Remanufacturing and Energy Savings

By

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ABSTRACT

The substantial growth in industrial production, demand for materials, and population has led to an increasing need for sustainable manufacturing processes to mitigate the negative impacts on the environment and meet the needs of future generations. One proposed direction is remanufacturing, which is a process whereby used products having reached their end-of-life, are restored back to useful service-life. Remanufacturing utilizes the energy and embedded value retained in a product upon reaching end-of-life. Remanufacturing can close the loop between disposal and supply chains, extend the service lifetime of products, conserve resources, and help mitigate environmental consequences attributed to landfilling. Moreover, by preserving the geometrical architecture of cores, remanufacturing can reduce the needs for raw material processing and many manufacturing processes, hence, saving energy.

A critical issue to consider when evaluating energy savings in remanufacturing is the product use phase: how well does the remanufactured device perform in the use phase compared to a similar new product from an energy standpoint? To answer this question, we utilize Life Cycle Assessments framework. Using this methodology, we quantify cumulative energy demands of a remanufactured product during its lifecycle and compare it to an equivalent new product. We conduct an analysis of lifecycle energy savings of remanufacturing for 19 different products in 8 distinct product case studies (4 product case studies discussed in detail in this thesis).

By performing lifecycle evaluations we conclude that remanufacturing can be a net energy-saving option for products that have energy requirements dominated by the production phase. Moreover, our energy analysis sheds light on the importance of considering use phase while evaluating the energy savings potential of remanufacturing. We conclude that from a total life cycle perspective, remanufacturing may be a net energy saving as well as a net energy expending end-of-life option. We argue that in investigating energy savings of remanufacturing as an end-of-life option, one should also evaluate large-scale critical factors in order to effectively address the systems challenges associated with remanufacturing. Our retrospective approach signifies the importance of studying critical factors such as technological improvements, policy interventions, economic incentives, and business models in order to draw inferences about energy and economic savings potential of remanufacturing. In addition, we argue that the generalized claims about remanufacturing as the ultimate end-of-life option are not only subject to dynamic global changes, but also restricted by the limitations in the lifecycle environmental methodologies. Lastly, we conclude that the evaluations for product remanufacturing and energy savings are more valuable and justified if conducted on a case-by-case basis.

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1.1 Motivation

Since the industrial revolution, the world has gone through major changes such as globalization, substantial rise in population, and extensive progress in industrialization. It is projected that the world population will increase from 6.7 Billion in 2008 to more than 8 Billion in 2050 (WorldBank). More than 90% of this growth will take place in developing countries, as depicted in Figure 1 below. The high rate of growth in population has caused ever-increasing demands for energy and natural resources.

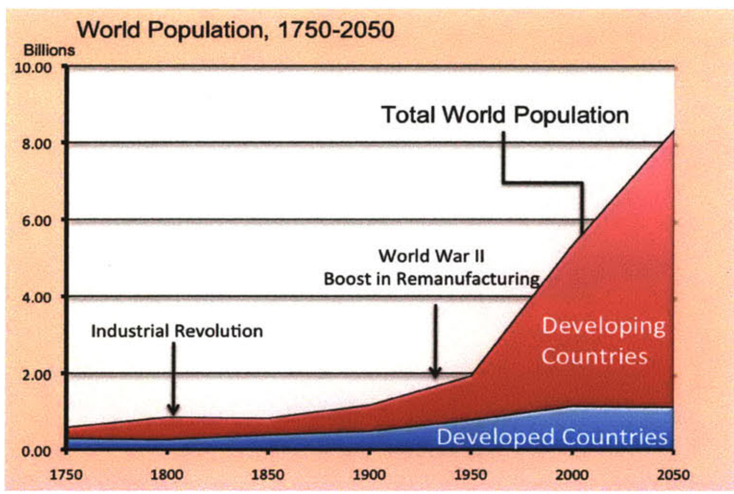


Figure 1 World population, 1750-2050 (WorldBank).

The global consumption of raw materials has increased from 6 to 10 Billion tonnes from 1970 to 1995 (U.S.G.S. ; Baker, Bournay et al. 2004). As developing countries emerge from pre- to post-industrial economies, it will cause even higher rates in global raw materials (e.g. oil, steel, aluminum, copper) consumption.

During the 20th century, industries have enhanced operational efficiencies while expanding distribution channels globally with groundbreaking achievements such as lean-manufacturing and just-in-time delivery. Such achievements have also influenced complex global challenges involving unsustainable practices in the supply chain. More specifically, the exponential growth in production in the past century has over-shadowed the urgent need for proper disposal and conservation of products as they reach end-of-life. As a result, in the last two decades of the 20th century, generation of waste has increased by 50% in developed countries (Baker, Bournay et al. 2004). In the U.S., municipal solid waste has grown substantially from 88 million tons in 1960 to 254 million tons in 2006 (EPA 2006). For example, the emergence of information technology has led to excessive global production, use, and waste generation of computing products. This has created environmental challenges in relation to the electronics waste management. The hazardous elements utilized in construction of electronics products cause serious threats such as earth contamination, human and species health risks. Moreover, increase in consumption patterns, technological obsolescence, and product proliferation have led to premature disposal of products without recovering the retained values invested into them. Such disposal protocols are unsustainable given that the material and energy used to manufacture the product are not effectively recovered.

The threats posed by a changing climate as well as vulnerability to resource scarcity have urged the global community to focus on energy and resource conservation and environmentally friendly actions. From an industrial perspective, environmentally benign manufacturing has become a critical strategic consideration in order to conserve energy, minimize anthropogenic emissions, prevent waste, and responsibly preserve natural raw materials resources (Kumar and Putnam 2008). More specifically, some manufacturing industries, governmental municipalities, and citizens are taking affirmative steps towards closing the loop between the supply and the removal chains by encouraging recycling, refurbishing, remanufacturing, and reuse. For example, since 1970's municipalities waste management systems have been steadily growing recovery facilities for recycling metals, and paper (EPA 2006).

Policy interventions have also been an influential driver in progressing towards environmentally conscious manufacturing and waste management systems. Some governmental agencies are advocating for preventing and managing municipal solid waste as well as hazardous waste (Kumar and Putnam 2008). One of the key efforts for environmentally friendly end-of-life is to close the loop between the consumer and the producer by means of the Extended Producer Responsibility (EPR). More specifically, such laws make the producer responsible for proper and environmentally conscious disposal of their products in the market (King, Burgess et al. 2006). The Waste Electrical and Electronic Equipment (WEEE) and the Restriction of Hazardous Substance (RoHS) directives are two examples of governmental efforts for promoting environmentally benign manufacturing and mandating the recovery of discarded products by closing the loop between consumer, municipalities, and producers.

The WEEE is a legislation by and for the European Union that restricts the use of hazardous substances and toxic elements (Union 2003) while promoting the recycling and collection of electrical and electronic equipment with heavy responsibilities put on manufacturers and producers. The WEEE has established product-return channels for consumers to bring their products to a collection facility upon reaching product end-of-life. The WEEE legislation is framed such that consumers are not entitled to pay for collection/recycling fees. The WEEE demands that hazardous substances such as lead, mercury, cadmium, hexavalent chromium be replaced by more environmentally-friendly alternatives.

The RoHS directive is currently enforced in the European Union, which enforces stringent limits on the use of certain hazardous substances in electrical and electronic equipments. More specifically, the RoHS policy restrictions are such that new electronic product entering the EU market must have below agreed limits in the amount of lead, chromium, mercury, hexavalent chromium, polybrominated biphenyl (PBB), and polibrominated diphenyl ether (PBDE) flame retardants. The maximum allowed amount of the above substances are 0.1% or 1000 parts-per-million (ppm) by weight (except Cadmium, which is 0.01% by weight) of homogeneous material.
In the U.S., the Environmental Protection Agency (EPA) provides information about mechanisms for adoptions of reduce, reuse, and recycle (Ferguson 2009). One of the main objectives of EPA is to promote recovery end-of-life options such as reduce, reuse, recycle by the consumers. EPA also encourages optimal use of product, reducing

extensive generation of waste, maximizing lifetime, and decreasing the requirements of new materials and products. The emerge of environmental policies in favor of the environment have led to extensive efforts for designing recycling guidelines- some of which are applicable to remanufacturing (Kutz 2007). For further discussion of the take-back laws, WEEE, and RoHS please refer to (WEEE 2000; O'Neill 2003; Stevels 2003; Sundin 2004; DOC 2005; Kumar and Fullenkamp 2005; Kumar and Putnam 2008).

Despite the improvements from the municipalities in the removal processes (e.g. enhanced efficiency of recycling processes), the management of waste is yet to be improved upon considerably to overcome operational bottlenecks that have been resolved in the supply stream. Core concerns with the removal processes demand much attention in the face of current and future environmental problems. The conventional end-of-life options such as incineration and land filling have a high potential for negatively impacting the environment. For example, between 25 to 50% of land contaminations and 34% of global methane emissions (one of the six greenhouse gases targeted for the reduction in Kyoto Protocol) are as a result of waste activities (King, Burgess et al. 2006). Moreover, composting produces greenhouse gas emissions while incineration operations lead to high emissions of CO_2 and N_2O.

In addition, despite the fact that recapturing of raw materials by recycling is highly beneficial to the environment, it fails to recover the embedded energy expended in various steps in the supply chain such as processing the material to its appropriate forms, transportation fuel costs, labor efforts, plant electricity, etc.

Amongst closed-loop supply chain alternatives beneficial to the environment, a proposed end-of-life solution is to extend service lifetime of products by remanufacturing. Remanufacturing thrives to restore a used product that has reached end-of-life to like-new conditions. In remanufacturing, the embedded energy and materials stored in a scrap product is recaptured while keeping the product geometry and architecture unchanged.

The purpose of this research is to study the impact of remanufacturing on the environment by studying it in the context of its energy savings potential. Moreover, we investigate remanufacturing energy savings in the broader context of macroscopic impacts such as pace of technological advancements, economic drivers, policy interventions, and market demands. The next sections in Chapter 1 provide an overview of remanufacturing, discuss prior academic and industrial work in remanufacturing, and conclude by conveying the research questions addressed in this thesis.

1.2 Remanufacturing Overview

1.2.1 Remanufacturing: History and Scope of the Industry

The history of remanufacturing goes back to Second World War where materials scarcity led to the practice of rebuilding old automotive engines and weapons (Sundin 2004). Ever since then, remanufacturing operations have grown substantially in various industries and have become common practices for some secondary aftermarkets. In the U.S., remanufacturing operations are predominantly carried out by third-party remanufacturers; remanufacturing by Original Equipment Manufacturers (OEMs) continues to be disengaged and relatively small (Guide Jr, Jayaraman et al. 2000). Remanufacturing practices are more advanced in European countries given existing take-back laws as well as higher environmental consciousness (Seitz and Peattie 2004; Sundin 2004).

Currently, the estimated number of remanufacturers in the U.S. is close to 2000 firms (Hauser and Lund 2008). These firms are widely distributed across different industries and multiple functional practices. Figure 2 below provides an illustration about the distribution of these 2000 firms across different industries. Of these 2000 remanufacturing establishments, 94% are small- to mid-sized businesses that employ about 10 employees or less (Hauser and Lund 2008). Moreover, there are business strategies taken in favor of remanufacturing in some large corporations and governmental agencies such as Xerox, Caterpillar, Pratt and Whitney, General Electric, Kodak, and U.S. Department of Defense (Kutz 2007). Most remanufactured products are sold to commercial, industrial, or governmental customers. This is because the users have experience with the product over time, and aspire to opportunities for cost savings, or have the means and know how to evaluate products for their intended use (Hauser and Lund 2008).

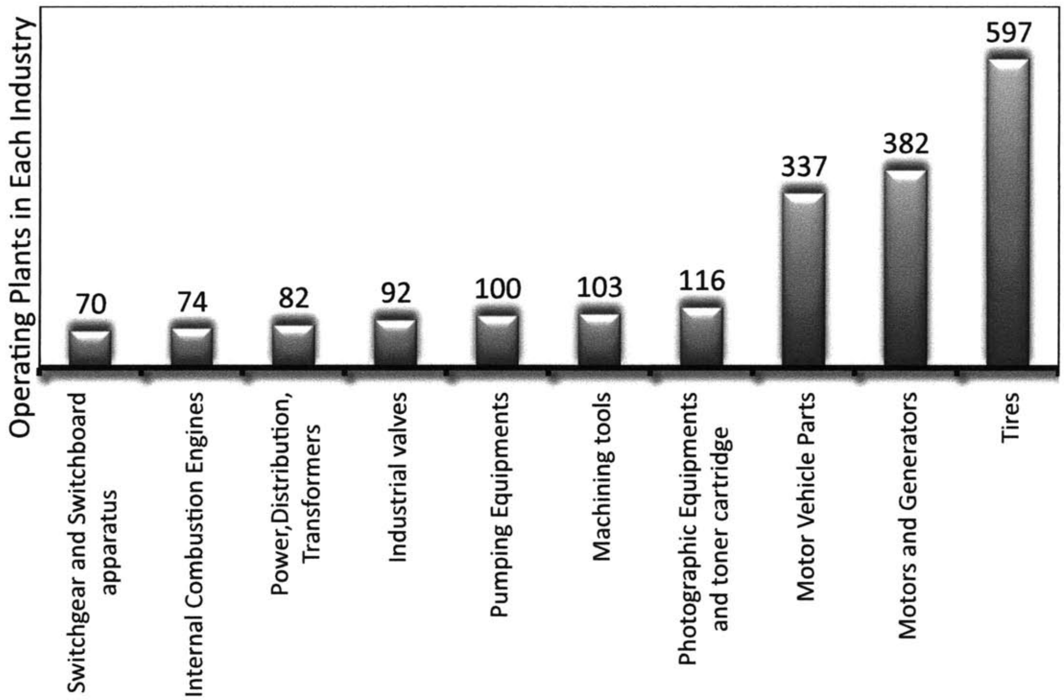


Figure 2 Operating plants in different divisions of the remanufacturing industry (data compiled from industry survey provided by (Hauser and Lund 2008) Appendix A).

The primary driver for remanufacturing is based on the residual value of used products upon reaching end-of-life. Therefore, this has led to development of business models by third parties to remanufacture the old products, and sell it for a reduced price. By providing like-new products at prices that typically range from 45% to 65% of comparable new products, remanufacturers can attract new buyers into a market where new product prices have been prohibitively high for them (Hauser and Lund 2008).

Certain OEMs have taken affirmative actions as they have realized the high values of used products as they reach end-of-life (Kutz 2007). For example, with the intention to gain leverage in competing with third-party remanufacturers, Lexmark, a manufacturer of printers and copiers, has developed a proprietary technology that limits third-party remanufacturers for recharging the used cartridge. On the other hand, given the high residual value of a scrap tire coupled with the high market demand for remanufactured (i.e. retreaded) fleet tires, OEMs have realized truck tire remanufacturing as a strategic opportunity for maximizing profit and gaining more market share. Also, some of the larger OEMs pursue remanufacturing as a business model in product leasing businesses (Kutz 2007).

1.2.2 Remanufacturing: Definition

There are multiple ways to define remanufacturing, but most are commonly referring to the basic concept of product rebuilding. Remanufacturing is a process whereby used-products (referred to as cores) having reached their end-of-life, are restored back to useful service-life. For similar definitions refer to (Seaver 1994; Amezquita 1996; Sundin 2004; Hauser and Lund 2008). Typically, in remanufacturing a core passes through a number of sequential steps such as inspection, disassembly, part replacement, part refurbishment, cleaning, reassembly, and testing to ensure it meets the desired product standards. Remanufacturing, in general, is becoming the generic concept for the processes involved in restoring discarded products to useful services (Hauser and Lund 2003).

Remanufacturing, as an end-of-life strategy, has a high potential for reducing the needs for processed raw materials, minimizing waste, and eliminating energy requirements during production and end-of-life phases. Remanufacturing achieves this by recovering the embedded energy and materials retrained in used products that reach end-of-life.

The remanufacturing processes can be put in different orders; steps can be added or omitted based on product type. For example, if the rebuilding of the scrap product is not involved, i.e., only few parts are to be replaced, either terms reconditioning or refurbishing is more suitable. Moreover, upon parts failure, used products can be re-used by repairing.

The definition of remanufacturing in this research is the process of restoring old products to service lifetime. Therefore, given that this thesis is analyzing remanufacturing from the viewpoint of extending service lifetime, the definition of remanufacturing as proposed in this thesis overlaps with similar end-of-life recovery options such as re-use, repair, and refurbish.

1.2.3 Remanufacturing Process

Remanufacturing processes span across many industries and functional practices. Similar to manufacturing, each remanufacturing process is distinctly different given variations in product criteria, market demands, core availability, and production volume. Twelve processes are most commonly utilized in remanufacturing processes as listed below (Kutz 2007):

1. Warehousing of incoming cores, parts, and outgoing products
2. Sorting of incoming cores
3. Cleaning of cores
4. Disassembly of cores and subassemblies
5. Inspection of cores, subassemblies, and parts
6. Cleaning of specific parts and subassemblies
7. Parts repair or renewal
8. Testing of parts and subassemblies
9. Reassembly of parts, subassemblies, and products
10. Testing of subassemblies and finished products
11. Packaging
12. Shipping

Most studies refer to steps 4 to 10 as processing steps involving remanufacturing of used products.

1.2.4 Remanufacturing and Other End-of-Life Options

Remanufacturing utilizes the discarded product (also referred to as core) and takes it through rebuilding processes, which restores it to useful lifetime. Figure 3 below distinguishes end-of-life options based on the final destinations of the discarded products in the closed-loop supply chain (e.g. raw materials processing plants, assembly plants, etc.). Moreover, Figure 3 illustrates that the smaller the loop, there is a higher probability for energy recovery.

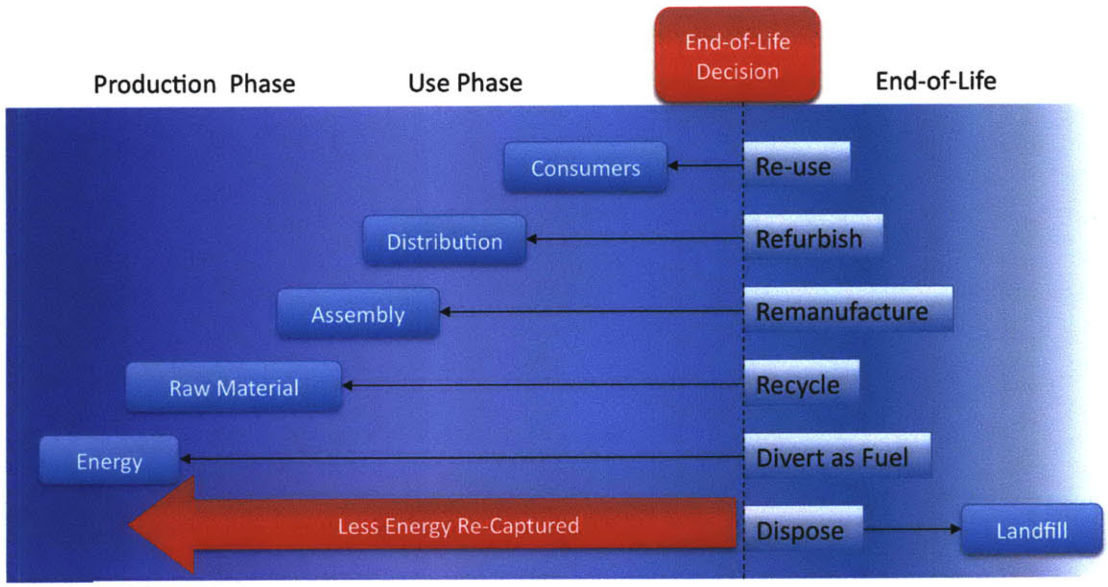


Figure 3 Product end-of-life options[1].

According to Figure 3, landfilling, the conventional end-of-life option, fails to recover energy and materials from the discarded products. As shown in Figure 3, recycling is one of the closed-loop end-of-life options. Recycling is an industrial process whereby useful raw materials included in a scrap product are recaptured in the form of shredded, cut parts and used as inputs in the raw materials processing stage in the supply chain.

Remanufacturing is distinctly different from recycling in that the product architecture and geometry is retained whereas in recycling parts are transformed into raw materials to be used in manufacturing (Kutz 2007). In other words, the key differentiation factor between the two end-of-life options is that remanufacturing retains the geometrical architecture of product and preserves the associated materials, energy, and economical value of products in the value chain.

[1] Credit for artwork. Malima Isabelle Wolf. Environmentally Benign Manufacturing Laboratory, MIT (2009).

It is more difficult to distinguish between refurbishing, reconditioning, repairing, and remanufacturing. Even though sometimes the terminologies for these end-of-life processes are used interchangeably, in reality they are distinctly different. According to (Kutz 2007), the U.S. Code of Federal Regulation effectively distinguishes remanufacturing from other options by referring to the extensive deconstruction of the product, systematic processes involving the replacements of worn parts, cleaning, and testing. Moreover, the keyword that differentiates remanufacturing from other recovery options, i.e. re-use, refurbishing, repairing, is restoring products to 'like-new' conditions (Hauser and Lund 2008). In other words, similar to remanufacturing, re-use and refurbishing may extend a discarded product's lifetime. However, those end-of-life options may cause a higher probability for products being subject to pre-mature failures and degradation in service.

The key distinguishing factor shared by re-use, refurbish, remanufacture end-of-life decisions is the utilization of discarded cores by retaining the geometry and architectural fixture of the product and extending service lifetime. Therefore, a definition useful for the meaning of remanufacturing in this thesis is the processes involved for restoring a discarded product to useful conditions. As such, the meaning of remanufacturing as per this thesis includes re-use, refurbish, and repair.

1.2.5 Enablers and Benefits in Remanufacturing

There are various enablers and benefits for remanufacturing products. One of the primary benefits of remanufacturing is resource recovery retained in waste products. Remanufacturing is highly beneficial for products that have a high replacement cost or have high value parts that can be re-used (Kutz 2007). More specifically, remanufactured products are typically sold for 45 to 65% of the prices of new products (Hauser and Lund 2003); the economic incentives have led to high demands in some replacement markets such as truck tires for fleet operators and aircrafts engines for aviation agencies.

Even though, remanufacturing is more established for third-party remanufacturers, there are stark benefits for an Original Equipment Manufacturer (OEM) to expand into remanufacturing. More specifically, the resources available to OEMs, enable them to effectively remanufacture their used products, as list below (Kutz 2007):

- Full knowledge about the durability, reliability, replacement parts, and methodologies for proper disassembly of their products that are discarded.
- Established network for supplying and distributing the finished goods.
- Established relationship with suppliers of parts and materials.
- Knowledge of consumer use patterns, consumer psychology, and potential reasons for wanting to utilize remanufactured products.
- Market power, established manufacturing platform, and available workforce to expand into remanufacturing practices.

From an environmental standpoint, remanufacturing recaptures the retained material and embedded energy in a scrapped product that would otherwise end up in landfills. Moreover, remanufacturing causes energy and material savings in the production phase by utilizing the core for another lifetime. Toffel *et al.* claims that remanufacturing has promising benefits such as reducing production costs, promoting an image of environmentally responsibility, protecting aftermarkets, and preempting regulations (Toffel 2004) .

More detailed discussion about enablers and benefits of remanufacturing can be found in (Toffel 2004; Kutz 2007; Hauser and Lund 2008).

1.2.6 Challenges and Inhibitors in Remanufacturing

There are considerable obstacles in establishing and operating remanufacturing facilities. One of the key drivers for success in remanufacturing is having access to a consistent flow of cores (Hauser and Lund 2008). Therefore, one of the primary challenges in remanufacturing is uncertainty in supply, distribution, and quality of cores. As a result, uncertainties in the quality and availability of cores cause serious obstacles in material flows, use of space, and available inventory levels (Sundin 2006).

Lower prices in remanufactured products are one of the primary reasons for growth of the remanufacturing sectors (Kutz 2007). Therefore, in order to make remanufacturing a profitable operation, the marginal cost for acquiring cores has to be significantly lower than the sales price of the remanufactured products.

Product design is an inherent challenge in remanufacturing. Given that most products are not designed for remanufacturing, remanufacturers experience challenges in dismantling cores, part replacements, cleaning, refurbishing (Hammond, Amezquita et al. 1998). In addition, unlike automated manufacturing operations, remanufacturing strongly relies on skilled and talented labor due to variations in core designs, remanufacturing guidelines, etc. Therefore, lack of employee skills can become a serious challenge in remanufacturing (Kutz 2007).

Product diversity and proliferation cause a significant disadvantage to remanufacturing. As a result, remanufacturers have to maintain a large inventory of replacement parts, implementing various standardized and non-standardized disassembly processes, enhancing lead time, and incur high costs in hiring labors whom possess in-depth skills in product remanufacturing (Kutz 2007).

Another challenge is sub-optimal performance due to use of parts that are not specifically tailored for the remanufactured core. For example, by replacing the refrigerant with a new kind, the refrigerator may not perform optimally given that such refrigerant may not be tailored specifically for it (Kutz 2007).

High product proliferations, technological advancements, extensive marketing campaigns for new products, and consumer perception of remanufactured products as being inferior compared to new are another set of challenges in remanufacturing (Kutz 2007). This coupled with uncertainties in reverse logistics and remanufacturing processes are large barriers to entry into aftermarket sectors. For detailed discussions of challenges and obstacles in remanufacturing refer to (Hauser and Lund 2008).

1.3 Literature Review

There is extensive literature on remanufacturing discussed from various perspectives in academic research publications, industrial social responsibility reports, and environmental policy guidelines. In order to effectively investigate into remanufacturing as an industrial operation, it requires acknowledgement of macroscopic impacts from various scopes such as economics, policy, industrials operations and strategies, as well as the environment. As such, our literature review reveals findings that span across multiple fields of study, domains of research, and industrial functional practices.

Sundin provides a brief history of remanufacturing beginning from primitive rebuilding practices in 1861 (NC3R ; Sundin 2004) . Hauser and Lund provide a general overview of remanufacturing including defining remanufacturing, operational problems and strategic considerations in remanufacturing, and specific case studies in relation to remanufacturing (Hauser and Lund 2003; Hauser and Lund 2003; Hauser and Lund 2008). Kutz gives a comprehensive overview of remanufacturing in the context of design for remanufacturing guidelines (Kutz 2007). Moreover, (Kutz 2007) reveals information about size of remanufacturing industry, remanufacturing business practices, including typical facility-level processes.

There is extensive literature on strategic considerations, competition, and industrial practices in remanufacturing. Scholars study the feasibility of remanufacturing in face of continuously growing product proliferation. Ferrer *et al.* addresses remanufacturing in the scope of industrial competition (Ferrer and Swaminathan 2006). Moreover, Ferrer *et al.* analyze the new and remanufactured products in various competition scenarios (e.g. monopoly and duopoly), and provide insights for remanufacturing as an effective end-of-life strategy. Ostlin explores ways for remanufacturers to become more competitive through effective analysis and management of material flows and remanufacturing processes (Ostlin 2008). For more detailed discussion about competition in remanufacturing refer to (Majumder and Groenevelt 2001; Hauser and Lund 2008; Mitra and Webster 2008).

Operational strategies and effective business models have great influences on the growth of remanufacturing. In relation to this, Ijomah *et al.* analyze key remanufacturing operational problems and success factors by presenting a process model for improving remanufacturing effectiveness (Ijomah, Childe et al. 2005). For discussions about strategies, types of remanufacturing business models, management, and consideration in remanufacturing refer to (Toffel 2004), (Zuidwijk and Krikke 2008), (King and Burgess 2005; Hauser and Lund 2008).

There is extensive literature on remanufacturing in the context of closed-loop supply chain. The literatures in this domain study problems in the scope of reverse logistics, optimization, and recovery management in remanufacturing. Kondoh, Nishikiori *et al.* discuss fundamental problems for realizing a closed-loop manufacturing system (Kondoh, Nishikiori et al. 2005). Kutz elaborates on the challenges in establishing a systematic reverse logistics that integrates collection, transport, inventory core inspection, remanufacturing, and re-selling (Kutz 2007). Ferguson addresses problems in choosing the appropriate reverse channel structure for the collection of used products from customers (Ferguson 2009). Moreover, Hammond, Ameziquita *et al.* conduct an industry-wide survey targeted to automotive remanufacturers, which reveals costly processes and bottlenecks experienced in remanufacturing (Hammond, Amezquita et al. 1998). Van Nunen and Zuidwijk discuss the inherent uncertainties in reverse logistics such as uncertainties in core availability, uncertainties in required operations and parts, uncertainties in design characteristics of the cores, uncertainty in quantity and quality of replacement parts and raw materials, and uncertainty in recovery processes (Van Nunen and Zuidwijk 2004). Guide Jr., Jayaraman *et al.* convey the main challenges facing remanufacturers in the coming decades such as being pressured to continuously reduce remanufacturing lead times, lack of formal systems and guidelines for operations, logistics, lack of high quality and relevant cores, and rapid technological changes (Guide Jr, Jayaraman et al. 2000).

Kumar and Putnam elaborate on the success of remanufacturing by integration of progresses in sustainable design, manufacturing, and waste management (Kumar and

Putnam 2008). Moreover, (Kumar and Putnam 2008) reveal that economic factors, regulatory pressures, and shift in consumer values towards environmentally friendly products are key driving forces for remanufacturing goods. For comprehensive literature reviews of applications, case studies, models and techniques proposed for the design, planning and optimization of closed-loop supply chain problems and reverse logistics management issues please refer to (Pokharel and Mutha 2009), (Fleischmann, Bloemhof-Ruwaard et al. 1997), (De Brito and Dekker ; Guide 2000; Toktay, Wein et al. 2000; Savaskan, Bhattacharya et al. 2004; Bostel, Dejax et al. 2005; Sundin 2006; Dhanda 2007; Guide and Van Wassenhove 2009).

Another important factor in influencing the use of remanufactured products is economic incentives. Linton provides detailed discussion about the factors that have a high impact on the profitability of remanufacturing (Linton 2008). In addition, Geyer, Wassenhove *et al.*convey that in order to optimize production cost-savings from remanufacturing it requires careful planning of product cost structure, product lifecycle, component durability, and collection rate (Geyer, Van Wassenhove et al. 2007). Hauser and Lund reveal that in order to make remanufacturing a profitable business enterprise a large market demand should exist for remanufactured products (Hauser and Lund 2003). According to Hauser and Lund such demands are more prevalent in the commercial and industrial sectors (Hauser and Lund 2008). For detailed discussions of the impact of remanufacturing in the economy and the macroeconomic significance of remanufacturing refer to (Ferrer and Ayres 2000).

The impact of policies on remanufacturing is an important factor to take into consideration. Kumar and Putnam provide a discussion about the environmental policies as the primary global driver for the cradle-to-cradle supply chain (Kumar and Putnam 2008) . Furuhjelm discusses the significant influences of environmental policies, government directives, and take-back legislations on promoting remanufacturing as an end-of-life decision (Furuhjelm 2000). Doppelt and Nelson provide a discussion about take-back laws, extended producer responsibility, effective approaches to environmental policy design (Doppelt and Nelson) . Moreover, Mitra and Webster examine the effects of governmental subsidies as a key driver in promoting remanufacturing (Mitra and Webster 2008).

The most relevant literature for this thesis is research that addresses the impacts of remanufacturing on the environment and industrial ecology. Hauser and Lund compare the conservation value in a product that is remanufactured versus one that is recycled; also, they discuss the potential materials and energy savings of remanufacturing in the production process (Hauser and Lund 2003). Furthermore, Rose, Ishii *et al.* provide a methodology for determining appropriate end-of-life strategies based on key product characteristics (Rose, Ishii et al. 1998). In addition, there is an extensive literature on analysis, identification, and implementation of design procedures in order to make product characteristics in favor of remanufacturing and the environment. For example, Bhamra discusses the subject of designing for the environment (i.e. eco-design) in order to help organizations with better environmental performances (Bhamra 2004). Authors such as Kutz and Bhamra discuss the optimal product characteristics for effective remanufacturing (Kutz 2007), (Bhamra 2004). Furthermore, Sundin and Bras discuss the impact of remanufacturing on reducing the environmental impacts from an industrial perspective (Sundin 2004), (Bras 1996). Some studies reveal that remanufacturing is one of the most desirable end-of-life options for savings in production and avoiding landfilling (Sundin 2004), (Graedel and Allenby 1996), (Jackobsson 2000), and (Steinhilper 1998).

We have found few research studies on quantitative assessment of the environmental impacts in remanufacturing. More specifically, the prior research in environmental impacts of remanufacturing appears to be qualitative and mostly focused on a specific product category. For example, Kerr and Ryan provide a quantitative assessment of remanufacturing for Xerox copy machines (Kerr and Ryan 2001) . The comparison is performed between a new copier that is designed to be remanufactured versus a new conventional copier. Two other environmental studies of remanufacturing are by Smith and Keoleian for gasoline engine and Sutherland, Adler *et al.* for diesel engines (Smith and Keoleian 2004), (Sutherland, Adler et al. 2008). Smith and Keoleian utilize life-cycle assessment (LCA) methodologies in order to evaluate the energy savings and pollution prevention of remanufacturing a mid-size automotive vehicle gasoline engine (Smith and Keoleian 2004). Jackobsson, Hauser, and Lund state that products that are good candidates for remanufacturing are those that do not undergo rapid technological changes (Jackobsson 2000), (Hauser and Lund 2003). In regard to extending product service lifetime, a relevant literature includes Kim, Keoleian *et al.*, which discuss the optimal household refrigerator lifetime in the U.S. (Kim, Keoleian et al. 2006). Similarly, Bole presents the optimal replacement intervals for residential clothes washers (Bole 2006). Lindahl, Sundin *et al.* convey general environmental costs and benefits with remanufacturing, focusing on multiple case studies (Lindahl, Sundin et al. 2006).

1.4 Objectives and Research Questions

The purpose of this research is to study the dynamic effects of remanufacturing on the environment in the context of lifecycle energy consumption of products. More specifically, the objective is to study energy savings in remanufacturing by quantifying cumulative energy demands of a remanufactured product during its entire lifecycle comparatively to an equivalent new product.

From a materials resource perspective, remanufacturing can be a highly important end-of-life option for recovering and re-using the retained values of products in production. In addition, due to fewer requirements in production processes, remanufacturing saves energy in the raw materials processing and manufacturing phases. Therefore, remanufacturing conserves the embedded material and energy in the production phase, hence, benefiting the environment in this regard.

In addition to studying remanufacturing in the production phase, we take into account the energy impacts of remanufacturing in the use phase in order to address remanufacturing and energy savings from a total lifecycle perspective. Scholars such as Sundin, Kutz, Hauser, Lund, Smith, and Keoleian suggest that remanufacturing energy savings can be subjected to the performance of remanufactured products in use (Sundin 2004),(Kutz 2007),(Hauser and Lund 2008), (Smith and Keoleian 2004). We perform a comprehensive assessment of the remanufacturing of 19 products in 8 separate industries in order to evaluate remanufacturing energy savings from an industrial scope.

More specifically, we analyze the implications of the consumer choice between extending the use of an old product by remanufacturing it, and disposing of the old product/replacing it with a new product. In this research, the primary question in addressing the objectives of this study is ***"Is product remanufacturing saving energy in comparison to new product manufacturing?"***

In addition to the primary objective of this thesis, we study the economic incentives in remanufacturing. Moreover, we investigate the economic feasibility of remanufacturing from a consumer's perspective. For this investigation, we utilize Life Cycle Costing (LCC) methodology to quantify the lifecycle monetary costs for both new as well as remanufactured products. Therefore, a second question posed in this research is ***"From a consumer's perspective, is product remanufacturing economically favorable in comparison to purchasing new products?"***

In addition to the above thesis objectives, our secondary objective is to provide a qualitative discussion of systems level influences that have an impact on remanufacturing and energy savings. More specifically, we address the impacts of innovation and technological advancements, policy interventions, changes in time, business models, and market dynamics on remanufacturing and energy savings.

1.5 Thesis Overview

This chapter introduces the reader to the motivations for studying remanufacturing, provides an overview of remanufacturing, discusses the scope of literature topics in regard to remanufacturing, and conveys the objectives and research questions addressed for analyzing remanufacturing and energy savings. Next, Chapter 2 discusses the methodologies utilized in this research for addressing energy savings as well as economic incentives for remanufacturing. Chapter 3 introduces the reader to the products and case studies that we have analyzed for a holistic investigation of remanufacturing energy savings. Furthermore, Chapter 3 provides an in-depth investigation of four case studies, namely, office furniture, household appliances, tires, and electric motors, and reveals the research results for each. Finally, Chapter 3 illustrates the results generated by compiling findings from all case studies. Chapter 4 provides a summary of the research findings, presents the conclusions of this study, and offers future research directions for environmental assessments of remanufacturing.

2. Data Acquisition and Methodology

The methodology used in this project for conducting environmental analysis is based on Life Cycle Assessment (LCA). In addition, this study utilizes Life Cycle Costing (LCC) for some products to evaluate the economic feasibility of remanufacturing from a consumer's perspective. This chapter provides an introduction to LCA; conveys the objectives, the scope, and the methodology; provides data sources and research approach; introduces LCC; and states the key assumptions and limitations.

2.1 Introduction to Life Cycle Assessment

Since its origination in the 1960s, LCA has advanced to an established field of study in industry, government, and academia (Hunt and Franklin 1996). LCA evaluates potential environmental impacts of products from cradle-to-grave. The terminology 'cradle-to-grave' refers to the entire lifetime of a product that begins from the extraction of raw materials from the earth to produce consumable goods, and ends at the phase where the goods are returned to earth (Curran 2006). LCA evaluates the cumulative environmental impacts resulting from the activities that take place within each phase of a product's life. In order to address environmental impacts, all activities associated to products and processes are considered in LCA.

Curran provides a comprehensive overview of the LCA including a brief history, benefits and limitations, methodology and analysis structure (Curran 2006). Hendrickson, Lave, and Matthews evaluate the methodology for analyzing environmental impacts through Economic Input-Output Life Cycle Assessment (EIO LCA) (Hendrickson, Lave et al. 2006). Hendrickson, Lave, and Matthews also provide examples of the applications of LCA from a midsize passenger car to residential buildings in the United States (Hendrickson, Lave et al. 2006). Suh and Huppes discuss various developed methodologies for determining the life cycle inventory impacts for LCA and provide a concrete comparison between the predominant methodologies (Suh and Huppes 2005). Similarly, Williams, Weber, and Hawkins discuss the uncertainties attributed to various

LCA approaches (Williams, Weber et al.). The LCA principles and framework outlined in (Curran 2006) as well as most LCA studies are based on a standardized process developed by the International Organization for Standardization (ISO) (ISO 2006).

The practitioners of LCA evaluate environmental issues encompassing industrial development, environmental initiatives, governmental policies, social impacts, strategy cost and benefit analysis, etc. (Williams, Weber et al.). For example, the choice of utilizing paper cups versus polystyrene cups has been debated in the food and services industry (Deutch and Lester 2008). Hocking reveals the complexity inherent in this choice based on underlying assumptions and scope of LCA (Hocking 1991).
In relation to legislative actions, LCA can show the consequential environmental impacts of proposed policies and regulations. For example, the California Low Carbon Fuel Standards (Farrell, Pelvin et al. 2006) and the National Renewable Fuel Standards (EISA 2007) mandate the use of bio-fuels. Reilly, Paltsev, DiPardo, and Lynd study bio-fuels from a life cycle perspective, remarking on its potential for reducing vehicle emissions (Reilly and Paltsev 2007),(DiPardo 2000),(Lynd 1996). They also discuss the environmental challenges stemming from aggressive land use and mass production of fuel ethanol from cellulosic biomass.

2.2 Life Cycle Assessment Framework

In this research, we utilize the systematic process as outlined by the International Organization for Standardization for LCA study. This process consists of four main components, namely, goal definition and scoping, life cycle inventory analysis, life cycle impact assessment, and interpretations (ISO 2006). Figure 4 illustrates the interdependence and interaction between these components. `

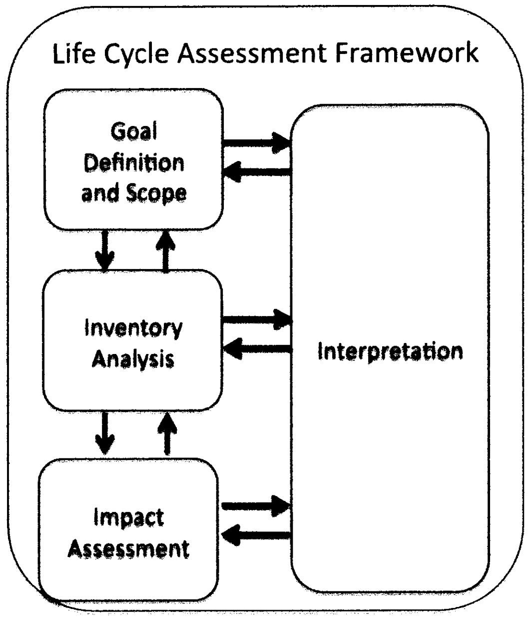


Figure 4. Life Cycle Analysis: framework (ISO 2006).

Goal Definition and Scoping

Define the objectives of the study, establish the scope of analysis, and identify the environmental impact indicators to take into account for assessment. Examples of environmental impact indicators would be the raw material requirements, energy demands, atmospheric emissions, waterborne emissions, solid wastes, and other releases.

Inventory Analysis

Quantify the environmental impact indicators for the entire life cycle of a product, process, or activity.

Impact Assessment

Discover the environmental impacts of the raw materials and primary energy flows based on results from the Inventory Analysis.

Interpretation

Identify the dominant contributing phases and processes, evaluate completeness, conduct sensitivity analysis, and perform consistency checks.

2.3 Objectives and Scoping

In this section, we define the primary objectives of LCA, establish the scope of analysis, and determine the environmental impact indicators to study.

2.3.1 Objectives of Life Cycle Analysis

The objective of this research is to determine the life cycle environmental impacts of products based on energy requirements. In doing so, the intention is to identify the life cycle phases that have the highest environmental impacts based on energy requirements. In addition, the objective of the analysis is to compare the life cycle energy impacts of a newly produced product with those of a remanufactured product. More specifically, the goal is to evaluate the total lifecycle energy savings achieved by remanufacturing an old product that has reached end-of-life (referred to as a core) and the environmental consequences attributed to prolonging service-lifetime.

By fulfilling the above objectives, we intend to provide industry guidance related to remanufacturing and generate public awareness about the environmental consequences of consumer choices for reusing, refurbishing, and remanufacturing products.

2.3.2 Scope of Life Cycle Analysis

A lifecycle of a product typically consists of the following phases from cradle-to-grave (also depicted in Figure 5 below):

1. Raw materials extraction and processing.
2. Transportation of processed raw materials to manufacturing and assembly plants.
3. Parts manufacturing and final unit assembly.
4. Distribution of finished products from plants to regional distributors, local retailers, and end-customers.
5. Use by the consumer.
6. Transportation of scrap products after reaching end-of-life through the removal chain.
7. End-of-life processes.

Note that items 2,4,and 6 are generally combined and expressed as the transportation phase in LCA.

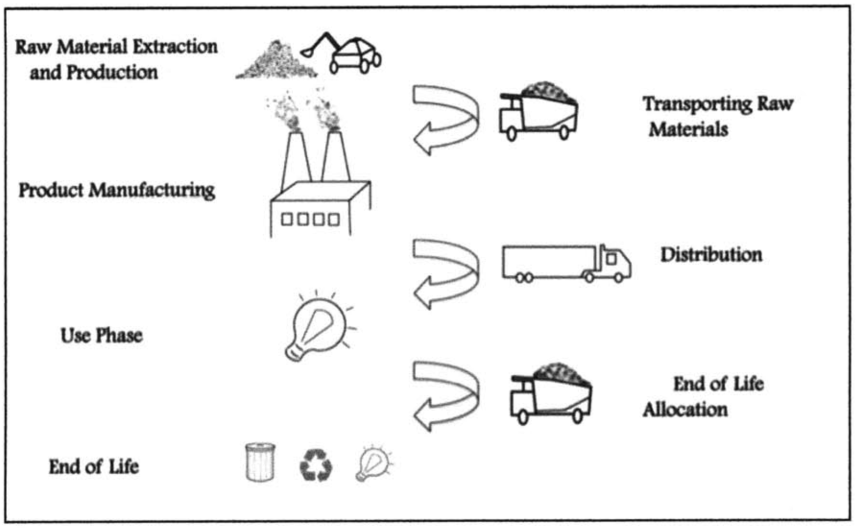


Figure 5. Life cycle stages of products from cradle-to-grave.

Raw Materials Extraction and Processing

The lifecycle of any product begins with the extraction of raw materials from the earth. For example, harvesting trees for paper production or extracting iron ore for steel production is considered as raw materials extraction. After extraction, raw materials are transformed into forms usable for product manufacturing and fabrication. Transportation of raw materials from the point of extraction to the processing location is typically included in this phase.

Manufacturing and Assembly

The manufacturing phase entails all activities and processes for producing and assembling a product from smaller components as well as raw materials.

Transportation

In general the transportation phase consists of three main stages: transport of processed raw materials to manufacturing and assembly plants, transport of products from manufacturing plants to customers, and transport of scrapped products through the removal chain (Combination of items 2, 4, 6 in the above list). This phase is most affected by the modes of transportation and the transportation distances.

Use

This phase encompasses the use of products by the consumer. The use phase includes all the activities involving the consumer after the product delivery. This includes energy demands for operation and environmental wastes generated from the use of the product.

End-of-Life

After reaching end-of-life, products are either sent to landfill, recycled, refurbished, re-used, or remanufactured. Each end-of-life option requires particular end-of-life processes that require energy and potentially other resources.

Of the total lifecycle spectrum of a product, the primary scope of analysis for this thesis is on the following life cycle phases:

- Raw material extraction and processing phase
- Manufacturing and assembly phase
- Use phase

Analyzing the raw materials extraction and processing phase as well as manufacturing phase is important for assessing the environmental benefits of remanufacturing in production process. Furthermore, we include the use phase in the primary scope of analysis to compare the environmental performance of a remanufactured product relative to that of a new product.

Even though a holistic life cycle assessment should include all the life cycle stages, our primary scope of analysis is predominantly based on the raw materials processing, manufacturing, and use. We neglect transportation due to scarcity of data for the products studied in this project. There exists a collection of data for distribution channels and supply chain paths, but most are based on a specific operation plant coupled with subjective assumptions for distance travelled and modes of transportation. We do use the available transportation data for sensitivity analysis in order to examine the contribution of transportation phase on total lifecycle of a product.

We also exclude the end-of-life phase from our primary focus due to the limitation of data. Moreover, for our comparison (discussed in detail in later section) between a new product and a remanufactured product, we assume that both products will face a similar end-of-life process after being scrapped. Therefore, in comparing the life cycle energy demands, we assume that the impact of end-of-life processes is the same for both new as well as remanufactured products. We use sensitivity analysis in order to capture the contribution of end-of-life processes on the total life cycle of the products.

2.3.3 Energy and Scope of Environmental Assessment

Environmental assessments can be based on various parameters such as raw materials requirements, energy demands, atmospheric emissions, waterborne emissions, solid wastes, and other releases. In this thesis, we conduct the environmental analysis by studying the energy requirements during a product lifecycle. In other words, we take energy demand as the environmental impact indicator for evaluating the environmental savings potential of remanufacturing. We note that other environmental indicators such as raw materials requirements are very critical parameters in assessing environmental impacts of remanufacturing. However, the focus of this project is on energy assessments of remanufacturing.

Cumulative energy demand (CED) is the total energy requirements for each phase of a product's life cycle. CED entails three distinct energy consumption factors: process, transportation, and material resources energy (primary energy) (Curran 2006). Primary energy is defined as the embedded energy in the natural resources such as natural gas, uranium, oil, coal, etc. that have not yet gone through anthropogenic transformations. Primary energy demand is used to determine energy requirements for extracting raw materials from nature and processing them into useful items for production, manufacturing and assembly, transport, use by the consumer, and end-of-life. Process energy is the energy to operate the activities of a sub-system such as reactors, pumps, blowers, combustion engines, and heat exchangers. Transportation energy is the energy required to power various modes of transportation such as heavy-duty trucks, trains, ships, airfreights, etc. We use Life Cycle Inventory (LCI) analysis in order to analyze life cycle energy requirements.

2.4 Life Cycle Inventory Analysis

Life Cycle Inventory (LCI) is the methodology for quantifying the raw materials requirements, energy demands, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity (Curran 2006). As shown in Figure 6, LCI utilizes input-output inventories for main life cycle phases, which are as follows: raw materials processing, manufacturing and assembly, transport, use, and end-of-life.

