinvent, index #1103 lead, at regional storage
Low Alloy Steel	28.0	Ecoinvent, index #1154, steel, low-alloyed, at plant
Low Carbon Steel	25	ICE, General Steel, World typical-world 39% recycled
Molybdenum	151	Ecoinvent, index #1116 molybdenum, at regional storage
Nickel	142	Recycled production mix. 74% Ecoinvent, index #1121 nickel, 99.5%, at plant. 26% Ecoinvent, index #8149 nickel, secondary, from electronic and electric scrap recycling, at refinery.
PCB, General	12,101	Ecoinvent (Bolin, 2013)
Stainless Steel	68	Ecoinvent, index #1152 steel, electric, chromium steel 18/8, at plant
Steel, 4140	33.5	Composite. 99% Ecoinvent, index #1154, steel, low-alloyed, at plant. 1% Ecoinvent, index #1073, chromium, at regional storage.
Steel, Bar & Rod	22	ICE, Bar & Rod - World typical 39%
Tin	321	Ecoinvent, index #1155 tin, at regional storage
Titanium	471	ICE, Titanium, general
Zinc	52	Ecoinvent, index #1156 zinc, primary, at regional storage

Table A2: Material recycling embodied energy values

Material	**Recycling EE Value (MJ/kg)**
Aluminum Alloy	26 [Ɨ]
Cast Aluminum	10.2 [ƗƗ]
Cast Iron	10.5 [Ɨ]
Copper	13.5 [Ɨ]
Epoxies	n/a
Ferromanganese (Fe-Mn)	7.95 [ƗƗƗ]
Ferrosilicon (Fe-Si)	7.95 [ƗƗƗ]
Lead	3.2 [ƗƗ]
Low Alloy Steel	8.6 [Ɨ]
Low Carbon Steel	7.3 [Ɨ]
Molybdenum	30.2 [ƗƗ]
Nickel	33 [Ɨ]
PCB, General	2,420.2 [ƗƗ]
Stainless Steel	12 [Ɨ]
Steel, 4140	7.95 [ƗƗƗ]
Steel, Bar & Rod	7.95 [ƗƗƗ]
Tin	64.2 [ƗƗ]
Titanium	87 [Ɨ]
Zinc	11 [Ɨ]

[Ɨ] Ashby mean recycling value for specific material

[ƗƗ] EE value was calculated as one-fifth of primary production EE

[ƗƗƗ] Average of Ashby's low alloy and low carbon steel recycling EE value

Table A3: Parameter distributions used in uncertainty analysis

Energy Intensity Parameter	Distribution
Aluminum Alloy	Log normal
Cast Aluminum	Log normal
Cast Iron	Log normal
Copper	Log normal
Epoxies	Triangular
Ferromanganese (Fe-Mn)	Log normal
Ferrosilicon (Fe-Si)	Log normal
Lead	Log normal
Low alloy steel	Log normal
Low Carbon Steel	Log normal
Molybdenum	Fixed Value
Nickel	Log normal
PCB, General	Triangular
Stainless Steel	Log normal
Steel, 4140	Log normal
Steel, Bar & Rod	Log normal
Tin	Log normal
Titanium alloys	Log normal
Zinc	Log normal
Transportation by Truck	Triangular
Transportation by Ship	Triangular

Table A4: Statistical data used for lognormal distributions in Monte Carlo simulation

Material	Average Energy Intensity (MJ/kg)	Standard Deviation (MJ/kg)	σ	μ
Aluminum Alloy	157.1	104.7	0.606242	4.467335
Cast Aluminum	157.1	104.7	0.606242	4.467335
Cast Iron	24.62	7.5	0.297897	1.970532
Copper	69.02	37.52	0.508828	3.495421
Ferromanganese (Fe-Mn)	31.25	16.5	0.495893	2.680406
Ferrosilicon (Fe-Si)	31.25	16.5	0.495893	2.680406
Lead	45.17	43.72	0.813051	3.44728
Low Alloy Steel	31.25	16.5	0.495893	2.680406
Low Carbon Steel	31.25	16.5	0.495893	2.680406
Nickel	164	43.59	0.26127	3.740697
Stainless Steel	45.68	28.84	0.5792	3.194027
Steel, 4140	31.25	16.5	0.495893	2.680406
Steel, Bar & Rod	31.25	16.5	0.495893	2.680406
Tin	84.44	87.83	0.85632	4.108761
Titanium Alloys	470.67	188.43	0.385561	5.164398
Zinc	59.8	25.16	0.403714	3.143763