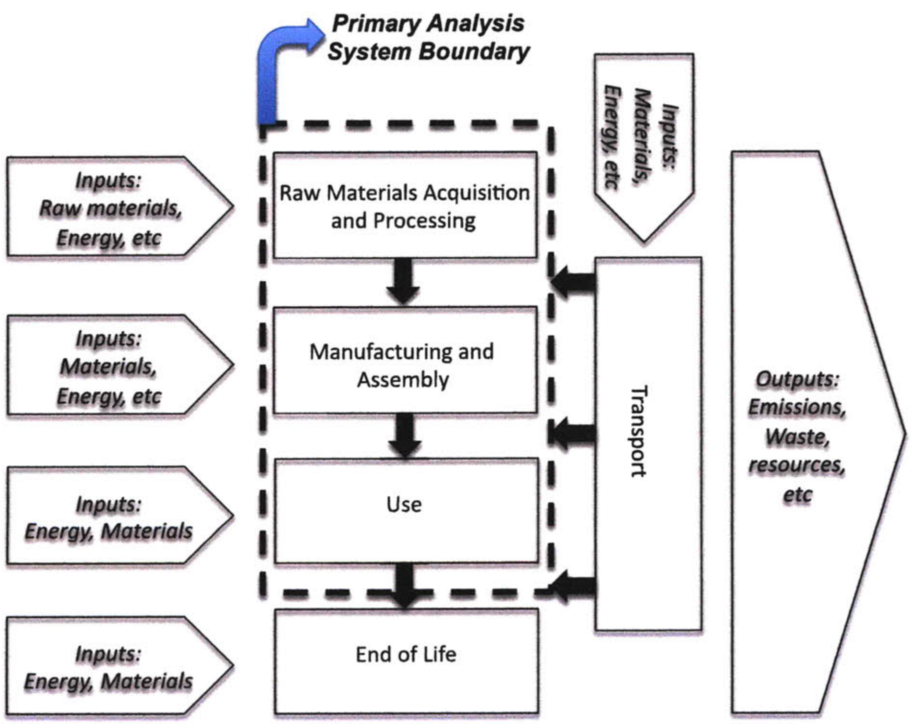


Figure 6. Life Cycle Inventory inputs and outputs. The dotted line reveals the primary scope of analysis for this thesis (modified version of an original figure taken from (Deutch and Lester 2008)).

In LCI each phase is considered to be a sub-system. Each sub-system requires inputs of materials and energy, and it has outputs associated to the activities and processes taking place in each stage. We choose energy consumption as inputs primarily for raw material acquisition and processing phase, manufacturing and assembly phase, and use phase, as shown by the dotted line in Figure 6. We gather all the relevant data, and organize it for compiling life cycle energy inventories. There are three main methodologies for compiling life cycle inventories: process LCI, economic input-output LCI, and hybrid LCI (Williams, Weber et al.). We utilize process LCI for the purposes of this thesis.

2.4.1 Process LCI

The most common form of LCI is the process LCI, which has originated from the ISO (ISO 2006). The analysis for this methodology is based on viewing lifecycle environmental impacts from the perspective of a single product unit. More specifically, the objective of process LCI is to track the raw materials and energy inputs for each constituent stage of a product life (Williams, Weber et al.). The analytics for process LCI utilizes process flow diagram methods as well as matrix inversion methods to perform environmental computations (Williams, Weber et al.),(Suh and Huppes 2005).

Process Flow Diagram

The purpose of process flow diagram LCI is to illustrate the commodity flow for each and every process in a product system. Each life cycle stage has various commodity inputs and outputs. Using simple algebra, the amount of commodities required for fulfilling a particular functional process is multiplied by the corresponding environmental requirements and consequences to determine the LCI values. Figure 7 below represents a simplified process flow diagram for a process.

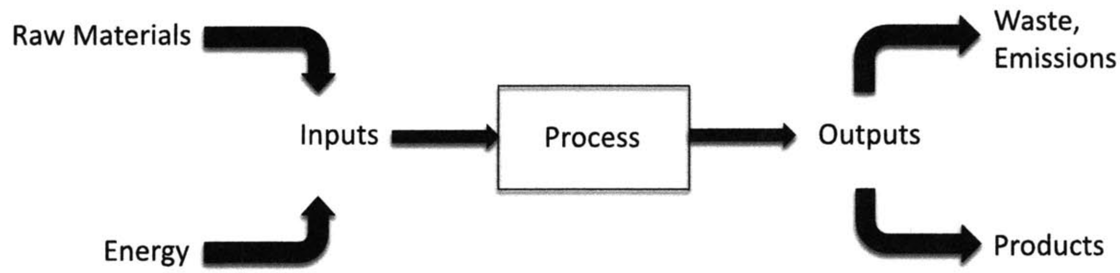


Figure 7. Process flow diagram (modified version of an original figure taken from (Deutch and Lester 2008)).

Matrix Representation of Product System

In cases where the process flow diagram has complex and extensive relationship with other stages, the inputs and outputs are modeled by a system of linear equations. Consequently, the analysis relies on principles and frameworks in linear algebra (Williams, Weber et al.).

The methodology for this study relies primarily on process LCI and process flow diagram to conduct the inventory accounting for compiling life cycle energy demands of products. We chose Process LCI approach since it is more appropriate for studying phenomena concerning specific products. In other words, process LCI methodology focuses on inventory flows in individual products and processes (as opposed to economic inputs and outputs in an industrial scale).

2.5 Research Approaches

In this section we discuss the research approaches for determining lifecycle energy demands.

2.5.1 Life Cycle Inventory: Energy Demands Analysis

Raw Material Acquisition and Processing

Each raw material requires energy to be produced. The energy requirements encompass extraction, processing, and purification that bring raw materials to useful conditions. We determine the amount of energy (in MJ per Kg for each raw material) required to acquire and process the raw materials used for constructing the product. For raw materials acquisition and processing, we start with a bill of materials (in Kg of raw materials) for each product. We use the bill of materials of the product in combination with the raw materials energy requirements in order to quantify energy demands for the raw materials production phase. For example, more than 50% of the mass of a mid-size refrigerator (47 Kg out of 84 Kg) is made from steel (Kim, Keoleian et al. 2006). According to (Smil 2008), it takes about 20 to 25 MJ to produce 1 Kg of Steel. As a result, it takes on average about 940 to 1,175 MJ to process the steel embedded in a mid-size refrigerator.

In general, we rely on two dominant sources for typical energy cost of raw materials, namely, (Smil 2008) and (Ashby 2009). These references provide a range of energy requirements for processing various raw materials. Though we use the entire range for computation purposes, we take the upper bounds as the final values for life cycle assessment in order to be conservative in identifying the upper bound limit for remanufacturing energy savings. For raw materials not covered in (Smil 2008) and (Ashby 2009) other sources from the literature are used [refer to Appendix A]. Also, for some products where a bill of materials was not obtainable, we utilize credible references, which have already computed the raw material processing energy demands. Refer to Appendix A for a comprehensive and detailed reference matrix for data sources used for quantifying raw material acquisition and processing energy.

Manufacturing and Assembly

We rely on literature data and research sources to determine the energy requirements for manufacturing and assembly processes for producing a product. Some of the references we consider use well-established sources that extensively study the manufacturing processes such as (Brown, Hamel et al. 1985),(Boustead and Hancock 1979),(Kirk-Othmer 1996). These references provide an overview of manufacturing processes and provide energy analysis of industrial practices by calculating the primary energy required to manufacture an artifact from raw materials to a finished product (Boustead and

Hancock 1979). Refer to Appendix A for a comprehensive and detailed reference matrix for data sources used for quantifying manufacturing energy.

Use

The trends for unit energy consumption, capacity, and efficiency of products as studied in this report are from various sources such as governmental agency reports, prior academic researches, and industrial reports. We estimate the annual energy use consumption of products from these sources. Furthermore, we amortize the annual values over average useful lifetime to determine the use phase energy consumption of the products.

Energy is obtained from various sources including coal, nuclear power, wind, solar energy, solid waste, wood biomass, and natural gas. The energy demands for producing electricity is correlated to the sources of fuel used to generate the electricity and the efficiency of the power generation (Curran 2006). Since the generated electricity is mixed in the transmission lines of the utility, it is difficult to distinguish the source of electricity in the grid. Therefore, typically, computational models utilize regional or national average fuel mix for producing electricity in the grid.

In determining the energy consumption of electronics products in the use phase, we taken into account the energy efficiency of the power generation as well as delivery transmission losses for the analysis. For example, theoretically 1 kWh of electricity can produce 3.6 MJ of energy (e.g. in the form of heat, etc). However, this value does not take into account the primary sources of energy that are consumed to produce and transmit 1 kWh of electricity to consumer's location. By taking into account power generation inefficiencies and transmission line losses, then 10.6 to 11.3 MJ of energy is required for 1 kWh of electricity delivered for useful work (e.g. variation in value is due to efficiency choices and transmission routes) (Curran 2006). The same discussion holds true for petroleum-based sources of energy such as automotive fuel. Therefore, for our studies for the use phase of electronics products we use 10.6 MJ/kWh (as opposed to 3.6 MJ/kWh) for quantifying the energy requirements. Similarly, for the use phase of products in automotive industry we use 142 and 146 MJ per one U.S. gallon of gasoline and diesel fuel, respectively (as opposed to 132 MJ/gallon). Refer to Appendix A for a comprehensive and detailed reference matrix for data sources used for quantifying manufacturing energy.

Transportation and End-of-Life

Based on the boundary conditions of our analysis, we do not include transportation and end-of-life phases in the primary analysis. However, these stages are considered in the sensitivity analysis in order to determine their relative impacts and significance in changing the conclusions (see the appliances case study). Refer to Appendix A for more information about transportation and end-of-life data. Following the above process, we evaluate the energy consumption contributions for each LCA stage in order to determine which LCA stages are more dominating than others.

2.5.2 Scope of Remanufacturing Analysis

In this section, we describe the analysis framework for assessing remanufacturing energy savings potential. We assume that when a used product reaches its end-of-life, the consumer has a decision to make: (1) to discard the old unit and purchase a new unit, OR (2) to remanufacture the old unit by restoring it to like-new conditions, hence, extending the service lifetime of the product. By remanufacturing the product, the consumer will utilize the retained embedded energy and material value of the old product. However, the old unit may be less energy efficient in comparison to a newly produced product. Therefore, for each decision there are energy consequences (confined by our boundary conditions and assumptions), which are illustrated in Figure 8 below.

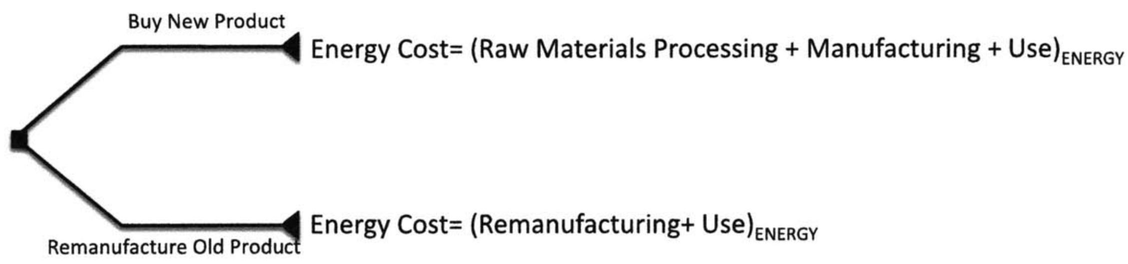


Figure 8. Decision-tree analysis for consumer.

According to Figure 8 above, the consumer decision to purchase a new product leads to the life cycle energy demands for raw materials processing, manufacturing and assembly, and use of the new unit. On the other hand, the consumer decision to remanufacture and re-use an older unit, would lead to energy demands for restoring the product to like-new condition (i.e. remanufacturing) and energy use of the old unit. We assume the same lifetime and the same end-of-life disposal mechanism for both choices. We assume that the remanufactured product would operate like-new, with the similar lifetime as the new one. For example, suppose that a consumer's household clothes washer that was purchased 10 years ago (this is the average lifetime for clothes washer) breaks down and reaches end-of-life. The consumer has a decision to make- he/she can either (1) purchase a new washer that was produced in year 2009, OR (2) remanufacture and re-use his/her washer, produced 10 years prior, in 1999. We assume that a new and a remanufactured washer have the same lifetime and the same end-of-life disposal mechanisms in 10 years (in year 2019). We assume that the remanufactured washer would operate like it were new (e.g. when bought in year 1999).

We analyze the energy consumption during raw material processing ($E_{rm,new}$) and manufacturing ($E_{m,new}$) for new product, remanufacturing ($E_{reman,old}$) for old product, and use ($E_{u,old}; E_{u,new}$) for both units as shown below:

$$LCI_{New} = E_{rm,new} + E_{m,new} + E_{u,new}$$
$$LCI_{\text{Reman}} = E_{reman,old} + E_{u,old} \qquad \text{Equation 1}$$

Given that remanufacturing entails part replacement, we assume that energy required for raw material processing is included in remanufacturing ($E_{reman,old}$) for old product. Note that the customer would be indifferent between new and remanufactured unit from energy standpoint when $LCI_{New} = LCI_{\text{Reman}}$.

We neglect the energy demands for transporting a core through the reverse logistics. Though studying the energy impacts in the reverse logistics is very important, it is beyond the primary scope of this research given the complexity inherent in studying reverse logistics and closed-loop supply chain. We perform sensitivity analysis to address the impacts of energy requirements in reverse logistics (refer to the appliances case study). Also, for some products studied in this study, the energy required for remanufacturing was considered to be minimal or negligible. Therefore, due to the given assumptions, the life cycle energy comparison analysis is biased in favor of remanufacturing.

2.6 Data Acquisition

For analysis, we have utilized data for specific products as well as composite, industry-average data. For energy demands, we used a compilation of data sources that encompass:

- Scientific journals, academic, and research publications
- Industry data reports, databases
- Government documents, reports
- Related/prior life cycle inventory studies
- Product-specific information
- Personal communication with industry/ government officials

Refer to Appendix A for a comprehensive and detailed reference matrix for data sources used in this research.

Data is organized and analyzed in terms of a functional unit of measure to make the basis of lifecycle comparison equivalent. For example, the functional unit of measure for the refrigerator case study is energy consumption per refrigerator volume (MJ/cubic meters). This adjusts for temporal and spacial variations in refrigerator sizes, and hence, enables effective comparison based on homogeneous measures. In general, equivalent service metrics can vary from volume to service output (Curran 2006).

2.7 Life Cycle Costing Analysis

In addition to the energy analysis, we utilize Life Cycle Costing (LCC), which is an analytical toolkit for examining the total lifecycle cost of the product (Dhilllon 1989). We conduct LCC for the majority of case studies focusing on cost valuation from a consumer's perspective. Many advances in life cycle costing have led to a large amount of readily available literature. LCC enables quantifying the procurement cost as well as the ownership cost for products' total life years (Dhilllon 1989). All economic valuations are performed in real dollar values, adjusting for inflation by utilizing U.S. consumer price index (CPI) published by the U.S. Department of Labor Bureau of Labor Statistics. For upfront costs we utilize consumer reports, industry agencies, academic research articles, personal communications with corporations, etc. Ownership includes the price of input energy sources (e.g. electricity price, petroleum price).

2.8 Key Assumptions and Limitations

In this section we identify the assumptions and discuss the limitations of the analysis for this study. Based on the primary boundary conditions, the transportation phase is neglected in the total life cycle analysis. Total lifecycle of a product from cradle-to-grave encompasses transition phases such as raw materials transportation to manufacturing plant, distribution channels in supply chain, inventory and storage. Moreover, supplementary life cycle phases such as product maintenance and repair are conditional yet important stages in a product's lifetime. Transportation energy costs are not taken into account for this study mainly due to scarcity of data and complexity in modeling supply chains for products. This is a limitation for this study.

Based on the primary boundary conditions, end-of-life phase is neglected in the total life cycle analysis. Depending on the end-of-life option, the product has to travel a particular distance in the removal chain and undergo various end-of-life processes. In this analysis, we assume comparative end-of-life destination for both the new and the remanufactured product. This is a limitation for this study.

The analysis ignores a critical stage in remanufacturing, which is transportation and process energy cost in reverse logistics. Contrary to conventional supply chain whereby products are distributed from a few locations to multiple locations in multiple regions of the world, the core retrieval process demands collection and transport of core items (scrap products) back to the remanufacturing plants. Due to the complexity of this process remanufacturers have come up with unique reverse logistics channels and various core-retrieval strategies for collecting cores, and remanufacturing them (Hauser and Lund 2008). Also, some remanufacturers do not follow a strict protocol within and amongst industry sectors for bringing products back to like-new conditions. Due to the vast differences in core handling and wide range of reverse logistics practices (i.e. based on product type, remanufacturing strategy, core quality, demand for remanufactured products), it is difficult to quantify energy costs associated to closed-loop supply chain.

Neglecting core retrieval energy cost is not realistic for remanufacturing and ignoring it makes the analysis biased in favor of remanufacturing. In other words, this assumption represents an idealized case in favor of remanufacturing whereby there is negligible energy consumption associated to reverse logistics. In reality reverse logistics and core availability are critical challenges of remanufacturing that should not be overlooked in general. A limitation of this study is that the results do not showcase the energy demands in reverse logistics.

For some products we assume that the energy required for remanufacturing is negligible. We study a list of products encompassing those that are re-used, refurbished, and remanufactured. For products that are extensively remanufactured we utilize data from available literature to quantify the energy requirements for remanufacturing. However, for other products, which are not commonly remanufactured, there are no data for remanufacturing energy requirements. Therefore, for the latter products, we assume that there is no energy consumed for bringing the product back to like-new conditions for re-use. Also, some of the products we have analyzed are not remanufactured in whole (i.e. household appliances), but instead can utilize remanufactured parts (i.e. pumps, compressors, etc.). We assume that for these products, through remanufacturing, the majority of production energy is saved to the extent that remanufacturing energy demands are negligible. This is a limitation for this study and another conservative assumption in favor of remanufacturing.

We assume that the remanufactured product would operate like new, with the similar lifetime as the new one. The objective of remanufacturing is to bring products back to like-new conditions. This assumption is conceivable for remanufacturing processes that have stringent quality controls for core retrieval, effective disassembly and refurbishing mechanisms, and multiple testing phases. However, improper or incomplete remanufacturing processes may cause pre-mature failure and degradation in performance in products. The notion that all remanufactured products behave 'like-new' in this analysis is a biased assumption in favor of remanufacturing.

We assume comparative lifetime and comparative end-of-life disposal mechanism for both new products as well as remanufactured products. The combination of above assumptions taken for the analysis makes the representation of results to be conservative and biased towards remanufacturing. Therefore, the outcomes of life cycle inventory analysis should be perceived as the upper bound in terms of life cycle energy savings for remanufacturing.

For cases whereby remanufacturing energy savings is unclear (e.g. results within the range of analysis uncertainty), further case-by-case investigation is required for insightful conclusions. Considering any additional stages (e.g. reverse logistics energy cost, core quality control complexities, etc) results in reducing the lifecycle energy savings of remanufacturing from the estimated results in this study. We perform sensitivity analysis to examine the assumptions put forth for our assessments.

3. Results and Discussions

3.1 Introduction

In this research study we evaluate the energy savings potential of remanufacturing from a total lifecycle viewpoint. More specifically, we utilize environmental assessment models to quantify the lifecycle energy demands for 19 different products that are produced in 8 distinct product categories. Each of the products analyzed has been carefully chosen based on having strong ties to topics related to remanufacturing, service lifetime extension, product reuse, as well as subject to technological improvements and policy interventions on end-of-life options. By studying a wide range of products, we are able to evaluate the feasibility of remanufacturing holistically. Furthermore, our conclusions illustrate the criticality of performing environmental analysis in the scope of complex macroscopic changes such as pace of technological innovations, impact of policies, and economic incentives, which lead to dynamic changes in time.

The research findings have led to the formulation of 8 case studies in relation to remanufacturing energy savings potential of 19 distinct products as listed below:

1. Appliance remanufacturing (reuse)
    a. Refrigerator
    b. Clothes washer
    c. Dishwasher
    d. Room AC
2. Cartridge remanufacturing (refilling)
    a. Laser cartridge
3. Internal combustion engine remanufacturing (overhaul)
    a. Diesel engine
    b. Gasoline engine
4. Electric motor remanufacturing (rewinding)
    a. 22 kW electric motor

    b. 200 kW electric motor
5. Office furniture remanufacturing (refurbishing)
    a. Office chair
    b. Office desk
6. Personal Computer remanufacturing (reuse)
    a. Desktop computer
    b. Laptop computer
    c. CRT monitor
    d. LCD monitor
7. Textile remanufacturing (re-selling)
    a. Viscose blouse
    b. T-shirt
8. Tire remanufacturing (retreading)
    a. Light duty passenger car tire
    b. Heavy truck tire

Each case study is designed to provide an assessment of remanufacturing energy savings in a specific context. A few main themes, however, are shared amongst the case studies. The case studies suggest that the environmental benefits of remanufacturing depend on the following considerations:

1. For products that have life cycle energy requirements dominated by the use phase, energy savings in the production phase by remanufacturing may be less beneficial compared to products with negligible energy requirements in the use phase.
2. Given that remanufactured products are generally equipped with older technologies than new products, then given pace of technological improvements, new products may be considerably more efficient than older remanufactured products. As a result, the additional energy required in the use phase may exhaust the energy saved by remanufacturing in the production phase.
3. Macroscopic drivers in the scope of political interventions and implementation of standards have led to substantial improvements in energy efficiency of some new

products. Therefore, the evaluation of remanufacturing energy savings and its costs and benefits requires rigorous assessments of the inter-connection between technology, policy, and society.

4. Remanufacturing energy savings is subject to the performances of the remanufactured products in the use phase. Some case studies are designed to study the degradation in performance due to remanufacturing and its impacts on lifecycle energy savings.
5. A few case studies showcase transformational (architectural) technological changes such as transforming from CRT monitors to LCD monitors. Products with new technologies are generally built to higher efficiency standards. Furthermore, these case studies evaluate the lifecycle energy savings by progressing from the older generations of technologies to the newer ones.
6. Given that some products have their energy requirements dominated by the use phase, then in order to address remanufacturing energy savings, some case studies illustrate the high sensitivity of product performance on the use phase energy expenditures.
7. Some products have negligible energy consumptions and material requirements in use phase. Therefore, remanufacturing these products leads to substantial savings in energy and material requirements, which most generally makes remanufacturing an environmentally friendly end-of-life option.

The matrix below summarizes the above list in a table format for all the case studies formulated in this research project. In

Table 1 below, the 'X' marks indicate the topics that are covered by each case study. In order to provide an overview of the above topics while minimizing redundancy, this chapter will provide four case studies that address the general themes and objectives as established in this research. These four case studies are: office furniture, appliance, tire, and electric motor.

Table 1 Topics covered in each case study in relation to remanufacturing and energy savings.

Cast Study	1	2	3	4	5	6	7
Appliance	X	X	X		X		
Cartridge				X			
Gasoline Engines	X	X	X				
Diesel Engines	X					X	
Electric Motor	X	X	X	X			
Office Furniture							X
PC		X			X	X	
Textile							X
Tire	x	x		x	x	x	

1	Use phase substantially dominates lifecycle energy requirements.
2	Technological (efficiency) improvements make remanufacturing net energy expending from a lifecycle viewpoint.
3	Energy efficiency standards lead to high efficiency improvements in new products.
4	Degradation in performance of remanufactured products can make them inferior to new products from a lifecycle energy perspective.
5	Transformational (Architectural) technological changes in products can make older remanufactured products inferior in performance and obsolete
6	Products with considerably high use-energy may be hypersensitive to slight variations in use phase performance
7	Remanufacturing of these products generally leads to lifecycle energy savings because production energy dominates lifecycle energy impacts

All case studies are archived as technical reports in the MIT Energy Initiative Publication Series and are available as a reference. For additional information about research approach, comparison context, and references for each case study, please refer to the MIT Energy Initiative Publication Series Reports as listed below:

MIT Energy Initiative Publication Series Report 2010-1:

a. Appliance Remanufacturing and Energy Savings (MITEI-1-a-2010).
b. Cartridge Remanufacturing and Energy Savings (MITEI-1-b-2010).
c. Electric Motor Remanufacturing and Energy Savings (MITEI-1-c-2010).
d. Engine Remanufacturing and Energy Savings (MITEI-1-d-2010).
e. Furniture Remanufacturing and Energy Savings (MITEI-1-e-2010).
f. Personal Computer Remanufacturing and Energy Savings (MITEI-1-f-2010).
g. Textile Remanufacturing and Energy Savings (MITEI-1-g-2010).
h. Tire Remanufacturing and Energy Savings (MITEI-1-h-2010).

Hereafter we refer to the MIT Energy Initiative Publication Series Report 2010-1 as (MITEI-1-2010). If addressing a specific case study, the letter that corresponds to the case study as shown above, is added at the end of 'MITEI-1'. For example, in this thesis the case study titled 'Appliance Remanufacturing and Energy Savings' will be referenced as (MITEI-1-a-2010).

3.2 Office Furniture Remanufacturing and Energy Savings Case Study

1. Introduction and Motivation

Furniture products are durable products used in households and office environments. The stages involved for supplying furniture encompass raw materials processing, parts manufacturing and unit assembly, and transport via distribution channels. All these operations demand energy and require raw materials; each corresponding process impacts the environment by emitting greenhouse gases and generating waste.

Household and office furniture typically have long lifetimes, at times exceeding more than 30 years of service (Spitzley 2006). In general, furniture products consume little or no energy during use. As a result, the lifecycle energy requirements are dominated by the operations involved in producing these products. Furniture items that have considerable use phase energy consumption are those that require input power such as desk lamps and light fixtures. Though such furniture products are prevalent, the focus of this report is on office furniture items such as office chairs and office desks, which are assumed to have no energy demands in use.

Well-maintained furniture that are in good conditions when reaching end of service life, are sold and re-used in secondary markets. Re-using furniture is a common practice in the U.S. especially for office use. Furthermore, used furniture can be acquired at a cost that is 45 to 65% the price of a new furniture (Hauser and Lund 2003). Therefore, consumers may be inclined to purchase used furniture from secondary market and re-use them as an economic savings strategy.

Old furniture restoration may require parts refurbishment and unit repair. Furniture remanufacturing can effectively restore the entire product to like-new conditions. The remanufacturing process includes product disassembly, parts refurbishment, parts replacement, unit repair, re-assembly, and testing. Given that the office furniture products in this case study have no energy demands in the use phase, then remanufacturing and re-use of old products can potentially lead to substantial energy savings. We utilize Life

Cycle Assessment frameworks for quantifying the environmental benefits of office furniture remanufacturing.

2. Methodology

2.1 Case Objectives

In this case study we present the lifecycle energy impacts of office furniture from cradle-to-grave. Furthermore, we evaluate the distribution of energy demands amongst the life cycle phases of office furniture. In addition, we evaluate the life cycle energy savings potential of extending service-lifetime of furniture by virtue of remanufacturing and reusing.

2.2 Scope of Life Cycle Analysis

Furniture equipments classify into many different classes of products based on the service and functional purposes. The product scope for this case study is based on two office furniture items produced by an office furniture company named Steelcase. Figure 9 below provides a graphical illustration of the product scope for this analysis.

Figure 9 Steelcase office chair (Siento) and Steelcase office desk (Garland) (SteelCaseII).

The product type and description of the office furniture studied in this report are given below.

Office Chair
Product Type: Office Chair from Steelcase/ Product Name: Siento
Description: Office chair with T-arms, aluminum base, and leather upholstery

Office Desk
Product Type: Office Desk from Steelcase/Product Name: Garland
Description: Double pedestal desk.

2.3 Life Cycle Inventory: Energy Demands Analysis

The Lifecycle Inventory for each product encompasses the following phases during the furniture life cycle:

- Acquisition and processing of raw materials; processing and fabrication of component parts
- Manufacturing and assembly of final product
- Transport of raw materials, parts, and final product
- Product use

Refer to Chapter 2 for more information about the lifecycle assessment methodologies utilized in this case study.

Raw Materials Acquisition and Processing, Manufacturing, and Packaging Phase

Spitzley utilizes data collected by Steelcase representatives for four main stages of Steelcase supply chain in order to determine parts and material composition; production process equipment use, energy intensity; product packaging; delivery and product distribution (Spitzley 2006). Spitzley provides the bill of materials for the office chair and the office desk (Spitzley 2006) as shown in Table 2 and Table 3 below.

Table 2 Raw material composition for Steelcase office chair: Siento.

Material	**Mass (Kg)**
Steel	14.7
Plastic	6.6
Non-ferrous metals	6.1
Leather	1.2
Other	0.8
Total	**29.3**

Table 3 Raw material composition for Steelcase office desk: Garland.

Material	**Mass (Kg)**
Particleboard	72.2
Steel	24.0
Plywood	18.2
Cherry	3.9
Other wood/paper	1.4
Adhesives and finishes	0.9
Backing material	0.7
Plastics	0.8
Total	**122.1**

In order to determine the energy requirements and environmental impacts, Spitzley uses the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) software tool developed by the U.S. Environmental Protection Agency.

Use Phase

Given that the office furniture products studied in this report do not require power in the use phase, then we assume that the energy requirements in the use phase are negligible.

2.4 Remanufacturing Decision Analysis

Consider a scenario whereby an office furniture product (i.e. office chair or office desk) has reached end of life due to parts failure, product aging, etc. The owner of the office furniture has a decision to make. He can either dispose the old office furniture and purchase new office furniture OR restore the old furniture unit to like-new conditions by remanufacturing it and reusing it for an extended period of time. Figure 10 below illustrates the decision-tree for the consumer:

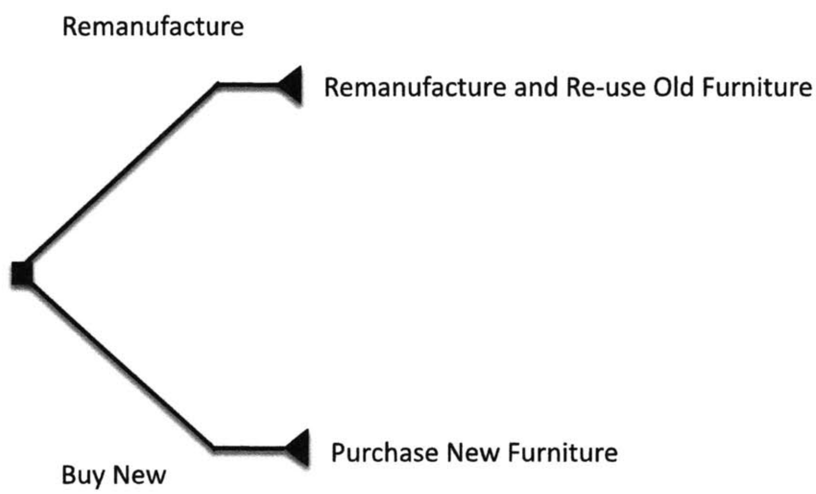


Figure 10 Remanufacturing decision-tree.

The refurbishment process may entail part replacement, part repair, woodwork, and finishing touches. We assume that the repair and refurbishment process is conducted mostly by labor (i.e. no heavy-equipment machinery used for remanufacturing) and requires negligible energy. Also, we assume that old unit is re-used by the same consumer and neglect transportation cost during remanufacturing process. Therefore, this leads to negligible energy demands during lifecycle of remanufactured office furniture. These assumptions are biased in favor of remanufacturing.

2.5 Life Cycle Costing Analysis

Life cycle costing is conducted from a consumer's perspective by taking into account two distinct costs, namely, upfront cost (e.g. capital cost) and ownership cost (e.g. operational cost). We take energy requirements as the environmental impact factor to study for each life cycle phase of the furniture. For office chair we take the functional unit as 30 years of office seating for one chair in an office environment (Spitzley 2006). For office desk we take the functional unit as 30 years of standalone work surface use including storage (Spitzley 2006).

2.6 Data Acquisition

Spitzley has conducted a focused case study on life-cycle assessment of three office furniture products, namely, an office chair, an office desk, and an adjustable desk (Spitzley 2006). The energy analysis, data sources, methodology and results in this case study are based on (Spitzley 2006). For economic assessments, we relied on market prices for Steelcase online store website (SeelCase),(SteelCaseII).

3. Results

3.1 Life Cycle Inventory: Energy Demands Results

According to Spitzley, the total lifecycle energy resource consumptions of a single unit of Siento Office Chair and Garland Office Desk are 1,350 MJ and 3,452 MJ, respectively (Spitzley 2006) as depicted in
Figure 11 and Figure 12 below. For more information about individual data please see (MITEI-1-e-2010).

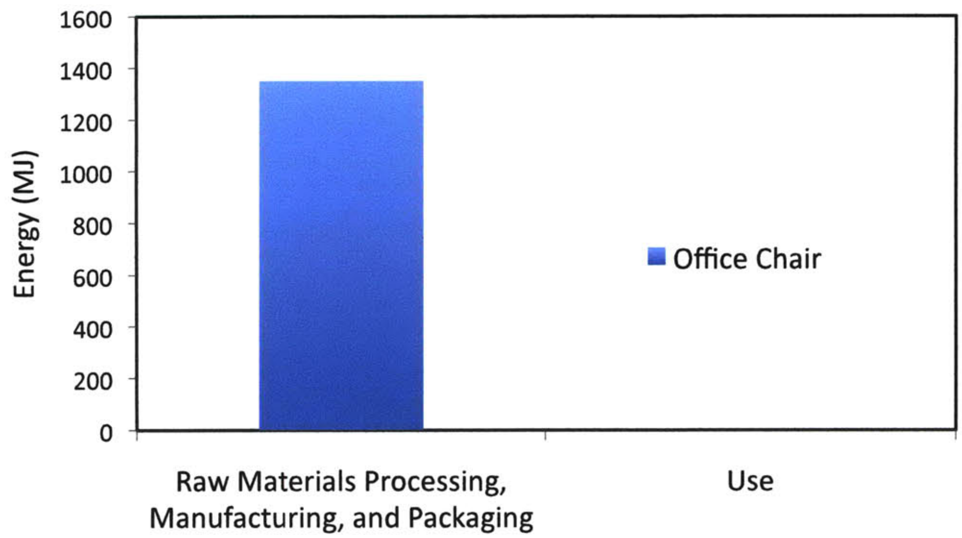


Figure 11 Lifecycle energy assessment of office Chair.

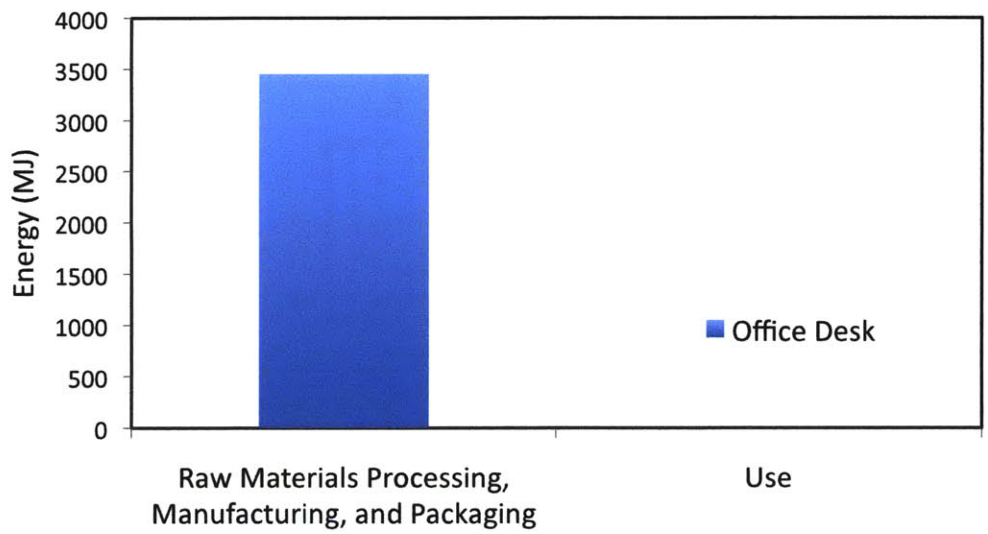


Figure 12 Lifecycle energy assessment of office desk.

3.2 Remanufacturing and Energy Savings

The comparison between lifecycle energy cost of new and remanufactured furniture is illustrated in Figure 13 below. Note that the dividing line in Figure 13 below represents the case where total lifecycle energy of the new and the remanufactured products are equivalent (e.g. $LCI_{New} = LCI_{Reman}$). Therefore, a data point that lies on the dividing line indicates that the lifecycle energy consequences of the new product as well as the remanufactured product are equivalent.

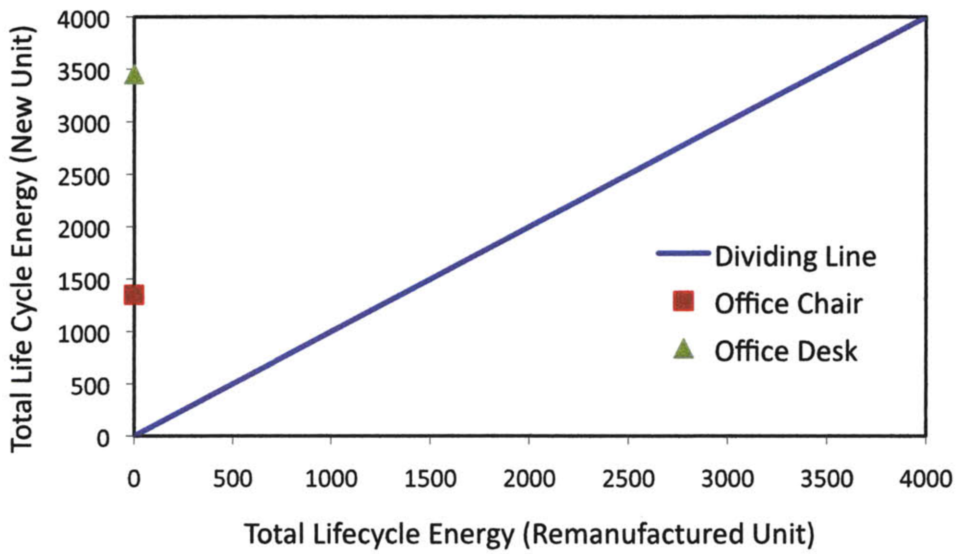


Figure 13 Total lifecycle energy comparison of new and remanufactured office furniture.

According to Figure 13, a new office chair and a new office desk require around 1,350 MJ and 3,452 MJ of energy during its entire lifecycle. Also, Figure 13 illustrates that by remanufacturing and re-using old furniture it leads to lifecycle energy savings.

3.3 Life Cycle Costing Results

We carry out the Life Cycle Costing from a consumer's perspective. According to Steelcase online store, the market value of Siento Chair and Garland office desk are $1,799 (SteelCaseII) and $3,200 (SeelCase), respectively. Note that these office items marketed for executive offices. Therefore, the price listings are higher than sales-weighted average prices for office furniture. In order to perform the analysis we make the following assumptions:

- The maintenance cost and other cost accrued in the use phase of the furniture is negligible (ownership cost is null).

- The cost to remanufacture the item (or to purchase a remanufactured furniture) is approximately 50% of new (Hauser and Lund 2003).

Based on the above assumptions, the life cycle economic cost for a new Siento office chair and new Garland office desk are $1,799 and $3,200 respectively from the consumer's viewpoint. Moreover, the life cycle cost of the remanufactured counterparts would be about $900 and $1,600, respectively.

4. Conclusions

The results from life cycle energy assessments signify that life cycle energy impact of office chair and office desk are dominated by raw materials processing and manufacturing phase (above 85% of total lifecycle for both office chair and office desk). We claim that by choosing to remanufacture and re-use old units instead of purchasing new it can lead to lifecycle energy savings of 1,350 MJ and 3,452 MJ for office chair and office desk, respectively. Moreover, we conclude that furniture remanufacturing is a highly favored environmental decision and an energy savings end of life option given that production energy demands dominate lifecycle energy impacts.

The results from life cycle costing indicate that if the consumer decides to remanufacture the old furniture unit instead of purchasing new, s/he will recover 50% of the life cycle economic cost of the furniture. Based on the life cycle assessment and life cycle costing, we can conclude that furniture remanufacturing is a beneficial end-of-life option both from energy and economic savings perspectives.

3.3 Appliance Remanufacturing and Energy Savings Case Study

1. Introduction and Motivation

Appliances are electro-mechanical products that are extensively used in the residential households as well as commercial sectors. Appliances accomplish some household functions such as cooking, refrigerating food, cleaning, and heating. Appliances are traditionally classified into two groups: major appliances (or white goods), and small appliances (or brown goods). White goods are large household appliances that are mostly utilized for cooking, heating, cooling, and cleaning. Examples of major appliances are refrigerator, freezer, dishwasher, clothes washer, room air conditioner, water heater, and microwave oven. On the other hand, brown goods are small electronic appliances that are generally for entertainment and communication. Examples of small appliances are television, telephone, CD and DVD player.

1.1 Appliances and the Environment

With high penetration rates in the households, appliances are considered as products with a high potential for impacting the environment. For example, the chloroflourcarbons (CFCs) used in refrigerators and freezers are stratospheric ozone depleters that must be disposed of properly. Moreover, as electronic devices, most appliances draw considerable energy in order to operate in the use phase, which in turn, directly impact the environment.

In 2008, the U.S. residential sector consumed 21.6 Quadrillion BTUs of energy (EIA 2009). This is equivalent to more than one fifth of U.S. energy-related consumption in 2008 (EIA 2009). According to the Energy Information Administration, total consumption of home appliances accounts for nearly one third of the nation's residential energy consumption and more than 6% of total national energy consumption (EIA 2005). This is largely due to appliances' high saturation rates in the residential sector (AHAM 2001). For example, a typical household in the U.S. is equipped with at least one refrigerator, clothes washer, and dryer. Also, most households have dishwashers as well (AHAM 2001). In certain parts of the country room air conditioners are common in the residential sector. The distribution of electricity consumptions for household appliances varies by type, size, and operational attributes. In this case study we analyze the dynamic changes in relation to energy efficiency of appliances in the past few decades. Furthermore, we will investigate the macroscopic influences on the feasibility of remanufacturing and reusing old appliances. For this, we address two important systems factors, namely, impact of technology progress and impact of policies in time.

1.2 Technology Improvements: Changes in Energy Performance of Appliances in Time

In the past two and a half decades new appliances have been built to higher efficiency standards. Over their lifetimes, newly produced appliances may save substantial amounts of energy compared to older units as shown in Figure 14.

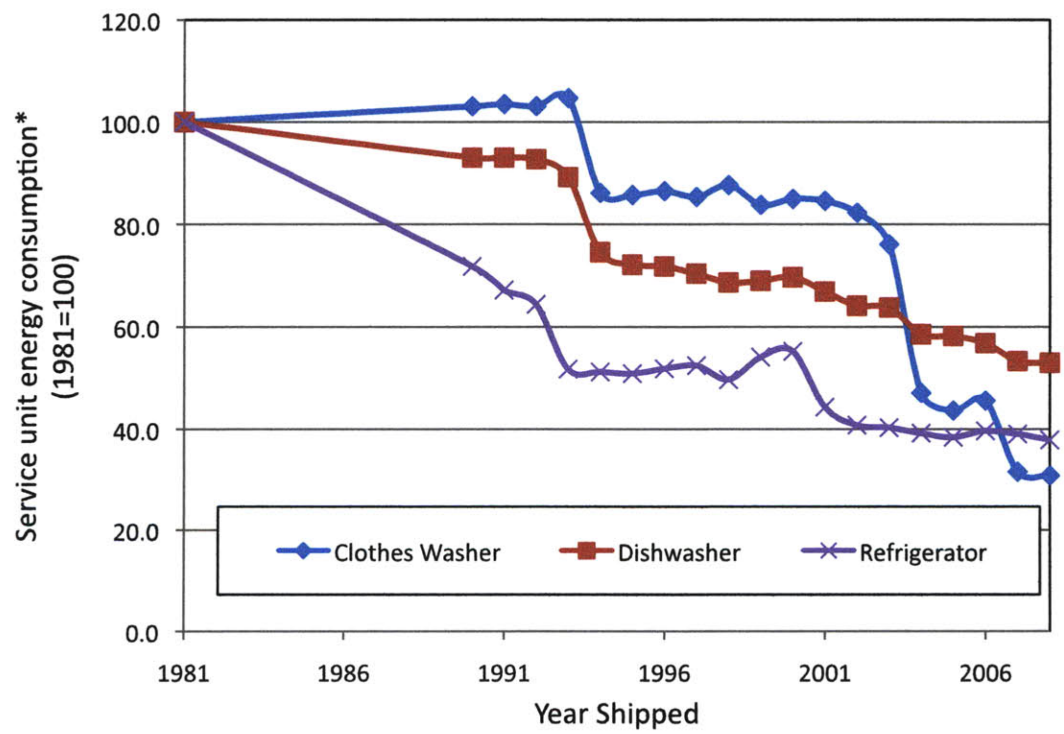


Figure 14 Change in energy consumption for major appliances (AHAM 2008). * Service unit for the clothes washer, the dishwasher, and the refrigerator as shown in this plot are energy consumption per cycle, energy consumption per cycle, and annual energy expenditures, respectively.

As discussed in detail in the forthcoming sections, we conclude that the improvements in energy efficiency of appliances have occurred because of technological advancements, rise in electricity cost, and series of federal and state policies standardizing minimum efficiency performance of appliances.

1.3 Impact of Policies on Life Cycle Energy Requirements of Appliances

Prior to the initiation of governmental standards in 1970s, efficiency of appliances were not a crucial focus for appliance manufacturers. For example, a refrigerator manufactured in 1970 consumed more energy during its use phase than its prior versions, mostly because of more energy intensive features as well as larger capacity. However, since the establishment of Energy Policy and Conservation Act in 1975 (EPCA 1975), we have witnessed substantial improvements in appliances energy performance during operation, as shown in Figure 14 above.

History of appliance standards in the U.S. goes back to 1960s where policy advocates were negotiating their interests in standards in order to help mitigate a series of multi-state blackouts in northeast states in 1965 (Nadel 1994). In 1970, concerns about environmental impacts of power plants in the west coast led to energy policy assessments including standards (Nadel 1994). The engagement of policy discussions concluded with the establishment of California Energy Commission with the authority to establish appliance standards under the 1974 Warren-Alquist Act (Nadel 1994). California was the only state with a state-wide appliance standards directive until New York began to adopt standards in 1976. These initiatives at the state level generated interest for federal standards, which led to the establishment of The Energy Policy and Conservation Act of 1975 (Greening, Greene et al. 2000).

Residential appliance mandatory standards were first legislated as part of the National Appliance Energy Conservation Act (NAECA) in 1987, which established energy conservation standards for major residential appliances (Dale, Antinori et al. 2009). This was the amended legislation to The Energy Policy and Conservation Act (EPCA) in 1975, which required the Federal Trade Commission (FTC) to generate a labeling program. Also, it required Department of Energy (DOE) to establish energy conservation programs for consumer goods other than automobiles, encompassing major household appliances and set voluntary efficiency targets (Greening, Greene et al. 2000). These legislations combined with the National Appliance Energy Conservation Amendment of 1988 enforced energy conservation standards for main classes of consumer appliances (Greening, Greene et al. 2000). Additional standards were written into law with the establishment of the Energy Policy Act of 1992. The Energy Policy Act required DOE to support the voluntary office products Energy Star program (Harrington and Damnics 2004). Energy Star is a joint-program between DOE and the U.S. Environmental Protection Agency (EPA), which identifies and promotes highly efficient products with low standby power consumption (Harrington and Damnics 2004). Furthermore, a presidential executive order in 2001 passed an order as part of the Federal Energy Management Program (FEMP) requiring all purchases by the governmental agencies to be Energy Star labeled (Harrington and Damnics 2004).

Most of the energy standards have been performance based, and not prescriptive type of regulation. This means that the efficiency technology to achieve regulatory compliance is determined by the manufacturers. Most of these standard directives have been by consensus among manufacturers and environmental advocates (Wenzel, Koomey et al. 1997). Minimum energy performance standards for each appliance are defined for various product classes specified by functionality, system performance. For detailed discussion about the protocols of DOE standards rulemaking refer to (MITEI-1-a-2010). A list of federal energy efficiency standards for residential appliances is shown below (Meyers, McMahon et al. 2003):

Table 4. Federal energy efficiency standards for residential appliances (Meyers, McMahon et al. 2003).

Product	Year Implemented	Updates
Refrigerators	1990	1993, 2001
Freezers	1990	1993, 2001
Central Air Conditioners and Heat Pumps	1992	2006
Room Air Conditioners	1990	2000
Clothes Washers	1988	1994, 2004, 2007
Clothes Dryers	1988	1994
Dishwashers	1988	1994
Water Heaters	1990	2004
Gas Furnaces	1992	2007
Oil Furnaces	1992	-
Ranges and Ovens	1990	-
Pool Heaters	1990	-
Direct Heating Equipments	1990	-

Appliance standards have been an effective catalyst in promoting technological progress in appliances manufacturing industry to produce products that serve consumer needs with less energy requirements. As shown in Table 4 above, since the establishment of the National Appliance Energy Conservation Act in 1987, there have been critical updates to the minimum energy requirements promoting further improvements in energy efficiency of appliances.

1.4 Extending Appliances Service Lifetime by Remanufacturing

Appliances are designed for endurance, and last longer than most household consumable goods. For example, an average lifetime of appliance varies from 8 years (e.g. microwave ovens) to 16 years (e.g. freezers) (AHAM 2001). According to the Association of Home Appliance Manufacturers (AHAM) Recycling Information Center, after the first ownership service, a portion of appliances are re-used, re-sold, and continue in use (AHAM 2001). Re-use of an old unit may be prone to degraded performance and pre-mature failure (Bole 2006). A way to restore the old appliances to 'like-new' conditions and to effectively mitigate the chances of pre-mature failure is to remanufacture it.

In this case study we evaluate the total lifecycle energy and economic savings potential of extending the service life of an old appliance by remanufacturing it. Appliance refurbishing and remanufacturing are a functional practice in the EU (Lindahl, Sundin et al. 2006). For the most part, appliance remanufacturing in the U.S. does not refer to the entire appliance, but rather to a part that is integral to operation and can be prone to failure such as compressors, valves, pumps, or control units (Hauser and Lund 2008). Once these units are found and reinstalled into the appliance, the appliance has a new life and can last until another component fails. In this study we assume that all worn parts are replaced with remanufactured parts, hence, extending the product life by an entire service lifetime. Therefore, the definition of 'remanufactured' appliance as presented in this case study overlaps with appliance reuse, resell, and refurbish (refer to Chapter 1 for more information).

Remanufacturing an old appliance may also be desirable for the consumer from an economic standpoint: it is much cheaper to purchase a remanufactured compressor for a refrigerator rather than an entirely new unit. Furthermore, the consumer may believe they are saving energy by reducing the energy demands for new goods. However, from a total lifecycle viewpoint, this may or may not be the case. In other words, despite the energy savings in production, remanufacturing an appliance that is a generation old to like-new conditions may expend more energy in the use phase compared to a new model. For relevant literature references about this visit (MITEI-1-a-2010).

In this case study we will analyze life cycle energy and economic valuation of appliances and the environmental savings potential of appliance remanufacturing. We document the evolution of energy efficiency trends to provide a retrospective assessment of the feasibility of appliance remanufacturing over time. We evaluate the impacts of energy conservation standards on life cycle energy and financial benefits of appliance remanufacturing.

2. Methodology

2.1 Study Objectives

Given long lifetime, change in energy performance, and high utilization rates of appliances, it is important to evaluate energy demands of appliances from a total lifecycle viewpoint. Such assessment provides an understanding about the distribution of energy impacts during the life cycle of appliances. Moreover, the goal of this study is to test the energy savings potential of extending old appliance service lifetime through remanufacturing practices.

We use Life Cycle Assessment (LCA) for determining the potential environmental impacts of a product from 'cradle-to-grave' (ISO 2006). We use life cycle inventory analysis, and focus only on energy consumption in order to quantify the environmental impact of new and remanufactured products (Bole 2006). Also, we use Life Cycle Costing (LCC) to assess economic savings potential of appliance remanufacturing (refer to Chapter 2 for more details).

2.2 Scope of Life Cycle Analysis

The scope of life cycle inventory analysis is based on three main lifecycle phases, namely, raw materials acquisition and processing, manufacturing, and use. The appliances presented in this case study constitute three major residential appliances, namely, refrigerator, clothes washer, and dishwasher.

We conduct Life Cycle Costing (LCC) by performing economic analysis of remanufacturing from a consumer's perspective. We consider two distinct economic costs for LCC, namely, upfront costs and ownership costs. Upfront costs refer to the initial monetary cost of purchasing a product while ownership costs refer to the monetary cost of a product in operation (refer to Chapter 2 for more information about the methodology).

2.3 Life Cycle Inventory: Energy Demands Analysis

In order to evaluate energy expenditures of a remanufactured appliance, we determine the energy consumptions in both the production phase and the use phase; we compare this with the requirements for a new appliance.

Raw Material Acquisition and Processing Phase

We find the raw materials energy embedded in each appliance by using data on the typical energy cost of common materials found in (Smil 2008), and (Ashby 2009).

Manufacturing and Assembly Phase

We researched for energy consumptions of typical manufacturing processes during the production of most appliances, including parts fabrication, refrigeration cycle assembly, unit assembly, etc. We rely on literature values for quantifying manufacturing energy demands for appliances.

Remanufacturing Phase

We assume that the energy requirements for remanufacturing an appliance to like-new conditions are negligible. This assumption is based on the fact that most appliances are not remanufactured in whole; this assumption causes remanufacturing to save all the energy required for producing a new appliance. This assumption is biased and highly in favor of appliance remanufacturing.

Use Phase

The trends for unit energy consumption, capacity, and efficiency of appliances studied in this report are mainly gathered from Association of Home Appliance Manufacturers (AHAM) report published in 2008 (AHAM 2008), which provides performance trends for appliances from 1981 to 2008. For refrigerators, an additional source (Rosenfeld 2003) was utilized to illustrate change in energy consumption and size of refrigerators from 1947 to 1981. According to AHAM, the published data are shipment-weighted average values compiled from producers in the appliances industry. Each appliance manufacturer provides shipment-weighted average values of their various models produced each year. Though AHAM is a voluntary-based data collection agency for home appliances, they claim that 95 to 96 per cent of manufacturers in this industry participate in their data survey (AHAM 2008).

Each producer is required to provide energy consumption characteristics of their products by following a stringent testing protocol enforced by Department of Energy's Energy Conservation program for consumer products. As part of the federal standards established by DOE, appliance manufacturers are required to abide by the Code of Federal Regulations (CFR). This is the codification of the general and permanent rules published in the Federal Registry by the executive departments and agencies of the Federal Government. By using the above data, we have determined the annual energy consumption of appliances. Furthermore, the annual values were amortized over average useful lifetime to determine the use phase energy consumptions.

2.4 Appliance Remanufacturing Analysis

We evaluate appliance remanufacturing and energy savings based on the following context: After an old appliance reaches end-of-life (due to component failure, malfunctions, unit break-down, approaching physical limits) the consumer faces a decision: (a) to purchase a new appliance (latest model) or (b) to bring the old appliance to 'like-new' conditions by replacing the malfunctioned components with remanufactured parts (i.e. remanufactured compressors, remanufactures pumps, etc.).

Given the system boundary above, we determine the total life cycle energy demands of new and remanufactured appliances by utilizing Equation 1. The analysis is conducted retrospectively to capture changes in appliance use-phase performance in time. The results of our analysis are shown mainly in two distinct forms:

1. Retrospective assessment illustrating total life cycle energy of new appliances
2. Retrospective assessment illustrating total life cycle energy comparison of a newly produced appliance and a remanufactured (1 lifetime/ generation older) appliance

2.5 Life Cycle Costing Analysis

In addition to energy analysis, this case study illustrates the economic feasibility of remanufacturing for appliances. In doing so, the purchase price and the use phase electricity costs were computed for appliance models produced in different years. All economic valuations were performed in real dollar values, adjusting for inflation by utilizing U.S. consumer price index (CPI) published by U.S. Department of Labor Bureau of Labor Statistics from 1913 to 2009. The market value of refrigerator was determined by consumer reports (Horie 2004); market pricing for clothes washer was found from (Dale, Antinori et al. 2009). The average retail price of electricity (adjusted for inflation) was used for determining the total electricity cost of a unit during its operational lifetime (EPA 2005). Finally, the values were normalized by the corresponding unit capacity of appliances to capture the changes in size effects.

2.6 Data Acquisition

In order to perform LCI analysis, we gathered information from various sources about the appliance, including a bill of materials, the use phase energy consumption data, and appliance average useful lifetime. The data sources for each life cycle stage are discussed in detail for each appliance.

2.7 Assumptions

We make a several assumptions for this analysis as listed below:

1. The remanufactured appliance will perform 'like-new.' This implies that the remanufactured product would function just like when it was purchased a few years prior.
2. For a particular appliance, product lifetime is the same regardless of when it was manufactured.
3. Raw material processing and manufacturing for appliances are based on a single model. Therefore, the dynamic changes in the product material compositions and/or

changes in the production energy intensity are not accounted for in this life cycle assessment.

4. For the most part, appliance remanufacturing in the U.S. does not refer to the entire appliance, but rather to a part that is integral to operation and can be prone to failure such as compressors, valves, pumps, or control units. Once these units are found and reinstalled into the appliance, the appliance has new life and can last until another component fails. In this study we assume that all worn parts are replaced with remanufactured parts, hence, extending the appliance life by an entire service lifetime. For conservative analysis in favor of remanufacturing, the energy requirements during remanufacturing processing are assumed to be zero.
5. For conservative analysis in favor of remanufacturing, the monetary cost of remanufacturing an appliance is assumed to be zero. We perform sensitivity analysis to examine this assumption.
6. Constant energy consumption throughout the appliance service life ignoring the appliance decline in efficiency over time (Johnson 2000).
7. Change in consumer behavior over time is not accounted for (e.g. constant input for number of washing cycles per year between 1981 and 2008).
8. Energy requirements during reverse logistics transportation and end-of-life options are ignored. This assumption is conservative in favor of remanufacturing. We perform sensitivity analysis to examine this assumption.

In the proceeding chapters we will provide detailed assessment of lifecycle energy and economic savings for remanufacturing three appliances, namely, refrigerator, clothes washer, and dishwasher.

3. Refrigerator

3.1 Introduction

In this section, we present a comparison of a new and a remanufactured refrigerator retrospectively from 1956 to 2008. The results below show that the lifetime energy consumption of the refrigerator is dominated by the use phase, so a change in operational efficiency has a tremendous effect on lifetime energy needs, an effect that can overwhelm the gains from using a remanufactured refrigerator.

3.2 Life Cycle Inventory: Energy Demands Analysis

Raw Material Acquisition and Processing

The raw materials processing and manufacturing energy consumption is based on a 1997 model refrigerator model (Kim, Keoleian et al. 2006). Refer to (MITEI-1-a-2010) for detailed information about the bill of materials.

We used ranges of energy intensity provided by (Smil 2008), (Ashby 2009) to determine the lower bound and the upper bound of energy expenditure associated to raw materials processing. More specifically, for embedded energies we used 20 to 25 MJ/kg for iron and steel, 190 to 230 MJ/Kg for Aluminum, 60 to 150 MJ/Kg for Copper, 119.8 MJ/Kg for rubber (refer to (MITEI-1-h-2010)for more information) 10 to 15 MJ/Kg for fiber and paper, 75 to 115 MJ/Kg for plastics, 15 to 30 MJ/Kg for glass (Smil 2008), (Ashby 2009). The refrigerator taken into account weighs 84 Kg. Based on this data, we estimate the energy consumed during the raw materials processing to be 3,432 to 4,983 MJ.

Manufacturing and Assembly Phase

The manufacturing process of a refrigerator consists of parts assembly, door assembly, cabinet assembly, refrigeration cycle assembly, plastic parts processing and assembly (Kim, Keoleian et al. 2006). Our literature review indicates that the manufacturing energy intensity for refrigerators varies from 12 MJ/Kg (Kim, Keoleian et al. 2006) to 22 MJ/Kg (Kemna, Elburg et al. 2005) depending on the boundary conditions, assumptions, and methodologies taken into account. Based on this, we estimate the manufacturing energy consumption to be in the range of 1,010 MJ to 1,864 MJ (12 MJ/Kg to 22 MJ/Kg).

As such, the total raw materials processing and manufacturing energy consumption ranges from 4,442 MJ to 6,847 MJ. This range corresponds well with values obtained by LCA analyses conducted by (Baldwin 2002) and (Truttmann and Rechberger 2006) for a midsize refrigerator. For this study, we choose the upper bound value, namely 6,847 MJ, as the total raw materials processing and manufacturing energy consumption for refrigerator.

Remanufacturing Phase

For the most part, appliance remanufacturing in the U.S. does not refer to the entire appliance, but rather to a part that is integral to operation and can be prone to failure such as compressors, valves, pumps, or control units. Once these units are found and reinstalled into the appliance, the appliance has new life and can last until another component fails. In this study we assume that all worn parts are replaced with remanufactured parts, hence, extending the appliance life by an entire service lifetime. We assume that the energy cost for generating and incorporating the remanufacturing parts to be negligible. This assumption is biased in favor of remanufacturing.

Use Phase

According to AHAM, average length of ownership of currently owned refrigerators is 9 years while average useful lifetime of refrigerators is 14 years (AHAM(NFO) 1996), (AHAM 2001). It appears rare for households to own a full-size refrigerator for the full duration of the product's physical lifetime of over 20 years. For the purpose of our study, average length of ownership (9 years) was taken as the use phase lifetime of a refrigerator. This is on the low end of the typical service lifetime range of refrigerators (i.e. 10-16 years) published in DOE's Building Energy Databook (DOE 2008).

The change in energy consumption of refrigerators over time is influenced by change in unit capacity. (AHAM 2008), (Rosenfeld 2003) provide average volume sizes of refrigerators from 1947 to 2008 as shown below.

Table 5 Change in refrigerator size 1947-2008 (AHAM 2008), (Rosenfeld 2003).

Year	Refrigerator Volume (Cubic Meters)	% Change: from prior generation	% Change: Cumulative
1947	0.233	-	-
1956	0.346	49%	49%
1965	0.444	28%	90%
1974	0.515	16%	121%
1983	0.575	12%	147%
1992	0.560	-3%	140%
2001	0.621	11%	167%
2008	0.605	-3%	159%

According to the Table above, when simulating the decision scenario in year 1956, the new model is 49% larger in size than a model produced 9 year prior (i.e. 1947), which will also consume more electricity due to greater service offerings. Therefore, we have performed our analysis by normalizing the findings by corresponding unit of service (e.g. m^3 refrigerator capacity) for realistic and accurate comparison.

Refrigerators annual energy consumption trends have been collected from California Energy Commission (1947-1990) (Rosenfeld 2003) and Association of Home Appliance Manufacturers (1990-2008) (AHAM 2008). Figure 15 below illustrates the change in average annual energy consumption.

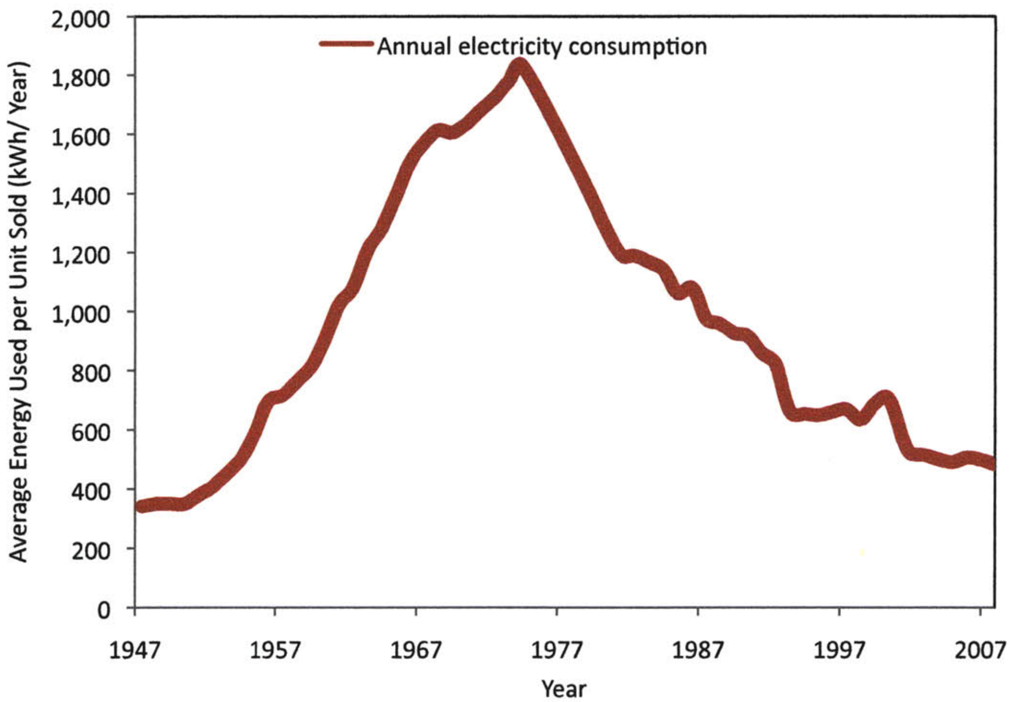


Figure 15 Average energy consumption of refrigerator sold in the U.S. 1947-2008 (Rosenfeld 2003; AHAM 2008).

According to the figure above, the annual energy consumption of refrigerators has increased substantially from 1947 to 1974 by more than 400%. This supersedes the 120% growth in refrigerator size for the same time period (refer to Table 5). As explained in detail later, the establishment of statewide and federal appliances minimum efficiency standards was a driving force for large improvements in energy efficiency of refrigerators from 1974 to 2008 (Rosenfeld 2003; AHAM 2008).

3.3 Remanufacturing Analysis

The remanufacturing comparison context is based on a consumer deciding between remanufacturing a refrigerator that has reached its end of first useful life (after 9 years of use) and purchasing a new refrigerator. This analysis was performed retrospectively, comparing refrigerators starting from year 1956. For example, in year 1956 the consumer would be choosing between extending the life of his/her old refrigerator that was purchased in 1947, or purchasing a new refrigerator produced in 1956. This scenario is repeated every 9 years till 2008; all comparisons are between a new model and a prior generation model. Since there were no data available for energy consumption of refrigerators in 2010 to compare with 2001 remanufactured, year 2008 was chosen as the comparison year. Therefore, the refrigerator models compared are showcased in Table 6 below:

Table 6 Comparison year between new and remanufactured refrigerator

Comparison Year	New Model (Year Made)	Remanufactured Model (Year Made)
1956	1956	1947
1965	1965	1956
1974	1974	1965
1983	1983	1974
1992	1992	1983
2001	2001	1992
2008	2008	2001

3.4 Results

3.4.1 Life Cycle Inventory: Energy Demands Results

Figure 16 below illustrates a retrospective life cycle energy assessment of refrigerators from 1956 to 2008. The functional unit of measure (i.e. the unit for service) chosen for the analysis is energy use of the refrigerator per unit volume (MJ/m^3). This normalization factor filters out the impact of changes in energy values due to size changes in refrigerators in time.

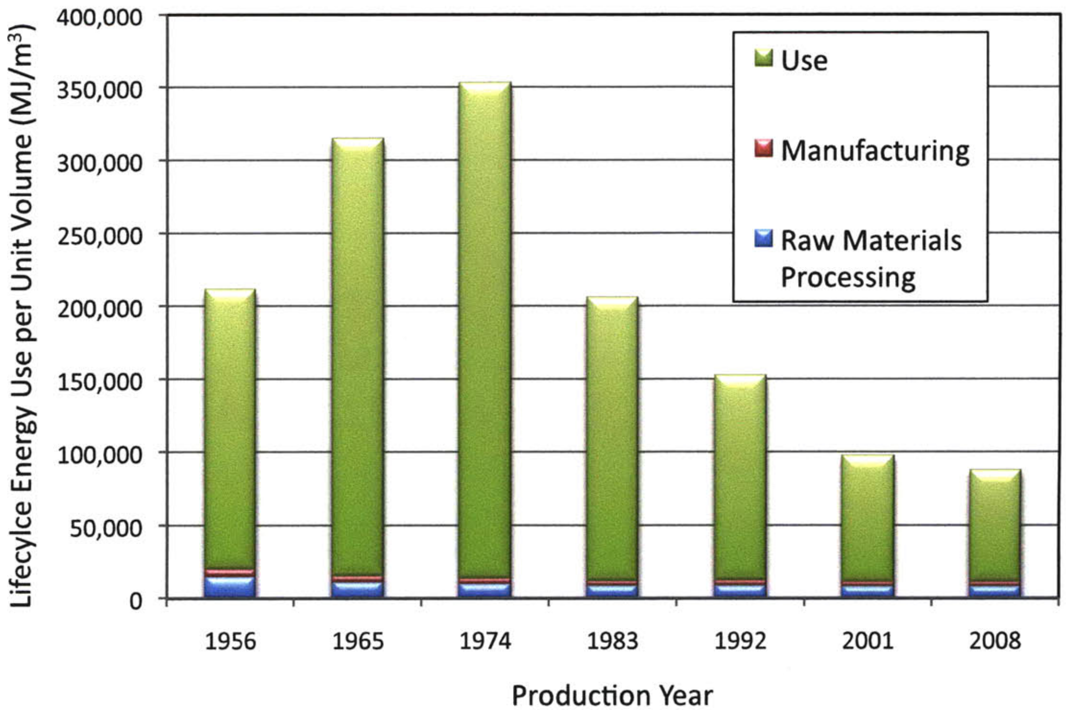


Figure 16 Refrigerator: Retrospective life cycle energy assessment of new model (normalized by refrigerator adjusted volume).

The raw material processing and manufacturing energy consumptions are 4,983 MJ and 1,864 MJ per unit, respectively (refer to 'raw materials processing and manufacturing' section above). Due to the scarcity of data, these values are taken as fixed from 1956 to 2008. The change in the contribution of the raw materials processing and manufacturing phase observed in Figure 16 above is due to normalizing the energy values by corresponding unit volume of conventional refrigerators sold in a particular year (refer to Table 5). Taking the raw material processing and manufacturing energy consumption as fixed in time has considerable limitations. For example, there have been substantial changes in the raw materials used for refrigerators due to changes in construction, design, service offerings, performance. The purpose of this study is to indicate the relative contribution of each lifecycle stage of the product from cradle to grave.

By utilizing the findings in Figure 16 we can infer that the use phase of refrigerator is the largest contributing phase in regard to energy consumption. Also, we can conclude that lifecycle energy expenditure of appliances have varied substantially in the past 50 years; since 1974, refrigerators have been consuming less and less energy in the use phase. Our analysis signifies that the total energy consumptions of refrigerators in absolute values have varied from roughly 70 GJ for a 1956 model to 180 GJ for a 1974 model, then declining to 50 GJ for a 2008 model. In other words, the retrospective life cycle assessment above indicates that the total lifetime energy of refrigerator per unit volume has increased by 67% from 1956 to 1974, and decreased by 75% from 1974 to 2008. For example, in comparing 1974 model and 1983 model, it is evident that purchasing a new but more efficient refrigerator is more beneficial than purchasing a remanufactured part that could extend the life of an older, less efficient refrigerator.

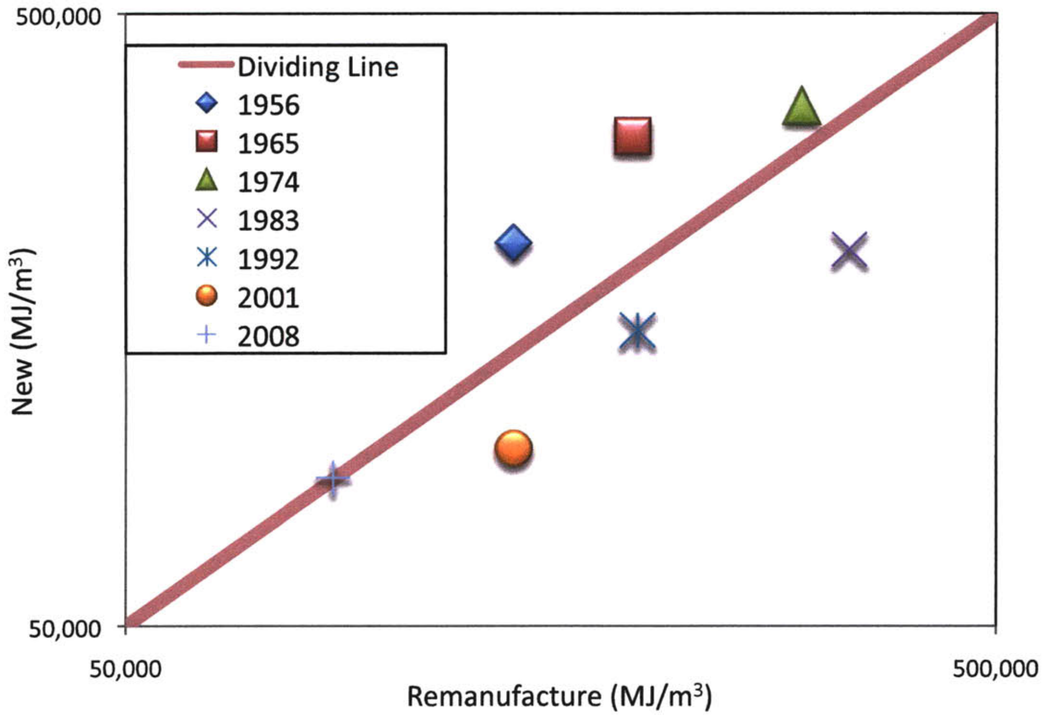
3.4.2 Remanufacturing and Energy Savings Results

Figure 17 (a) below illustrates the total lifecycle energy comparison between a new and a remanufactured refrigerator. The dividing line represents the case where the consumer would be indifferent between purchasing a new unit and remanufacturing an older unit from an energy standpoint. The top triangle in the plot indicates the region where the decision to remanufacture is an energy savings opportunity. In the bottom triangle, in order to save energy from a total life cycle perspective, the consumer should buy a new appliance and discard the old unit.

Figure 17 (b) below depicts remanufacturing total lifecycle energy savings. More specifically, the formula for determining these savings is shown below,

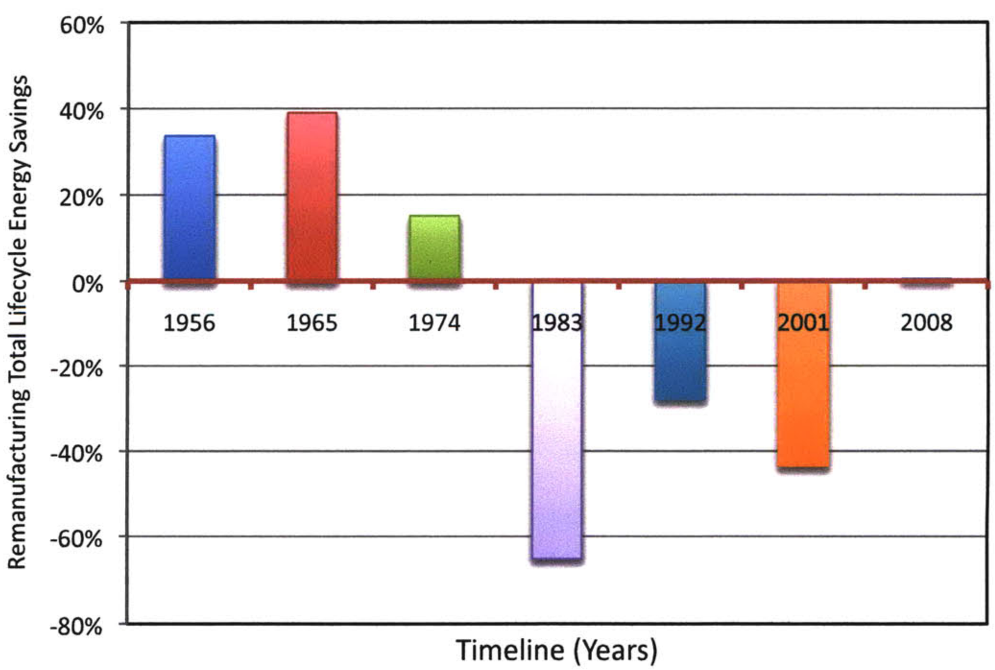
$$\% \text{ Energy Savings} = \left[\frac{LCI_{\text{New}} - LCI_{\text{Reman}}}{LCI_{\text{New}}}\right] \times 100 \qquad \text{Equation 2}$$

where % Energy Savings, LCI_{New}, and LCI_{Reman} are remanufacturing total lifecycle energy savings percentage, total lifecycle energy demands for new product, and total lifecycle energy demands for remanufactured product (see Equation 1).



500,000
50,000
Dividing Line
1956
1965
1974
1983
1992
2001
2008
New (MJ/m³)
50,000
500,000
Remanufacture (MJ/m³)

(a)



60%
40%
20%
0%
-20%
-40%
-60%
-80%
1956
1965
1974
1983
1992
2001
2008
Remanufacturing Total Lifecycle Energy Savings
Timeline (Years)

(b)

Figure 17 Refrigerator: Retrospective life cycle energy comparison of new and remanufactured. (a) This plot illustrates the total life cycle energy comparison in MJ per cubic meters of a newly produced refrigerator against 1 generation (lifetime) older remanufactured refrigerator. (b) This is a retrospective plot revealing the net energy savings by remanufacturing a refrigerator. This plot reveals the divergence of the data point in (a) from the break-even line in the form of % lifecycle energy savings of remanufacturing.

Figure 17 (b) illustrates the total percentage lifecycle energy savings. More specifically, it depicts that in years 1956, 1965, and 1974, remanufacturing an older generation refrigerator would lead to 34%, 39%, 15% savings in total life cycle energy consumptions, respectively. On the other hand, same decision in 1983, 1992, and 2001 would cause 65%, 28%, 44% increase in life cycle energy consumption , despite energy savings in manufacturing phase (Assumption 4). Therefore, refrigerator remanufacturing was an energy savings option prior to 1974. However, since 1974, remanufacturing an older model refrigerator would lead to more energy consumption in the use phase, which exceeds the energy savings during the manufacturing phase, hence, making 'buying new' the energy savings decision.

The comparison between 2001 and 2008 models in year 2008 reveals that on average the additional energy expenditure of a remanufactured unit in the use phase breaks even with the savings in the production phase. This is due to a slow pace in energy efficiency improvements and successful progress from OEMs in achieving federal standards in the past 9 years (refer to Figure 15). Therefore, depending on the future of technology improvements, and the premises of DOE standards to be implemented in 2014, remanufacturing may or may not be a viable energy savings end-of-life option. The next section assesses another driving factor in remanufacturing, which is financial savings.

3.4.3 Life Cycle Costing Results

The total life cycle cost of refrigerator was determined by utilizing the Life Cycle Cost assessment (refer to section above). Figure 18 below reveals the results:

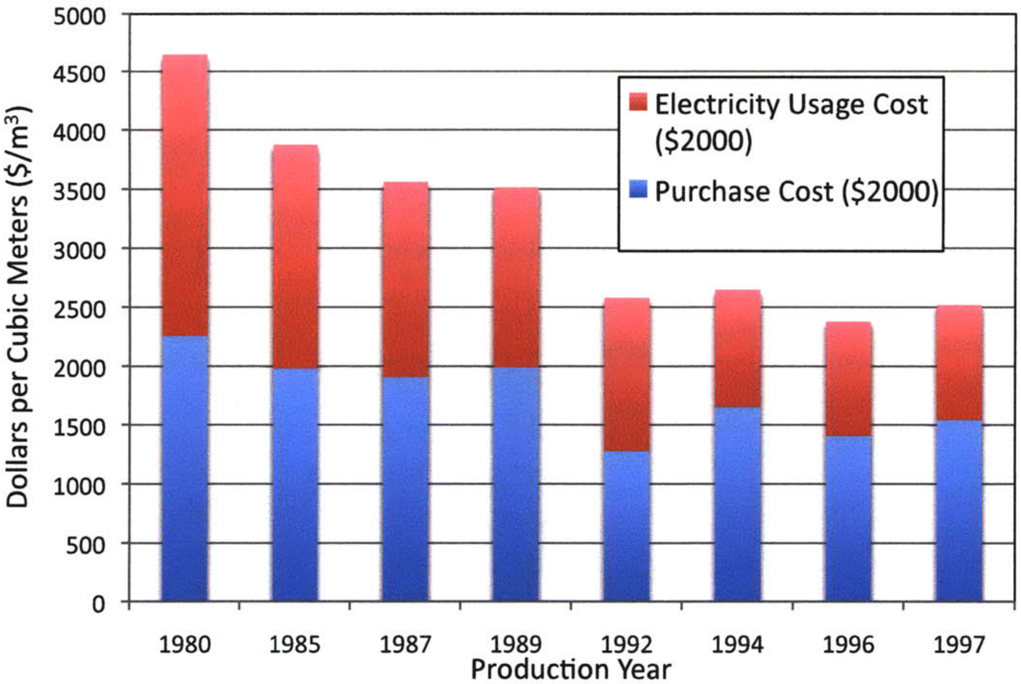


Figure 18 Refrigerator: retrospective total Life Cycle Costing. The costs are normalized to 2000 dollars using the Bureau of Labor Statistics' consumer price index for all year.

According to Figure 18 above, since 1980, the investment cost of a new conventional refrigerator has dropped by 30% while the operational cost (adjusted for inflation) amortized during 9 years of service has declined by close to 60%. This is mainly because the refrigerators have become more energy efficient. Table 7 below illustrates the total lifetime financial savings due to remanufacturing a used-refrigerator as opposed to purchasing a new model. The results convey two distinct scenarios: (Scenario I) the cost of remanufacturing a refrigerator being zero, hence, total lifecycle economic cost of a remanufactured product is equivalent to total use-phase electricity cost, (Scenario II) cost of purchasing remanufactured parts and refurbishing the refrigerator is about 50% of the cost of a new unit (Hauser and Lund 2003). Table 7 illustrates the total life cycle economic comparison in dollars (normalized by unit volume) of a newly produced refrigerator against 1 generator (lifetime) older remanufactured refrigerator.

Table 7 Retrospective life cycle economic comparison of newly produced and remanufactured refrigerators.

SCENARIO I (Remanufacturing Cost= $0)	Total Economic Cost: New Unit ($/cubic meters)	Total Economic Cost: Remanufactured Unit ($/Cubic Meters)	Total Lifetime % Economics Savings
1994	2644	1891	28.5%
1996	2377	1648	30.7%
1997	2518	1518	39.7%
SCENARIO II (Remanufacturing Cost=50% price of New)	Total Economic Cost: New Unit ($/cubic meters)	Total Economic Cost: Remanufactured Unit ($/Cubic Meters)	Total Lifetime % Economics Savings
1994	2644	2718	-2.78%
1996	2377	2353	1.01%
1997	2518	2291	9.00%

According to table above, remanufacturing a refrigerator is a beneficial economic option for SCENARIO I. More specifically, re-using a refrigerator could lead to 30 to 40% percent savings on average in total lifetime cost of a refrigerator. On the other hand, if we consider SCENARIO II, the economic savings of refrigerator remanufacturing gets reduced.

Results illustrate that the consumer will be spending 50 to 90 per cent more in electricity payments by re-using an older less efficient refrigerator. It also reveals that this expenditure is less significant than savings in investment cost, which are between one to two times greater than the total electricity costs. This is because a major component of total lifecycle economic assessment of refrigerators is purchase cost (refer to Figure 18). Note that our initial conservative assumption is that the cost of remanufacturing is null.

However, our sensitivity analysis indicates that if the cost to remanufacture is 50% of market value of new refrigerator, then economic savings in investment phase may break-even with the additional lifetime electricity cost. This makes the consumer financially in-different between buying new and remanufacturing old. Next section addresses the political and technological changes as the main driving forces affecting appliance remanufacturing and energy savings.

3.5 Macroscopic Qualitative Assessments: Technological Improvements and Policy Implications

The substantial reductions in energy requirements of refrigerators are caused by establishment of statewide and federal standards. Since establishment of EPCA, there have been three critical national regulatory milestones for enforcing restrictions on refrigerator energy consumption (Bole 2006). The first standard was enforced in 1990 by DOE, which provided energy conservation standards for 18 product classes for refrigerators and freezers (e.g. refrigerator and refrigerator with manual defrost, automatic defrost, etc) (EERE1 2009), (EERE2 2009). In 1993 and 2001, the first and second standard updates took place, which made energy requirements more stringent and enforced manufacturers to produce refrigerators that consumed lesser energy per year on average (EERE 2005), (EERE 2007).

In addition to the federal standards, voluntary efficiency programs provide more stringent requirements. These voluntary programs are Energy Star, The Federal Energy Management Program (FEMP), and the Consortium for Energy Efficiency (CEE). DOE has put forth technologies and methods to utilize for increasing the energy consumption of refrigerator-freezer, which OEMs have followed (EERE 2005) such as using high efficiency compressors, using variable-capacity compressors, and using high-efficiency evaporator and condenser fans. For more information refer to (MITEI-1-a-2010).

3.6 Conclusions

The statewide and federal minimum efficiency standards for refrigerators have pushed the manufacturers to reduce energy consumption of units produced. This has led to substantial technological innovations since 1974 in novel ways to reduce life cycle energy cost of refrigerators. Due to this, remanufacturing an older and less efficient refrigerator causes higher energy expenditure in the total life cycle of the product.

Since the latest standard implemented in 2001, refrigerator efficiency improvement has been moderate. This leads to making refrigerator remanufacturing an energy-neutral end-of-life option as shown in Figure 17. Energy Independence and Security Act in 2007 has asked DOE for a publication of updated standards by December 31, 2010, which will take effect January 1, 2014 (EERE 2007). Depending on stringency limits, remanufacturing may or may not be an energy savings option in the future.

4. Clothes Washer

4.1 Introduction

The applications of clothes washer are eminent in both household and commercial sectors. It is estimated that 87 million households in the U.S. (about 75% of U.S. households) have clothes washers (U.S.-Bureau-of-the-Census 1995). This translates to 34 Billion loads of laundry washed each year in the U.S. consuming less than 5% of household energy use (HomeEnergy 1996). The energy efficiency of average conventional clothes washer has increased by 72% from 1981 to 2008 as a combination of 27% increase in tub volume and 69% decrease in average kWh electricity use per cycle (AHAM 2008).

Household clothes washers are permanently installed appliances that perform washing at 30 to 95 degrees C, rinsing, and spinning. Commercial clothes washers are automatic washing and spinning machines that, similar to household clothes washers, wash, rinse, and spin dry the laundry. However, typically these machines have a smaller capacity of 5 to 7 kg of laundry load, a much shorter washing time, slightly larger washer drum, and a much longer effective life. Since the focus of this report is on residential appliances, the remanufacturing energy savings potential for commercial clothes washers is out of the scope of this study. The following sections will evaluate the impact of these efficiency improvements on clothes washer remanufacturing.

4.2 Life Cycle Inventory: Energy Demands Analysis

Raw Material Acquisition and Processing

Bole provides a compilation of data for industry average washer bill of material produced in 1977, 1997, 2005 (Bole 2006), (AHAM 2005). For this study we have chosen the industry average washer in year 2005, which encompasses both vertical-axis washers as well as horizontal-axis washers (Bole 2006), (AHAM 2005). We utilize a methodology for computing raw materials energy consumption similar to the refrigerator (refer to the refrigerator section). Visit (MITEI-1-a-2010) for detailed information about the bill of materials used for clothes washer in this study. The analysis finds that raw material processing for a 58 Kg clothes washer consumes between 2,301 to 3,118 MJ in energy. For this study we take the upper bound value, which is 3,118 MJ as the energy value for raw materials processing.

Manufacturing and Assembly Phase

Similar to refrigerator analysis, we rely on literature data for manufacturing energy consumption. Due to scarcity of data, we assume that the manufacturing energy consumption of clothes washer is similar to refrigerator (12 to 22 MJ/Kg) (Kemna, Elburg et al. 2005; Kim, Keoleian et al. 2006). As such, we choose, 22 MJ/Kg as the manufacturing energy consumption for this analysis. We estimate the manufacturing energy consumption of clothes washer to be 1,294 MJ. Therefore, the total raw material processing and manufacturing energy consumption is 4,412 MJ on average for producing a clothes washer.

Remanufacturing Phase

Similar to the analysis for refrigerators, we assume that the energy costs for generating and incorporating the remanufacturing parts to be negligible. This assumption is biased in favor of remanufacturing.

Use Phase

The lifetime of household clothes washers used in the U.S. is taken as 11 years (ApplianceMagazine 2008). The average number of washing loads per year is estimated to be 392 cycles for residential applications (EERE3 2009). In this analysis we utilize survey results from (AHAM 2008), which provide energy consumption per unit in terms of kWh per Cycle. This data set is based on shipment-weighted averages of clothes washers sold between 1981 and 2008. The operation energy requirements in (AHAM 2008) are determined by following a standardized testing procedure, which includes variations in spins with warm (100 degrees F) and cold (60 degrees F) rinse water (refer to (10CFRPart430 2003) for more information). Therefore, in this lifecycle analysis the heating of water is included by virtue of the provided data (AHAM 2008).

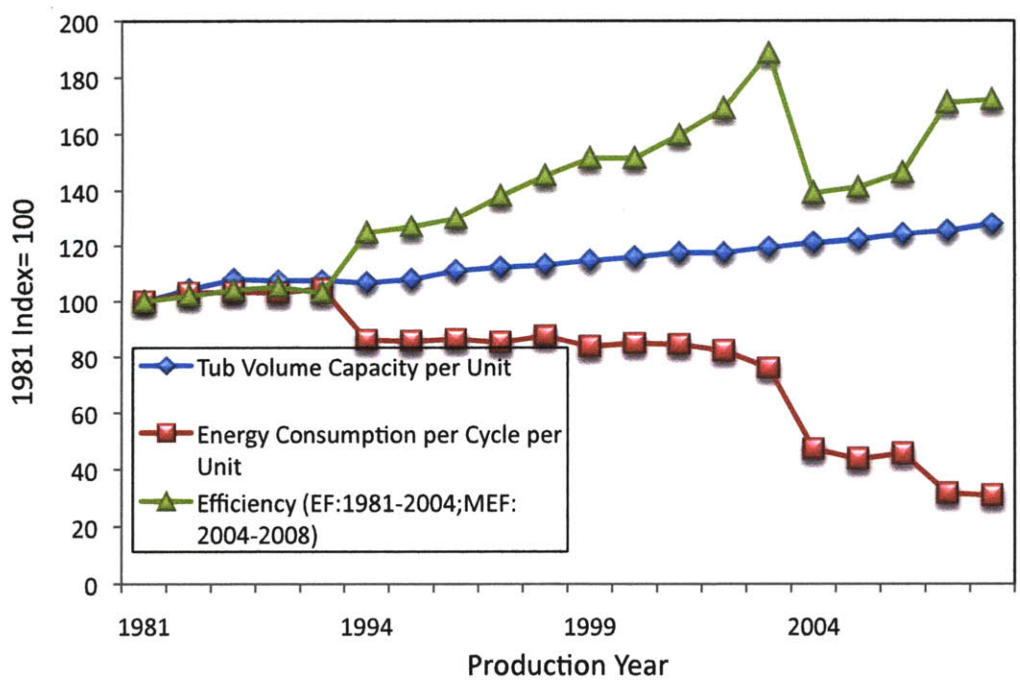


Figure 19 The annual energy consumption and volume capacity trend per a conventional clothes washer.

According to Figure 19 above, the energy consumption of conventional clothes washers have dropped by almost 70 percent while tub volumes have increased by 27% from 1981 to 2008. For information about the efficiency metric for clothes washer (refered to as Modified Energy Factor), refer to (MITEI-1-a-2010).

Water heating consumes the largest share of energy consumption (about 88 per cent) while agitation would consume about 12% of the energy drawn for the clothes washer (Bole 2006). A gas or electric water heater may provide the water heating energy (EnergyStar). The efficiency of an average natural gas powered water heater and an electric water heater is 59% and 90.5%, respectively (Bole 2006).

4.3 Remanufacturing Analysis

The comparison context is based on a consumer deciding between remanufacturing a residential clothes washer that has reached its end of first useful life (after 11 years of use) or purchasing a new clothes washer. AHAM provides energy consumption and efficiency patterns for years 1981 to 2008 (AHAM 2008). Table 8 below shows the comparison year and models for clothes washer remanufacturing energy analysis.

Table 8 Comparison year and model between purchasing new clothes washer and remanufacturing and re-using an older model.

Comparison Year	New Model (Year Made)	Remanufactured Model (Year Made)
1992	1992	1981
2003	2003	1992
2008	2008	1997

4.4 Results

4.4.1 Life Cycle Inventory: Energy Demands Results

We utilized the above information in order to determine the life cycle assessment of household clothes washers as shown in Figure 20 below. Note that the energy values are normalized by tub volume. These values are much larger than the actual life cycle energy values due to clothes washers having volume capacities less than 0.1 cubic meters (AHAM 2008).

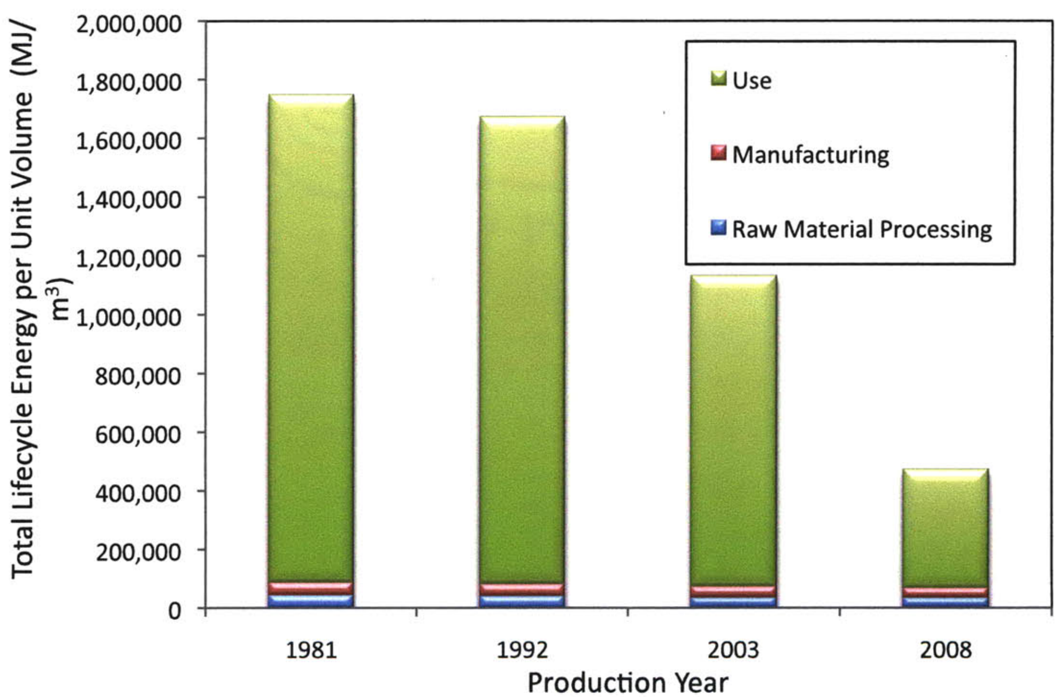


Figure 20 Residential clothes washer: retrospective life cycle assessment of new model.

4.4.2 Remanufacturing and Energy Savings Results

According to Figure 20 above, the total life cycle energy assessment for clothes washers has been substantially reduced in the past two and a half decades. In addition, Figure 20 illustrates that the use phase dominates lifecycle energy demands by consuming 97 to 99 percent of total energy. Furthermore, Figure 20 above illustrates that from 1981 to 2008, the lifetime use phase energy costs for a newly manufactured clothes washer have shrunk by more than 70%.

It is evident that, given this pace of improvement in energy efficiency, it is more energy efficient to purchase a new clothes washer than to extend the life of an older clothes washer. Table 9 below shows the lifecycle energy comparisons for new and remanufactured clothes washers.

Table 9 Clothes washer lifecycle energy comparison new versus remanufactured.

Year	Total Lifecycle Energy: New Unit (MJ/cubic meters)	Total Lifecycle Energy Cost: Remanufactured Unit (MJ/Cubic Meters)	Remanufacturing Total Lifetime % Energy Savings
1981	1,720,804	-	
1992	1,647,807	1,658,972	-1%
2003	1,108,194	1,590,310	-44%
2008	449,418	1,260,508	-180%

According to Table 9 above, remanufacturing is not a viable energy savings strategy due to the steep enhancements in energy efficiency of clothes washers. In other words, the savings in the production phase due to remanufacturing are overshadowed by extra energy expenditure in the use phase of older units. According to our analysis, by extending the life of a used 1997 model clothes washer that has reached end-of-life in 2008, the production phase energy savings sum up to 12% of the usage energy of a 2008 model clothes washer that has operated for 11 years. Furthermore, such production energy savings is nullified by over-expenditure in the use phase energy consumption, which is nearly two times greater than the lifetime usage energy of a 2008 model clothes washer.

Retrospectively, our analysis concludes that in 1992 (prior to federal standards) remanufacturing clothes washers was an energy-neutral end-of-life option. This changed in 2003 and 2008, which made clothes washer remanufacturing an energy-expending option. The next section provides the main factors impacting clothes washer remanufacturing and energy savings including transformational (architectural) technological improvements in products and impacts of efficiency standards.

4.4.3 Life Cycle Costing Results

The total lifecycle economic cost of clothes washers normalized by cubic meters of volume has dropped by close to 40% as illustrated in Figure 21 below. Note that the shorter time span in retrospective evaluation (compared to energy assessments) is due to scarcity of data for market prices of clothes washers prior to 1981.

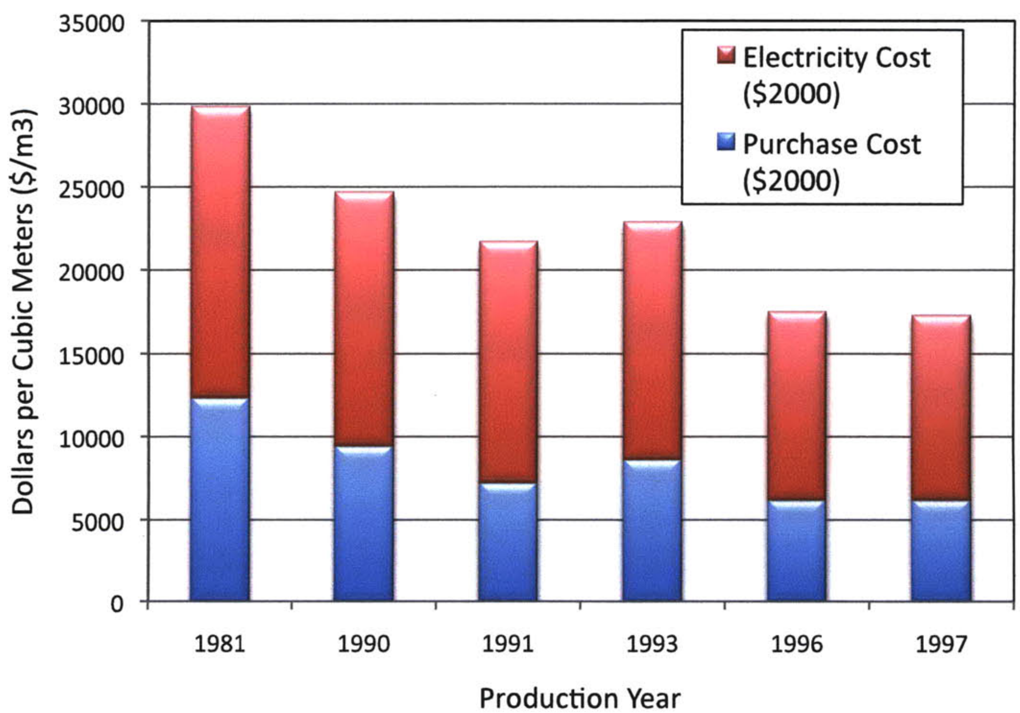


Figure 21 Clothes washer: retrospective life cycle costing 1981-1997. Costs normalized to 2000 dollars using the Bureau of Labor Statistics' consumer price index for all year.