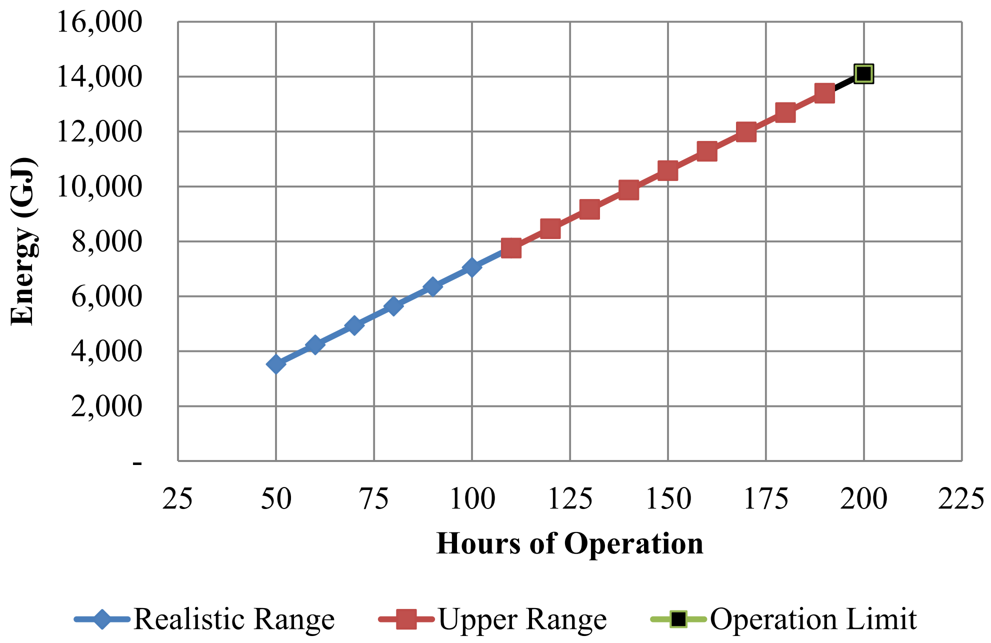

Figure A1: Energy demand per hours of operation

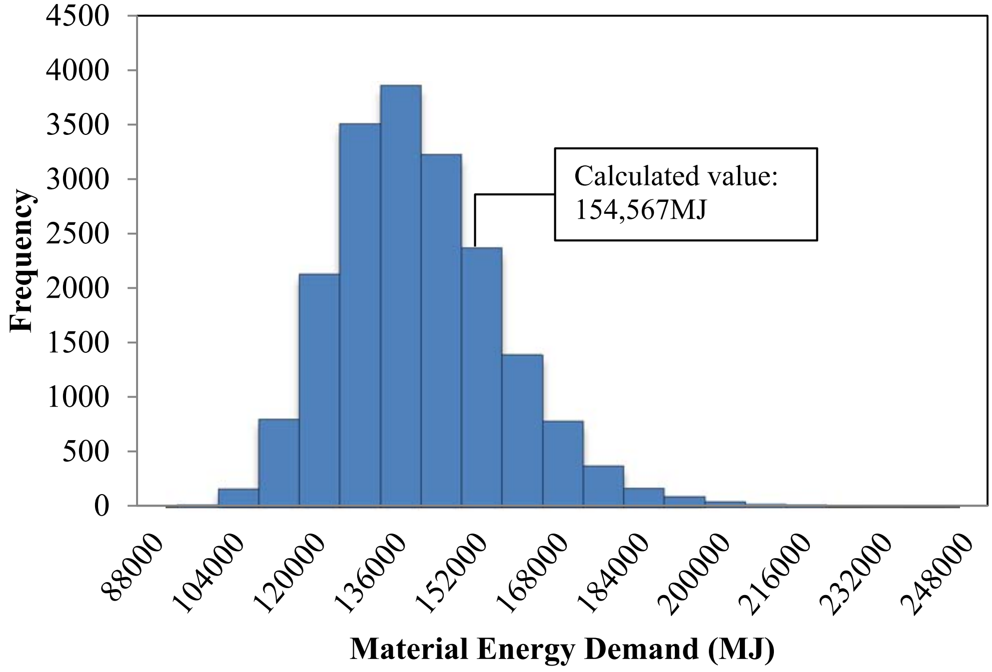

Figure A2: Monte Carlo material energy demand simulation results

SIGNATURE PAGE

This is to certify that the thesis prepared by Kelly Benton entitled "A Life Cycle Assessment of a Diesel Generator Set" has been examined and approved for acceptance by the Department of Environmental Engineering, Montana Tech of The University of Montana, on this 26th day of April, 2016.

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