Note that the actual economic cost can be determined by multiplying the above values by the volume of the clothes washer, which will translate the above data to more than \$2000 in 1981 and about \$1300 in 1997.

The total life cycle financial costs of a newly built 1993 model and a remanufactured/re-used 1981 model (assuming no upfront cost) will amount to total lifecycle economic costs of $22,870 per Cubic Meters and $17,517 per Cubic Meters, respectively. This leads to 23% savings in total lifecycle economic costs of remanufacturing a clothes washer in 2008. Our sensitivity analysis shows that if the cost of purchasing a remanufactured clothes washer is 50% of new (Hauser and Lund 2003), then the upfront economic saving breaks-even with additional electricity costs; in this case, the user becomes financially in-different between purchasing new and remanufacturing old. Next section will provide information two macroscopic changes that impacted clothes washers, namely, transformational (architectural) technological improvements and efficiency standards.

4.5 Clothes Washer Technological Changes and Improvements in Energy Efficiency

In the past two decades the main driver for substantial efficiency improvements of new clothes washers has been the technological transformation (architectural changes) from top-load-vertical-axis washers to front-load-horizontal-axis washers (Bole 2006). Figure 22 below illustrates graphical representations of vertical-axis washer as well as horizontal-axis washer.

Vertical-Axis Clothes Washer

Horizontal-Axis Clothes Washer

Figure 22 Graphical representations of vertical-axis (old technology) and horizontal-axis (advanced technology) clothes washers (Image Source: Whirlpool).

Vertical-axis washers suspend clothes loaded from top in a tub immersed in water and generate a mechanical centrifuge agitating the clothes inside. On average, vertical-axis clothes washers consume 40 gallons of water per a load cycle (WashingtonStateUniversity 2003).

Technological advancements in clothes washers led to the creation of horizontal-axis washers, which became commercially available in 1997 (Bole 2006). The horizontal-axis washers (shown above) are predominately more efficient than vertical-axis counterparts, widening the efficiency gap between the most efficient washer and conventional washers in the market (Bole 2006). By 2004, the most efficient horizontal-axis washer was more than 76% more efficient than the average washer (EPA 2005), (AHAM 2005). The main efficiency improvements are influenced by advances in water resource management (Bole 2006).

Horizontal-axis washers (front-load) wash clothes by repeatedly tumbling (instead of agitation) while consuming considerably less water as an input source. The technological advancement in clothes washers in combination with standard enforcements make clothes washers highly advanced from resources and energy savings perspective. For more information about transformational technological changes in clothes washer refer to (MITEI-1-a-2010).

4.6 Policy implications

The main driving force behind the transformational technological improvements in clothes washers is the implementation of policy standards, first in 1994 and then in 2004. For detailed assessments of standards and Energy Star requirements for clothes washers please refer to (MITEI-1-a-2010).

According to (AHAM 2008), the total shipment-weighted average modified energy factors in 2008 is 1.67, which is 32% greater than current federal minimum efficiency standards, but is 7.2% less than current Energy Star criteria. If the trend for Energy Star labeled clothes washers was to continue growing, then it is evident that remanufacturing less efficient non-Energy Star clothes washers will continue to be an energy expending end-of-life options.

4.7 Conclusions

Our retrospective energy analysis of clothes washer signifies that use phase substantially dominates its lifecycle energy demands. We conclude that due to transformational technological improvements coupled with implementation of efficiency standards, new models of clothes washers have become highly more efficient. As a result, by remanufacturing an old 1997 model, it will lead to 181% more energy requirements than if the unit was replaced with a new 2008 model clothes washer (see Figure 20). Moreover, our economic assessments indicate that if the cost of remanufacturing a clothes washer is negligible, then clothes washer remanufacturing may provide an economic incentive for consumers.

5. Dish Washer

5.1 Introduction

The first ever dishwasher machine was patented as a hand-operated device in 1850 (Koeller&Company 2007). In 1947, the dishwashers were produced for the household residential sector and were progressively demanded by household owners (Koeller&Company 2007). The market usage of dishwashers has been growing from 42% in 1985 to about 58% in 2003 (Koeller&Company 2007). In the same time period, there have been technological improvements, which have greatly improved energy efficiency, water management, and cleaning impact of household dishwashers in the North American marketplace (Koeller&Company 2007).

The U.S. market for dishwashers is dominated by 17 manufacturers, which produce a total of 565 different dishwasher models (Koeller&Company 2007). 486 of the models, or 86% of the total market-share, are compliant to Energy Star standards and protocols (Koeller&Company 2007). This is an indication that Energy Star and other governmental agencies have significantly impacted the improvements in energy efficiency of dishwashers. This section explores the energy savings potential of remanufacturing dishwashers in light of the dynamic changes in use-phase energy trends for dishwashers.

5.2 Life Cycle Inventory: Energy Demands Analysis

Raw Material Acquisition and Processing Phase

Kemna, Elburg *et al.* provide the bill of material for a conventional dishwasher that weighs 58 Kg produced in 1995 (Kemna, Elburg et al. 2005). The energy intensity for each substance is taken from (Smil 2008), (Ashby 2009) to determine the raw material processing energy costs. For detailed information about the materials composition of the dishwasher studied in this analysis refer to (MITEI-1-a-2010).

In order to compute the energy expenditure for raw materials processing we used a range of energy intensity values from (Smil 2008), (Ashby 2009). Based on this, we estimate that the raw material energy consumption is between 2,856 MJ and 3,971 MJ per dishwasher unit. We take the upper bound, namely, 3,971 MJ per dishwasher unit for this analysis. This value is in agreement with energy estimation for raw materials processing of domestic dishwasher in (Kemna, Elburg et al. 2005).

Manufacturing and Assembly Phase

Manufacturing energy consumption is taken from (Kemna, Elburg et al. 2005), which conveys that it takes 14.4 MJ/Kg to manufacture a dishwasher. This translates to 847 MJ for the aforementioned dishwasher. Therefore, it costs between 3,703 MJ and 4,818 MJ to process raw materials and manufacture a conventional dishwasher. Though changes in appliance manufacturing practices and production efficiency would change the production value, for this study the upper energy value, namely 4,818 MJ, will be used for all models.

Remanufacturing Phase

Similar to the refrigerator and clothes washer analyses, we assume that the energy cost for generating and incorporating the remanufacturing parts to be negligible. This assumption is biased in favor of remanufacturing.

Use phase

The efficiency metric of dishwasher is denoted by the energy factor (EF), which is expressed in terms of cycles per kWh.

$$EF = \frac{1}{M + W} \qquad \text{Equation 3}$$

where EF, M, and W are energy factor, machine electrical energy per cycle (kWh/Cycle), and water heating consumption per cycle (kWh/Cycle), respectively; the higher the EF the more efficient the dishwasher. As shown in Equation 3 efficiency of dishwasher is only a function of unit energy consumption and not capacity; therefore, for this analysis, we assume that the capacity of the dishwasher has remained unchanged. As such, all the energy analyses are performed per unit dishwasher.

The use phase is determined by multiplying the average energy consumption of a dishwasher per cycle by the average numbers of washing cycles per year (215) and 10 years of service (ApplianceMagazine 2008; EERE3 2009). Figure 23 below illustrates changes in energy consumption and efficiency trends for dishwashers between 1981 and 2008 (AHAM 2008).

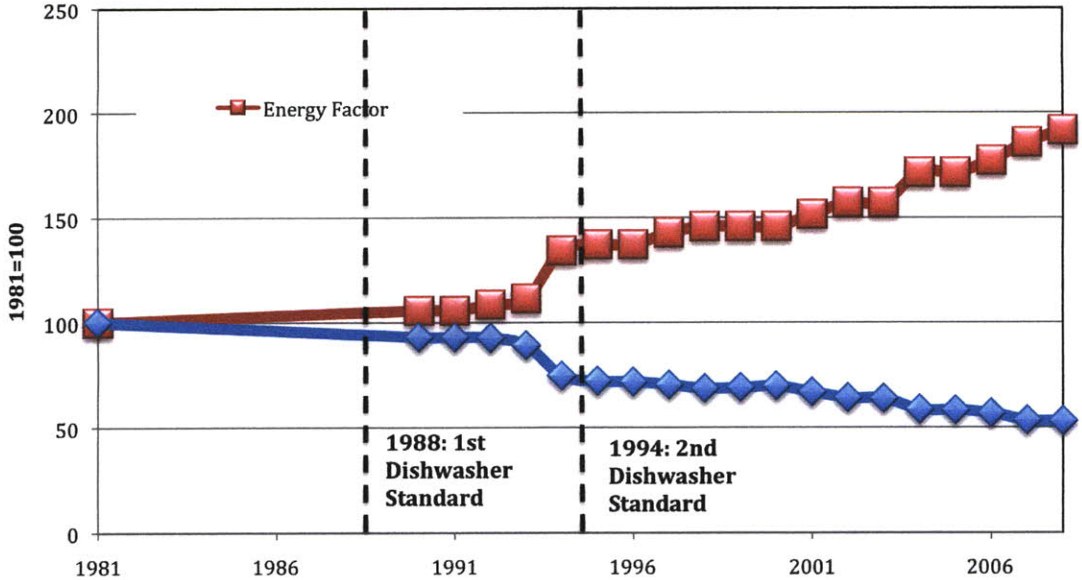


Figure 23 Energy consumption and energy factor per cycle of new dishwasher sold in the U.S. 1981-2008 (shipment-weighted average) (AHAM 2008).

5.3 Remanufacturing Analysis

The remanufacturing comparison scenario is based on choosing to purchase a new dishwasher versus remanufacturing a unit that has reached its end-of-life after 10 years of service use. Table 10 below shows the comparison year and clothes washer models for remanufacturing energy analysis.

Table 10 Comparison year and model between purchasing new dishwasher and remanufacturing and re-using an older model.

Comparison Year	New Model (Year Made)	Remanufactured Model (Year Made)
1991	1991	1981
2001	2001	1991
2008	2008	1998

5.4 Results

5.4.1 Life Cycle Inventory: Energy Demands Results

Figure 24 below illustrates the total life cycle energy assessment of a newly produced dishwasher in years 1981,1991, 2001, and 2008.

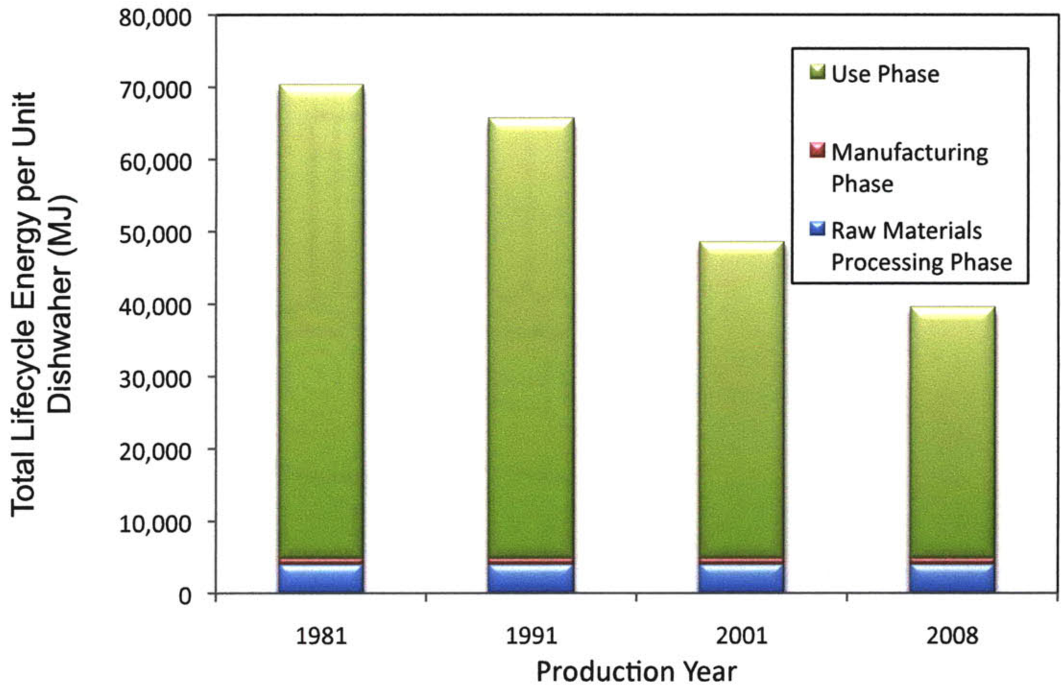


Figure 24 Dishwasher: retrospective life cycle energy analysis of new model.

5.4.2 Remanufacturing and Energy Savings Results

Table 11 Dishwasher: Retrospective life cycle energy comparison of new and remanufactured.

Year	Lifetime Energy Consumption New (MJ)	Lifetime Energy Consumption Remanufacture (MJ)	Lifecycle Energy Savings due to Remanufacture
1991	65,668	65,407	0%
2001	48,575	60,849	-25%
2008	39,459	44,896	-14%

According to Table 11 above, total lifecycle energy savings due to remanufacturing is negligible in 1991. Moreover, in 2001 and 2008, remanufacturing becomes more energy consuming from a lifecycle perspective. In other words, by remanufacturing an old dishwasher in 2001 and 2008 (10 years old), the consumer would expend on average 25% and 14% more energy, respectively. As mentioned earlier, this is due to the stringent performance standards for dishwashers introduced in 1994, which led to more energy efficient dishwashers produced in 2001.

To further assess energy savings potential of dishwasher remanufacturing, it is important to analyze the comparison between energy savings in production versus energy expenditure in the use phase due to remanufacturing. Our analysis indicates that the savings associated with dishwasher remanufacturing causes savings in the production phase, which are 0.07 to 0.14 (7% to 14%) of the use phase of a new model (assuming E_{Reman}=0). Moreover, for years 1991, 2001, and 2008, remanufacturing an older unit would lead to 7%, 39%, and 29% increase in the use-phase energy consumption. As a result, the over-expenditure in the use phase of a remanufactured unit supersedes savings in the production phase. The following section provides a qualitative discussion about the two main drivers in efficiency improvements of new dishwashers in the past two decades, namely, technological (efficiency) improvements and policy enforcements for minimum efficiency performance standards.

5.5 Technological Changes and Improvements in Energy Efficiency

Since the origination of Energy Star in 1997, dishwasher technology has improved substantially. Examples of technology improvements are improved water filtration, and more efficient jets (EnergyStar). For more information about technological improvements in dishwashers refer to (MITEI-1-a-2010).

5.6 Policy Implications

According to Figure 23 the 2nd Federal Standard implemented in 1994, caused considerable changes in energy efficiency and consumption of dishwashers. The first

Federal residential dishwasher standard was introduced in 1988 a year after Congress passed a legislation to establish the National Appliance Energy Conservation Act (NAECA). The first standard required manufacturers of dishwashers to provide the freedom to the user to choose the option to dry without heat. Following this standard, in 1994 (refer to Figure 23), the first federal testing procedure and minimum efficiency performance based on efficiency factor was established. In 1997, Energy Star expanded its product scope to include dishwashers to maintain stringent efficiency improvement standards to be followed voluntarily (Koeller&Company 2007). For detailed description of minimum efficiency standards for dishwashers refer to (MITEI-1-a-2010).

5.7 Conclusions

Based on energy assessments, we conclude that dishwasher remanufacturing is currently a net-energy expending end-of-life option. Our retrospective assessments suggest that technological (efficiency) improvements as well as efficiency standards have been the main drivers for making remanufacturing older (less-efficient) dishwashers less favored from an energy standpoint. For example, our findings indicate that prior to standards dishwasher remanufacturing would be nuanced (refer to year 1991 in Table 11)

According to AHAM, in 2008 the shipment-weighted average energy consumption of dishwashers per cycle and EF were 1.52 kWh/cycle and 0.67, respectively (AHAM 2008). Assuming 215 washing cycles annually (EERE3 2009), the annual dishwasher energy consumption translates to 327 kWh with EF 0.67. This industry average complies with current Energy Star criteria levels for standard dishwashers, which is a reflection of the direct impact of DOE's regulatory and voluntary initiatives for efficiency improvements in dishwasher manufacturing.

If the industry were to aggressively pursue Energy Star compliance, the annual energy consumption must be reduced by 6% to 32% (depending on the equipment type) by 2011. A dishwasher produced in 2001 (about to retire in 2011 after 10 years of service) would be consuming 413 kWh annually; this is 34% greater than annual consumption of Energy Star labeled standard dishwashers produced in 2011. Therefore, if the dishwashers were to comply by Energy Star requirements by 2011, then dishwasher remanufacturing would remain to be an energy expending option from a total life cycle perspective.

6. Sensitivity Analysis

The life cycle assessments conducted in the appliance case study focuses on three lifecycle phases, namely, raw materials processing, manufacturing, and use. Such scope of analysis ignores the environmental impacts in the transportation phases as well as end-of-life phase for appliances. Since the objective is to evaluate energy demands of appliances for all lifecycle phases from cradle-to-grave we evaluate the environmental impacts of the neglected phases in the form of sensitivity analysis. More specifically, for this sensitivity analysis we focus on clothes washers. Furthermore, we determine the transportation and end-of-life energy demands and compare it to the lifecycle stages considered for the original analysis.

Transport

For transportation distances and modes of transportation for clothes washer we rely on data provided by (Bole 2006), which provides a hypothetical transportation path of a Whirlpool vertical-axis washer. The transportation distance between steel processing plant in Gary, Ohio to Whirlpool's Clyde Ohio assembly plant is given as 247 miles. For determining the distribution transport (Bole 2006) assumes a population-weighted average distance to the top 20 metropolitan cities in the United States. According to this, the washer travels an average distance of 1,102 mile from Whirlpool assembly in Clyde Ohio to local distributors in the U.S. We estimate from (Bole 2006) the average distances from a local distributor to the home of consumer and from home to scrap yards or landfills to be each 50 miles. The transportation modes for these phases take place domestically and are by heavy tractor-trailer diesel trucks. Table 12 below provides a summary of transportation modes and distances for the sensitivity analysis for clothes washers.

Table 12 Transportation distances and modes for vertical-axis Whirlpool clothes Washer in the U.S.

Transportation Phase	From	To	Transportation Mileage	Transportation Mode
Raw Materials Processing to Manufacturing	Steel Production [Gary, Indiana]	Whirlpool Assembly Plant [Clyde, Ohio]	274	Diesel Truck
Distribution Stage 1	Whirlpool Assembly Plant [Clyde, Ohio]	Local Distributors	1,102	Diesel Truck
Distribution Stage 2	Local Distributors/Retailers	Customers	50	Diesel Truck
End-of-Life	Customers	Recycling Facility/Land fill	50	Diesel Truck

From (Keoleian, Kar et al. 1997) the typical transportation energy of a diesel-operated tractor-trailer is about 2.05 MJ per ton-mileage of transport. Therefore, for a clothes washer unit that weighs about 59 Kg the energy estimates for the supply chain transport is as follows,

Table 13 Transportation energy expenditures in supply chain for clothes washer.

Transportation Type	Energy Consumption (MJ/Unit)
Raw Materials Processing to Manufacturing	33
Distribution Stage 1	133
Distribution Stage 2	6

End-of-Life

We take the end-of-life options of a clothes washer to be re-use, re-sell, recycle, and landfill. According to Association of Home Appliance Manufacturers, an estimated 41 million appliances in 2000 reached their end of useful life and over 34 million (83%) were sent for recycling or disposal (AHAM). Nationwide, 84% of major appliances were recycled in 2000 (AHAM). Landfilling is the least common end-of-life option for appliances. According to AHAM, the appliances that entered the municipal solid waste stream in 2000 comprised about 1% of total municipal solid waste (AHAM). For a variety of reasons consumers may terminate the use of an appliance before it reaches end of useful life. Consumers can leave the appliance by the curb and ask for municipal solid waste collection services to pick it up. If consumers are purchasing a new appliance, the retailer can also manage the end of life of the used appliance. According to Environmental Protection Agency, 60% of the appliances taken away by the retailers are sent to recycling facilities. The remaining 40% that are in good conditions are re-sold in a secondary markets.

<u>Appliance Recycling</u>

Currently there are over 11,000 recycling facilities in the U.S. that appliances are delivered to (AHAM). The appliance recycling process includes the following stages:

1. Collection
2. Dismantling and Separation Processing
3. Shredding

1. Collection: Collection services provided by municipal solid waste operators typically transport the scrapped appliances to a local reclaim and recycling facility. The transportation distance for landfilling and recycling is assumed to be around 50 miles. For appliance re-use we assume that the appliance is repaired and used in the same household. As such, we assume that there is negligible transport for re-use. For appliance re-sale we assume that the transport distance from consumer home to local retailer and

from retailer to another consumer is in total 100 miles (50 miles for each step) (see Table 12 for more information).

2. Dismantling and Separation Processing: Once arrived in recycling facility, the appliances are dismantled. The separation process involves removing components such as motors and compressors, compressor oil, copper tubing and wiring, and refrigerant chemicals, for separate recycling.

3. Shredding: At a metal shredding facility, appliances are fed to a hammermill (also referred to as shredder), which turns it into small-sized pieces of scrap. The pieces are transported on conveyor belts and passed through magnets in order to separate the iron and steel from other metals and other materials.

According to (Keoleian, Kar et al. 1997) the energy intensity of separation and metal shredding processes is on average about 26 KJ/Kg and 74 KJ/Kg, respectively. For a clothes washer unit that weighs about 59 Kg, which includes 47 Kg of scrap metal, the recycling energy consumption is estimated to be around 5 MJ per unit. Table 14 below provides the energy demands for each recycling step.

Table 14 Energy demands for clothes washer recycling.

Recycling	Energy Use (MJ/Kg)	Clothes Washer (MJ/Unit)
Dismantling Process	-	-
Separation Process	0.026	1.53
Shredding Process	0.074	3.51
Total Recycling Energy	NA	5.04

We assume that the energy requirements for end-of-life processes for re-use, landfill, re-sale are negligible. Furthermore, we assume that the scrap clothes washer is transported by diesel-operated tractor-trailers. Given the available data, we estimate that the transport energy demands for landfilling, recycling, re-use, and re-sale of a clothes washer to be around 6.03 MJ/unit, 6.03 MJ/Unit, 0, and 12.06 MJ/unit, respectively. The total energy consumption for each of life option for a clothes washer is summarized below.

Table 15 Energy requirements for clothes washer end of life options.

End of Life Stages	Recycling (MJ/Unit)	Re-Use (MJ/Unit)	Re-Sale (MJ/Unit)	Landfill (MJ/Unit)
End-of-Life Transport	6.03	0	12.06	6.03
Processing	5.04	0	0	0
Total	**11. 07**	**0**	**12.06**	**6.03**

The total transportation energy cost for a clothes washer from cradle-to-grave (assuming land-fill as EOL option) is around 178 MJ per a clothes washer unit. Based on the sensitivity analysis, the transport and end-of-life energy expenditures are insignificant compared to the raw material processing, the manufacturing, and the use phases for a clothes washer as shown in Figure 25 below.

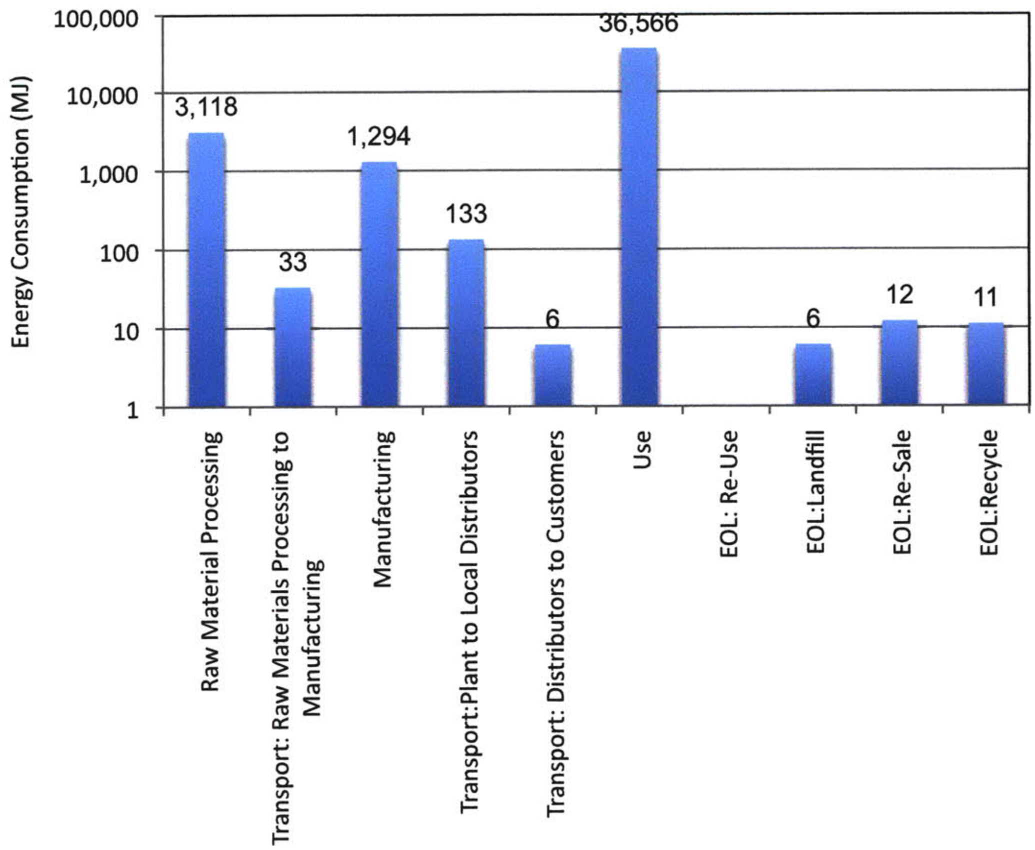


Figure 25 Total lifecycle energy assessment of clothes washer including the transport and the end-of-life phases. Results are plotted in log-scale. The use phase energy expenditure is for a 2008 clothes washer that consumes about 0.8 kWh of electricity per washing cycle.

According to Figure 25 the total transport energy requirements consist of less than 0.5% of the lifecycle energy requirements for a clothes washer from cradle-to-grave. Furthermore, the end of life processes for a clothes washer consume negligible amount of energy compared to other lifecycle phases. The sensitivity analysis concludes that there are minimal energy impacts from the transport and the end-of-life phases during the lifecycle of clothes washers; this justifies our decision to neglect these impacts from the main analysis of this case study.

7. Conclusions

This appliance case study sheds light on the importance of considering the use phase while assessing the energy savings potential of remanufacturing. Our analysis concludes that remanufacturing/re-using/repairing/refurbishing appliances have the potential for considerable savings in the raw materials processing and the manufacturing phases. However, from a total life cycle perspective, remanufacturing may be a net energy-savings or a net energy expending end-of-life option, depending on the use phase. In this case study, we have illustrated the impacts of macroscopic effects such as state-level and federal policies on remanufacturing. Moreover, we have shown the role of policy impacts as critical driving forces in promoting technological changes and energy efficiency improvements for new appliances. Since the establishment of the National Appliance Energy Conservation Act in 1987, there have been critical updates to the minimum energy requirements promoting further improvements in energy efficiency of appliances.

In Figure 26 we illustrate the cumulative energy savings in lifetime the use phase by replacing a dishwasher, clothes washer, and refrigerator produced in 1981 with newer models.

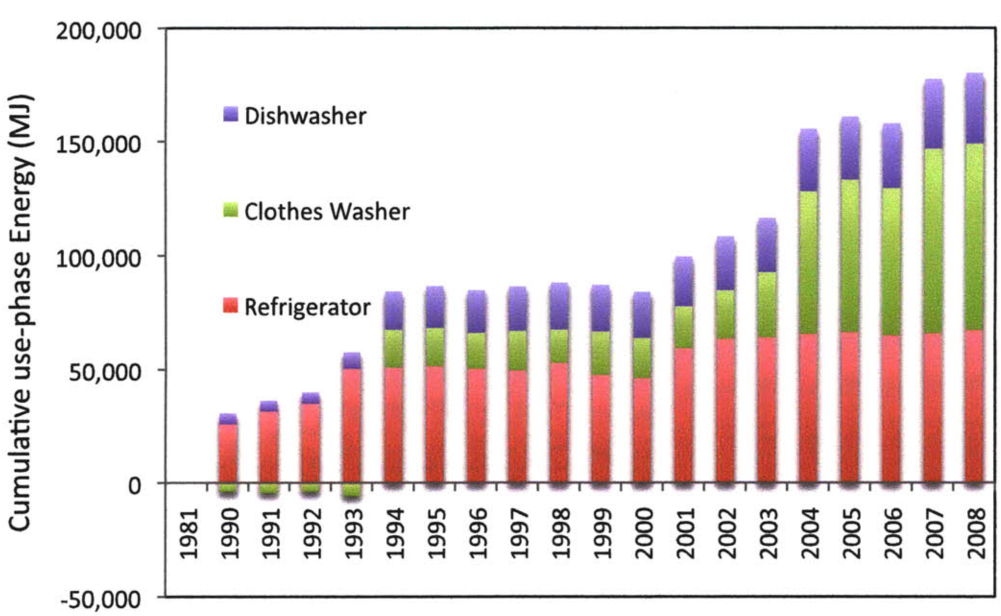


Figure 26 Cumulative use phase energy savings by replacing 1981 appliance models (refrigerator, clothes washer, dishwasher) with a newer model.

According to Figure 26, by replacing a dishwasher, clothes washer, and refrigerator (all produced in1981) with new 2008 models, then it will amount to greater than 150 GJ in cumulative energy savings in the use phase. If the trend observed in Figure 26 continues in the future, then remanufacturing appliances will be a net energy expending end-of-life option. On the other hand, if the energy saving trends remains steady or declines, then remanufacturing would be highly feasible since it would save both materials and energy in the production phase. Also, we conclude that the economic feasibility of remanufacturing and re-using an old appliance is based on the costs to remanufacture and the relative electricity spending compared to a new unit. Our economic analysis implies that if the remanufacturing costs are minimal, then it leads to lifecycle economic savings by remanufacturing an old unit. The sensitivity analysis depicts that if the economic costs of remanufacturing are about 50% of new, then the economic feasibility is less clear.

3.4 Tire Remanufacturing and Energy Savings Case Study

1. Introduction and Motivation

The transportation sector is one of the major energy consuming sectors in the U.S. and worldwide. In the U.S. alone nearly 28% of the national energy expenditure takes place within the transportation sector. Amongst all transportation modes, the use of on-road vehicles has grown enormously in the past few decades. Figure 27 below illustrates energy consumption of on-road transportation sector by mode.

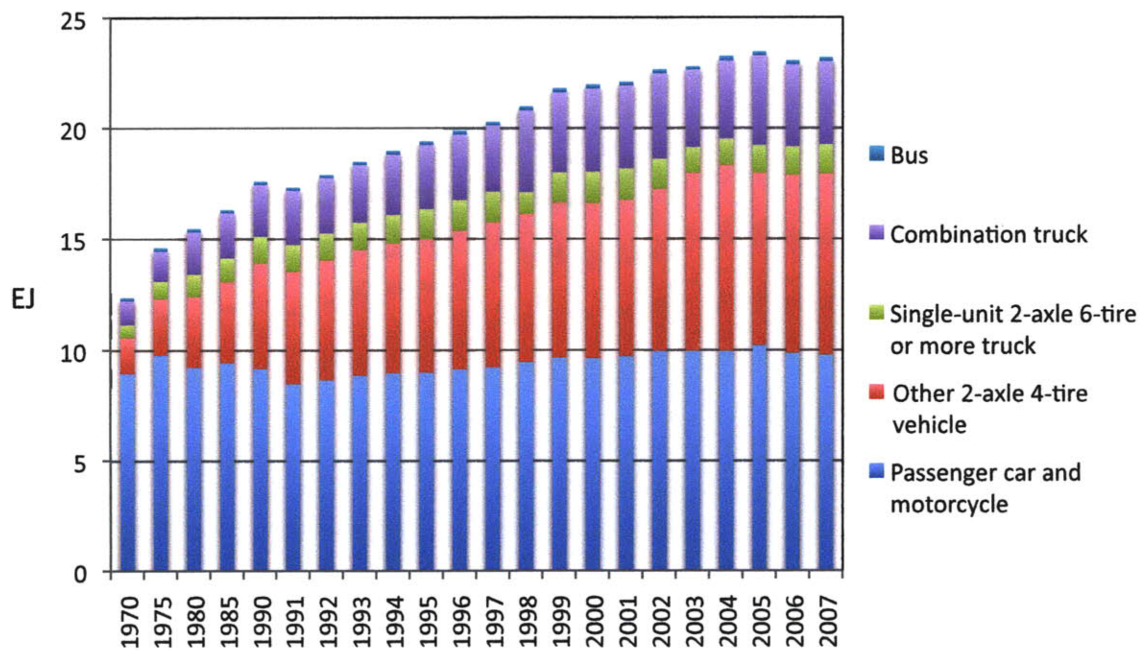


Figure 27 U.S. energy consumption by on road transportation mode (1970-2007) (BTS 2008).

The rise in energy consumption and fossil fuel demand of on-road transportation modes is coupled with a substantial rise in demand for raw materials and generation of waste. Rising concerns about global changes, volatility in fuel prices, and continued growth in transportation demands have caused policy advocates and industry officials to take critical steps towards saving energy, minimizing emissions, and reducing depletion and production of waste. Ever since the introduction of Corporate Average Fuel Economy (CAFE) in the U.S., passenger car vehicles have become more fuel-efficient. Since a considerable amount of energy during a life cycle of a vehicle is expended in operation, it is important to evaluate the energy savings improvements for each of the components in the vehicle that contribute to losses.

The tread of a tire encompasses only 10 to 20 per cent of the construction weight of the tire; scrap tires retain high material and energy values that can eventually be recaptured (Ferrer 1997). This has led to diversified applications of scrap tires beyond the conventional disposal path of being sent to land fills. For example, the sectors that utilize scrap tires extensively are using it for tire-derived fuel applications (cement industry, pulp and paper industry, industrial boilers), electricity co-generation (electric utilities), and civil engineering purposes. Another promising market for scrap tires is tire remanufacturing (commonly referred to as tire retreading). Tire retreading is the process of remanufacturing a used tire to like-new by applying a new tread to the tire. A retread is a previously-worn tire that has gone through a remanufacturing process designed to extend its service life. The tire retreading industry is reportedly the largest sector of remanufacturing industry in the United States with 597 remanufacturing (retreading) plants (refer to Figure 2) (Hauser and Lund 2008). Retreads are considerably cheaper than new tires. As such, retreads are widely used in large-scale operations such as bussing, trucking, and commercial aviation. With the cost of retreaded tires being 45% to 65% less than the cost of a new tire, it makes them appealing to truck fleet operators that travel extensively and demand higher rates of tire replacement. More specifically, the demand for retreaded tires from fleet operators is the largest in the tire retreading industry for a variety of reasons:

1. Tire maintenance and replacement is the third highest cost for fleet operators after labor and fuel.
2. With the advancement in tire retreading for heavy-duty tires, some OEMs offer warranties for retreaded tires that are originally applied to the purchase of new tires.
3. One of the key success factors for effective retreading is retrieving cores that have been properly maintained during the use phase. Given that fleet operators consistently monitor the inflation pressure, and other operations characteristics of their tires, in general the used truck tires are in ideal conditions upon reaching end-of-life.

4. The turn-over rate for tire replacement is much higher for heavy truck fleets. As such, tire retreading is desirable from an economic and material savings standpoint.

According to (Weissman, Sackman et al.) retread tires encompass 44% of the total tire replacement market for heavy-duty truck tires. The success of tire retreading in truck tires, has not been observed in the light duty vehicle sector.

Tire retreading leads to energy and materials savings in the production process due to minimization of raw materials requirements and manufacturing energy consumptions. However, the ultimate energy savings strategy depends on whether it could save energy in all life cycle stages of the product including the use phase. In this case study we analyze the life cycle energy savings potential of tire retreading.

2. Case Study Objectives

Retreading has the potential to save a substantial fraction of the energy required for processing the raw materials and manufacturing of tires. This is because more than 80% of embedded energy is retained in the casing of the tire, which is saved after the tires reach end of life. In other words, a tire is scrapped due to tread wear; the tread only takes 10 to 20% of the entire material and energy retained in a tire. Tire remanufacturing benefits the environment since is recovers the high energy and material values in scrap tires. Moreover, tire remanufacturing reduces the energy demands and materials requirements in production of tires. According to (Ferrer 1997), (TRIB) tire retreading can reduce the production energy demands by as high as 66%.

A fraction of vehicle fuel input is consumed to overcome the rolling resistance of tires. As the vehicle sets in motion, tires undergo cycling visco-elastic deformations leading to dissipative energy losses in the form of heat. According to Kromer *et al.* the largest share in the cumulative energy input of a tire (more than 95%) is made in the use phase, due to the vehicle fuel requirements for overcoming rolling resistance of tires (Kromer, Kreipe et al. 1999).

The rolling resistance energy losses of tires depend on various product factors such as tire design, architecture, construction, and materials used. Since tire remanufacturing involves re-use of an old casing, the type of casing utilized for remanufacturing and the quality of remanufacturing process influence the energy performance of retreads in the use phase. Furthermore, if new tires become more energy efficient compared to older remanufactured tires, then this may cause retreads to consume more energy in the use phase that could potentially negate energy savings in the production phase. Therefore, we evaluate the energy savings potential of tire remanufacturing by studying it from a lifecycle perspective.

3. Scope of Study

We consider three life cycle phases for evaluating the environmental impacts of tires, namely, the raw material processing, the manufacturing, and the use phases. Analyzing these phases will determine the relative energy savings in production process as well as relative changes in energy demands between using new tires and re-using old retreaded tires.

In order to holistically evaluate retreading energy savings, we perform our analysis in four distinctly different contexts:

1. Tire retreading and energy savings in the context of transformational (architectural) technological changes in tires
2. Tire retreading and energy savings in the context of transitional technological changes in tires
3. Tire retreading and energy savings in the context of degradation in rolling resistance of retreaded tires compared to equivalent new tires
4. Tire retreading and energy savings in the context of variations in performance of different models of tires

Tire Retreading and Energy Savings in the Context of Transformational Technological Changes in Tires

In the past few decades, technologists, OEMs, and research centers have improved the performance of tires in the use phase. Technological milestones have been achieved through innovative changes to tire architecture, construction, and design. These changes have effectively improved the performance of tires in the use phase (e.g. increased durability, traction, efficiency). For example, one of the major transformational technological changes in tires is progressing from bias-ply to radial-ply tire construction. (refer to Appendix B1 for more detailed information).

Moreover, ever since introduction of radial tires (commonly referred to as dual radials), tire rolling resistance has been reduced considerably. For example, consumers today can procure fuel-efficiency enhancing low rolling resistance (LRR) radial tires. These tires are designed for minimizing rolling resistance heat losses, and saving automotive fuel. These improvements have been led by transformational (architectural) changes in the tread composite and tire design.

Promotion of single wide-base truck tires is another transformational (architectural) technological progress in tires. Most tractor-trailer trucks currently utilize a dual assembly on the drive and the trailer axles, with two sets of wheel on each end of the axle. Truckers and fleet operators are advised to replace dual radial tires with a single wide-base tire to reduce the weight of the vehicle and save on fuel consumption. A single wide-base tire is simply a wider tire providing improved floatation versus conventional size truck tires. A single wide-base tire weighs less than two radial tires resulting in reduced weight of the truck. By using single wide-base tires on drive and trailer axles, it can increase load capacity and/or reduce fuel consumption. Single wide-base tires can offer lower rolling resistance, lower aerodynamic drag, and avoid the frictional losses existing between radial tires.

Tire transformational (architectural) technological improvements from bias to radial, from radial to advanced low rolling resistance radial, and from advanced radial to single-wide, can lead to making the use performance of the prior generation of tires inferior. Since tire remanufacturing utilizes old tires, it may expend more energy than new products in the market. For this matter, in this report, we study the energy savings potential of retreading truck tires in the context of past, current, and future transformational technological changes in tire industry.

Tire Retreading and Energy Savings in The Context of Transitional Technological Changes

The transformational technological improvements in tires have been accompanied by shorter time-scale (annual) improvements in technology employed in tires. For example, Original Equipment Manufacturer (OEM) tires have become continuously more efficient in the past three decades. One of the primary driving forces behind this is the implementation of Corporate Average Fuel Economy (CAFE) standards for automakers in 1975.

Figure 28 below illustrates the reduction in rolling resistance coefficient of Original Equipment Manufacturer (OEM) passenger car tires (bias-ply as well as radial-ply) between 1975 and 2004 (LaClair 2005), (Calwell 2003).

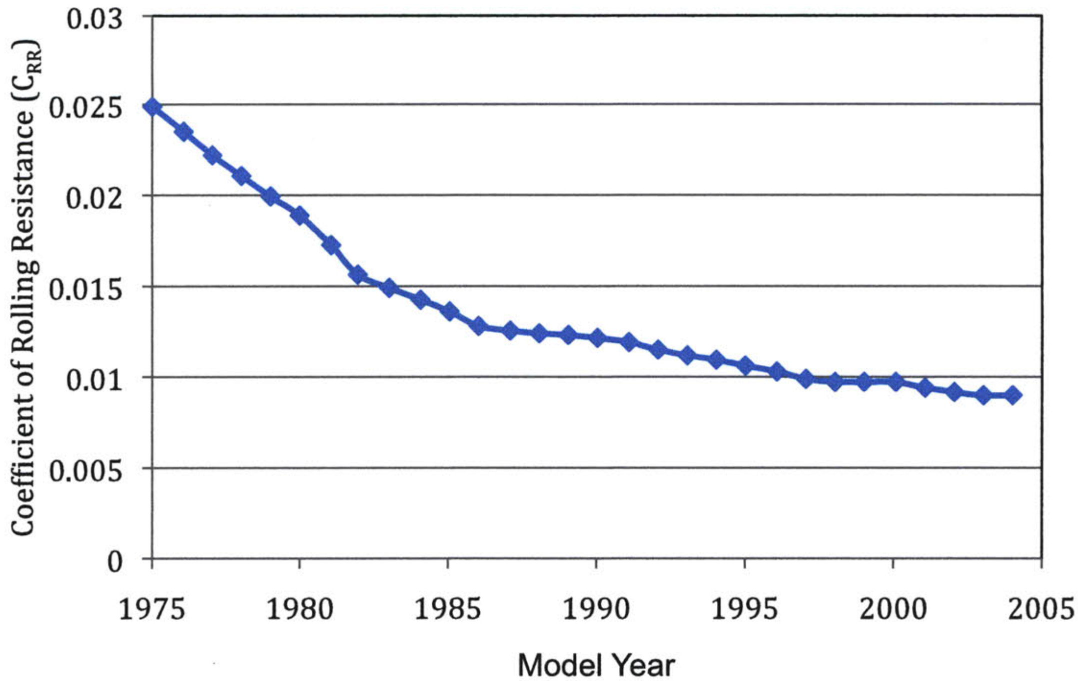


Figure 28 Estimated original equipment manufacturer (OEM) tire rolling resistance, 1975-2004 (LaClair 2005), (Calwell 2003).

Corporate Average Fuel Economy (CAFE) standard:

According to Figure 28 the reduction of coefficient of rolling resistance can be broken into two distinct eras: (1) 1975-1986, and (2) 1986-2004. According to Figure 28, average coefficient of rolling resistance was halved between 1975 and 1986. Moreover, between 1986 and 2004, the reduction in coefficient of rolling resistance was less aggressive.

This phenomenon can be explained by the policy standards enforcing minimum efficiency performance for vehicles under the Corporate Average Fuel Economy (CAFE) standards. First enacted by the U.S. congress in 1975, the purpose of CAFE standards is to reduce the energy consumption of passenger car vehicles and light trucks. The standards were implemented in year 1978 under the responsibility of National Highway Traffic Safety Administration (NHTSA). As a result, automakers began providing explicit rolling resistance design parameters to their tire suppliers. More specifically, automakers demanded improved technology for OEM tires as a key strategy for achieving CAFE across vehicles they sell. This led to substantial improvements in tire technology between 1975 and 1986 and increased demand for radial tires over bias tires. However the pace in reduction of coefficient of rolling resistance for OEM tires was more moderate thereafter. This correlates directly with the change in CAFE standards, as shown in Figure 29 below.

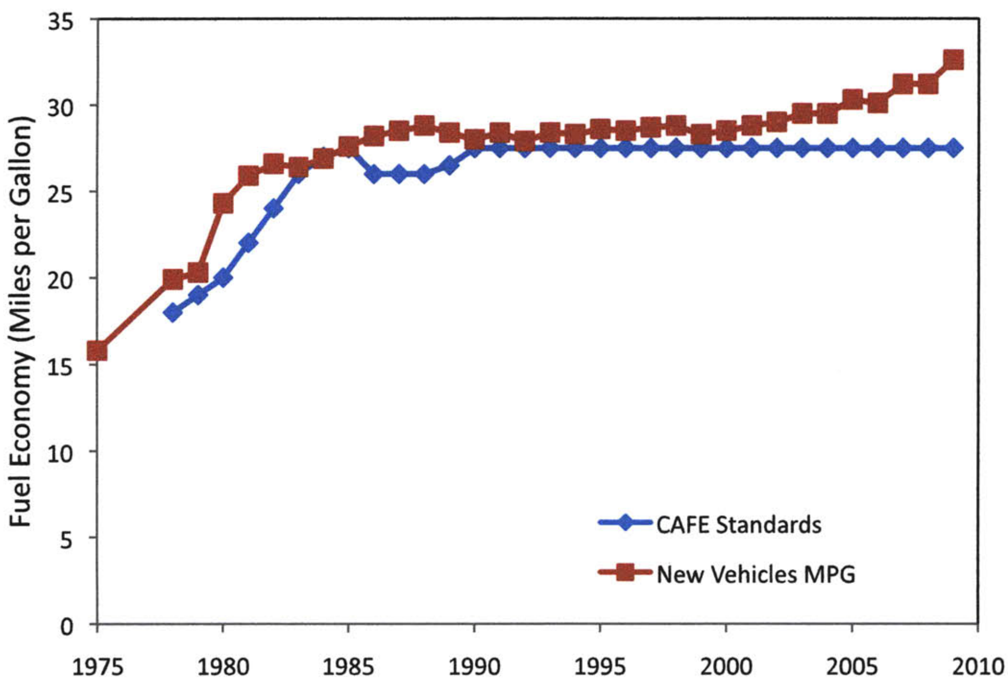


Figure 29 CAFE standards 1975-2009 (Davis and Diegel 2009).

According to Figure 29 above, after 1985, CAFE standards for passenger vehicles have remained steady at around 27.5 miles per gallon. Similarly, as shown in Figure 28, after 1985 the pace of reduction in coefficient of rolling resistance for OEM tires became more moderate.

Under President Obama's administration, the CAFE standards will increase by five percent each year, reaching 35.5 mpg by 2016. In other words, in 7 years the national average CAFE has to increase by 8 mpg per vehicle. Therefore, drastic changes in fuel standards can potentially cause OEM tires to become more efficient at a faster rate, perhaps similar to improvements observed during 1975-1985 era (see Figure 28).

In this case study, we analyze the performance of retreaded tires for passenger cars in the context of transitional technology changes. Assuming a passenger car tire lasts for 3 years (Calwell 2003), would retreading and re-using the set of old tires result in lifecycle savings when compared to newly produced tires? How would the conclusions of the analysis change if we perform the assessments retrospectively?

Tire Retreading and Energy Savings in the Context of Degradation in Efficiency

The primary analysis for this study is conducted by assuming that old tires are retreaded to like-new conditions. This means that after retreading old tires, they would perform with similar rolling resistance characteristics and mileage lifetime as when it was first produced. Though retreading technology has been advanced to bring tires to like-new conditions, some retreading processes may not achieve this objective. Kromer *et al.* performs analysis for remanufacturing passenger car tires based on two scenarios: (1) increase of 3% in rolling resistance of retreaded tires (claims to be best in class), (2) increase of 10% in rolling resistance of retreaded tires (claims that this is the average change in rolling resistance) (Kromer, Kreipe et al. 1999). We perform sensitivity analysis to reveal the impacts of increase in rolling resistance of retreaded tires on lifecycle energy savings.

According to Tire Retread and Repair Information Bureau (TRIB) retreaded tires may last 75% to 100% of the lifetime of a new tire based on the quality of retreading process (TRIB). An important question to address is how does this affect the energy savings potential of tire remanufacturing. We perform sensitivity analysis for assessing degradation in mileage lifetime of retreaded tires for both trucks as well as passenger cars (refer to (MITEI-1-h-2010)).

Tire Retreading and Energy Savings in the Context of Product Variations

There is a wide range for types of tires sold in the market due to variations in design, performance requirements (e.g. high traction, high durability, low rolling resistance), construction, size, speed rating. Therefore, each set of tire casings has performance attributes that are unique and different from other tire cases on the market. When comparing lifecycle energy demands of a retreaded tire with a new tire, the results may strongly depend on which casings are compared in the wide range of product offerings for tires. For this scope of study, we provide a qualitative discussion about the existence of wide range of rolling resistances for both retreaded as well as new truck tires. As discussed in detail later, data suggest that a strong analysis requires careful identification of the type of products studied in order to achieve strong conclusions about tire retreading and energy savings.

In summary, we conduct the tire remanufacturing energy savings analysis in the four inter-related contexts, as discussed above in detail. More specifically, we analyze remanufacturing energy savings for truck tires in the context of transformational technological changes, degradation in performance, and product variations. For passenger car tires, the scope of study consists of retrospective assessment of transitional technological changes, and degradation in performance of retreaded tires and its impacts on remanufacturing energy savings potential.

4. Methodology

In order to evaluate the life cycle energy savings potential of tire retreading, we rely on Life Cycle Assessment models (refer to Chapter 2 for more details).

4.1 Life Cycle Inventory: Energy Demands Analysis

Raw Material Acquisition and Processing Phase

The two main components of a tire are the tread and the casing. Prior to manufacturing the tire by vulcanizing the tread and the casing, different materials utilized in the generation of tire must be produced. In order to get a holistic perspective on tire manufacturing it is critical to start by the very initial processes involving extraction and transport of raw materials. A conventional tire is typically made of synthetic rubber, plastic rubber, carbon black, fabric-type materials, plasticizers and other additives.

Table 16 below is the summary of energy intensity for raw material extraction and production of core components in vehicle tires. Refer to (MITEI-1-h-2010) for a detailed discussion of the procedures involved for the processing of each raw material.

Table 16. Energy intensity of raw materials assembled in a tire

Tire Material	**Energy Intensity (MJ/Kg Material)**
Natural Rubber	9.3
Synthetic Rubber	119.8
Carbon Black	126.5
Steel	25
Plasticizers	42
Fabric	43.5

Manufacturing and Assembly Phase

Tire manufacturing is the process of producing the tread and the casing and assembling the core parts to build a unit of tire. The energy cost of tire manufacturing is reported in Amari et al. as 11.7 MJ per 1 Kg of tire (Amari, Themelis et al. 1999). In this study 11.7 MJ per Kg is chosen as the energy intensity for manufacturing a tire. Refer to (MITEI-1-h-2010) for detailed information about tire manufacturing.

Remanufacturing (Retreading) Phase

The remanufacturing process of tires is an industrial process, which requires industrial machines, skilled labors, and high quality development process. This study considers a conventional tire retreading process. Refer to (MITEI-1-h-2010) as well as (NHTSA 2008) for detailed discussions of tire remanufacturing and the steps involved.

Tire retreading is a remanufacturing process that effectively utilizes the core value of a used tire and by doing so extends its use phase roughly by another full lifetime. As reported by industry sources, only 10 to 20 percent of a tire gets consumed during its first lifetime. Nearly all of the material consumption is from the tread, which can be replaced by a retreading process.

Light Duty Passenger Car Tires

Ferrer states that it takes on average 26.4 liters of oil to produce a new passenger car tire. Moreover, retreading the passenger car tire requires only 9 liters of oil (34% of new) (Ferrer 1997).

Heavy Duty Truck Tires

The Tire Retread and Repair Information Bureau claims that a retreaded truck tire requires 7 gallons of oil compared to production of new truck tire, which takes up 22 gallons of oil (RMA 2009). Therefore, we will assume that the remanufacturing (retreading) energy for truck tires is approximately 32% (7/22) of raw materials processing and manufacturing.

Given the above information, it appears that tire remanufacturing is an energy savings strategy in the production phase. However, as will be seen, it is important to extend the analysis to include the use phase.

Use Phase

In order to quantify the use phase energy consumption of tires it is critical to first understand the sources of heat dissipation and energy losses associated to a tire in operation. More specifically, the issue to address is the impact of rolling resistance on energy performance of tires. Refer to Appendix B2 for supplement information about tire rolling resistance and the use phase energy losses.

In this study, we take the contribution of rolling resistance on vehicle fuel consumption to be on average 15% for passenger cars, and 24% for heavy trucks (TRB 2006),(Bradley 2000). Furthermore, we illustrate the results based on the range for the contribution of rolling resistance on vehicle energy expenditure. We consider the range of contribution to be 10 to 20% for passenger cars and 15 to 33% for heavy trucks (TRB 2006),(Bradley 2000). Refer to (MITEI-1-h-2010) for detailed literature review of the contributions of rolling resistance losses on vehicle fuel consumption.

How can one translate the changes in tire efficiency to changes in energy consumptions? Industry officials, researchers, and tire manufacturers have been studying this for decades in order to improve the energy performance of tires. The assessments encompass various testing approaches such as experimental observations using standardized testing procedures, stress-strain simulations, numerical modeling (refer (MITEI-1-h-2010) for more information).

One common approach for conveying the contribution of tire rolling resistance on fuel consumption is to determine the changes in total vehicle fuel consumption based on the changes in rolling resistance of tires. Reports publish this unit of measure and commonly refer to it as 'return factor', 'return ratio', 'energy return'.

$$Z = \text{Return Factor} = \frac{\left(\Delta E_T / E_T\right)}{\left(\Delta F_{RR} / F_{RR}\right)} = \frac{\left(\dfrac{E_T^{'} - E_T^{o}}{E_T^{o}}\right)}{\left(\dfrac{F_{RR}^{'} - F_{RR}^{o}}{F_{RR}^{o}}\right)} \qquad \text{Equation 4}$$

where E_T^0, $E_T^{'}$, F_{RR}^{o}, $F_{RR}^{'}$, and Z are the vehicle fuel energy consumption with initial set of tires (taken as the reference), modified vehicle fuel energy consumption due to modified tires, rolling resistance of initial set of tires, rolling resistance of the modified set of tires, and the return factor.

In this study, E_T^0 is computed based on the following equation,

$$E_T^o = \frac{\text{Distance Travelled [Miles]} \times \text{Fuel Heat Content [MJ/Gallon of Fuel]}}{\text{Vehicle Fuel Efficiency [Miles per Gallon of Fuel]}} \qquad \text{Equation 5}$$

Return factor provides a relation between the change in rolling resistance and its corresponding impact on vehicle energy consumption. Rolling resistance is the energy loss per unit distance travelled (J/m or N), where the higher the value the more vehicle fuel input required for overcoming tire energy losses (refer to Appendix B2).

In this study, we are interested, however, in the impact of change in coefficient of rolling resistance on vehicle fuel energy consumption. Coefficient of rolling resistance is a dimensionless measure of tire efficiency that is defined in terms of rolling resistance force generated per unit load applied (RMA). Therefore, coefficient of rolling resistance is linearly correlated to rolling resistance as expressed below (refer to (MITEI-1-h-2010) for detailed information)

$$C_{RR} = \frac{F_{RR}}{W} \qquad \text{Equation 6}$$

where C_{RR} and W are the tire coefficient of rolling resistance and vehicle load on tires. Based on this relation, we can show that fractional changes in coefficient of rolling resistance is equivalent to fractional changes in rolling resistance,

$$\frac{\Delta C_{RR}}{C_{RR}} = \frac{C_{RR}^{'} - C_{RR}^{o}}{C_{RR}^{o}} \cong \frac{F_{RR}^{'} - F_{RR}^{o}}{F_{RR}^{o}} = \frac{\Delta F_{RR}}{F_{RR}} \qquad \text{Equation 7}$$

where C_{RR}^{o} and $C_{RR}^{'}$ are the coefficient of rolling resistance of the initial set of tires (reference case) and the modified set of tires. Based on this, we can re-write Equation 3 as follows,

$$Z = \text{Return Factor} = \frac{\left(\Delta E_T / E_T\right)}{\left(\Delta C_{RR} / F_{RR}\right)} = \frac{\left(\frac{E_T^{'} - E_T^o}{E_T^o}\right)}{\left(\frac{C_{RR}^{'} - C_{RR}^o}{C_{RR}^o}\right)} \qquad \text{Equation 8}$$

The equation above can be re-arranged to solve for the modified vehicle fuel energy consumption, $E_T^{'}$, as a result of utilizing the modified set of tires,

$$E_T^{'} = E_T^o + Z.E_T^o.(\frac{C_{RR}^{'} - C_{RR}^o}{C_{RR}^o}) \qquad \text{Equation 9}$$

The total energy consumption of a vehicle, E_T^o, consists of a combination of energy expending components. In this study we break them into energy losses due to rolling resistance of tires, E_{RR}^o , and losses due to all the other components $\overline{E_{RR}^o}$ (i.e. engine losses, transmission losses, aerodynamic losses).

$$E_T^o = E_{RR}^o + \overline{E_{RR}^o} \qquad \text{Equation 10}$$

Utilizing Equation 9 for E_{RR}^o we end up with the following equation,

$$E_T^o = Z.E_T^o + (1 - Z).E_T^o \qquad \text{Equation 11}$$

We assume that the changes in rolling resistance of the tires do not change the energy requirements of other vehicle components. In other words,

$$\overline{E_{RR}^o} = \overline{E_{RR}^{'}} \qquad \text{Equation 12}$$

In addition to the assumption above, we take a range of values for return factor in order to compensate for potential variations in other vehicle components due to changes in rolling resistance (see Figure 34 and Figure 35). Based on the given assumption we can show that the energy required for overcoming rolling resistances of all tires on a vehicle can be expressed as,

$$E_{RR}^{o} = Z.E_{T}^{o} \qquad \text{Equation 13}$$

where E_{RR}^{o} is the use phase energy consumption of all tires operating on a vehicle.

In addition, based on the above assumption, we can compute the use phase energy cost of a new set of tires by taking into account the following expression,

$$E_{T}^{'} = E_{RR}^{'} + \overline{E_{RR}^{'}}$$

Equation 14

$$E_{RR}^{'} = E_{T}^{'} - \overline{E_{RR}^{'}} = E_{T}^{'} - (1-Z).E_{T}^{o}$$

Using Equation 9, we substitute for $E_{T}^{'}$ to come up with the following equation,

$$E_{RR}^{'} = Z.E_{T}^{o}.(\frac{C_{RR}^{'} - C_{RR}^{o}}{C_{RR}^{o}} + 1) = E_{RR}^{o}.(C_{RR}^{'}/C_{RR}^{o}) \qquad \text{Equation 15}$$

where $E_{RR}^{'}$ is the energy requirement for overcoming rolling resistance energy losses of the modified set of tires on a vehicle.

Use Phase Analysis for Passenger Car Tires

Given average annual travel miles of passenger car vehicles in the U.S., a replacement tire would last for about 3 to 4 years (assuming proper operation and maintenance of the tire) (Davis and Diegel 2009). We perform the energy analysis retrospectively in two distinct years, namely, years 1980 and 2004 (more information later in remanufacturing analysis). We take the fuel economies of 1977 and 2001 passenger vehicles to be around 15.8 and 28.8 mpg, respectively (Davis and Diegel 2009).

The wear life of the passenger car OEM tire is taken to be 41,500 miles (Norberg and Commission. 2002). The mileage lifetime of such tires have changed considerably in the past few decades. But for simplicity we keep the mileage lifetime to be the same for both 2004 as well as 1980 analysis. In addition, low heat value (LHV) gasoline was chosen as the fuel input during the operational lifetime of the passenger vehicle. The primary production and feedstock energy of LHV gasoline is estimate to be 142.4 MJ per 1 U.S. gallon (Davis and Diegel 2009).

Values for return factor Z are taken to be on average 0.15, with a range of 0.1 to 0.2 (TRB 2006), (Gyenes and Mitchell 1994). We assume that the contribution factor has remained in the same range between 1977 and 2001. Finally the results for passenger car analysis are showcased in terms of relative lifecycle energy savings due to retreading OEM tires.

Use Phase Analysis for Heavy Truck Tires

We assume that the truck analyzed has an average vehicle fuel economy of 5.5 mpg (Davis and Diegel 2009). This is the average value for mpg of trucks between years 1970 and 2005 (mean: 5.5; std. deviation +/- 0.34). Also, we assume that the truck consumes conventional diesel fuel with volumetric heating content of 146.34 MJ per gallon of fuel (Davis and Diegel 2009).

Truck tire lifetime has greatly improved as tires transformed from bias to radial, some estimating doubling the tire lifetime[I]. Moreover, the current pace of improvements in wear performance of radial tires has been steady[I]. The typical lifetime of a heavy truck tire may range from 80,000 to 100,000 miles. Some high performing truck tires under proper maintenance are capable of travelling for more than 200,000 miles during one lifetime[I]. In this analysis, the average mileage lifetime of a replacement heavy truck tire is taken as 100,000 miles[I]. In addition, for energy analysis, we assume that retreaded tires and new tires have comparable mileage lifetime.

[I] Source: Argonne National Laboratory, personal communication Tim LaClair, June, 2009.

For the analysis, the base case (reference) is considered to be for retreading old radial tires to like-new and re-using them for another 100,000 miles. In other words, we assume that retreading the old radial tires to like-new conditions would have no impact in terms of changing fuel economy of the truck (keeping the fuel economy at 5.5 mpg across multiple driving cycles).

Also, as discussed above, we assume that on average 24% of input fuel is expended (range: 15 to 33%) for overcoming rolling resistance energy losses of all tires on a heavy load tractor-trailer combination truck (Bradley 2000). We use this parameter to determine the relative changes in truck fuel consumption and rolling resistance energy losses of tires. Lastly, the energy analysis is performed such that the impact of rolling resistance is analyzed per total vehicle tires for an 18-wheeler tractor-trailer with 3 axles (steer axle; drive axle; and trailer axle). The values for coefficient of rolling resistance for bias ply, radial, advanced radial, and single wide-base tires are average industrial values taken from DOE 2000.

We assume that by remanufacturing the tires will be brought back to like-new conditions. In other words, based on this assumption, the retreading process doesn't degrade or enhance energy performance of a tire casing relative to when it was first manufactured. In reality, depending on the quality of the retreading process, tires can be degraded in performance during the use phase (Kromer, Kreipe et al. 1999), (Michelin). We examine this assumption with sensitivity analysis.

For truck tires, we assume that retreaded tires can be utilized on the drive and trailer axles only. In reality, the steer axle cannot be equipped with retreaded tires for safety precautions. For single wide-base tires, only 8 single wide-base tires are required for the drive and trailer axles (instead of 16 for dual radial tires). Since single wide-base tires cannot be used on the steer axle we assume that the steer axle utilizes two radial tires of similar rolling resistance attributes as the single wide-base tires. Therefore, the energy demands for producing 8 single wide tires and two radial tires is determined as follows:

$$E_{tp} = 2.E_{mr} + 8.E_{ms} \qquad \text{Equation 16}$$

where E_{tp}, E_{mr}, and E_{ms} are total production energy costs for all tires utilized for the truck, production energy demands for a radial tire, and production energy demands for a single wide-base tire, respectively.

4.2 Remanufacturing Analysis

Light Duty Passenger Vehicle Tire

A report by Transportation Research Board reveals that the average coefficient of rolling resistance for replacement tires has changed only slightly between 1994 and 2005 (data encompasses radial tires only) (TRB 2006). Therefore, based on this fact, we presume that by retreading an old replacement tire to like-new conditions, it would save energy compared to purchasing a new replacement tires (assuming that the retreaded tire performance in the use phase is similar to that of a new tire). Some recent studies, however, comment on the energy savings benefits of the new low rolling resistance fuel-efficiency enhancing (eco-efficient) tires. A 2003 California Energy Commission (CEC) preliminary study estimated that the adoption of low rolling resistance replacement tires can reduce fuel consumption of a vehicle by about 4% compared to current radial tires (Calwell 2003). Therefore, if the retreaded tires are of conventional type and are being compared to new low rolling resistance replacement tires, then the conclusions may be that new low rolling resistance replacement tires provide more energy savings. This requires quantitative assessments in order to achieve concrete conclusions; due to lack of data, we refrain from quantitative assessment of energy savings potential of replacement tire retreading for light duty vechiles.

The industry efforts for promoting energy efficient replacement tires have been less pronounced than for Original Equipment Manufacturer (OEM) tires. Since the CAFE standards in 1975, tire manufacturers have improved the energy efficiency of OEM tires in order to comply with automotive fuel efficiency standards. Also, consumers in general have been less keen on the environmental incentives for procuring more efficient replacement tires; instead the primary focus in the replacement tire market has been to optimize the decision choice based on the quality of performance and the desire to save on upfront costs. According to LaClair, average coefficient of rolling resistance of OEM tires has been reduced by more than 60% from 1975 to 2004 (LaClair 2005). Therefore, the consumer choice between remanufacturing OEM tires and purchasing new OEM tires may or may not lead to energy savings. Therefore, the objective of analysis for OEM tires is to reveal the energy savings benefits of retreading despite improvements in tire efficiency.

Consider a scenario whereby a consumer has purchased a new passenger car vehicle in 2001 (i.e. 2001 model), which came with OEM tires produced in 2001. After 3 years of use (average operational life of OEM tire (Davis and Diegel 2009),(Norberg and Commission. 2002)) the OEM tires reach end-of-life and must be replaced. For the purpose of addressing retreaded OEM tires performance only, we assume that the options available are only based on utilizing OEM tires. This is not a realistic representation since in majority of instances worn tires are replaced with replacement tires. However, due to scarcity of data and for effective comparison, we establish the scenario based on OEM tire choices only. Therefore, as the set of old OEM tires of the vehicle become worn-out, the owner of the vehicle has a decision to make:

1. To remanufacture the set of four old OEM tires and re-use them (2001 model tires)
2. To dispose the set of old OEM tires and replace it with a set of four new OEM tires (2004 model tires)

We determine the energy impacts of changes in rolling resistance coefficient between 2001 and 2004 models by utilizing Equation 14. Since the comparison is between tires that are only 3 years apart in terms of production year, the outcomes of the energy savings evaluations will be in the scope of transitional technological changes in OEM tires.

As shown in Figure 28 the improvements in rolling resistance coefficient of OEM tires in 2000's have been relatively moderate compared to the improvements during the 70's an the 80's. According to Figure 28 the rate of reduction in coefficient of rolling resistance of OEM tires has been about 1.5% annually between 1995 and 2005. In comparison, the rate of reduction during 1975-1985 and 1985-1995 has been 4.5% annually and 2.2% annually, respectively. In order to capture the dynamic changes in rate of efficiency improvements in tires, we perform the same analysis retrospectively during 1975-1980 timeline. We consider a situation where a consumer has purchased a1977 model passenger vehicle in year 1977, which came with OEM tires that were produced in 1977. After 3 years of use, the tires have reached end of life and must be replaced. The owner of the vehicle has a decision to make:

1. Remanufacture the old set of four OEM tires and re-use them (1977 model tires)
2. Dispose the set of old tires and replace with a set of four new OEM tires (1980 model)

Figure 30 below illustrates the decision tree for evaluating the energy benefits of retreading OEM tires.

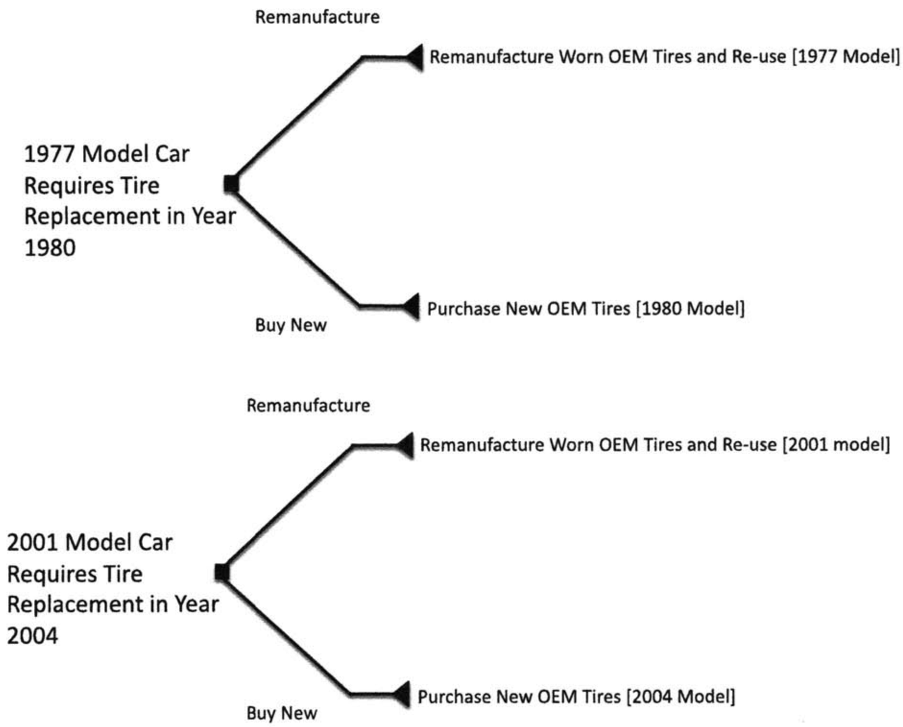


Figure 30 Decision-tree analysis: consumer decision retreading OEM passenger car tires.

Each decision has particular consequences for lifecycle energy requirements. If the consumer decides to remanufacture old tires and re-use them, then the lifecycle energy cost is taken to be the energy to remanufacture old tires and the energy demands in the use phase. If the consumer chooses to purchase new tires, then the energy consequences to be taken into account are for producing raw materials, manufacturing the tires, and using them (refer to Chapter 2 for information about lifecycle assessments).

Heavy Duty Truck Tire

The objective of the analysis for truck tires is primarily to evaluate lifecycle energy savings potential of remanufacturing radial tires (most utilized tires). The assessments are performed in the scope of transformational (architectural) technological advancements in tires. For truck tires, the evolution of tire advancements can be broken into three critical transformation steps (Bradley 2000):

1. Transformation (architectural changes) from Bias-Ply tires to Radial-Ply tires (past)
2. Progression in Technological advancement and efficiency gains in Radial-Ply tires including low rolling resistance tires (present)
3. Transformation (architectural changes) from efficient radial tires to single wide-base tires (most recent)

According to a Department of Energy report, the technological advancements from bias-ply tires to single-wide tires has led to an average reduction of 44% on average in coefficient of rolling resistances (Gaines, Stodolsky et al. 1998). We establish a decision scenario for evaluating lifecycle energy savings potential of truck tire remanufacturing. The scope of this analysis is based on evaluating tire retreading in the context of transformational technological changes in tires. Consider a Class 8 tractor-tailor combination truck, which is reaching a point where all tires are worn-out and have to be replaced at once. We assume that the tires that were used and now reached end of life are radial tires (conventional tires currently used in the market).

The truck owner has to make two decisions in series. The first decision is whether to utilize remanufactured tires or to utilize new tires. The second decision that follows is, which tire technology to choose for replacing the tires. For the case where the owner chooses to utilize remanufactured tires, we assume that there are three options available:

1. To purchase remanufactured bias-ply tires.
2. To remanufacture the worn radial tires and re-use them.
3. To dispose worn radial tires and purchase remanufactured radial tires.

For the case where the owner decides to dispose the old tires and purchase new tires, we assume that there are three other options available:

4. To purchase new radial tires.
5. To purchase new advanced radial (low rolling resistance) tires.

6. To purchase new single wide-base tires.

Figure 31 below illustrates all the options available to the consumer in the form of a decision tree.

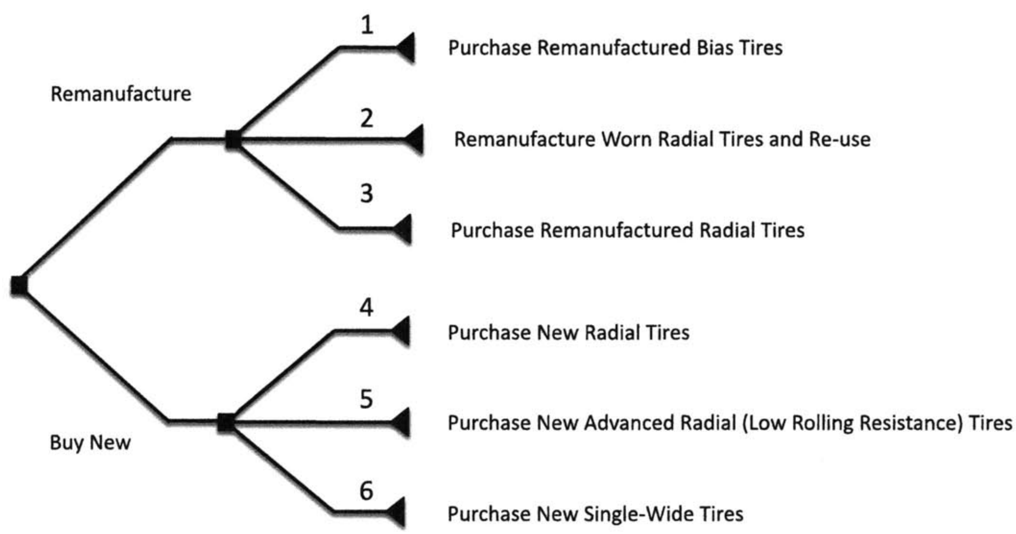


Figure 31 Decision-tree: Consumer decision alternatives for replacing worn tires.

We assume that the energy performance of retreaded radial tires in decision 2 and decision 3 are similar in the use phase. Another decision studied in this report is about utilizing remanufactured bias tires (decision 1). Note that decision 1 is not necessarily a realistic decision in the U.S. given that bias tires have become obsolete. However, in order to capture the past transformational changes in tire designs and architectures, we keep decision 1 included in the evaluations.

We assume that the retreading processes bring worn tires back to like-new conditions. We also assume that the rolling resistance attributes of new radial tires are similar to those of older radial tires. This is a realistic assumption given that truckers go through the full lifetime of their tires in a much faster rate than passenger car owners. Fleets use trucks more often and travel longer distances than passenger cars. Therefore, we presume decisions 2, 3, and 4 to have similar energy impacts in the use phase.

4.3 Data Acquisition

4.3.1 Passenger Car Vehicles

The data sources for each phase is as follows:

Raw Material Acquisition and Processing Phase
Bill of materials: (RMA).

Energy intensity values for each raw materials: (Amari, Themelis et al. 1999),(Boustead 2005), (Lutsey and Sperling 2005), (Kirk-Othmer 1996), (Smil 2008).

For tire mass, we assume that radial and bias ply tires have similar mass of 9.1 Kg (Lutsey and Sperling 2005).

Manufacturing and Assembly Phase
We rely on the literature data to reveal the energy requirements for manufacturing a passenger car tire: Manufacturing: (Amari, Themelis et al. 1999), (Brown, Hamel et al. 1985).

Remanufacturing Phase
Remanufacturing Energy: (Ferrer 1997).

Use Phase

Passenger vehicle fuel economy for 1977 and 2001 models (Davis and Diegel 2009).

Return Factor (Z): (TRB 2006).

Lifetime mileage of tires: (Norberg and Commission. 2002).

Fuel heating content: (Davis and Diegel 2009).

4.3.2 Heavy Duty Trucks

The data sources for each phase is as follows:

Raw Material Acquisition and Processing Phase
Bill of materials and tire mass: (RMA).

For tire mass, we assume that radial and bias ply tires have equivalent masses (55 Kg) (RMA) while single-wide tires have a mass of 81 Kg (Michelin).

Energy intensity values for each raw materials: (Amari, Themelis et al. 1999),(Boustead 2005), (Lutsey and Sperling 2005), (Kirk-Othmer 1996), (Smil 2008).

Manufacturing and Assembly Phase
We rely on the literature data to reveal the energy requirements for manufacturing a truck tire: Manufacturing: (Amari, Themelis et al. 1999), (Brown, Hamel et al. 1985).

Remanufacturing Phase
Energy requirements: (TRIB).

Use Phase
Truck Fuel Economy: (Davis and Diegel 2009).

Fuel Heat Content: (Davis and Diegel 2009).

Return Factor (Z): (Bradley 2000)

Mileage: (ANL June, 2009)

Coefficient of rolling resistance for bias ply, radial ply, advanced radial, and single-wide (Gaines, Stodolsky et al. 1998).

5. Results

5.1 Lifecycle Inventory Results: Energy Demands for Light-duty Passenger Car Tires

Raw Material Acquisition and Processing, Manufacturing and Assembly Phases

A conventional passenger car tire is typically made of synthetic rubber, plastic rubber, carbon black, fabric-type materials, plasticizers and other additives. We have used the raw materials composition provided by the Rubber Manufacturers Association (RMA) for determining passenger car tire raw materials processing and manufacturing energy. For more detailed information see (MITEI-1-h-2010). Table 17 below reveals the materials compositions of a passenger car tire, energy intensity, and total raw materials processing and manufacturing energy.

Table 17. Raw materials processing and manufacturing energy consumption: passenger car vehicle.

Tire Material	Composition %	Energy Intensity (MJ/Kg Material)	Energy (MJ/Kg Tire)
Natural Rubber	14	9.3	1.3
Synthetic Rubber	27	119.8	32.3
Carbon Black	28	126.5	35.4
Steel	15	25	3.8
Plasticizers (Fillers)	5	42	2.1
Fabric (Rayon, Nylon, Polyester)	11	43.49	4.8
Average Mass (New) Kg	11.3	Raw Materials Processing (MJ/Tire)	903.7
		Manufacturing (11.7 MJ/Kg tire)	132.7
		Total (MJ/Tire)	1036.4

Therefore, for a set of four new passenger car tires, it would take about 4,145 MJ to extract the raw materials, process it, and manufacture the tires.

$$E_{\text{Production}} = E_{rm} + E_m = 4{,}145 \text{ MJ per set of four tires}$$

Equation 17

where $E_{\text{Production}}$, E_{rm}, and E_m are total production, raw materials processing, and manufacturing energy requirements. We assume that energy values for raw materials processing and manufacturing of new tires have remained similar between 1977 and 2004.

Remanufacturing (Retreading) Phase

According to Ferrer et al. retreading a passenger car tire takes up 34% of the total energy required for producing a new tire. This translates to 352.4 MJ of energy required for remanufacturing a passenger car tire. Therefore, by retreading a passenger car tire, 684 MJ of the energy that is otherwise required for processing the raw materials and manufacturing a new tire is saved. Retreading a set of four used tires would require about 1,380 MJ, as shown below.

$$E_{\text{Remanufacturing}} = 1{,}380 \text{ MJ per set of four tires} \qquad \text{Equation 18}$$

where $E_{\text{Remanufacturing}}$ is the total energy requirements for the tire remanufacturing process. We assume that energy values for tire remanufacturing have not changed between 1977 and 2004.

Use Phase

The objective of the use phase analysis, as expressed earlier, is to determine the relative energy savings potential of retreaded tires (produced 3 years prior) that has been restored to like-new conditions compared to new tires (produced today).

For OEM passenger car tires, we perform the assessment by computing the relative changes in the vehicle fuel energy consumption of vehicle by choosing to purchase a set of four new tires as oppose to remanufacture and re-use the set of four old tires. To start, we compute the total fuel consumption of the 2001 vehicle. We take this to be the total fuel consumption of the vehicle with like-new retreaded 2001 OEM tires ($C^{o}_{RR} = 0.0094$).

$$E^{o}_{T2001} = \frac{41{,}500 \text{ [miles]}}{28.8 \text{ [mpg]}}.142[{}^{MJ}/_{gallon}] = 204{,}618[{}^{MJ}/_{Vehicle}] \qquad \text{Equation 19}$$

Given C^{o}_{RR}, $C^{'}_{RR}$, and Z to be 0.0094, 0.0089, and 0.15, respectively we can determine $E^{'}_{T}$ by using Equation 8.

$$E^{'}_{T2001} = 203{,}608\ {}^{MJ}/_{Vehicle} \qquad \text{Equation 20}$$

This is the modified vehicle fuel energy consumption by utilizing a set of four new OEM tires produced in 2004 ($C^{'}_{RR} = 0.00899$).

Similarly, we perform the calculation for a 1977 model vehicle that requires tire change in year 1980. The base case for vehicle fuel consumption is the decision to retread, bring to like-new, and re-use 1977 old OEM tires.

$$E^{o}_{T1977} = \frac{41{,}500 \text{ [miles]}}{15.8 \text{ [mpg]}}.142[{}^{MJ}\!/_{gallon}] = 372{,}975[{}^{MJ}\!/_{Vehicle}] \qquad \text{Equation 21}$$

Given C^{o}_{RR}, $C^{'}_{RR}$, and Z to be 0.0222, 0.01888, and 0.15, respectively, we determine the modified total fuel consumption $E^{'}_{T}$ by using Equation 8,

$$E^{'}_{T1977} = 289{,}488\,{}^{MJ}\!/_{Vehicle} \qquad \text{Equation 22}$$

<u>LCA Results for Decision Analysis in Year 2004</u>

According to the results, the vehicle's fuel energy requirements reduce on average by 1,339 MJ for the 41,500 miles of tires' lifetime. This reduction has been caused by utilizing a set of four new tires (2004 OEM tires) instead of remanufacturing and re-using a set of four 2001 OEM tires. Given the range of return factor (0.1 to 0.2), by choosing to use new tires in 2004, the vehicle owner saves around 0.5% to 1% in fuel energy consumption of the vehicle during the service lifetime of the tires. Given the information above, the relative lifecycle energy requirements are plotted (refer to Figure 32). The plot reveals a range allotted for the results. This variation is due to performing the analysis by taking the range for the contribution of overcoming passenger car tires rolling resistance on vehicle fuel consumption (10 to 20% of total energy). Moreover, the average values illustrate the case where overcoming OEM tire rolling resistance consumes 15% of the passenger car fuel consumption. The lower-bounds and upper-bounds reveal rolling resistance losses to be 10% and 20%, respectively of total input fuel energy expenditure for passenger car.

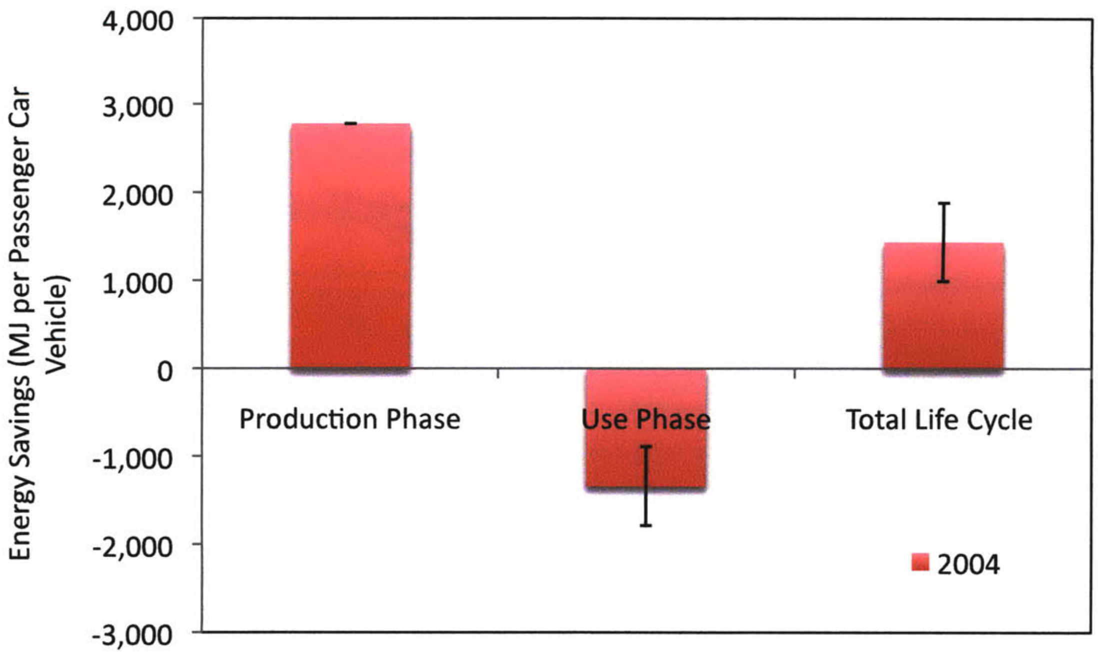


Figure 32 Lifecycle energy savings by retreading and re-using old passenger car tires. The energy comparison in this figure is between a set of four retreaded 2001 OEM tires and a set of four new 2004 OEM tires.

According to Figure 32 above, by remanufacturing and re-using a set of four passenger car tires in 2004 it saves about 2,777 MJ in the production phase compared to a set of four new tires. Moreover, the retreaded tires expend on average about 1,339 MJ more in the use phase than new tires. Therefore, the savings in the production phase dominates the over-expenditure in the use phase. As such, from a total life cycle perspective tire retreading saves on average 1,439 MJ per set of four tires in year 2004. The results conclude that improvements in tire rolling resistance coefficient for OEM tires between 2001 and 2004 have not been as substantial, hence making tire retreading an energy savings end-of-life option.

<u>LCA Results for Decision Analysis in Year 1980</u>

By remanufacturing and re-using a set of four passenger car tires in 1980 it saves about 2,777 MJ in the production phase compared to a set of four new tires. In the use phase, the choice of utilizing a set of four new OEM tires (1980 models) instead of retreading and re-using old OEM tires (1977 models) saves the consumer on average 6,643 MJ. Given the range of return factor (0.1 to 0.2), by choosing to use new tires in 1980, the vehicle owner saves around 1.5% to 3% in fuel energy consumption of the vehicle during the service lifetime of the tires.

The energy over-expenditure of retreaded 1977 tires in the use phase cancels out the savings in the production phase. The analysis concludes that in year 1980, from a total life cycle perspective, retreading will cost on average 3,865 MJ more per set of four passenger car tires compared to purchasing new. Figure 33 below showcases the results for year 1980. Similar to the year 2004 analysis, the average values illustrate the case where overcoming OEM tire rolling resistance consumes 15% of the passenger car fuel consumption. The lower-bounds and upper-bounds reveal rolling resistance losses to be 10% and 20%, respectively of total input fuel energy expenditure for passenger car.

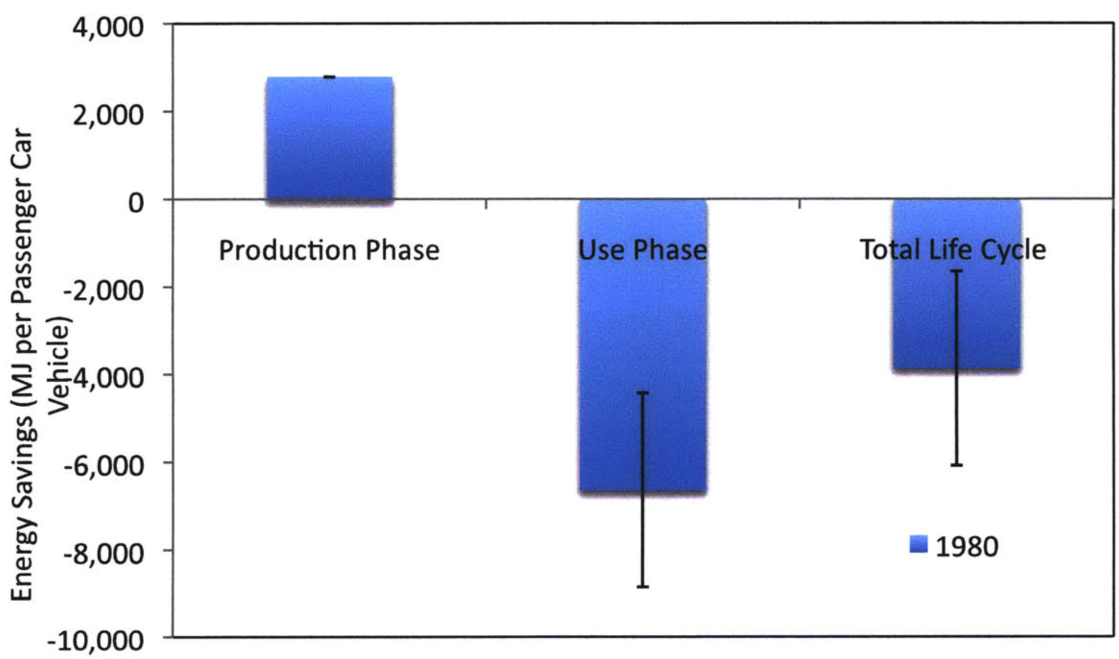


Figure 33 Lifecycle energy savings by retreading and re-using old passenger car tires. The energy comparison in this plot is between a set of four retreaded 1977 OEM tires and a set of four new 1980 OEM tires.

Figure 34 below illustrates the retrospective lifecycle assessment for years 1980 and 2004 combined in a single plot.

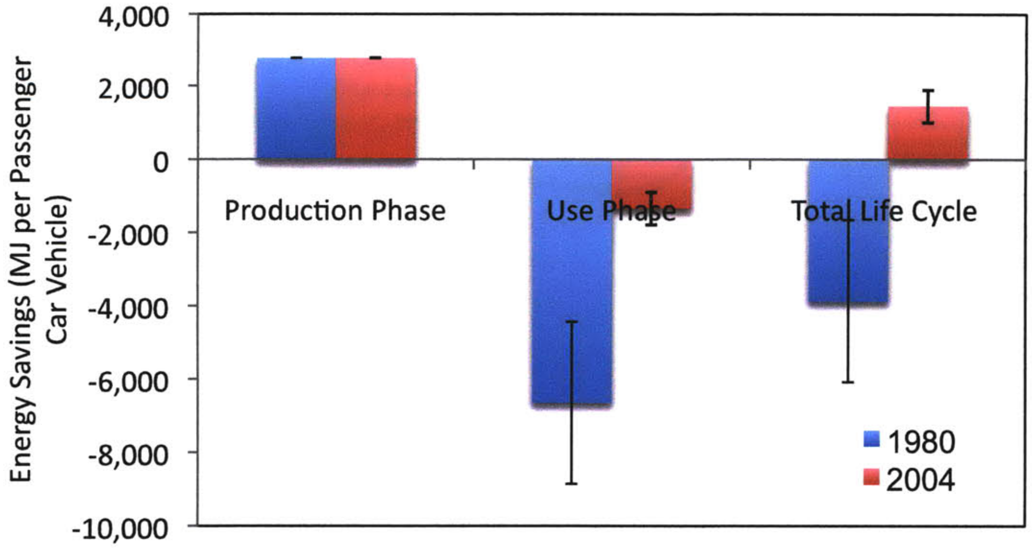


Figure 34 Lifecycle energy savings by retreading and re-using old passenger car tires. The energy comparison in this plot is between a set of four retreaded 1977 (2001) OEM tires and a set of four new 1980 (2004) OEM Tires.

5.2 Lifecycle Inventory Results: Energy Demands for Heavy Duty Truck Tires

Raw Material Acquisition and Processing, Manufacturing and Assembly Phases

The material composition, specific energy of material, and total raw material and manufacturing energy consumption of a typical heavy-size truck tire are presented in

Table 18 below.

Table 18 Material consumption and energy expenditure for raw material processing and manufacturing of a new heavy truck tire.

Tire Material	Material Composition (%) (RMA2)	Specific Energy (MJ/Kg Tire)	Total Raw Materials Production Energy (MJ/Kg tire)	Percent of Total Energy (%)
Natural rubber (Lutsey and Sperling 2005)	27	9.3	2.5	3.8
Synthetic rubber (Amari, Themelis et al. 1999; Boustead 2005)	14	119.8	16.8	25.5
Carbon black (Kirk-Othmer 1996)	28	126.5	35.4	53.8
Steel (Smil 2008)	15	25	3.8	5.7
Fabric, fillers, accelerators, antioxidants (Amari, Themelis et al. 1999)	16	43.5	7.4	11.2
Average Mass:	New 55 Kg			
			Total Raw Material Processing per Tire [MJ]:	3,622
			Manufacturing Energy Intensity [MJ/Kg] (Brown, Hamel et al. 1985; Amari, Themelis et al. 1999):	11.7
			Manufacturing per Tire [MJ]:	643.5
			Production Process Total per Tire [MJ]:	4,265

According to Table 18, it takes about 4,265 MJ of energy to process raw materials and manufacture a heavy-duty truck tire. As a result for a tractor-trailer combination heavy-duty truck, the total production energy consumption for a set of 18 tires would be 76,770 MJ per truck.

Note that the above bill of materials is for a conventional radial tire that weighs about 55 Kg. We assume that bias ply and advanced radial tires have approximately similar material compositions and sizes. For single wide-base tire, we assume it has similar materials composition as radial tires. We determine the mass of a single wide-base tire to be on average around 81 Kg (50% heavier than a radial tire) (Michelin). Therefore the total raw materials processing and manufacturing for a single wide-base tire is estimated by multiplying the production energy requirements for a radial tire by 1.5. This makes the energy requirements for raw materials processing and manufacturing for a single wide-base tire to be around 6,281 MJ/Tire.

The energy requirements for the raw materials processing and manufacturing phases for the three decisions related to purchasing new tires are (refer to Figure 31),

$$\begin{aligned}
E_{\text{Production}}(Decision4) &= E_{rm} + E_{m} = 76{,}770 \text{ MJ per Truck} \\
E_{\text{Production}}(Decision5) &= E_{rm} + E_{m} = 76{,}770 \text{ MJ per Truck} \\
E_{\text{Production}}(Decision6) &= E_{rm} + E_{m} = 58{,}221 \text{ MJ per Truck}
\end{aligned} \qquad \text{Equation 23}$$

where $E_{\text{Production,}} E_{rm}$, and E_{m} are total production energy, raw materials processing energy, and manufacturing energy for each alternative option. Note that the raw materials processing and manufacturing energy for decision 6 is less than decisions 4 or 5, because only 8 single wide-base tires are needed for drive and trailer axles as opposed to 16. Even though a single wide-base tire is heavier than a single radial tire, it is lighter than two conventional radial tires.

Remanufacturing Phase

The Tire Retread and Repair Information Bureau claims that a retreaded truck tire consumes 7 gallons of oil compared to production of new truck tire, which takes up 22 gallons of oil (TRIB). Therefore, we will assume that the remanufacturing (retreading) energy for truck tires is approximately 32% (7/22) of manufacturing energy consumption, or 1,365 MJ per conventional truck tire. Equivalently, the total energy requirements for remanufacturing for a truck (e.g. 18 wheeler) is as follows:

$$E_{\text{Remanufacturing}}(Decision1,2,3) = 24{,}570 \text{ MJ per Truck} \qquad \text{Equation 24}$$

where $E_{\text{Remanufacturing}}$ is the energy demands for the remanufacturing processes. This value is taken to be same for all three decisions related to utilizing remanufactured tires (refer to Figure 31).

Use Phase

The objective of the analysis for the use phase is to quantify the impact of technological changes on energy performance of truck tires. We establish the base case for the use phase to be for retread and re-use of old radial tires. Assuming, that the radial tires perform like-new, then the fuel economy of the truck will remain unchanged. Given 5.5 MPG truck fuel economy, 100,000 tire wear life, 146.34 MJ/gallon heat content of diesel fuel, we compute the total energy consumption of a heavy truck during the mileage lifetime of truck tires. Where E_T^o is the total energy consumption of the heavy truck with retreaded radial tires.

$$E_T^o = 18{,}182[gallons] = 2{,}654{,}545[MJ] \qquad \text{Equation 25}$$

Considering an average return factor of 0.24, we compute the total rolling resistance losses for a heavy truck with retreaded radial tires to be,

$$E_{RR}^o = Z.E_T^o = 641{,}515[MJ \text{ per Truck}] \qquad \text{Equation 26}$$

This is taken as the average value for energy consumption of retreaded radial tires in the use phase (Decision 2/3 in Figure 31). Given that we assume new radial truck tires to be similar in performance to old radial truck tires, then the use phase energy for decision 4 would be equivalent to decision 2/3. In short, for decisions 2, 3, and 4 (see Figure 31), the average use phase energy for all tires is taken as 641,515 MJ. Given C_{RR}^o, C'$_{RR}$, and Z we can determine the relative energy for decision 1, 5, and 6.

$E_{RR}^{'}$(decision 1) = 915,102 MJ per entire tires operating on a truck

$E_{RR}^{'}$(decision 5)=575,477 MJ per entire tires operating on a truck

$E_{RR}^{'}$(decision 6) = 509,439 MJ per entire tires operating on a truck

The average change in energy consumption for overcoming rolling resistance due to improvement in rolling resistance coefficient is presented in Table 19 below:

Table 19. Use phase energy requirements for truck tires.

Tire Type	Coefficient of Rolling Resistance	% Change in Coefficient of Rolling Resistance from base case (radial tires)	% Change in Vehicle Fuel Consumption	Total Energy Consumption (MJ)	**Use Phase Energy Consumption: Total Tires (MJ)**
Conventional Bias tires	0.0097	42.6%	10.31%	2928133	**915,102**
Radial tires	0.0068	-	-	2654545	**641,515**
Improved Radial tires (including Low Rolling Resistance tires)	0.0061	-10.3%	-2.49%	2588507	**575,477**
New Single-Wide Tire	0.0054	-20.6%	-4.98%	2522469	**509,439**

Given the information above, the total lifecycle energy requirements for each consumer decision is plotted (refer to Figure 31). The plot reveals a range allotted for the results. This variation is due to performing the analysis by taking the range for the contribution of overcoming truck tires rolling resistance on truck fuel consumption (15 to 33% of total energy). Moreover, the average values illustrate the case where overcoming truck tire rolling resistance consumes 24% of the truck fuel consumption. The lower-bounds and upper-bounds reveal rolling resistance losses to be 15% and 33%, respectively of total input fuel energy expenditure for truck.

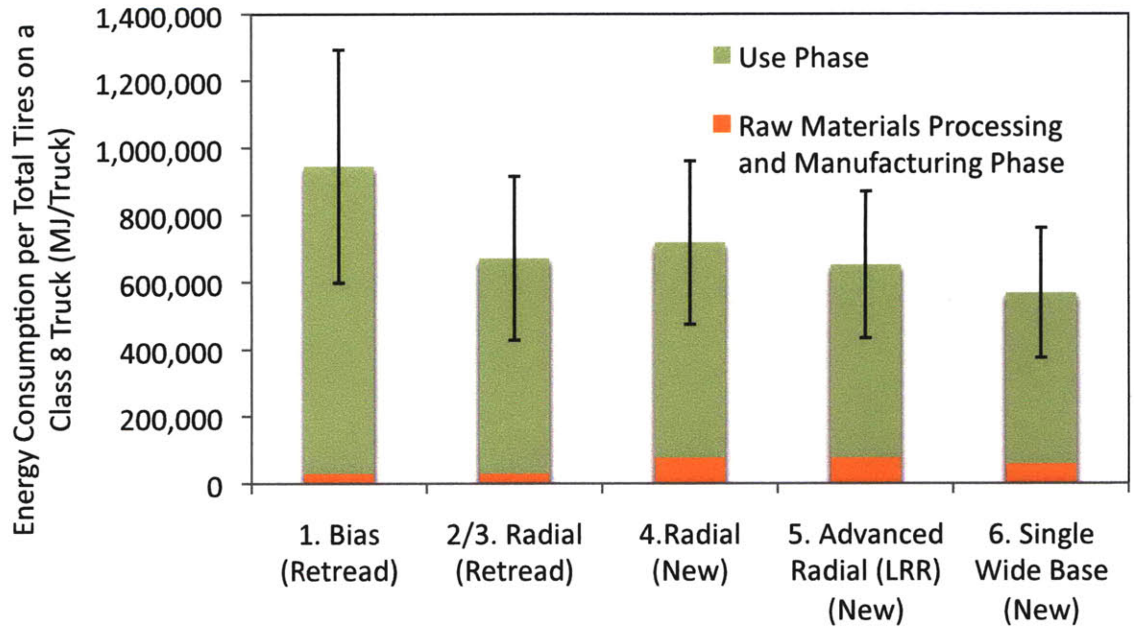


Figure 35 Life cycle assessment of truck tires performing for a tractor-trailer (Class 8) heavy duty vehicle. This figure illustrates changes in lifecycle energy consumption of heavy truck tires due to technological improvements in tires.

6. Sensitivity Analysis

6.1 Passenger Car Tires

Increase in Rolling Resistance Due to Remanufacturing

The core assessments for lifecycle assessment of passenger car tires are conducted by assuming that retreaded tires perform like-new. This is a biased assumption in favor of tire remanufacturing. Depending on the quality of retread, some retreaded tires may experience an increase in rolling resistance (reduction in efficiency). In relation to this, (Kromer, Kreipe et al. 1999) reveals a case where the rolling resistance coefficient of retreaded tires may increase by 3 to 10%. Similarly, we perform a sensitivity analysis for life cycle energy savings of retreading where by we assume three scenarios: (1) no degradation in coefficient of rolling resistance due to retreading (i.e. like-new), (2) 4% increase in coefficient of rolling resistance due to retreading, (3) 10% increase in coefficient of rolling resistance due to retreading. Figure 36 below illustrates the results for all three scenarios.

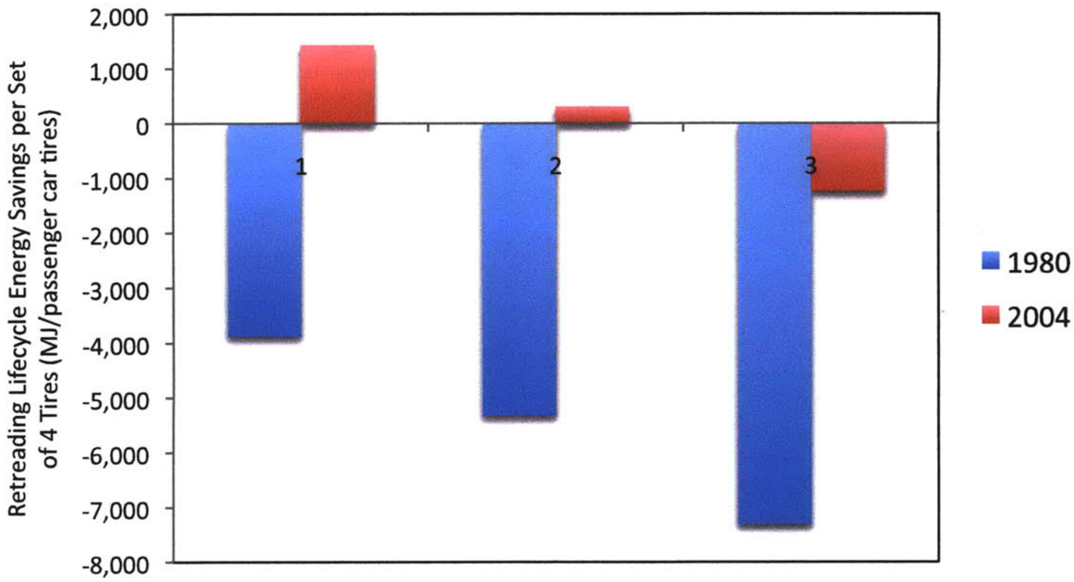


Figure 36 Sensitivity analysis: life cycle energy savings potential of passenger car retreading. 1. retreaded tires that perform like-new.2. retreaded tires with increase in coefficient of rolling resistance of 4%. 3.retreaded tires with increase in coefficient of rolling resistance of 10%.

Scenario 1 in Figure 36 shows the base case results where retreaded tires perform like-new for both year 1980 and year 2004 analysis (refer to Figure 22).

According to Figure 36 above, for year 2004 analysis, increase in coefficient of rolling resistance, can lead to retreading life cycle energy savings to be nuanced or even negative. For 1980 analysis, degradation in coefficient of rolling resistance will make the life cycle energy cost of retreading even more substantial.

Decrease in Mileage Lifetime due to Remanufacturing

The analysis in this case study makes the assumption that retreaded tires can last as long as new tires. This assumption is biased in favor of tire remanufacturing. Tire Retread Industry Bureau (TRIB) reveals that a retreaded tire can last anywhere between 75% and 100% of the lifetime of an equivalent new tire (TRIB).

In order to examine the assumption for this study, we conduct a sensitivity analysis by assuming that the retreaded tire lasts shorter than an equivalent new tire. As such, it has to be retreaded once more to last as long as a new tire. The objective of this sensitivity analysis is to address whether an extra retreading energy cost would change the conclusions. By performing another retreading, the total energy cost for a retreaded tire doubles to 705 MJ per tire. Table 20 below shows the OEM passenger car tire retreading relative energy savings.

Table 20 OEM passenger car tire retreading relative energy savings.

	Production Phase (MJ/Vehicle)	Use Phase (MJ/Vehicle)	Total Life Cycle (MJ/Vehicle)
1980	1,409	-6,643	-5,233
2004	1,409	-1,339	71

According to Table 20 above, the sensitivity analysis reveals that if lifetime mileage of retreaded tires in year 2004 are degraded compared to new, then retreading lifecycle energy saving is nuanced. Given that energy savings in the production phase is reduced, retreading old tires becomes even more energy expending in 1980.

6.2 Heavy-Duty Truck Tire

Change in Rolling Resistance of Retreaded Truck Tires

The above analysis was conducted assuming that for a particular tire model, the retreaded-version would have no degradation in rolling resistance in comparison to a reference new tire.A more realistic scenario would be to analyze new radial tires (i.e. advanced and single-wide) against retreaded radial tires by taking into account the potential degradations in efficiency performance of retreaded tires. In general, two elements to retreading have to be taken into account when talking about increases in rolling resistance of retreaded tires[I]:

1. Due to the deep penetration effect of the buffing stage in the retreading process, some base rubber has to be added back to increase the thickness of the under-

tread. This will generate additional heat in the retreaded tire use phase, in turn increasing the rolling resistance coefficient of retreaded truck tires.

2. As a result, the retreading industry has been utilizing treads that are shallower in depth than new tire treads in order to compensate for the extra heat generated. This would result in reduction of rolling resistance and relatively reduced lifetime mileage at times.

Due to the combination of these two effects, on average the rolling resistance coefficient of a retreaded truck tire in comparison to a new truck tire would increase by 0.0004 to 0.0005[I].

Michelin assesses the energy consumption of Michelin retreaded tires based on a tire model XZA1+ drive tire, which has a rolling resistance coefficient of 0.0054. As mentioned above, Michelin energy analysis concludes that due to retreading, the rolling resistance coefficient would increase by 0.0004 to 0.0005 (7- 9 per cent increase in C_{RR}) [I].

If we consider 8% increase in rolling resistance coefficient of remanufactured radial truck tires, we will get the following changes in total energy consumption of tires. Table 21 below show the increase in tire energy consumption due to increasing in rolling resistance of retreads.

[I] Source: Michelin Center of Technologies, Research and Development, personal communication with Don Baldwin, July, 2009.

Table 21 Increase in tire energy consumption due to increase in rolling resistance of retreaded tire

Scenario 1 (Lower Bound): Return Factor Z=0.15

	Performance Condition	Production (MJ/Truck)	Use (MJ/Truck)	Life Cycle Energy (MJ/Truck)
Radial (retread)	**8% increase in C_{RR}**	**30,370**	**430,036**	**460,406**
Radial (retread)	Like-New	30,370	398,182	428,552
Radial (new)	-	76,770	398,182	474,952

Scenario 2 (Upper Bound): Return Factor Z=0.33

		Production (MJ/Truck)	Use (MJ/Truck)	Life Cycle Energy (MJ/Truck)
Radial (retread)	**8% increase in C_{RR}**	**30,370**	**1,262,210**	**1,292,580**
Radial (retread)	Like-New	30,370	884,848	915,218
Radial (new)	-	76,770	884,848	961,618

According to the sensitivity analysis, for the case where return factor is 15%, an 8% increase in C_{RR} can make the lifecycle energy savings of retreaded radial tires nuanced compared to purchasing new radial tires. On the other hand, for the case where return factor is 33%, an 8% increase in C_{RR} makes retreading an energy-expending end-of-life option.

Tire Lifetime Usage Mileage

In the analysis, we assumed that retreaded truck tires last as long as new tires. In a personal communication with the Technology Specialist at Michelin's R&D, Mr. Baldwin, he mentioned that[I],

> "In the past the retreaded tire would travel considerably less number of miles (in some cases as great as 50 per cent reduction in usage mileage). However, with technological advances in retreading processes, improvement in tread compounding, and casing being designed for retreading, retreaded tires can currently achieve comparatively similar mileage as their new counterparts."

Michelin Center of Technologies, Research and Development, claims that retreaded Michelin truck tire model XDN2 under proper maintenance and driving conditions can achieve mileage life of 200,000 to 250,000 miles[I]. Therefore, our assumption that current retreaded truck tires in the market can travel the same mileage as equivalent new tires for the similar category of tires is credible and representative of current retreaded truck tires.

[I] Source: Michelin Center of Technologies, Research and Development, personal communication with Don Baldwin, July, 2009.

Product Variation and Its Impact on Analysis of Life Cycle Energy Savings Potential of Tires

One major limitation of the analysis above is the average-based nature of the assumptions and data considered. In order to address the limitation of average-based approaches on modeling and analysis, it is important to consider ranges, probabilities, and sensitivity analysis. For example, it is wise to ask how the conclusion above would change if energy savings of a retreaded tire with high rolling resistance dual radial tire casing is compared with a new low rolling resistance wide-base tire? In relation to this, Michelin has a plot (see Figure 37) comparing the rolling resistance coefficient of dual radial tires to single wide radial tires (XONE) as well as retreaded tires (Michelin2).

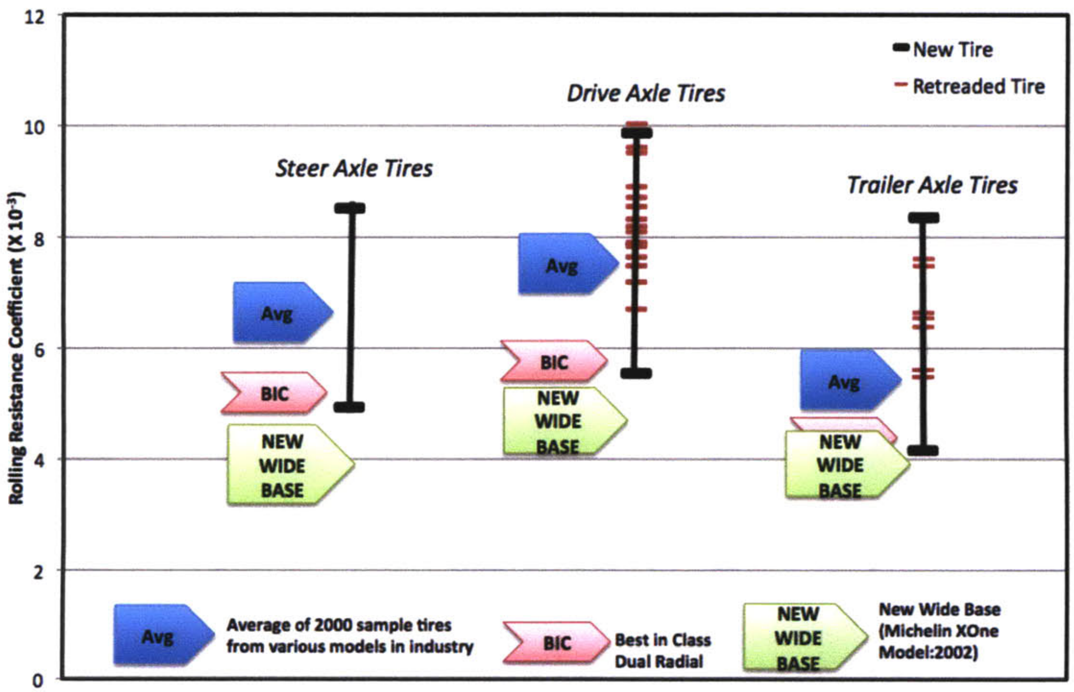


Figure 37. Tire rolling resistance coefficient ranges: dual radials and wide-base; new and retread. The data for retreaded tire is most likely for Michelin tires only.

Figure 37 above depicts the rolling resistance coefficient of retread tires compared to the best-in-class (BIC) highly efficient dual radial tires, aggregated average tires, as well as single-wide base tires. On the other hand, the data shows that Michelin retreaded tires have rolling resistance coefficients that are within the industry range of rolling resistance coefficient for new tires. Therefore based on the type of tire casings compared between new and retreaded tires, the conclusions for energy savings potential may alter.

According to Mike Wischhusen[I], Director of Industry Standards and Government Regulations at Michelin, one cannot find an industry-wide quantitative assessment of the performance of retreaded tires because of the complexity in the variables associated with producing retreaded tires. In order to analyze the performance of retreaded tire, Wischhusen added, three distinct factors have to be analyzed, namely, the casing, the tread, and the retreading process.

Therefore, in order to achieve concrete and insightful conclusions about the energy savings potential of tire retreading, it is important to compare the energy assessments based on similar casings, with similar characteristics.

7. Conclusions

We conclude that tire retreading, as an end-of-life option, can be both energy saving and energy expending. The conclusions for retreading energy savings strongly depend on the boundary conditions chosen for the analysis. If the analysis strictly focuses on the production process, then tire retreading is an energy savings end-of-life option. However, if the analysis takes into account the use phase of tires, then tire retreading may or may not save energy from a total lifecycle perspective. Also, this case study evaluates energy savings potential of tire remanufacturing by analyzing it in four distinct contexts:

1. Transitional technological changes in tires.
2. Transformational technological changes in tires.
3. Degradation in performance due to retreading.

[I] Source: Michelin Industry Standards and Government Regulations, personal communication with Mike Wischhusen, Director, July, 2009.

4. Tire casings variations and its corresponding impacts on conclusions for retreading energy savings potential.

If a retread tire exhibits more rolling resistance than a new tire, then it consumes more energy during its use phase. The increased consumption of energy in the use phase can be more than offset the savings attained in retreading process. In other words, the energy savings attained in retreading process can be virtually canceled out by the higher petroleum (fuel) consumption in the use phase.

7.1 Passenger Car Tires

Data suggest that since coefficient of rolling resistance for replacement tires has not improved substantially, then by retreading replacement tires, one can save energy in the production phase.

For OEM tires, the analysis concludes that currently by retreading OEM tires, it would save energy. This is due to modest improvements in coefficient of rolling resistance of tires. Also, the sensitivity analysis shows how the conclusions drawn by average-based assessments could change if we consider degradation in performance of retreaded tires (between 4 to 10% increase in coefficient of rolling resistance).

- Given that coefficient of rolling resistances for replacement tires has remained similar on average since 1994 (TRB 2006), we conclude on qualitative basis that replacement tire retreading is a potentially feasible energy savings end of life option (TRB 2006).
- By retreading and remanufacturing old OEM tires instead of purchasing new it saves energy in the production phase. Moreover, depending on the rate of enhancement of tire efficiency (i.e. coefficient of rolling resistance), retreaded tires may expend more energy in the use phase than new tires.
- Retreading and re-using old OEM tires in year 2004 saves energy from a total lifecycle perspective.

- Retreading and re-using old OEM tires in year 1980 costs energy from a total lifecycle perspective.
- Given less energy savings by retreading in 1980, it illustrates that the pace of technology improvements in improving efficiency of tires between years 1975 and 1980 were much more substantial than in years 2001 to 2004. Furthermore, our analysis reflects upon the impact of the pace of technological changes and efficiency improvements on the energy savings potential of tire retreading.
- Conclusion remarks on the importance of considering transitional and transformational technological improvements in tires, and its impact on tire remanufacturing energy savings potential.
- The life cycle inventory analysis indicates that the use phase energy consumption of the tire is a critical factor to take into account when evaluating the energy savings potential of tire retreading.

Moreover, by performing the assessment retrospectively for OEM tires, we conclude that when the pace of improvement in coefficient of rolling resistance was more aggressive (during 1975-1985) tire retreading was a net energy consuming end of life option. This retrospective assessment remarks on the impacts of macro-scale effects (i.e. pace of innovation in the tire industry, policies, mandates, market demand, etc.) on tire remanufacturing energy savings potential. For example, under President Obama's administration, the CAFE standards will increase by five percent each year, reaching 35.5 mpg by 2016. As shown in our retrospective assessments, changes in fuel standards can potentially cause OEM tires to improve in efficiency at a faster rate. Perhaps if the pace of improvement is similar to those observed during 1975-1985, it could potentially make tire retreading a net energy expending option.

7.2 Heavy Truck Tires

A trucking fleet will save energy in the production phase by retreading or purchasing retreaded truck tires. However, depending on the technology transitioning stages, the fleet will expend additional incremental energy in the use phase by purchasing retreaded tires.

Based on the decision-making options available (refer to Figure 31), the following conclusions can be made:

- Bias tire technology is the least efficient tire technology, and using remanufactured bias tires is not an effective energy savings options since it leads to the highest life cycle energy requirements compared to other options.
- Remanufacturing and re-using old radial tires compared to purchasing new radial tires leads to lifecycle energy savings. This assessment is based on the assumption that retreaded tire would perform like-new. The sensitivity analysis shows that the outcome can change, if we change this assumption.
- Remanufacturing and re-using old radial tires lead to negligible energy savings compared to the decision to purchase new low resistance radial tires. This assessment is based on the assumption that retreaded tire would perform like-new. The sensitivity analysis concludes that degradation in coefficient of rolling resistance due to retreading (7-9% increase in C_{RR}) makes utilizing low rolling resistance tire more favorable in terms of lifecycle energy savings.
- Replacing old radial tires with new single wide-base tires leads to lifecycle energy savings compared to remanufacturing and re-using old radial tires; in particular, the lifecycle energy requirements would decline by 11.3 to 16%.
- The sensitivity analysis reveals the wide range of rolling resistances observed for both retreaded and new tires. In relation to this, we conclude that in order to draw insightful conclusions about tire remanufacturing energy savings potential the analysis should be conducted on a case-by-case basis. In other words, the conclusions on tire retreading energy savings can vary substantially depending on the types of casings compared between retread and new tires.

In summary, we conclude that tire retreading, as an end-of-life option, can be both energy saving and energy expending. The energy savings attribute of tire retreading strongly depends on the boundary conditions of the analysis. By considering only the manufacturing phase, retreading can be a very promising energy savings option. However, when taking the use phase into account, this case study concludes that a series of inter-related factors determine the outcome. We conclude that the evaluations for tire retreading and energy savings is more valuable and justified if conducted on a case-by-case basis.

8. Assumptions and Limitations

Though the intention is to be objective and concrete in evaluations, we acknowledge the limitations that stem from assumptions, data scarcity, and analysis approach. The following assumptions are made for the purpose of analysis that may be prone to scrutiny:

1. The use phase energy consumption of tires was determined by utilizing return factor/energy ratio as opposed to experimental analysis.
2. The coefficient of rolling resistances stated in this report and in literature are determined in steady state laboratory settings; these are not necessarily similar to actual values for tires on the road.
3. The contribution of rolling resistance is equally distributed amongst tires. This may be true for passenger car tires, but it is not the case for truck-trailer combination tires.
4. The fuel economy of the vehicle is taken to be constant during the lifetime of the tire. In reality, the fuel economy of the vehicle changes considerably between different driving cycles. We have compensated for this by taking a range of return factor/energy ratio for contribution of rolling resistance to overall fuel consumption.
5. The experimental values produced by standardized procedures are prone to up to +/-20% in error due to the experimental setup and procedural errors.
6. The analysis above was conducted based on ideal and steady operational conditions. In reality, the change in rolling resistance is directly inter-related with other tire attributes such as wear, traction, inflation, temperature, driving behavior, speed, road effects.
7. The study assumes that tires operate with proper tire inflation pressure and constant vehicle load. Low tire inflation, as well as heavy vehicle load, can also affect vehicle fuel economy (CEC). Lower inflation pressure or heavier vehicle load leads to higher tire distortion, increased friction, and greater energy absorbed by the tires, hence reducing vehicle fuel efficiency. According to the Rubber Manufacturers' Association,

when a tire is under-inflated by 1 pound per square inches (psi), the tire's rolling resistance increases by approximately 1.1%. Therefore, there are strong reasons for encouraging vehicle owners to maintain proper tire inflation pressure. This will not only lead to savings in fuel consumption, but may also contribute to longer tire lifetime and improvement in vehicle safety (CEC).

8. In the analysis for passenger car tires, we assume that raw materials processing and manufacturing energy consumptions are similar for tires produced between 1977 and 2004. In reality, raw materials processing and manufacturing steps may have become more efficient in the past few decades, making production energy expenditures less. However, due to data limitations we overlook the dynamic changes in energy demands for producing tires.
9. In the analysis for truck tires, we assume that bias ply, radial ply, advanced radial ply, and single wide-base tires to have similar materials compositions. This is a limitation given that the construction of each tire type is distinctly different from the rest. However, due to data limitations we overlook the variations in production energy costs.
10. In the analysis for truck tires, we assume that new radial truck tires have similar coefficient of rolling resistance than old retreaded tires. This assumption is true for cases where the fleet travels long-distances and has a high turnover rates for tires, hence, retreading used tires that are relatively up-to-date in terms of tire technology.

3.5 Electric Motor Remanufacturing and Energy Savings Case Study

1. Introduction and Motivation

Electric motors are devices that intake electrical energy and convert it into mechanical work. Electric motors are ubiquitous; their applications span across products used commonly in residential and commercial sectors (e.g. household and commercial appliances, power tools, etc). In addition, electric motors are actively used in the industry (e.g. industrial fans, pumps, blowers compressors). In the U.S. industrial sector alone over 13.5 Billion electric motors are in use (Scheihing, Rosenberg et al.). As a result, 70% of the industrial electricity demands are directly or indirectly related to motor-driven applications (Xenergy 1998).

2. Motor Classifications

Electric motors can be classified into different groups based on operational mechanism, design, power ratings, size, speed.

Operational Mechanism

Electric motors can be classified based on the mechanisms by which electrical power intake is converted to mechanical work. In this regards, three types of motors are most common: (1) AC induction, (2) AC synchronous, (3) DC. Nadel *et al.* provide a comprehensive discussion about each motor (Nadel, Elliott et al. 1992),(Website4). Refer to (MITEI-1-c-2010) for further detailed information about each motor classifications.

Design

Motors are also classified by the electric system construction and design as well as the type of enclosures used. For example, motor enclosures can be classified into two broad categories: (1) Machines with open enclosures (i.e. Open Drip Proof), and (2) Totally Enclosed Enclosures (i.e. Totally Enclosed Fan Cooled).

The National Electrical Manufacturers Association (NEMA) is in charge of classifying the types of electric motors based on design and construction. According to NEMA, the most commonly used electric motor design is induction motor design B (Nadel, Elliott et al. 1992). Refer to (MITEI-1-c-2010) for further detailed information about motor classifications based on design.

Power Rating and Size

Motors are constructed with power ratings that vary from as small as 1 hp (746 Watts) to more than 500 hp (373 kilo-watts). Small motors can be found in window or attic fans while large motors are used in industrial operations such as chemicals processing, paper production, food processing (Xenergy 1998).

Speed

Rotation of the motor shaft (measured in revolutions per minute [RPM] or Hz) defines the speed of operation. The rotational speed has a strong impact on the output power of the motors. Motors are also classified based on the range of operating speeds.

3. Electric Motor Efficiency

In order to understand the economic and environmental impacts of motors we discuss the performance of motors in the use phase. Motor performance is characterized by the efficiency in converting electrical energy to mechanical energy as shown below:

$$Efficiency = \frac{\text{Output Mechanical Work}}{\text{Input Electrical Work}} \qquad \text{Equation 27}$$

The efficiency of the electric motor is bound by energy losses due to its construction, operational circumstances, and thermodynamic limits of converting electrical energy to mechanical energy. Usable energy is lost from various regions of the stator and rotor winding, through friction and winding, the core, and miscellaneous losses that encompass leakage of flux. (Nadel, Elliott et al. 1992).

Impact of Efficiency on Use Phase Energy Consumption

Equation below represents the general formula for computing the energy consumed by a motor during use:

$$E_{Total}[kWh] = (\text{Motor Rating[kWh]}).\frac{1}{\eta}...$$
$$...(\text{\% of Rated Load}).(\frac{\text{Operating Hours}}{\text{Year}}).(\text{Total Use Years}) \qquad \text{Equation 28}$$

where E_{Total}, Motor Rating, η, % of Rated Load, Operating Hours per year, and Total Use Years are the total energy consumed by the motor, output power for the motor, the operational efficiency at a given operational load, actual load served by the motor as a % of the rated full-load capacity of the motor, annual hours of operation, and the operational lifetime of the motor, respectively.

Motor efficiency has a large impact on its energy performances. Consider the example of an industrial motor with motor rating of 74.6 kW (100 hp). Industrial motors of this magnitude can have a physical lifetime limit of as long as 28.5 years (Andreas 1992). Assuming the motor is operating at 100% of rated full-load capacity with efficiency of 90% for 4,163 hours/ year (Nadel, Elliott et al. 1992), then the use energy consumption during the lifetime of the motor is 9,843,363 kWh.

If the efficiency of the motor drops by 2 units (i.e. η=88%) then the use energy rises to 10,057,902 kWh. An increase of nearly 224 MWh due to 2% decline in absolute efficiency illustrates that motor performance has a significant impact on the energy demands for operating electric motors. Therefore, from an energy standpoint, it is most preferable to utilize motors that have higher efficiency metrics during operation as long as other operational requirements are met. In relation to this, there have been industrial interventions and policy directives standardizing motor efficiency as well as promoting the use of new motors built with higher efficiencies.

4. Policy, regulation, and standards

Enhancing motor efficiency has been an active policy-related issue for the past two decades leading to implementation of minimum performance efficiency standards as well as adoption of voluntary standards. Efforts for enhancing efficiency of electric motors have led to the introduction of a new class of motors referred to as Energy-Efficient motors by the National Electrical Manufacturers Association (NEMA). NEMA is the main industrial agency for advocating voluntary-based energy efficiency standards for electric motors since the 1970s. NEMA continues to update efficiency standards as new raw materials are introduced and manufacturing processes become more technologically advanced.

Under the Energy Policy Act (EPAct) of 1992, the U.S. Department of Energy (DOE) utilized the NEMA efficiency standards to set mandatory requirements for minimum operational efficiency of new general purpose electric motors. Motors that were manufactured or imported in the U.S. by October 1997 had to comply with the new DOE EPAct efficiency standards. Refer to (MITEI-1-c-2010) for detailed information about the EPAct mandates and the types of motors chosen to meet EPAct policy requirements.

In 2001, NEMA established more stringent efficiency standards referred to as 'NEMA Premium.' NEMA Premium efficiency standards stemmed from two distinct initiatives: (1) efforts led by the Consortium of Energy Efficiency (CEE) for establishing premium-efficiency specifications and (2) the initiation of Energy Star label by the Environmental Protection Agency (EPA).

In summary, the industrial and governmental directives for standardizing minimum efficiency performance of electric motors are:

1. NEMA standards (1970s to 1990s / Voluntary).
2. EPAct minimum efficiency standards (1992/ Mandatory).
3. NEMA Premium efficiency standards (2001/ Voluntary).

In this study, the electric motors that are do not necessarily comply to any standards only are referred to as Standard motors. Furthermore, motors that comply with NEMA and EPAct standards are referred to as Energy Efficient motors in this study. Lastly, motors that abide by NEMA, EPAct, and NEMA Premium standards are referred to as NEMA Premium motors in this report.

In addition, the Energy Independence and Security Act (EISA) of 2007 will adopt the NEMA Premium as a mandatory minimum efficiency standard by enforcing the following directives, which will take effect in December 2010:

- All motors as defined by the EPAct of 1992 must abide by the NEMA Premium motors standards by 2010.
- Motor types with power rating between 1 to 200 horsepower that were not included in the 1992 EPAct standards must comply with the EPACT standards.
- Motors between 201 to 500 horsepower (initially excluded from EPAct) must be manufactured such that they meet minimum efficiency standards in EPAct of 1992.

Figure 38 illustrates the efficiency standards for different motor sizes.

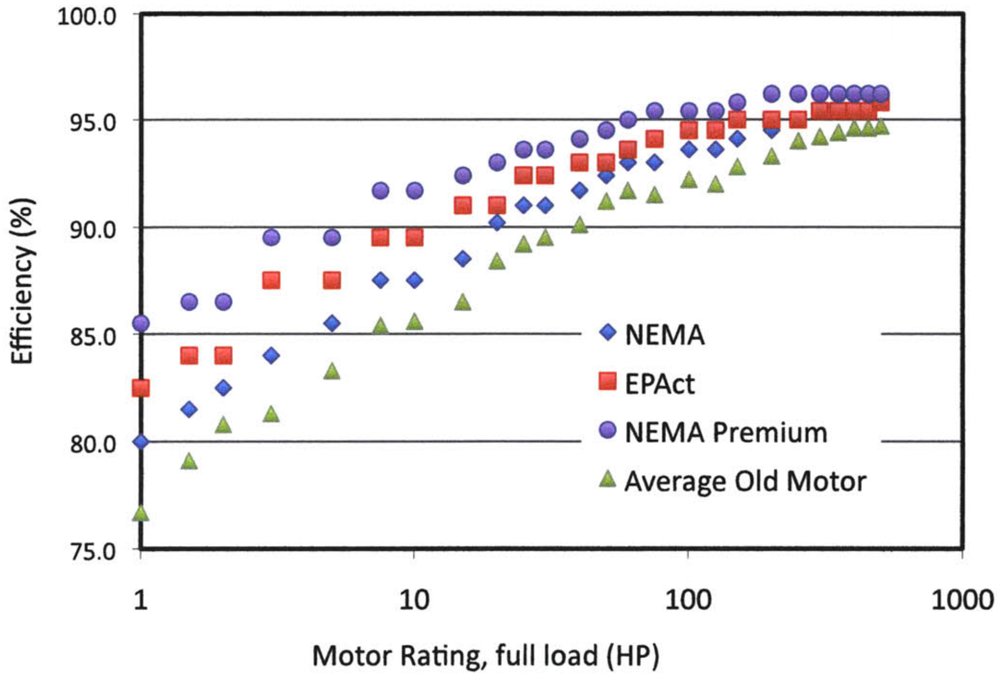


Figure 38 Efficiency standards of different motors compared with the average old motors before NEMA standardizations (EPA 2007).

5. Electric Motor Remanufacturing

Electric motors break down due to various reasons such as corrosion, friction, contamination, power supply anomalies, overloading. A common reason for motors breaking down is winding and bearing failure. Unfavorable operating conditions (electrical, mechanical or environmental) can cause the electric motor to overheat, which in turn, damages the insulation and ventilation channels. Such damages can eventually damage the winding and bearing and cause pre-mature failure of the motor.

Conventionally, electric motors that have reached end-of-life are restored to like-new conditions by motor rewinding (an industry-specific term for motor remanufacturing). When an electric motor reaches end-of-life the user can send the motor to be rewound in order to restore it to like-new conditions and extend its operational services.

The process of electric motor rewinding is an industrial process that consists of initial testing, coil removal process, stator winding, post-winding tests, varnish insulations, and final testing (Penrose, Inc et al. 1997). Note that the rewinding processes can vary from rewinder to rewinder.

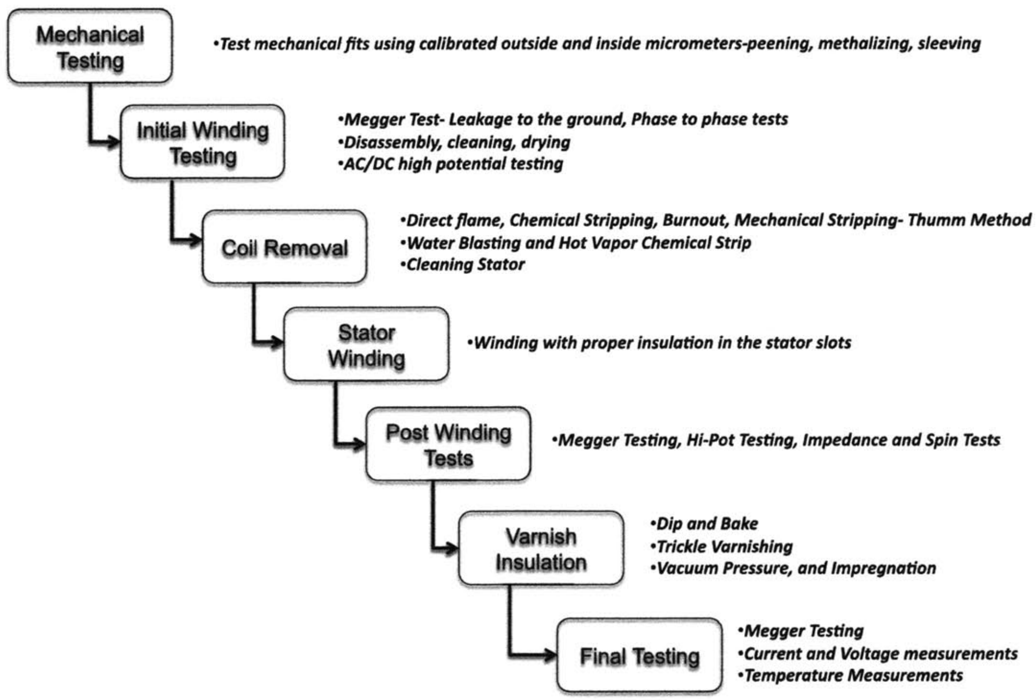


Figure 39 Electric motor rewinding (remanufacturing) process (Penrose, Inc et al. 1997).

Nadel *et al.* states that on average, an electric motor fails every 5 to7 years, which means that electric motors (especially industrial motors) are rewound about 4 to 6 times prior to being permanently scrapped (Nadel, Elliott et al. 1992). Given that motors are extensively remanufactured, it is critical to understand the impacts of rewinding on the efficiency of electric motors.

5.1 Impact of Remanufacturing (Rewinding) on Motor Energy Efficiency

The effects of motor rewinding on efficiency have been studied extensively in literature. Though the intention of rewinding is to bring motors back to like-new conditions, some rewinders may not adhere to strict regiments. As a result, the rewound motor could potentially be less efficient than a new motor. Penrose, Cao *et al.*, and Nadel *et al.* discuss the changes in full-load efficiency due to rewinding (Cao and Bradley 2006),(Penrose, Inc et al. 1997),(Nadel, Elliott et al. 1992),(EASA 2002),(EERE). More specifically, we have compiled information from the Department of Energy (DOE) and Energy Efficiency and Renewable Energy (EERE). Based on the gathered information it appears that by rewinding an electric motor it decreases the efficiency of performance for motors that are less than 40 hp (30 kW) by 1%. The corresponding degradation in efficiency for motors that are larger than 40 hp (30 kW) is about 0.5% (AEMT 2003).

6. Methodology

6.1 Case Study Objectives

The objective of this study is to quantify the energy savings potential and economic feasibility of electric motor rewinding. The scope of analysis for evaluating life cycle energy savings of motor rewinding is focused on two primary concepts: (1) the impact of rewinding on efficiency of electric motors, and (2) improvements in energy efficiency of new electric motors due to industrial and governmental standards.

6.2 Product Scope

We study two distinct types of electric motors (based on size), namely, an AC low voltage cast iron 22 kW (less than 30 hp) electric motor and an AC low voltage cast iron 200 kW (about 270 hp) electric motor, both produced by ABB.

6.3 Life Cycle Assessment

We utilize Life Cycle Assessment (detailed in Chapter 2) in order to quantify the life cycle energy consumptions of electric motors. The Life Cycle Assessment is based on three main lifecycle phases:

Raw Material Acquisition and Processing Phase

Extraction and production of the raw materials needed for manufacturing the motors

Manufacturing and Assembly Phase

All processes entailing parts manufacturing, fabrication, and assembly are included in this phase

Use Phase

Use of the electric motor by the user

The above phases define the boundary conditions of life cycle assessment for this study. We conduct Life Cycle Costing from a consumer's perspective taking into account two main stages for economic costing, namely, upfront cost (product initial price or rewind price) and operational cost (ownership costs during use-phase)

Moreover, we showcase the impact of motor rewinding on total lifecycle energy and economic savings of electric motors.

6.4 Data Sources

For each phase of the product lifecycle we rely on literature information to quantify the energy and economic impact indicators for LCI and LCC. For the use phase we have utilized Motormaster+ database, which is a software for economic analysis of electric motors recommended by DOE (EERE).

The data sources for each phase of Life Cycle Inventory are as follows,

- Raw material acquisition and processing: (de Almeida, Ferreira et al. 2008)
- Manufacturing: (de Almeida, Ferreira et al. 2008)
- Use:
  - Usage hours: (Xenergy 1998)
  - Usage years: (Nadel, Elliott et al. 1992)
  - Efficiencies: (EERE)

The data sources for each phase of Life Cycle Costing are as follows,

- Price listing for new, installation cost of new, rewind cost, discount rates: (EERE)
- Electricity prices: (DOE 2009)

6.5 Life Cycle Inventory: Energy Demands Analysis

Life cycle assessment for the two motors is broken into the three primary phases- raw materials processing, manufacturing, and use phase.

Raw Material Acquisition and Processing

In order to determine the energy requirements for this life cycle stage, we use the bill of materials as provided by (de Almeida, Ferreira et al. 2008) and assign the amount of energy required to produce each raw material. The bill of materials used in this study is a modified version of those provided in (de Almeida, Ferreira et al. 2008). More specifically, the bill of materials in (de Almeida, Ferreira et al. 2008) are for 1.1 kW, 11 kW, and 110 kW motors. We observed that the motor weight and specific energy to process the raw materials scaled linearly with size (i.e. motor kW rating). As such, we performed linear extrapolations of 11 kW and 110 kW motors in (de Almeida, Ferreira et al. 2008) to determine the raw materials energy requirements for 22 kW and 200 kW motors. Further details about the studied electric motors are provided in (MITEI-1-c-2010). For comparison, we utilized energy intensity values from (Smil 2008),(Ashby 2009) and determined the processing energy for each raw material and conclude that they are similar to those expressed in (de Almeida, Ferreira et al. 2008) as shown in Table 22 below.

Table 22 Materials compositions for the two products under study (de Almeida, Ferreira et al. 2008).

	22kW			200kW	
Material	**Standard Efficiency**	**Energy Efficient**	**NEMA Premium**	**Standard Efficiency**	**NEMA Premium**
Electrical Steel	79	106	134	620	800
Other Steel	21	22	23	134	154
Cast Iron	29	22	29	600	600
Aluminum	20	17	24	36	50
Copper	14	20	24	108	140
Insulation Material	0	0	0	2	2
Impregnation Resin	2	2	2	10	10
Paint	1	1	1	2	2
Total (Kg)	**166**	**190**	**238**	**1,512**	**1,758**
Energy using (Smil 2008) (MJ)	**13,779**	**15,419**	**19,716**	**90,040**	**109,860**
Energy from (de Almeida, Ferreira et al. 2008)(MJ)	**13,216**	**15,590**	**16,754**	**98,822**	**101,316**

For this study, we utilize the energy consumption values for raw materials extraction and processing provided by (de Almeida, Ferreira et al. 2008). The total energy for raw materials extraction and processing is 13,216 MJ, 15,590 MJ, and 16,754 MJ for the 22 kW Standard Efficiency, Energy Efficiency, and NEMA Premium electric motors, respectively; for 200 kW motors the energy expenditures amount to 98,822 MJ and

101,316 MJ for the 200 kW Standard Efficiency and NEMA Premium motors, respectively (de Almeida, Ferreira et al. 2008).

Manufacturing and Assembly Phase

Similar to raw materials processing, we computed the manufacturing energies for 22kW and 200kW motors, by scaling (i.e. linearly extrapolating) the results for the 11 kW and the 110 kW motors as provided in (de Almeida, Ferreira et al. 2008). For more information about this stage refer to (MITEI-1-c-2010).

Remanufacturing (Rewinding) Phase

The energy requirement for rewinding is underestimated in this study. This is because the analysis considers the energy requirements for rewinding to be only the amount of copper wiring required to rewind the motor. In reality, each and every process outlined in Figure 39 above incurs energy in order to successfully rewind motors. But due to lack of data we neglect the processing energy cost, and hence, bias the energy savings calculations in favor of motor rewinding. Therefore, based on these assumptions, the energy required to rewind a 22 kW and 200 kW motor is just the energy required to produce copper winding and paint (refer to Table 22).

Use Phase

In order to determine the use phase energy consumptions we utilize Equation 28 above. According to this, the input parameters for determining energy consumption of electric motors are:

- Rated power of motor
- Load at which the motor is operating (% of full load)
- Efficiency of motor at that load
- Total annual hours of operation
- Total years of operation between subsequent rewinds

This study assumes that the load of operation is 75%, as explained by Campbell *et al.* and Nadel *et al.* (Campbell 1997), (Nadel, Elliott et al. 1992) Motor efficiencies are taken from Motormaster + whereby the database showcases average efficiencies of motors in years 2005 and 2006 (EERE). The efficiency values are average values for every motor category (NEMA, EPAct, NEMA Premium). According to the discussions above, the rewinding process would degrade efficiency of 22 kW and 200 kW motors by 1% and 0.5%, respectively. As such, the efficiencies of motors analyzed in this report are as shown below:

Table 23 Efficiencies of motors analyzed (EERE)

22 kW MOTOR	Efficiency
Standard	90.2%
Standard after rewind	89.2%
Energy Efficient	93.2%
Energy Efficient after rewind	92.2%
NEMA Premium	94.1%
NEMA Premium rewind	93.1%
200 kW MOTOR	Efficiency
Standard	94.1%
Standard after rewind	93.6%
NEMA Premium	96.3%
NEMA Premium rewound	95.8%

Nadel *et al.* estimates that the years between subsequent rewind is about 5-7 years (Nadel, Elliott et al. 1992). We use 6 years as the average operational time of motors in-between subsequent re-windings. Hirzel and Montgomery comment on the deterioration of motor efficiency during the use phase of the motor (Hirzel 1994), (Montgomery 1984). One example is aging of the core steel leads to internal losses. Since no quantitative data was found, we assume that there is no on-going deterioration in energy efficiency during the use phase.

6.6 Life Cycle Costing Analysis

Life Cycle Costing is carried out in this report by focusing on the monetary costs and benefits for the consumer. From a consumer's perspective, there are two main costs associated to operating a motor:

1. Upfront Cost: Purchase price for a new electric motor or the price to rewind an existing motor.
2. Ownership Cost: Operational cost, which is predominantly based on electricity cost in this study.

Upfront costs

If a consumer is considering between purchasing a new motor and rewinding an old motor he/she will be concerned about the purchase price of the new motor as well as the rewinding costs. The purchase price is the market value of new motors available for sale. (EERE) provides data for the average price of motors in year 2005. Rewinding cost is based on fees charged by third party motor rewinding officials. The rewinding fee may vary between workshops and it could be negotiated. (EERE) provides average fees collected in year 2005 for motor rewinding; this data is used in this study. Also there is an installation and maintenance cost associated with purchasing new motors. For this, we utilize data from (EERE). Industrial motors are seldom sold at the list price; discounts are typically applied to incentivize prospective customers to purchase new motors. The extent of discounting depends on the manufacturer, dealer, motor type, etc; this study uses the discount rate give by (EERE).

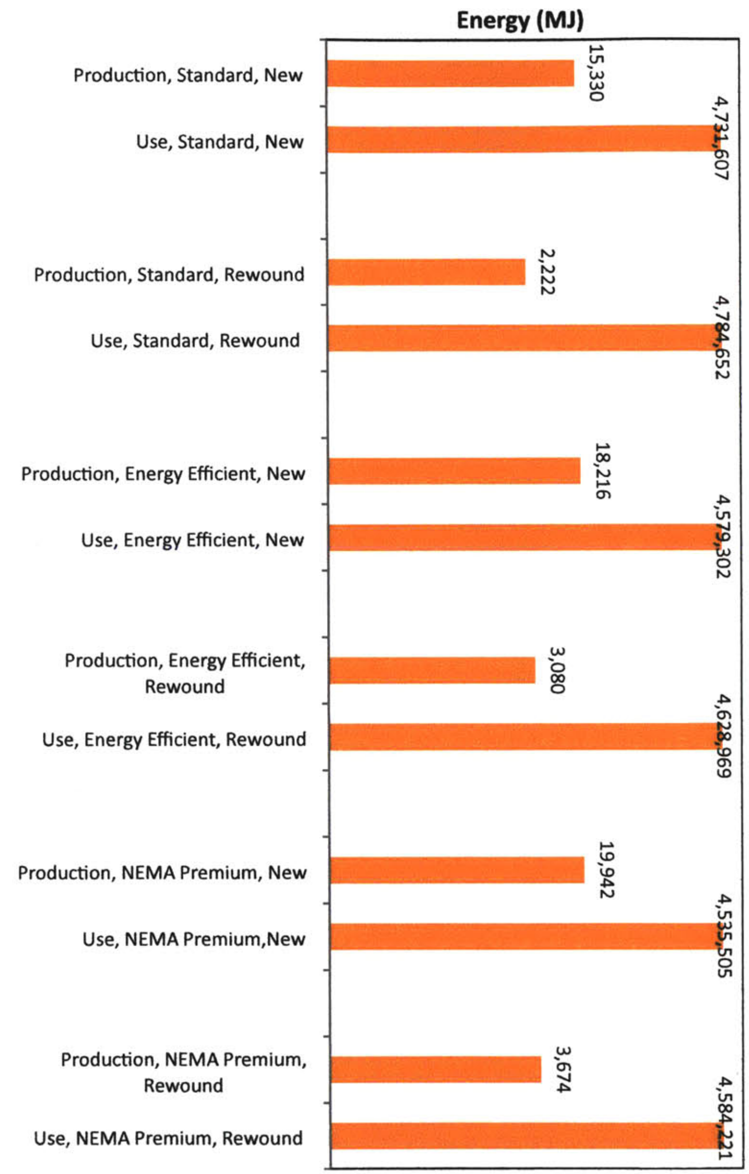
Ownership Costs

The ownership costs are computed based on electricity cost only, which is one of the main costs in the use phase for operating a motor. The price of electricity was obtained from (DOE 2009) and the operating cost was estimated similarly to the energy calculations for the use phase in LCA. Though cost of maintenance and repair may be significant for industrial motors, due to lack of data, they are ignored in this study. Using the above information, we compute the use phase energy consumption of the three classes of electric motors, namely, Standard, Energy Efficient, and NEMA Premium.

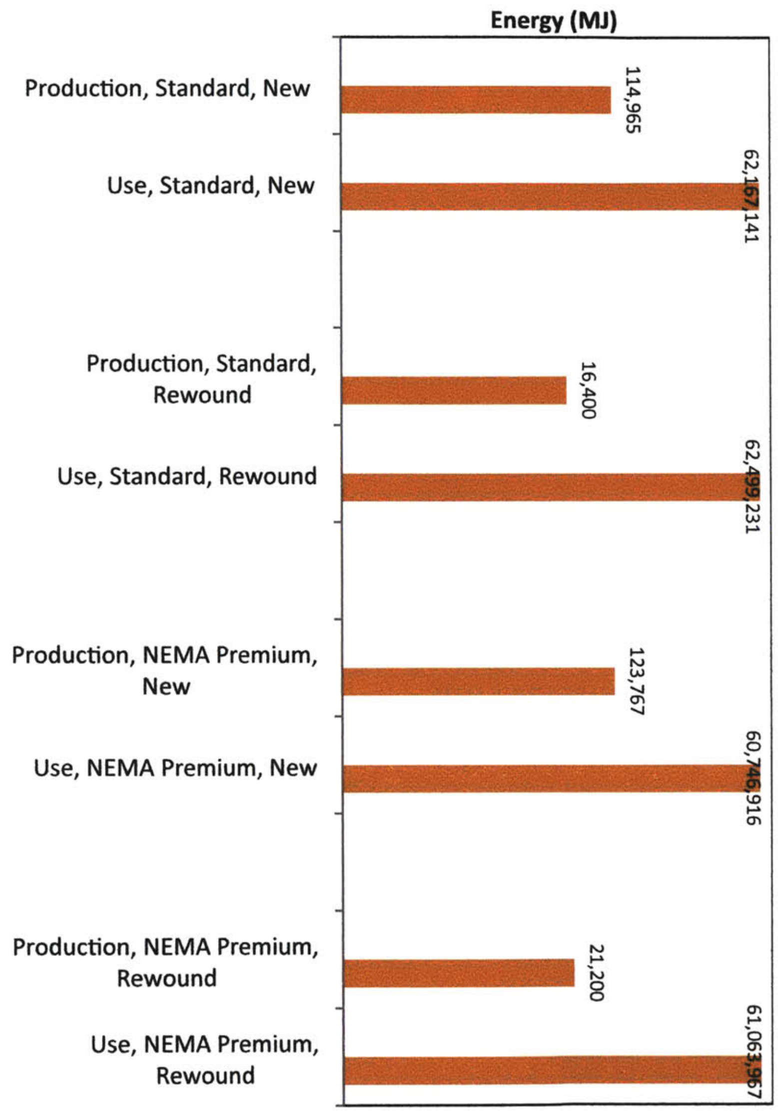
7. Results

7.1 Life Cycle Inventory Results: Energy Demands Analysis

The energy analysis above leads to total life cycle energy costs (in logarithmic scale) as shown in Figure 40 below.


Energy (MJ)
Production, Standard, New
15,330
Use, Standard, New
4,731,607
Production, Standard, Rewound
2,222
Use, Standard, Rewound
4,784,652
Production, Energy Efficient, New
18,216
Use, Energy Efficient, New
4,579,302
Production, Energy Efficient, Rewound
3,080
Use, Energy Efficient, Rewound
4,628,969
Production, NEMA Premium, New
19,942
Use, NEMA Premium,New
4,535,505
Production, NEMA Premium, Rewound
3,674
Use, NEMA Premium, Rewound
4,584,221

(a)


Energy (MJ)
Production, Standard, New
114,965
Use, Standard, New
62,167,141
Production, Standard, Rewound
16,400
Use, Standard, Rewound
62,499,231
Production, NEMA Premium, New
123,767
Use, NEMA Premium, New
60,746,916
Production, NEMA Premium, Rewound
21,200
Use, NEMA Premium, Rewound
61,063,967

(b)

Figure 40 Life Cycle Inventories for the different motor classes for (a) 22 kW motor; (b) 200 kW motor (based on the case with efficiency deterioration).

The initial observation from Figure 40 is that life cycle energy cost of electric motor is substantially dominated by the use phase. Secondly, more efficient electric motors consume considerably less energy in the use phase. Thirdly, due to potential degradation in efficiency caused by rewinding, then rewinding could lead to substantial life cycle energy costs (1% and 0.5% degradation in efficiency for 22 kW and 200 kW electric motor, respectively, translates to 50 GJ and 300 GJ of extra energy expended). The final observation demonstrates the hypersensitivity of the use phase energy consumption to changes in efficiency.

7.2 Electric Motor Remanufacturing (Rewinding) Analysis Results

Considering the dominance of the use phase in a motor's lifecycle, then efficiency changes caused by motor rewinding may not be beneficial from an energy standpoint. Considering the remanufacturing scenario takes place in year 2005, whereby the consumers' electric motor has broken down (due to overheating, internal failures). The consumer has two options at this point: (1) rewind the old electric motor and prolong its lifetime, (2) purchase an equivalent or more efficient electric motor. The product studied for this analysis are broken into two sub-groups, namely, 22kW electric motors, and 200kW electric motors. Furthermore, if we purchase a new motor, then we assume that the consumer would pick a motor with equivalent or higher efficiency classes. We assume the same motor classes studied in the preceding section, are used in this particular scenario: Standard Efficiency, Energy Efficiency, and NEMA-Premium. For example, a consumer has a 22 kW electric motor that classifies as a Standard Efficiency motor (i.e. referred to as Standard below). As this motor breaks down, then the consumer can either rewind the motor, or purchase a Standard, Energy Efficienct, or NEMA Premium electric motors.

Depending on the choice of new motor, there are three unique comparisons between rewinding and replacing a 22 kW motor:

- Rewinding an old 22 kW Standard Efficiency motor versus purchasing a new 22 kW Standard Efficiency motor
- Rewinding an old 22 kW Standard Efficiency motor versus purchasing a new 22 kW Energy Efficient motor
- Rewinding an old 22 kW Standard Efficiency motor versus purchasing a new 22k kW NEMA Premium motor

Figure 41 below illustrates the decision options above in graphical form,

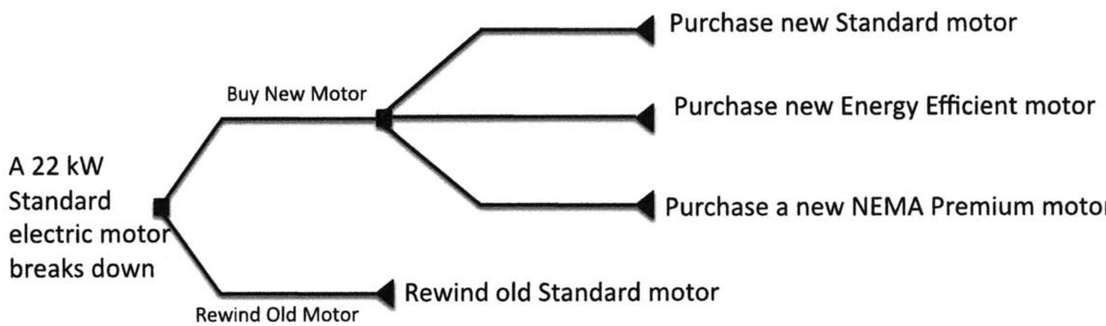


Figure 41 Motor rewinding decision-tree analysis.

By performing similar comparison analysis for an Energy Efficient motor and NEMA Premium motor, we end up with three further scenarios as listed below:

- Rewinding an old 22 kW Energy Efficient motor versus purchasing a new 22 kW Energy Efficient motor.
- Rewinding an old 22 kW Energy Efficient motor versus purchasing a new NEMA Premium motor.
- Rewinding an old 22 kW NEMA Premium motor versus purchasing a new 22 kW NEMA Premium motor.

Therefore, based on the above, there are 6 distinct scenarios for comparing impact of remanufacturing on lifecycle energy of 22 kW electric motors.

Moreover, for the 200 kW motor, similar scenario comparison is conducted, as shown below:

- Rewinding an old 200 kW Standard Efficiency motor versus purchasing a new 200 kW Standard Efficiency Motor
- Rewinding an old 200 kW Standard Efficiency motor versus purchasing a new 200 kW NEMA Premium motor
- Rewinding an old 200 kW NEMA Premium motor versus purchasing a new 200 kW NEMA Premium motor

Since 200 kW electric motors have not undergone mandatory policy measures, then there is no specifications similar to Energy Efficiency standard (e.g. EPACT), hence, only 3 comparison scenarios are shown. For each comparison scenario, there are two possibilities taken into consideration:

1. By rewinding the old motor it is restored to like-new conditions with no changes observed in motor efficiency.
2. By rewinding the old motor the motor efficiency degrades by 1% for 22 kW electric motor, and 0.5% for 200 kW electric motor (EERE).

The total lifecycle energy comparisons of new and rewound electric motors are plotted below. Furthermore, for each scenario the horizontal lines capture the variation in life cycle assessment energy of each rewound based on the degradation in efficiency (propagating between 0 to 1% degradation in efficiency for 22kW motor and 0 to 0.5% degradation in efficiency for 200 kW motor.

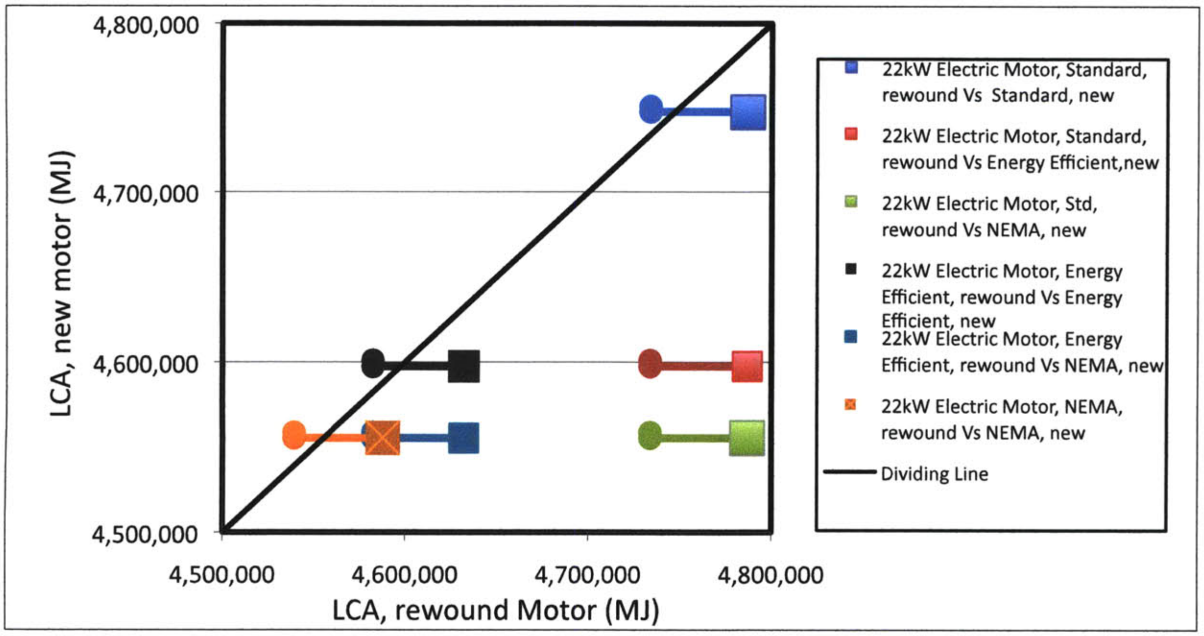


Figure 42 Replace/Rewind energy consumption comparisons for 22 kW motors. The squares represent the case when rewinding impacts the motor efficiency and degrades it, while the circles represent the case when rewinding has no influence on the efficiency of the motor. The energies are given in mega joules.

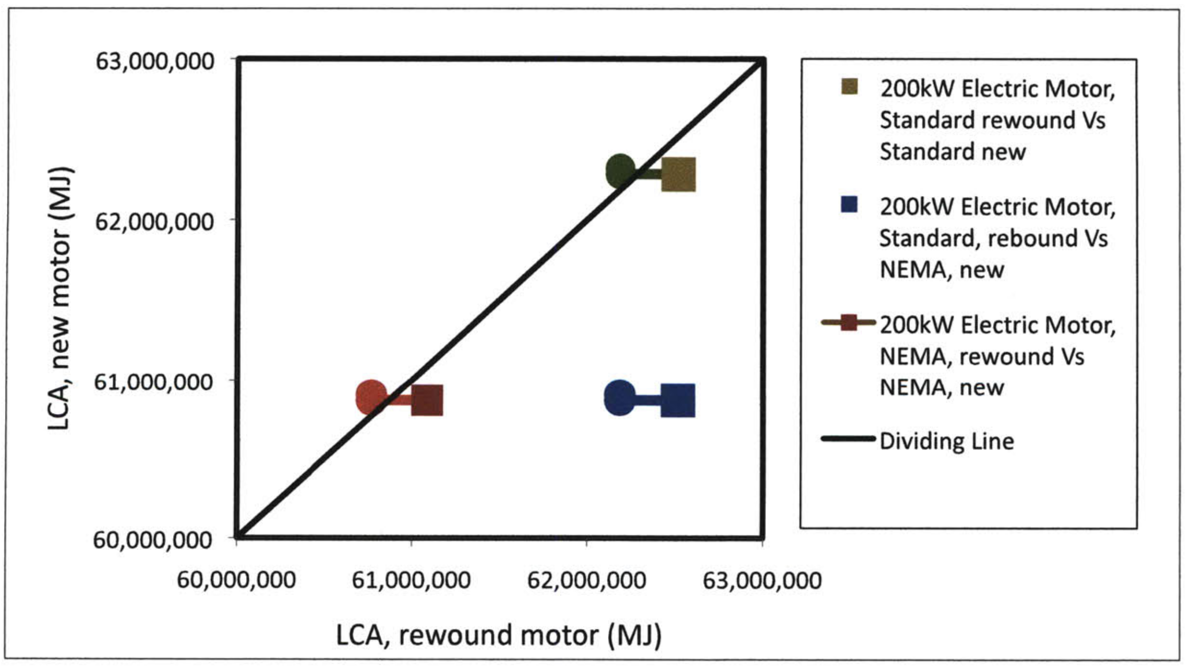


Figure 43 Replace/Rewind energy consumption comparisons for 200 kW motors. The squares represent the case when rewinding impacts the motor efficiency and degrades it, while the circles represent the case when rewinding has no influence on the efficiency of the motor. The energies are given in mega joules.

There are various observations to be drawn from these graphs:

- When the choice is between rewinding an old motor versus purchasing a motor that is of a more efficient class, for all conditions fixed, then the consumer should purchase new in order to save energy.
- As shown in Figure 42 and Figure 43, when considering the decision to rewind/replace motors in equivalent efficiency class (e.g. Standard vs. Standard), depending on the use performance, rewinding energy savings can be energy-saving or energy-expending.

This study illustrates that the lifecycle energy cost of electric motor is dominated by use phase. Moreover, it shows that this use phase is hypersensitive to changes in performance efficiency of the motor. Therefore, the reported degradation in efficiency due to rewinding makes it not a feasible activity for energy savings.

Assumptions

The case study relies on available literature sources. We acknowledge that the robustness of the conclusions is bounded by the estimations, assumptions, approximations, generalizations, etc. Some of the assumptions that are taken into consideration are:

- Life cycle assessment was carried out only for the raw materials processing, manufacturing, and the use phase. In other words, all other phases were assumed to have negligible impact due to the dominance of the use phase.
- The bill of materials shown in Table 22 above is interpolated from data provided by (de Almeida, Ferreira et al. 2008), which provides BOM for 11 kW and 110 kW motors. Due to data limitations, the exact raw materials processing and manufacturing energy for actual 22 kW and 200 kW motors may be varied from the results in this study. Due to the substantial dominance of the use phase we suspect that changes in raw materials processing and manufacturing would not change the conclusions of the analysis.
- We relied on (EERE) to model degradation in efficiency of motors in the use phase

- We assume that degradation in efficiency during the use phase is negligible
- The rated operating load for the motor is assumed to be 75% of full-capacity load. In reality, the operating load can dynamically change based on operational speed, desired output power, etc.

7.3 Life Cycle Costing Results

Figure 44 and Figure 45 below illustrate the total life cycle economic cost for both 22kW and 200 kW electric motors with various efficiency characteristics.

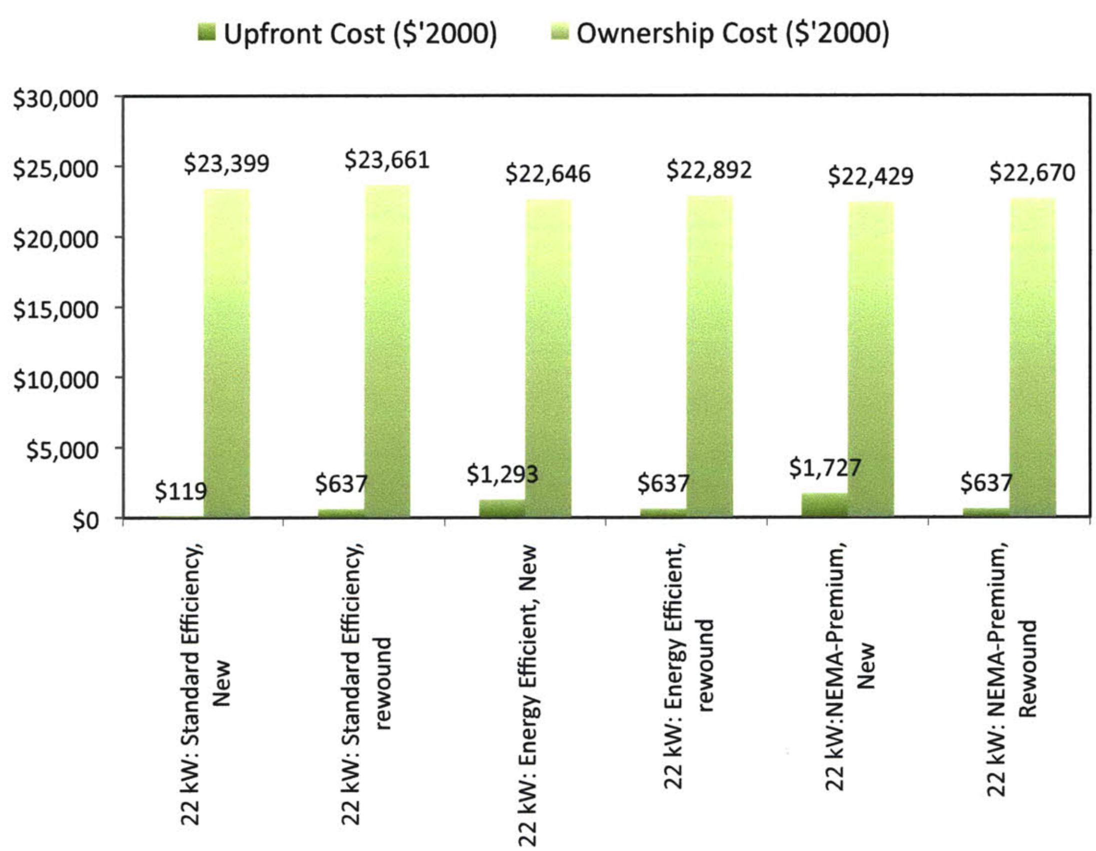


Figure 44 Life Cycle Costing: new and rewound 22 kW electric motors. Costs are normalized to 2000 dollars using the Bureau of Labor Statistics' consumer price index.

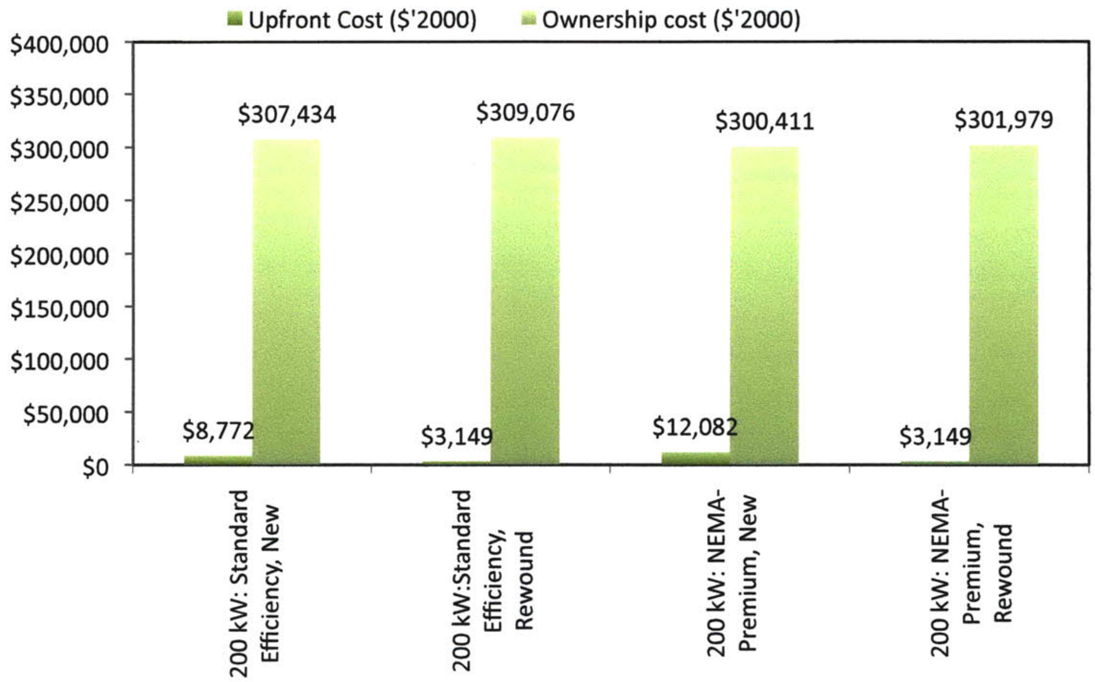


Figure 45 Life Cycle Costing for 200 kW electric Motors. Life Cycle Costing: new and rewound 200 kW electric motors (values in $ '2000). Costs are normalized to 2000 dollars using the Bureau of Labor Statistics' consumer price index for all year.

According to Figure 44 and Figure 45 total lifecycle costs of electric motors is dominated by the use phase.

Similar to energy analysis, the total lifecycle cost of electric motors was compared. Note that the decision scenario is based on similar scenarios put-forth above.

Figure 46 and Figure 47 below illustrate the Life Cycling Costing comparison between new motor and rewound motors.

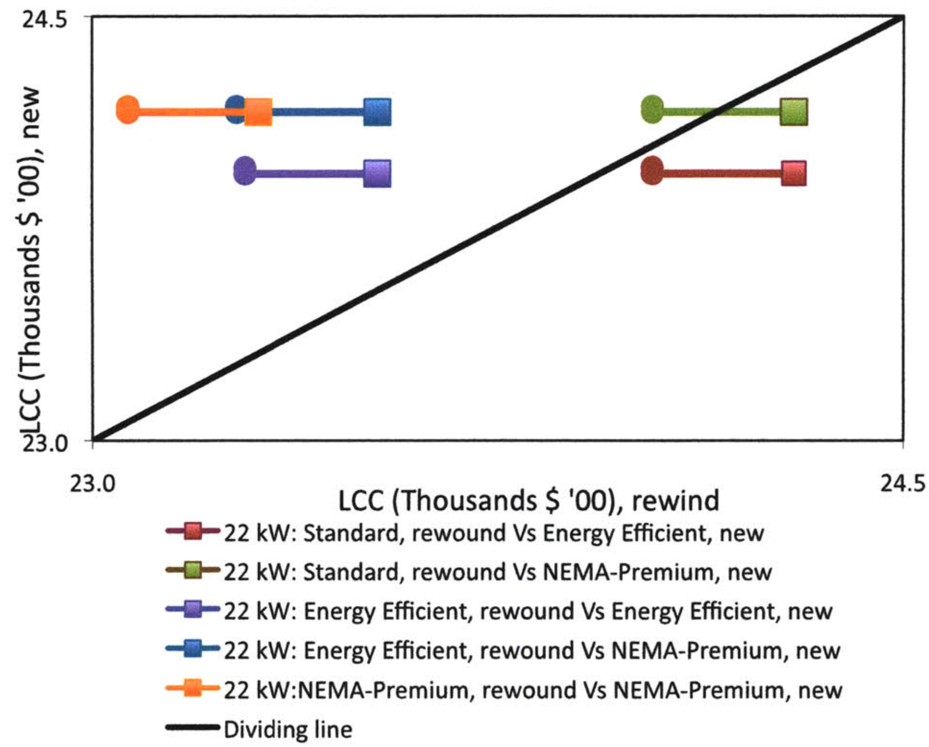


Figure 46 Life Cycle Costing comparisons between new and rewound 22 kW electric motors. The costs are normalized to 2000 dollars using the Bureau of Labor Statistics' consumer price index for all year.

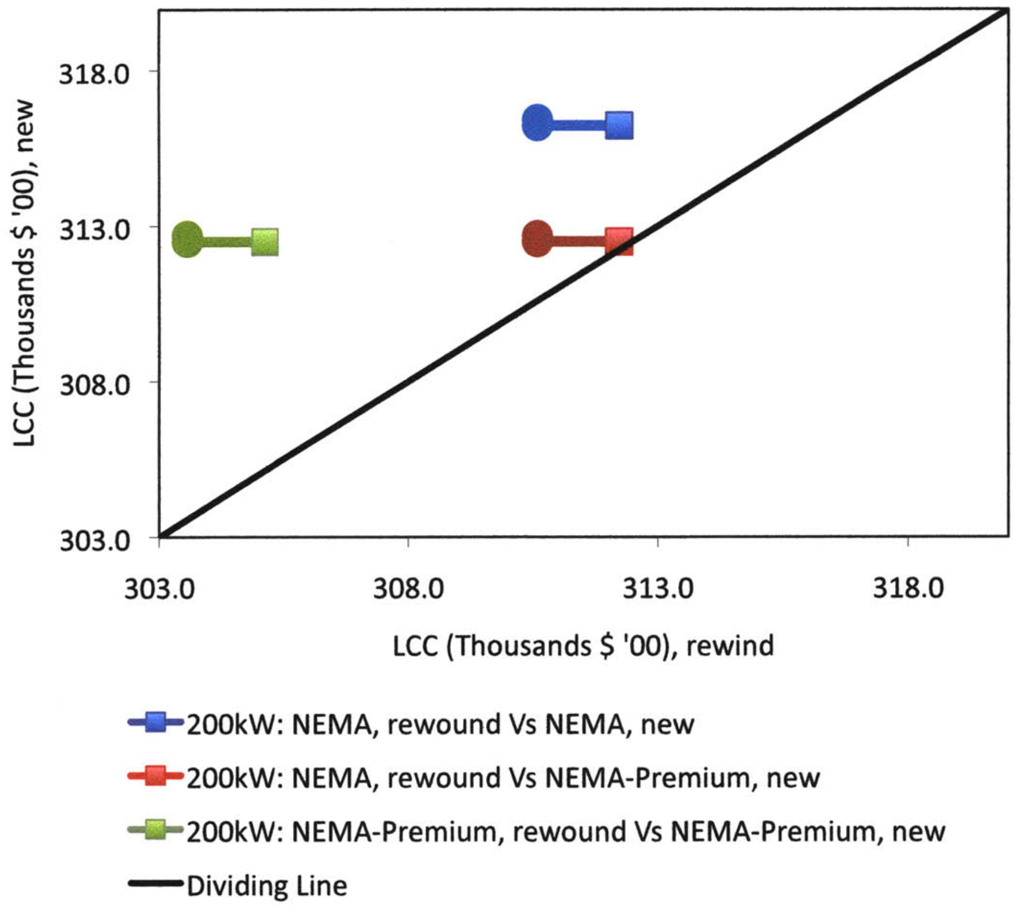


Figure 47 Life Cycle Costing comparisons between new and rewound 200 kW electric motors. The costs are normalized to 2000 dollars using the Bureau of Labor Statistics' consumer price index for all year.

The economic analysis shows that a pattern of economic savings due to rewinding exists. We can draw the following conclusions from the above plots,

- For 22 kW motors, replacing motors with equivalent or more efficient motors, in general, may lead to more economic cost than rewinding.
- For 200 kW motors, rewinding can save between 0 to $10,000 in life cycle cost
- The length of the error bar is an indication to sensitivity of the use phase.
- The findings depict that the % savings by rewinding are less than 5%. Even though such savings may be substantial in absolute terms, it appears minimal in percentage savings. In addition, if we assume that the general error associated with Life Cycle Costing, then the economic savings potential of rewinding is nuanced.

Though the conclusions are nuanced, the general observation here is that the dominating nature of the use phase makes motor rewinding a sensitive topic when it comes to energy savings. Our study illustrates that minor degradations, as cited by literature, can make motor rewinding a net energy expending option. The economic analysis reveals that electric motor rewinding can be an economic feasible option. This may be the reason for motor rewinding having become a common industrial practice despite the degradation in efficiency performance of rewound motors.

8. Conclusions

In this case study we focused on lifecycle energy and economic saving potential of electric motor rewinding. We chose two distinct electric motor sizes, namely, a 22 kW motor and a 200 kW motor, for analysis and studied the gross energy and economic requirements by utilizing Life Cycle Assessment and Life Cycle Costing models. In general our research findings hinted to motor rewinding as being an energy-saving as well as energy-expending end-of-life option. We determined that the dominating influence of the use phase is the primary reason for hypersensitivity of lifecycle energy of rewound motor. For both energy and economic analysis, we found that the percentage savings due to rewinding is within 10% range. By assuming that the inherent error associated with LCA and LCC is within 10% to 15%, then no strong conclusion can be drawn at this point. We claim that remanufacturing energy and economic assessments should be conducted on a case-by-case basis in order to draw insightful conclusions.

3.6 Comprehensive Results

The four in-depth case studies discussed in the preceding passages namely, office furniture, appliances, tires, and electric motor, provided both quantitative as well as qualitative assessments of remanufacturing and energy savings. More broadly, in this research we conduct an in-depth analysis of lifecycle energy savings of remanufacturing. We have studied 19 different products in 8 distinct product case studies (refer to '3. Result and Discussions-Introduction'). We have compiled our research findings into 3 plots in order to show remanufacturing energy savings findings from a holistic perspective:

1. Distribution of energy requirements amongst lifecycle phases of products studied in this research (see Figure 48).
2. Lifecycle energy comparison between new and remanufactured products (see Figure 49).
3. Relative lifecycle energy saving by remanufacturing (see Figure 50).

For additional information about research approach, comparison context, and references for each case study, please refer to the MIT Energy Initiative Publication Series Reports (MITEI-1-2010) (see '3. Results and Discussions- Introduction'). For each product case study, we quantified the energy demands for the production and the use phases. The results of our lifecycle analysis for the distribution of energy impacts are depicted in Figure 48 below. Figure 48 shows that the distribution of energy between the production phase and the use phase varies considerably based on the type of product and operational services.

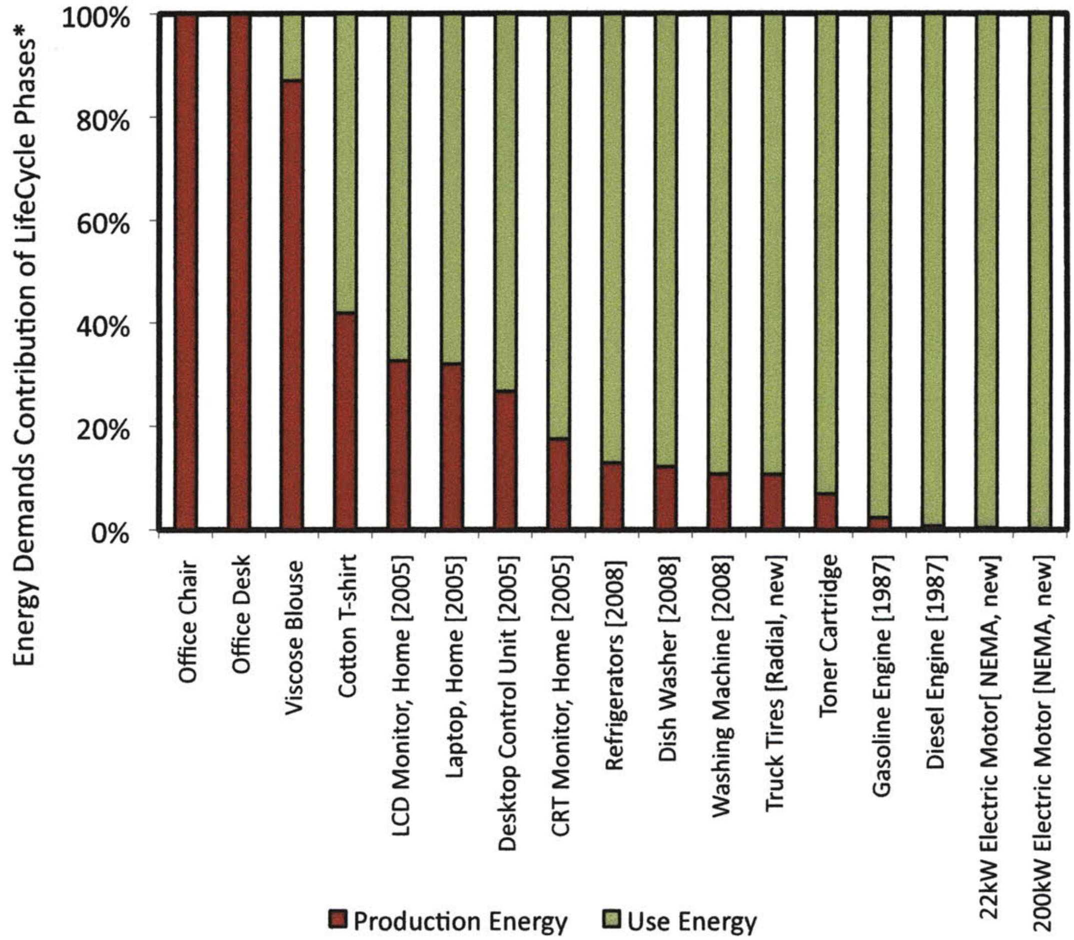


Figure 48 Distribution of energy requirements amongst lifecycle phases of product. The information in the brackets reveal the model/characteristic of the product.* Refer to Table 24 for detailed information about the products shown in this plot.

Figure 49 below depicts the life cycle energy consumption, in absolute terms, of new products versus remanufactured products in log-log form for all products studied in this research project. Our lifecycle assessment illustrates that the lifecycle energy expenditure of products varies by a few orders of magnitude (see Figure 49).

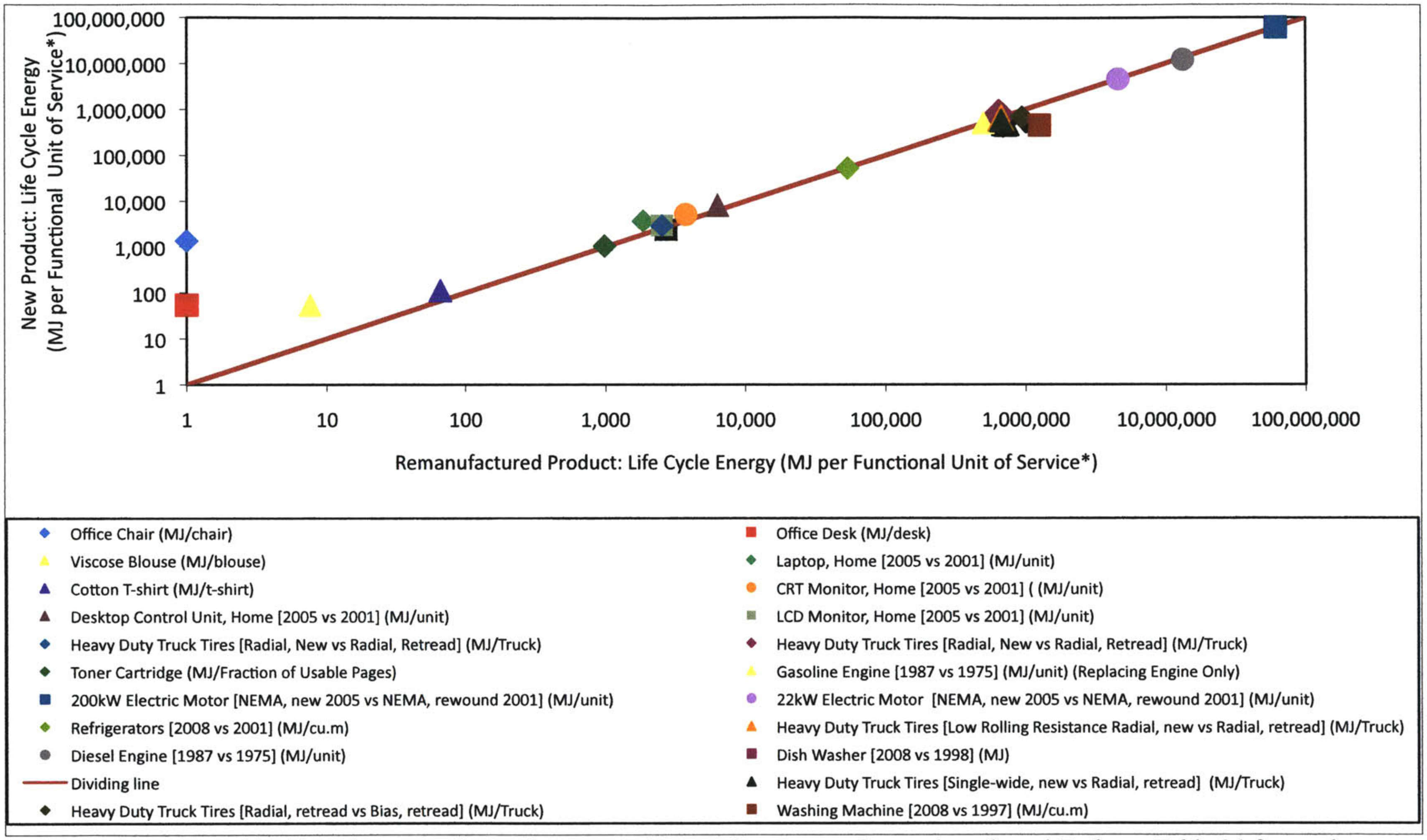


Figure 49 Lifecycle energy demands: new product against remanufactured product. * Refer to Table 24 for product description.

Given that Figure 49 is in log-log scale, it is difficult to characterize the lifecycle energy savings of remanufacturing. Therefore, Figure 50 depicts percentage lifecycle energy savings of products shown in Figure 49. Moreover, Figure 50 illustrates the wide variation of lifecycle energy savings of remanufactured products.

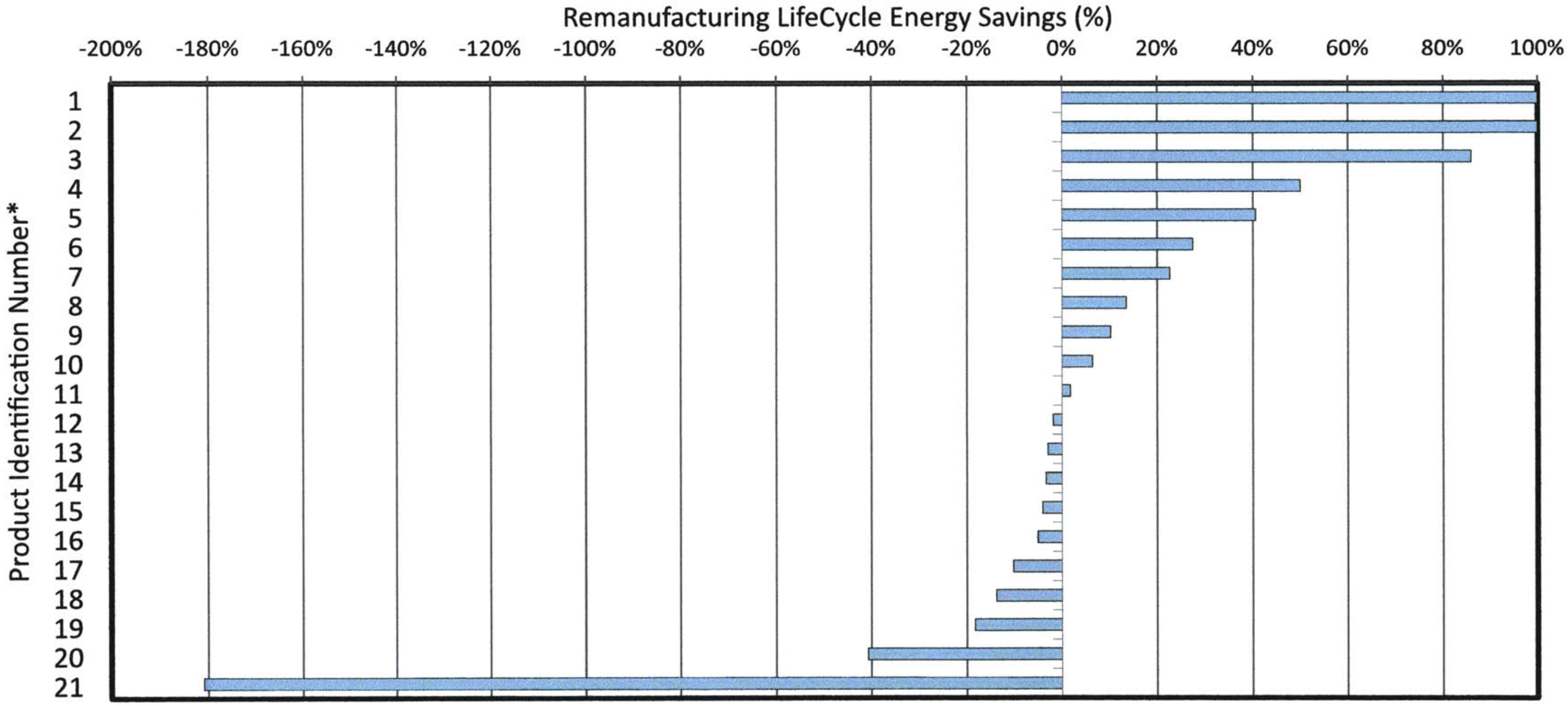


Figure 50 Life cycle energy savings: remanufacturing with respect to new. * Refer to Table 24 for product description.

Table 24 Product code, product name, functional unit of service, remanufacturing and remanufacturing comparison analysis.

Product Identification Number	**Product Name**	**Functional Unit of Service**	**Remanufacturing Comparison Analysis**	
			New Model Type/Year	**Remanufactured Model Type/Year**
1	Office Chair	MJ/chair	NA	NA
2	Office Desk	MJ/desk	NA	NA
3	Viscose Blouse	MJ/blouse	NA	NA
4	Laptop, Home	MJ/unit	2005	2001
5	Cotton T-shirt	MJ/t-shirt	NA	NA
6	CRT Monitor, Home	MJ/unit	2005	2001
7	Desktop Control Unit, Home	MJ/unit	2005	2001
8	LCD Monitor, Home	MJ/unit	2005	2001
9	Heavy Duty Truck Tire	MJ/Truck	Radial, New	Radial, Retread
10	Toner Cartridge	MJ/ fraction of usable pages)	NA	NA
11	Gasoline Engine	MJ/unit	1987	1975
12	Refrigerator	MJ/cubic meter volume	2008	2001
13	Heavy Duty Truck Tire	MJ/truck	Low Rolling Resistance Radial, New	Radial Retread
14	22kW Electric Motor	MJ/unit	NEMA new 2005	NEMA rewound 2001
15	22kW Electric Motor	MJ/unit	Energy Efficient, new 2005	Standard, rewound 2001
16	22kW Electric Motor	MJ/unit	NEMA, new 2005	Standard, rewound
17	Diesel Engine	MJ/unit	1987	1975
18	Dish Washer	MJ/unit	2008	1998
19	Heavy Duty Truck Tire	MJ/truck	Single-wide, new	Radial, retread
20	Heavy Duty Truck Tire	MJ/truck	Radial, retread	Bias, retread
21	Washing Machine	MJ/ unit	2008	1997

4. Conclusions

4.1 Summary of Quantitative Research Results and Conclusions

In this research we have addressed energy saving in remanufacturing by quantifying cumulative energy demands of a remanufactured product during its lifecycle and comparing it to an equivalent new product. Remanufacturing can close the loop between disposal and supply chains, extend the service lifetime of products, conserve resources, and minimize environmental consequences attributed to landfilling. Moreover, by preserving the geometrical architecture of cores, remanufacturing can save energy in the raw material processing and the manufacturing phases. Therefore, remanufacturing as an end-of-life option benefits the environment by conserving raw material and energy in the production of products in addition to minimizing waste disposal in landfills. In relation to this, we have shown in the office furniture case study that remanufacturing saves a large portion of lifecycle energy for office chair and office desk. Furthermore, by performing lifecycle evaluations we conclude that remanufacturing can be a net energy-saving option for products that have energy requirements dominated by the production phase, (i.e. office desk, office chair, and viscose blouse) (see Figure 49 and Figure 50).

Prior research on remanufacturing supports such claims by revealing remanufacturing as a desirable end-of-life option in conserving raw material and energy in producing products (Hauser and Lund 2003), (Sundin 2004), (Bras 1996), (Graedel and Allenby 1996), (Jackobsson 2000), and (Steinhilper 1998). On the other hand, prior research on environmental impacts of remanufacturing has suggested that remanufacturing energy-saving can be subjected to the use phase dynamics (Sundin 2004),(Kutz 2007),(Hauser and Lund 2008), (Smith and Keoleian 2004), (Hauser and Lund 2003), (Jackobsson 2000).

In order to address remanufacturing energy savings from a holistic view, we extended the analysis to include the use phase. Our findings indicate that the distribution of energy demands varies extensively between the production phase and the use phase based on the type of product and operational services (see Figure 48). More specifically, the results illustrate that the use phase dominates the lifecycle energy demands for many of the products especially those that are powered by internal combustion engines or relying on electric power (see Figure 48). For example, the high consumption of energy in the use phase causes electric motors, engines, appliances, and tires to have high life cycle energy costs. High use energy requirements are leading to global challenges in regard to energy conservation. For example, the proliferation of electric and electronic products amounts to one of the largest sources of power demand globally. According to International Energy Agency (IEA), information and communication technologies and consumer electronics represent 15% of global residential electricity consumption (IEA 2009). The IEA expects that the energy use by these technologies to increase threefolds in the next two decades (IEA 2009). This trend will grow even more as many products continue evolving from passive products (i.e., no electricity or fuel requirements for use operations) to active products (i.e., actively drawing power from electricity or fuel sources).

Our energy analysis sheds light on the importance of considering use phase while evaluating the energy savings potential of remanufacturing products upon reaching end-of-life. We conclude that from a total life cycle perspective, remanufacturing may be a net energy saving as well as a net energy expending end-of-life option (see Figure 50). If the inherent error associated with LCA and LCC is within 10% to 15%, then our results illustrate that for a majority of the products remanufacturing energy savings is unclear. More specifically, Figure 50 illustrates this phenomenon by indicating a large group of products where energy savings is within the +/- 10% to 15% error range associated with Life Cycle Analysis model. No concrete conclusions can be drawn for such findings given that a +/- 10% to 15% margin of error exists due to the approximations and inaccuracies inherent in Life Cycle Assessments models. Therefore, we argue that the generalized claims about remanufacturing as the ultimate end-of-life option are not only subject to data inaccuracies and approximations, but also restricted by the limitations in the methods.

4.2 Qualitative Conclusions

In this research we have shown that when taking the use phase into account, a series of inter-related factors determine the energy impact of remanufacturing. These critical factors include technological improvements, policy interventions, and economic incentives, which affect any inferences about energy and economic savings potential of remanufacturing.

The first of these critical factors is technology improvements. In general, a product that undergoes remanufacturing has been used for an entire service lifetime. Therefore, the use performance of a remanufactured product is bounded by the technology and the product architecture available at the time it was first produced. As a result, any efficiency improvement in a new product could end up saving considerable energy in use phase compared to the remanufactured product. If the technology (efficiency) improvement leads to substantial energy savings in the use phase of the new product, then remanufacturing an older (lesser efficient) product will amount to energy expenditures from a lifecycle perspective. On the other hand, if there is limited or no efficiency improvement, then the remanufactured product would not be inferior in performance in comparison to the new product; this makes remanufacturing environmentally beneficial end-of-life option since it saves both materials and energy during the entire lifecycle of products.

In relation to impact of technology improvements on remanufacturing, we conclude that when products undergo transformational technological changes in architecture and performance (e.g. transformation from bias ply to radial tire construction), then replacing old products with new models may save large amounts of energy (refer to appliances and tires case studies). For example, we can infer from Figure 49 that the lifecycle energy requirements for heavy-duty truck bias retreads are 274 GJ (41%) more than radial retreads (see Figure 50). Similarly, as shown in the appliance case study, the drastic shift in clothes washers from vertical-axis to horizontal-axis has led to enormous savings in electricity consumption and usage: as shown in Figure 50, the consumer choice to remanufacture a vertical-axis washer produced in 1997 instead of replacing it with a new 2008 model can end up increasing lifecycle energy requirements by 181%.

The second of these critical factors is governmental policy that impacts on remanufacturing energy savings, for example, state-level and federal policies that establish minimum efficiency performance standards for appliances and OEM passenger car tires. By promoting energy conservation in the use phase of new products, such policies have the potential to make remanufacturing older (and less efficient) products a net energy expending option.

On the other hand, legislations targeted towards production or end-of-life phases may promote conservation of energy and materials in production processes. For example, The Waste Electrical and Electronic Equipment (WEEE) and the Restriction of Hazardous Substance (RoHS) directives promote environmentally benign manufacturing and mandate the recovery of discarded products by closing the loop between consumer, municipalities, and producers. Such policies can incentivize manufacturers to recapture and remanufacture older products for another service lifetime. Therefore, policy interventions and governmental standards can serve as a catalyst in promoting as well as hindering the environmental savings potential of remanufacturing.

We conclude that the integrative impacts of policy interventions coupled with technology improvements may lead to stark changes in performance of products that, in turn, affect remanufacturing and energy savings. Moreover, by studying the integrative impacts of technology and policy retrospectively, we observe the importance of analyzing remanufacturing energy savings dynamically. For example, Figure 49 and Figure 50 show a static situation in relation to refrigerator remanufacturing and energy savings. More specifically, Figure 50 shows that in year 2008, by remanufacturing a 2001 model refrigerator instead of purchasing a 2008 model, one will consume 2% more energy from a lifecycle perspective. However, as shown in Figure 17, our retrospective analysis reveals the dynamic changes in efficiency of refrigerators (driven by technology improvements and efficiency standards), which, in turn, changes the conclusions drawn for remanufacturing energy savings. More specifically, Figure 17 shows that prior to efficiency standards in 1974, remanufacturing would have saved energy from the entire lifecycle. In addition, Figure 17 demonstrates that after 1974 the pace of efficiency improvements and efficiency standards has made refrigerator remanufacturing more energy expending. Our retrospective lifecycle assessments imply that evaluation of energy savings in remanufacturing should be done on a case-by-case basis while taking into account critical factors that stem from dynamic changes in technology, policy, society, and economics.

We argue that degradation in performance of remanufactured products is a critical factor that must be taken into account when assessing remanufacturing and energy savings. As we have shown in the electric motors and tires case studies, the conclusions drawn for remanufacturing energy savings could change there is degradation in performance of remanufactured products.

The third critical factor is economic feasibility of remanufacturing. More specifically, by performing Life Cycle Costing analysis from a consumer's perspective, we show that the economic drivers for remanufacturing are often distinctly different from the energy and environmental impacts of remanufacturing. In the motor case study, though motor rewinding may expend more energy in the use phase, the additional electricity cost in use is less significant than the economic savings provided by rewound motors in purchasing phase. We argue that one potential strategy for promoting energy savings in remanufacturing is to escalate the prices of energy resources (e.g. electricity, automotive fuel) during the use phase such that the economic incentives are more aligned with the energy savings benefits.

The fourth critical factor is business models and strategic considerations in relation to remanufacturing. The residual energy values, material values, and economic values retained in discarded products have led to the growth in number of third-party remanufacturers. OEMs have taken different business strategies in dealing with the residual values of their products as they reach end-of-life. There are industrial examples of OEMS that have changed their business models to promote remanufacturing, and other examples of OEMs that have taken serious steps to inhibit remanufacturing. For example, tire retread operations were initially provided by third-party remanufacturers only, which utilized the high residual values in scrap tires. The presence of a retreaded tires in the replacement market coupled with high demands for retread tires in the trucking industry made OEMs such as Bridgestone and Goodyear realize the potential business opportunity in remanufacturing as a business model. Today, the tire remanufacturing industry is one of the largest and most active remanufacturing industries in the U.S. (Hauser and Lund 2008). Another strategic business consideration in remanufacturing is proper management of core retrieval. Remanufacturing is more feasible for core products that can be readily retrieved in high volumes. For example, Kodak established an effective business model for recapturing and remanufacturing core single-use cameras. More specifically, Kodak invested in a closed-loop supply platform by retrieving disposed single-use cameras from photo developing centers.

Also, there are examples of OEMs that have taken serious business steps to suppress remanufacturing. As a result, remanufacturers face fierce competition due to rivalry with other remanufacturers as well as OEMs. For example, to sustain leverage in competing with third-party remanufacturers, Lexmark has developed a proprietary technology that limits third-party for recharging discarded cartridges (Bras 1996). Moreover, Kodak has designed the single use camera such that it is difficult to disassemble and reload film by third-party remanufacturers (Bras 1996).

In summary, we address the dynamic effects of remanufacturing on the environment in the context of lifecycle energy savings. We quantified cumulative energy and economic demands of remanufactured products and compared them to new products from a lifecycle perspective. We conclude that energy savings potential of remanufacturing should be addressed from both microscopic as well as macroscopic scales in order to solve the complex challenges in relation to remanufacturing.

4.3 Future Work

This study provides an evaluation of remanufacturing and energy savings based on product-specific quantitative analysis and large-scale qualitative assessment. By doing so, we have come to acknowledge the value in using an integrative approach for addressing engineering problems in energy and sustainability. In addition, this study demonstrates that remanufacturing energy savings potential is a systems problem and studying it requires acknowledgement about many micro- and macroscopic factors that affect its outcomes. Given the objectives set for this research coupled with time and resource limitations, we have only focused on a few critical problems in realm of remanufacturing and energy savings. Nevertheless, by selectively addressing key problems in energy conservation, this research can serve as an introductory foundation for promising future work in energy, industrial ecology, and sustainability.

Many other factors are equally important to address in relation to remanufacturing, energy, and environment that are beyond the scope of this research. For example, a promising future work is to study the complexities in reverse logistics and evaluate the optimal strategies for closed-loop supply chain.

We have studied relative energy savings achieved by the alternative end-of-life options for appliances. A promising future work is to quantify such factor for all products in order to come up with a quantitative method for effectively identifying the optimal end-of-life options, i.e. recycling, remanufacturing, re-using, based on products as well as industrial characteristics.

In closing, this research provides a perspective that goes beyond remanufacturing. For example, the research findings in relation to high lifecycle energy consumptions of products signify how our current practices can lead to ever-increasing dependence on supply of energy and raw material from the limited natural resources in the future. Therefore, in addressing environmental impacts of any large-scale change, an important question to address is "How does a proposed solution meet the global challenges in sustainability?"

5. Bibliography

ABBREVIATIONS

ANL	Argonne National Laboratory
AHAM	Association of Home Appliance Manufacturers
BTS	Bureau of Transportation Statistics
CEC	California Energy Commission
CFR	Code of Federal Regulation
DOE	Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
NHTSA	National Highway Traffic Safety Administration
NRC	National Research Council
NRDC	National Resources Defense Council
RMA	Rubber Manufacturers Association
SAE	Society of Automobiles Engineers
TRIB	Tire Retread & Repair Information Bureau

10CFRPart430 (2003). Energy Conservation Program for Consumer Products: Test Procedure for Clothes Washers.

AEMT (2003). The Effect Of Repair/Rewinding On Motor Efficiency. EASA/AEMT Rewind Study and Good Practice Guide to Maintain Motor Efficiency.

AHAM. "INFOBulletin #1: Recycling Major Home Appliances ".

AHAM (2001). Appliance Recycling Information Center.

AHAM (2005). Clothes Washers Energy Efficiency and Consumption Trends.

AHAM (2008). Energy Efficiency and Consumption Trends.

AHAM(NFO) (1996). Average Useful Life of Major Home Appliances National Family Opinion Inc.

Ahluwalia, S. (2008). "Real Questions Real Answers: Tires and Truck Fuel Economy and a New Perspective." Bridgestone Special Edition Report on Fuel Economy tests.

Ahmadi, A., B. Williamson, et al. (2003). "Life-cycle inventory of toner produced for xerographic processes." Journal of cleaner production **11**(5): 573-582.

Allwood, J., S. Laursen, et al. (2006). "Well Dressed." The present and future sustainability of clothing and textiles in the United Kingdom. University of

Cambridge Institute for Manufacturing.[WWW document]. URL http://www. ifm. eng. cam. ac. uk/sustainability/(accessed on 28 February 2008).
Amari, T., N. Themelis, et al. (1999). "Resource recovery from used rubber tires." Resources Policy **25**(3): 179-188.
Amezquita, T., Bras, B. (1996) (1996). Lean remanufacture of an Automobile clutch. Proceedings of First International Working Seminar on Reuse, Eindhoven, The Netherlands.
Andreas, J. (1992). Energy-efficient electric motors: selection and application, Marcel Dekker.
ANL (June, 2009). Argonne National Laboratory, personal communication Tim LaClair.
ApplianceMagazine (2008). Retieved from Energy Star Life Cycle Cost Estimate for Energy Star Qualified Residential appliances.
Ashby, M. (2009). Materials and the Environment: Eco-informed Material Choice, Butterworth-Heinemann.
Baker, E., E. Bournay, et al. (2004). Vital waste graphics, United Nations Pubns.
Baldwin, S. (2002). The Future of Generation: Technologies and Fuels Efficiency and Renewables.
Barrand, J. and J. Bokar (2008). "Reducing Tire Rolling Resistance to Save fuel and lower emissions." SAE Technical paper series(Michelin).
Bendtsen, H. (2004). "Rolling Resistance, Fuel Consumption." Danish Road Institute. Technical Note 23
Bhamra, T. (2004). "Ecodesign: the search for new strategies in product development." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture **218**(5): 557-569.
Bole, R. (2006). Life-cycle optimization of residential clothes washer replacement. Dep. Natural Resources and Environment, Univ. of Michigan, Ann Arbor.
Bostel, N., P. Dejax, et al. (2005). "The design, planning, and optimization of reverse logistics networks." Logistics Systems: Design and Optimization: 171-212.
Boustead, I. (2005). "Eco-profiles of the European Plastics Industry, Olefins." PlasticsEurope, Brussels, Belgium.
Boustead, I. and G. F. Hancock (1979). Handbook of industrial energy analysis, Halsted Press.
Bozeat, N. (2008). "Impact Assessment Study on Possible Energy Labelling of Tyres." European Commission Directorate-General Transport and Energy.
Bradley, R. (2000). "Technology Roadmap for the 21st Century Truck Program: A Government-Industry Research Partnership." 21CT-001, Office of Heavy Vehicles Technologies of US Department of Energy, Oak Ridge, Tennessee, December, http://www.osti. gov/fcvt/21stcenturytruck. pdf.
Bras, B., Hammond, R. (1996). Design for Remanufacturing metrics. Proceedings of First nternational Working Seminar on Reuse, Eindhoven, The Netherlands.
Brown, H. L., B. B. Hamel, et al. (1985). Energy analysis of one hundred and eight industrial processes.
BTS (2008). National Transportation Statistics. Research and Innovative Technology Administration. Energy Consumption by Mode of Transportation.
Calwell, C. (2003). California State Fuel-Efficient Tire Report, Volume II, California Energy Commission, January.

Campbell, B. (1997). "Failed motors: rewind or replace?" IEEE Industry Applications Magazine **3**(1): 45-50.
Cao, W. and K. Bradley (2006). "Assessing the impacts of rewind and repeated rewinds on induction motors: is an opportunity for Re-designing the machine being wasted?" IEEE Transactions on Industry Applications **42**(4): 958-964.
Curran, M. A. (2006). Life Cycle Assessment: Principles and Practice. Cincinnati, Ohio, National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency. **EPA/600/R-06/060**.
Dale, L., C. Antinori, et al. (2009). "Retrospective evaluation of appliance price trends." Energy Policy **37**(2): 597-605.
Davis, S. and S. Diegel (2009). Transportation Energy Data Book: Edition 28, ORNL/TM-2007/070, Oak Ridge National Laboratory (ORNL).
de Almeida, A. T., J. Ferreira, et al. (2008). " Eup lot 11 motors." University of Coimbra.
De Brito, M. and R. Dekker "Reverse logistics a framework." Econometric Institute: 2002-2038.
Deutch, J. and R. Lester (2008). Applications of Technology in Energy and Environment, Lecture 1.
Dhanda, K. (2007). "Reverse Logistics And Clean Technology Adoption: The Case Of The Steel Industry." International Business & Economics Research Journal **6**(9).
Dhilllon, B. S. (1989). Life Cycle Costing, Gordon and Breach Science Publishers.
DiPardo, J. (2000). Outlook for Biomass Ethanol Production and Demand, Energy Information Administration.
DOC (2005). International Market Insight, WEEE-RoHS: Requirements for Recycling Waste of Electronc and Electrical Equipment and Reduction of Hazardous Substances in the EU, U.S. Commercial Service, Department of Commerce, United States of America.
DOE (2008). Building Energy Databook.
DOE (2009). Average Retail Prices of Electricity 1960-2008.
Doppelt, B. and H. Nelson "EXTENDED PRODUCER RESPONSIBILITY AND PRODUCT TAKE-BACK."
EASA (2002). "THE RESULTS ARE IN: MOTOR REPAIRíS IMPACT ON EFFICIENCY."
EERE1, D. (2009). Direct Final Rule and Proposed Rule." DOE Federal Test Procedure 10 CFR 430.23. **Appendix J1**.
EERE2, D. (2009). 430.31: 10 CFR Ch. II.
EERE3, D. (2009). Energy Savers: Tips on saving energy and money at home.
EERE. "Motormaster+ ver 4." from //www1.eere.energy.gov/industry/bestpractices/softwaremotormaster
EERE, D. (2005). TECHNICAL REPORT: Analysis of Amended Energy Conservation Standards for Residential Refrigerator-Freezers.
EERE, D. (2007). Energy Conservation Program for Consumer Products: Test Procedure for Clothes Washers.
EIA (2005). Residential Energy Consumption Survey.
EIA (2009). Annual Energy Review.
EISA (2007). Energy Independence and Security Act.

EnergyStar. "Appliances Key Product Criteria." Retrieved 10/01/2009, from http://www.energystar.gov/index.cfm?c=appliances.pr_appliances

EnergyStar Energy Star Program Requirements for Computers, Version 5.0.

EPA (2005). Market Analysis and Proposed Changes to the ENERGY STAR Criteria for Clothes Washers.

EPA. (2006). "Municipal Solid Waste in the United Stated 2007 Facts and Figures." Retrieved 01/13/2010, from http://www.epa.gov/epawaste/nonhaz/municipal/pubs/msw07-rpt.pdf

EPA (2007). Proposed new motor efficiency standards can save industry energy and money. Energy Matters.

EPCA (1975). Energy Policy and Conservation Act of 1975, PL.

Farrell, A. E., R. J. Pelvin, et al. (2006). "Ethanol can contribute to energy and environmental goals." Science **311**(Journal Article): 506-508.

Ferguson, M. (2009). Strategic Issues in Closed-Loop Supply Chains with Remanufacturing. http://www.gsb.stanford.edu/facseminars/events/oit/documents/oit_03_09_ferguson_relatedpaper.pdf.

Ferrer, G. (1997). "Economics of tire remanufacturing." Resources, Conservation and Recycling **19**(4): 221-255.

Ferrer, G. and R. Ayres (2000). "The impact of remanufacturing in the economy." Ecological Economics **32**(3): 413-429.

Ferrer, G. and J. Swaminathan (2006). "Managing new and remanufactured products." Management Science **52**(1): 15.

Fleischmann, M., J. Bloemhof-Ruwaard, et al. (1997). "Quantitative models for reverse logistics: a review." European Journal of Operational Research **103**(1): 1-17.

Furuhjelm, J. (2000). Incorporating the end-of-life aspect into product development: Analysis and a systematic approach, Department of Mechanical Engineering, Link^pings universitet.

Gaines, L., F. Stodolsky, et al. (1998). "Lifecycle analysis for heavy vehicles." Centre for Transportation Research, Argonne National Laboratory.

Geyer, R., L. Van Wassenhove, et al. (2007). "The economics of remanufacturing under limited component durability and finite product life cycles." Management Science **53**(1): 88-100.

Goodyear (2003). "Radial Truck Tire and Retread Service Manual." The Goodyear Tire and Rubber Company Report: 700-862-932-505.

Graedel, T. and B. Allenby (1996). Design for environment, Prentice Hall.

Greening, L., D. Greene, et al. (2000). "Energy efficiency and consumption-the rebound effect- a survey." Energy Policy **28**(6-7): 389-401.

Guide Jr, V., V. Jayaraman, et al. (2000). "Supply-chain management for recoverable manufacturing systems." Interfaces **30**(3): 125-142.

Guide, V. (2000). "Production planning and control for remanufacturing: industry practice and research needs." Journal of Operations Management **18**(4): 467-483.

Guide, V. and L. Van Wassenhove (2009). "OR FORUM---The Evolution of Closed-Loop Supply Chain Research." Operations Research **57**(1): 10-18.

Guiney, D. (2009). "Tire Rolling Resistance- Tire Testing and Data Analysis." California Energy Commission Staff workshop.

Gyenes, L. and C. Mitchell (1994). "The Effect of Vehicle-Road Interaction on Fuel Consumption." Vehicle-road interaction: 225.

Hammond, R., T. Amezquita, et al. (1998). "Issues in the automotive parts remanufacturing industry: a discussion of results from surveys performed among remanufacturers." Engineering Design and Automation **4**: 27-46.

Harrington, L. and M. Damnics (2004). "Energy labelling and standards programs throughout the world." Report to The National Appliance and Equipment Energy Efficiency Committee **2.0**.

Hauser, W. and R. T. Lund (2003). Remanufacturing an American Resource Boston University.

Hauser, W. and R. T. Lund (2003). The Remanufacturing Industry: Anatomy of a Giant. Boston, Boston University.

Hauser, W. and R. T. Lund (2008). Remanufacturing: Operating Practices and Strategies. Boston, Boston University.

Hendrickson, C. T., L. Lave, B. , et al. (2006). Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach. Washington, DC, Resources for the Future.

Hirzel, J. (1994). Impact of rewinding on motor efficiency.

Hocking, M., B. (1991). "Paper versus polystyrene: a complex choice." Science **251**(4993): 504-505.

HomeEnergy (1996). Revolution, Not Agitation: A New Spin on Clothes Washing **Vol. 13, No. 6**.

Horie, Y. (2004). "Life Cycle Optimization of Household Refrigerator-Freezer Replacement." Centre for Sustainable Systems: University of Michigan.

Hunt, R. and W. Franklin (1996). "LCA- How it came about." The International Journal of Life Cycle Assessment **1**(1): 4-7.

IEA (2009). Gadget and Gigawatts- Executive Summary. www.iea.org/Textbase/npsum/Gigawatts2009SUM.pdf.

Ijomah, W., S. Childe, et al. (2005). A robust description and tool for remanufacturing: a resource and energy recovery strategy.

ISO (2006). Environmental management - Life cycle assessment - Principles and framework. **ISO 14040**.

IVF (2007). IVF Industrial Research and Development Corporation. Lot 3, personal computers (desktops and laptops) and computer monitors.

Jackobsson, N. (2000). "Emerging product strategies: Selling services of remanufactured products. Licentiate thesis, IIIEE. Lund University, Lund, Sweden." IIIEE Dissertations **6**.

Johnson, R. W. (2000). The Effect of Blowing Agent on Refrigerator/Freezer TEWI. Polyurethanes Conference. Boston, Massachusetts.

Kemna, R., M. V. Elburg, et al. (2005). Methodology Study Eco-Design of Energy Using-Products, Van Holsteijn en Kemna BV and European Commission.

Keoleian, G., K. Kar, et al. (1997). Industrial ecology of the automobile: A life cycle perspective, Society of Automotive Engineers.

Kerr, W. and C. Ryan (2001). "Eco-efficiency gains from remanufacturing A case study of photocopier remanufacturing at Fuji Xerox Australia." Journal of cleaner production **9**(1): 75-81.

Kim, H., G. Keoleian, et al. (2006). "Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost." Energy Policy **34**(15): 2310-2323.
King, A. and S. Burgess (2005). "The development of a remanufacturing platform design: a strategic response to the Directive on Waste Electrical and Electronic Equipment." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture **219**(8): 623-631.
King, A., S. Burgess, et al. (2006). "Reducing waste: repair, recondition, remanufacture or recycle?" Sustainable Development **14**(4): 257-267.
Kirk-Othmer (1996). Kirk-Othmer Encyclopedia of Chemical Technology. New York, NY, Wiley.
Koeller&Company (2007). "Potential Best Management Practices."
Kondoh, S., Y. Nishikiori, et al. (2005). A Closed-loop Manufacturing System focusing on Reuse of Components.
Kromer, S., E. Kreipe, et al. (1999). "Life cycle assessment of a car tire." Continental, Hannover, Germany. Accessed April **20**: 2006.
Kumar, S. and J. Fullenkamp (2005). "Analysis of European Union environmental directives and producer responsibility requirements." International Journal of Services and Standards **1**(3): 379-398.
Kumar, S. and V. Putnam (2008). "Cradle to cradle: Reverse logistics strategies and opportunities across three industry sectors." International Journal of Production Economics **115**(2): 305-315.
Kutz, M. (2007). Environmentally conscious mechanical design, Wiley.
LaClair, T. J. (2005). Rolling Resistance. In The Pneumatic Tire. National Highway Traffic Safety Administration, Washington, D.C.: pp. 475–532.
Lindahl, M., E. Sundin, et al. (2006). Environmental issues within the remanufacturing industry.
Lindahl, M., E. Sundin, et al. (2006). Environmental issues within the remanufacturing industry.
Linton, J. (2008). "Assessing the Economic Rationality of Remanufacturing Products." Journal of Product Innovation Management **25**(3): 287-302.
LLCFourElementConsulting (2008). Laserjet Cartridge Lifecycle Environmental Impact Comparison Refresh Study.
Lutsey, N. and D. Sperling (2005). "Energy efficiency, fuel economy, and policy implications." Transportation Research Record: Journal of the Transportation Research Board **1941**(-1): 8-17.
Lynd, L. R. (1996). "Overview and evaluation of fuel ethanol from cellulosic biomass: technology, economics, the environment, and policy biomass: technology, economics, the environment, and policy." Annu. Rev. Energy Environ(21): 403-465.
Majumder, P. and H. Groenevelt (2001). "Competition in remanufacturing." Production and Operations Management **10**(2): 125-141.
Meyers, S., J. McMahon, et al. (2003). "Impacts of US federal energy efficiency standards for residential appliances." Energy **28**(8): 755-767.

Michelin2. "Radial vs. Bias Ply." Retrieved 07/22/2009, from http://www.michelinag.com/agx/en-US/products/advantages/bias_radial/bias_radial.jsp.
Michelin. "Americas Truck Tires." Retrieved 12/30/2009, from http://www.michelintruck.com/michelintruck/tires-retreads/tiresRetreads-landing.jsp.
MITEI-1-a-2010 Appliance Remanufacturing and Energy Savings. MIT Energy Initiative Publication Series 2010-1.
MITEI-1-b-2010 Cartridge Remanufacturing and Energy Savings. MIT Energy Initiative Publication Series 2010-1.
MITEI-1-c-2010 Electric Motor Remanufacturing and Energy Savings. MIT Energy Initiative Publication Series 2010-1.
MITEI-1-d-2010 Engine Remanufacturing and Energy Savings. MIT Energy Initiative Publication Series 2010-1.
MITEI-1-e-2010 Furniture Remanufacturing and Energy Savings. MIT Energy Initiative Publication Series 2010-1.
MITEI-1-f-2010 Personal Computer Remanufacturing and Energy Savings. MIT Energy Initiative Publication Series 2010-1.
MITEI-1-g-2010 Textile Remanufacturing and Energy Savings MIT Energy Initiative Publication Series 2010-1.
MITEI-1-h-2010 Tire Remanufacturing and Energy Savings. MIT Energy Initiative Publication Series 2010-1.
Mitra, S. and S. Webster (2008). "Competition in remanufacturing and the effects of government subsidies." International Journal of Production Economics **111**(2): 287-298.
Montgomery, D. (1984). "The motor rewind issue -- A new look." IEEE Transactions on Industry Applications **20**(5): 1330-1336.
Nadel, S. (1994). "The Take-Back Effect: Fact or Fiction." American Council for an Energy Efficient Economy, Washington.
Nadel, S., R. Elliott, et al. (1992). "Energy-efficient motor systems: A handbook on technology, programs, and policy opportunities."
NC3R. "Remanufacturing Industry Timeline." from http://www.reman.rit.edu/timeline.aspx.
NHTSA (2008). "Commercial Medium Tire Debris Study " U.S. Department of Transportation **DOT HS 811 060**.
Norberg, T. and P. g. C. E. Commission. (2002). A Tire Industry Perspective on Tire Rolling Resistance. California Energy Commission.
O'Neill, M. (2003). WEEE & RoHS and Trends in the Environmental Legislation in European Union. Proceedings of EcoDesign–03, Japan, Tokyo.
Ostlin, J. (2008). On Remanufacturing Systems Analysing and Managing Material Flows and Remanufacturing Processes, Linkopings Universitet Institute of Technology. **LINKÖPING STUDIES IN SCIENCE AND TECHNOLOGY,** .
Penrose, H., D. Inc, et al. (1997). "Anatomy of an energy efficient electric motor rewind." IEEE Electrical Insulation Magazine **13**(1): 14-19.
Pokharel, S. and A. Mutha (2009). "Perspectives in reverse logistics: A review." Resources, Conservation & Recycling **53**(4): 175-182.

Reilly, J. and S. Paltsev (2007). Biomass energy and competition for land, MIT Joint Program on the Science and Policy of Global Change. **145**.
RMA2 "Typical Materials Composition of a Truck Tire."
RMA. "Typical Materials Composition of a Truck Tire." Retrieved 07/22/2009, from http://www.rma.org/scrap_tires/scrap_tire_markets/scrap_tire_characteristics/#anchor135840.
RMA (2009). Scrap Tire Markets in the U.S. . **9th Biennial Report**.
Roberson, J., G. Homan, et al. (2002). "Energy use and power levels in new monitors and personal computers." Lawrence Berkeley National Laboratory, Berkeley, CA.
Rose, C., K. Ishii, et al. (1998). How product characteristics determine end-of-life strategies.
Rosenfeld, A. H. C. E. C. (2003). The California Vision: Reducing Energy Intensity 2% Per Year. ACEEE Conference on Energy Efficiency as a Resource.
Savaskan, R., S. Bhattacharya, et al. (2004). "Closed-loop supply chain models with product remanufacturing." Management Science: 239-252.
Scheihing, P., M. Rosenberg, et al. United states industrial motor-driven systems market assessment: Charting a roadmap to energy savings for industry.
Seaver, W. B. (1994). Design Considerations for remanufacturability, recyclability and reusability and reusability of user interface modules. Proceedings of IEEE International Symposium on Electronics and the Environment, (IEEE-94), San Francisco, CA, USA.
SeelCase. from http://www.csnstores.com/Steelcase-TS5TLB24272-SCA1137.html#ProdDetails.
Seitz, M. and K. Peattie (2004). "Meeting the closed-loop challenge: the case of remanufacturing." California Management Review **46**(2): 74-89.
Smil, V. (2008). Energy in nature and society, Cambridge, MA: MIT Press.
Smith, V. and G. Keoleian (2004). "The value of remanufactured engines: life-cycle environmental and economic perspectives." Journal of Industrial Ecology **8**(1): 193-221.
Spitzley, D. V. (2006). Life-Cycle Assessment of Furniture Products, Center of Sustainable Systems. University of Michigan Ann Arbor.
SteelCaseII. from http://store.steelcase.com/go/products/detail/499121SX/.
Steinhilper, R. (1998). Remanufacturing, the Ultimate Form of Recycling, 1998, Fraunhofer IRB Verlag, Stuttgart, Germany), ISBN 3-8167-5216-0.
Stevels, A. (2003). An Industry Vision on the Implementation of WEEE and RoHS. Proceedings of EcoDesign–03, Japan, Tokyo.
Suh, S. and G. Huppes (2005). "Methods in Life Cycle Inventory of a product." Journal of cleaner production **13**(7): 687-697.
Sundin, E. (2004). Product and process design for successful remanufacturing, Production Systems, Department of Mechanical Engineering, Link^pings Universitet.
Sundin, E. (2006). How can remanufacturing processes become leaner. Proceedings of LCE.
Sutherland, J., D. Adler, et al. (2008). "A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production." CIRP Annals-Manufacturing Technology **57**(1): 5-8.

Toffel, M. (2004). "Strategic management of product recovery." California Management Review **46**(2): 120-141.
Toktay, L., L. Wein, et al. (2000). "Inventory management of remanufacturable products." Management Science **46**(11): 1412-1426.
TRB (2006). Tires and Passenger Vehicle Fuel Economy. Transportation Research Board.
TRIB. "Retread Facts." Retrieved 11/04/2009 , from http://www.retread.org/Facts/index.cfm/ID/225.htm.
Truttmann, N. and H. Rechberger (2006). "Contribution to resource conservation by reuse of electrical and electronic household appliances." Resources, Conservation & Recycling **48**(3): 249-262.
U.S.-Bureau-of-the-Census (1995). American Housing Survey for the United States.
U.S.G.S. "U.S. Geological Survey." Retrieved 01/13/2010, from http://www.usgs.gov/.
Union, E. (2003). "Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment." Official Journal of the European Union **37**: 19-23.
Van Nunen, J. and R. Zuidwijk (2004). "E-enabled closed-loop supply chains." California Management Review **46**(2): 40-54.
WashingtonStateUniversity (2003). Energy Efficiency Factsheet, Cooperative Extension Energy Program.
Website4. "Energy efficiency guide for industry in asia." from www.energyefficiencyasia.org.
WEEE (2000). "Directive 2000/53/EC on End-of-Life Vehicles." Official Journal of the European Communities
Weissman, S. L., J. L. Sackman, et al. "Extending the Lifespan of Tires." Sympletic Engineering Corporation. Institute for Transportation Studies. University of California at Berkeley.
Wenzel, T., J. Koomey, et al. (1997). "Energy data sourcebook for the US residential sector." Lawrence Berkeley National Laboratory, Report **40297**.
Williams, E., D., C. L. Weber, et al. Hybrid Framework for Managing Uncertainty in Life Cycle Inventories.
Woolridge, A., G. Ward, et al. (2006). "Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: An UK energy saving perspective." Resources, Conservation & Recycling **46**(1): 94-103.
WorldBank World Population Growth.
Xenergy, I. (1998). "United States Industrial Electric Motor Systems Market Opportunities Assessment." Prepared for the United States Department of Energyís Office of Industrial Technology and Oak Ridge National Laboratory. Burlington, Massachusetts.
Zuidwijk, R. and H. Krikke (2008). "Strategic response to EEE returns: product eco-design or new recovery processes?" European Journal of Operational Research **191**(3): 1206-1222.

APPENDIX

Appendix A: Data Sources and References for Life Cycle Environmental Analysis

<table>
<tr><th>PRODUCT</th><th>BILL OF MATERIALS/RAW MATERIALS PROCESSING/MANUFACTURING</th><th>USE</th><th>Life Cycle Assessment: Model/Year</th><th>EOL ALTERNATIVES</th><th>TRANSPORTATION</th></tr>
<tr><td>Gasoline engine</td><td>1995 Gasoline Engine[1]</td><td>12 years operation[2]</td><td>1975,1987, 1999</td><td>NA</td><td>Negligible[1]</td></tr>
<tr><td>Diesel Engine</td><td>Caterpillar Diesel Engine[3,1]</td><td>12 years operation[2]</td><td>1970, 1982, 1994</td><td>NA</td><td>Negligible[1]</td></tr>
<tr><td rowspan="5">Desktop Control Unit, Laptop, CRT Monitor, LCD Monitor</td><td rowspan="2">Desktop PC, characterized by 3 GHz processor (or equivalent), built-in graphics card, 512 MB RAM, 80 GB HDD[4]</td><td>2001 Model Use Phase[5]</td><td rowspan="5">2005, 2009</td><td rowspan="3">Desktop / Laptop: 70% Storage/Reuse; 22% Landfill</td><td rowspan="5">NA</td></tr>
<tr><td rowspan="2">2005 Model Use Phase[4]</td></tr>
<tr><td>Notebook PC -Mobile 1.7 GHz processor (or its equivalent), good 3D graphics performance, 15"-screen, 512 MB RAM and 60 GB HDD[4]</td></tr>
<tr><td>LCD display, 17”, resolution 1280 by 1024[4]</td><td rowspan="2">2009 Model Use Phase[6]</td><td rowspan="2">Monitor: 65% Storage/Reuse; 26% Landfill</td></tr>
<tr><td>CRT display, 17”[4]</td></tr>
</table>

Electric Motor	22kW AC induction motor[7] 200kW AC induction motor[7]	6 Years of Operation[8]	2005	NA	NA
Printer Cartridge	Laser Jet Cartridge Casing[9]; Laser Jet Toner[10]	Used cartridge ISO page yield = 6,000 Self calculated use phase (electricity + paper)	HP LaserJet Q2610A Black Print Cartridge	recovery of 3%[9]	1%[9]
Textile	Cotton T-Shirt[11] [12]	NA	25 washes at 60 degrees C followed by tumble drying and ironing[11]	For textiles in general (UK Average): 43% reuse; 22% filling materials; 7% reclaimed fibers; 7% waste	7MJ (6.4% of LCA)[11]
	Viscous Blouse[11 12]	NA	25 washes at 40 degrees C followed by hand drying. No ironing needed,	EOL = Incineration, saving 3 MJ of energy (-3MJ) [University of Cambridge]	3MJ (5.9% of LCA)[11]
Office Furniture	Steelcase Siento Chair[13]	Assumed to be zero	Steelcase Siento	-	5.47% of LCA[13]

			Chair[13]		
	Steelcase Garland Desk[13]	Assumed to be zero	Steelcase Garland Desk[13]	-	15.8%[13]
Passenger Car Tire	Conventional Passenger Car Tire[14 15 16 17 18]	41,500 miles[15], Energy Ratio (RF) 0.1-0.2[19] Specified fuel economy[2]	1980, 2004	Tire-derived fuel (48.76%);Civil Engineering Applications (15.47%); Land Disposed (13.33%); Used as Ground Rubber (11.79%); …	4.2 MJ/Tire [Based on 200 miles of travel][21]
Truck Tire	Conventional Heavy Duty Truck Tire[14 15 16 17 18]	100,000 miles[22], Energy Ratio (RF) 0.33[23 24 25 26], Fuel Economy 5.5 miles per gallon[24]	Bias-Ply vs. Radial Ply vs. Single-Wide[22]	Tire-derived fuel (48.76%);Civil Engineering Applications (15.47%); Land Disposed (13.33%); Used as Ground Rubber (11.79%); …	20.5 MJ/Tire [Based on 200 miles of travel][21]
Refrigerator	Average Top-Bottom Refrigerator: 1997 Model[27 33] *	Use Phase:1947-1991[28] Use Phase: 1991-2008[29]	1947, 1956, 1964, 1973, 1982, 1991, , 1999, 2001, 2008	Re-use (38%); Re-sale (31.6%);Recycle (29.7%); Landfill (0.7%)	Less than 1% of total LCA

Clothes Washer	2005 Industry Average Washer[30 33*]	1981-2008[29]	1981, 1992, 1997, 2003, 2008	Re-use (22%); Re-sale (33%);Recycle (43.9%); Landfill (1.1%)	Less than 1% of total LCA
Dishwasher	1995 Model[31 33*]	1981-2008[29]	1981, 1991, 1998, 2001, 2008	Re-use (40%); Re-sale (23%);Recycle (35.9%); Landfill (1.1%)	Less than 1% of total LCA
Room AC	1990 Mitsubishi Model [32 33*]	1981-2008[29]	1980, 1990, 1999, 2008	Re-use (37); Re-sale (41.6%);Recycle (20.5%); Landfill (0.9%)	Less than 1% of total LCA

	References	Year Published	Notes
*	Raw Materials Energy intensity Values from (Smil 2008),(Ashby 2009)	2008/2009	From some products a * indication represents partial use of Smil values for some materials (not the entire material composition)
1	(Smith and Keoleian 2004)	2004	
2	(Davis and Diegel 2009)	2009	
3	Personal conversation with Caterpillar Official Dan Adler	2009	Production Energy Values match (Sutherland, Adler et al. 2008)
4	(IVF 2007)	2005	
5	(Roberson, Homan et al. 2002)	2001	
6	(EnergyStar)	2009	
7	(de Almeida, Ferreira et al. 2008)	2002	Doubts about the boundary conditions and analysis for manufacturing
8	(EERE)	2005	
9	(LLCFourElementConsulting 2008)	2008	
10	(Ahmadi, Williamson et al. 2003)	2003	
11	(Allwood, Laursen et al. 2006)	2006	
12	(Woolridge, Ward et al. 2006)	2006	
13	(Spitzley 2006)	2006	
14	(RMA)	2008	
15	(Lutsey and Sperling 2005)	2005	Energy Intensity Values for Some of the Raw Materials Production
16	(Brown, Hamel et al. 1985)	1985	Manufacturing Energy Consumption (11.7 MJ/Kg)
17	(Boustead 2005)	2005	Energy Intensity Values for Synthetic Rubber
18	(Amari, Themelis et al. 1999)	1999	Energy Intensity Values for Some of the Raw Materials

			Production
19	(TRB 2006)	2006	
20	(Davis and Diegel 2009)	2009	
21	(Keoleian, Kar et al. 1997)	1997	
22	(Gaines, Stodolsky et al. 1998)	1998	
23	(Gyenes and Mitchell 1994)	1994	
24	(Bradley 2000)	2000	
25	(Ahluwalia 2008)	2008	
26	(Barrand and Bokar 2008)	2008	
27	(Kim, Keoleian et al. 2006)	2004	
28	(Rosenfeld 2003)	2003	
29	(AHAM 2008)	2008	
30	(Bole 2006)	2006	
31	(Truttmann and Rechberger 2006)	2005	
32	Mitsubishi CSR Report	2000	Also have BOM from Techato et al. 2009
33	(Kemna, Elburg et al. 2005)	2005	

Appendix B: Tires Supplemental Information

B1 Two Examples of Tire Transformational (Architectural) Technological Changes in the Past Few Decades

Prior to analyzing the change evolution in rolling resistance of passenger car and truck tires, it is important to describe the two greatest technological advancements in tire rolling resistance improvements: transforming from tube tires to tubeless; transforming from bias-ply tires to radials.

Technology advancement in tires: Tubeless vs. Tube

According to Goodyear, by transforming from tube type truck tire to tubeless tires on all wheels, an over-the-road tractor-trailer can gain 2 per cent in fuel economy at 80,000 gross curb weight (GCW) (Goodyear 2003).

Technology advancement in tires: Bias Ply vs. Radial Ply

Figure 51 below shows the differentiation in structuring of bias-ply tires and radial-ply tires.

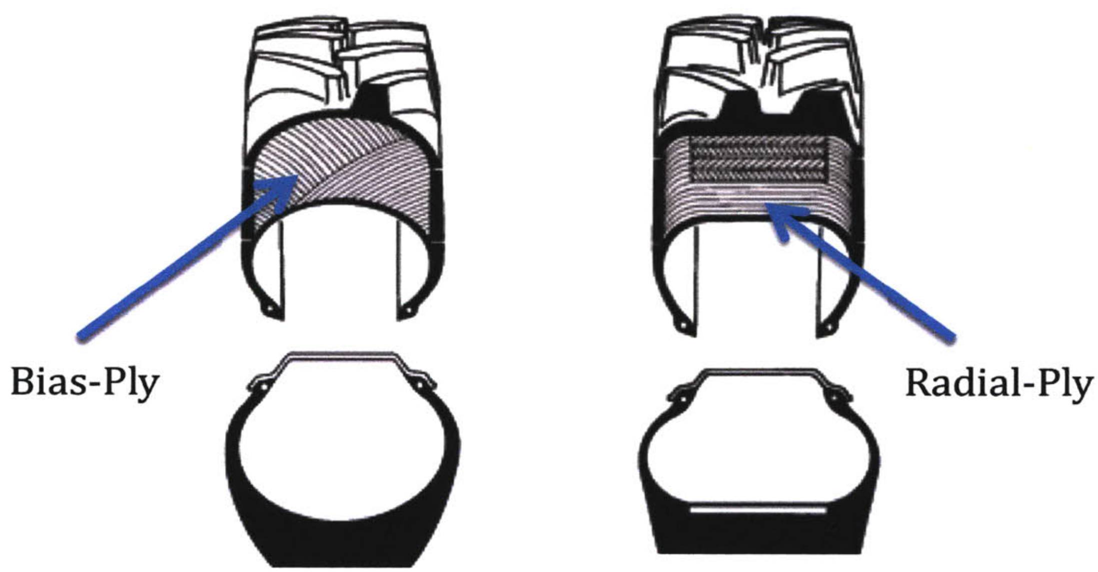


Figure 51. Illustration of the design comparison between bias-ply and radial-ply construction (Michelin2).

Radial-ply tires were introduced in the U.S. tire market in the 1970s and mass-produced in the 1980s; since then, it has steadily replaced bias-ply tires fully (TRB 2006). The bias-ply tires were the predominant passenger tires used in the United States prior to 1980s but no-longer produced due to the advancement of tires to radial-ply configuration (TRB 2006). Bias-ply tires were pneumatic tires in which the ply cords that extend to the tire beads (refer to Figure 51 above) are laid at alternate angles of +60 and -60 degrees to the centerline of the tread (TRB 2006).

Comparatively, radial-ply tires are constructed by extending the ply cords at approximately 90 degrees (perpendicular) to the centerline of the tread (refer to Figure 51 above). Patented and introduced by Michelin in 1946, radial-ply tires were first introduced to the market in Europe in 1950s, and penetrated into the U.S. tire market in the 1970s (TRB 2006),(Michelin2).

In bias-ply tires, the tread and the sidewalls share the same casing plies, which results in direct transmission of sidewall flexing motion to the tread causing tread distortion (buckling) throughout the contact patch. This phenomenon causes disadvantages such as (Michelin2):

- Large deformations in tread contact patch
- Rapid wear
- Reduction in traction
- Higher shear effects from the surface
- Increased rolling resistance coefficient and fuel consumption

On the other hand, the radial-ply configuration has the following advantages (Michelin2):

- Superior traction capabilities enabling flat stable tread crown
- Better distribution of air pressure leading to reduced soil compaction
- Reduction in chances of tire slip
- Reduced rolling resistance coefficient
- Longer tread life
- Better comfort and handling while on the road

According to Goodyear, new radial ply tires on average can provide fuel savings of six percent or greater compared to bias ply wheels in over-the-road tractor-trailer application (Goodyear 2003).

Despite the fact that bias-ply tires no longer exist in the U.S. tire market, it is still heavily produced in developing countries such as Mexico, and emerging economies such as China[I]. Therefore, the discussion around the energy performance degradation of bias-ply compared to radial tires is still an important topic for the global tire supply industry.

[I] Source: Michelin Industry Standards and Government Regulations, personal communication with Mike Wischhusen, Director, July, 2009.

B2 Rolling Resistance, Tire Efficiency, and Use Phase Energy Consumption

The total fuel consumption of a vehicle is use to overcome rolling resistance, accelerate and stop the vehicle, to overcome energy losses in the transmission, engine and drive train, to power auxiliary components such as compressors, air conditioners, and heaters, and aerodynamic resistance (Gyenes and Mitchell 1994).

Understanding the energy consumption to overcome rolling resistance of tires demands a clear illustration of the meaning of rolling resistance as a physical phenomenon. As a tire rolls on the road, it undergoes repeated viscoelastic (rubber) compression and tension as it deforms under the vehicle's load. Due to viscoelastic nature of rubber, only a portion of the compression energy is stored as the tire deforms. Upon changing energy state, the remaining unrecovered energy by the rubber is dissipated as heat (Bendtsen 2004). The conversion of absorbed energy to dissipated heat, along with the internal friction between the tread, the casing, and the tire and its rim, generates what is defined as hysteresis losses (Calwell 2003). Hysteresis losses are one (and the largest) of the contributing losses associated with rolling resistance. Hysteresis losses accompanied by the tire-road friction losses as well as tire aerodynamic drag are irrecoverable energies, and combine to generate a total resistive force on a moving vehicle. This drag force is commonly defined as rolling resistance (or rolling resistance force). In the case of a free rolling tire, the rolling resistance can be defined as a force that opposes vehicle motion (Calwell 2003). Tire rolling resistance is also defined as the energy a tire consumes per unit distance of travel (Calwell 2003). The standard metric units of rolling resistance are Joules per meter (J/m) or Newtons (N); the comparable English unit for rolling resistance is pounds (Calwell 2003).

Rolling resistance of tires is a function of hysterises, tire-road friction, and aerodynamic drag. Given that tires operate under various loading conditions based on the particular vehicle in use, rolling resistance is often divided by the vehicle weight (distributed based on the load undertaken by each individual tire) in order to come up with a dimensionless measure of tire efficiency, known as the rolling resistance coefficient (Calwell 2003). In other words, rolling resistance coefficient is a dimensionless parameter that can be conveyed in terms of rolling resistance force generated per unit load applied. The following equation and graphical representation sums up the definition of rolling resistance and rolling resistance coefficient (Barrand and Bokar 2008).

$$C_{RR} = \frac{F_{RR}}{Z}$$

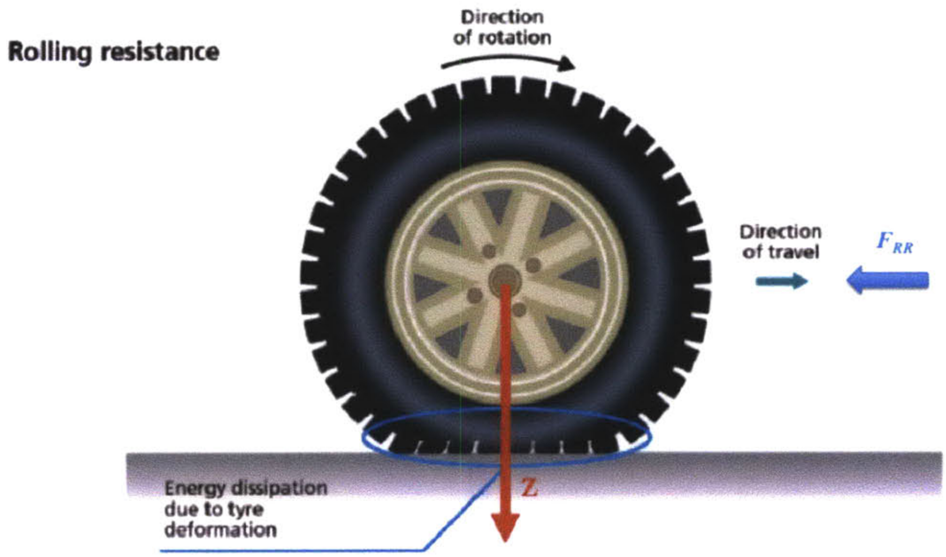


Figure 52. The inter-dependence relation between rolling resistance coefficient (C_{RR}), rolling resistance force (F_{RR}), and vehicle load (Z) (Barrand and Bokar 2008).

The Society of Automobiles Engineers (SAE) defines rolling resistance force and rolling resistance coefficient as follows (Guiney 2009):

"F_{RR} = Rolling Resistance Force :
Rolling resistance of the free-rolling tire is the scalar sum of all contact forces tangent to the test surface and parallel to the wheel plane of the tire.

C_{RR} = Coefficient of Rolling Resistance :
Rolling resistance coefficient is the ratio of the rolling resistance to the load of the tire."

In the U.S. tire industry rolling resistance coefficient is becoming more identified as a parameter for tire efficiency. According to this, the Rubber Manufacturers' Association (RMA) states, "Rolling resistance coefficient, is an appropriate expression of efficiency and suitable as the basis for a consumer tire energy efficiency rating system."

In the U.S. tire industry, rolling resistance coefficient is commonly expressed in formats listed below (Calwell 2003):

(1) Fractional value between 0 and 1 with lower values corresponding to higher measures of efficiency (i.e. pounds rolling resistance per pounds vehicle load)
(2) Kg per 1000 Kg (i.e. Kg/ton). The purpose of this is to express rolling resistance in whole numbers (e.g. 0.001 rolling resistance coefficient is 1 Kg/ton)

The heat loss generated in motion of tires is distributed heterogeneously across tire's body. The design and architecture of tire components places a critical role in the performance of tires. As such, section below provides and introduction to the components utilized in tires.

In general, the level of impact for the three main loss contributors associated with tire rolling resistance is as follows (LaClair 2005), (Bradley 2000):

(1) Tire hysteresis losses in the sidewall and tread: 80 to 95 per cent
(2) Tire-road interaction and surface frictional losses: 0 to 15 per cent
(3) Tire aerodynamic drag and air circulations: 0 to 5 per cent

In addition, each tire component has a distinct impact on heat dissipation and rolling resistance. For light-duty passenger car tires the component impacts associated with rolling resistance are as follows (Bozeat 2008):

(1) Tread: 60 to 70 per cent
(2) Sidewall (the portion of the tire between the tread and the bead): 10 to 20 per cent
(3) Bead Core (continuous high-tensile wire wound in the plane of tire rotation to form high-strength unit): 15 to 20 per cent

For truck tires, 35 to 50 per cent of the rolling resistance is caused by the tread design and tread compounding while 50 to 65 percent of the rolling resistance is cause by the design and compounding of the casing (including sidewalls, bead, and belts) (Ahluwalia 2008). The distribution of losses is for tires operating in steady-state conditions. Dynamic changes in driving cycle, low tire inflation pressure, etc. may change the contribution of each tire component.