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Remanufacturing and Energy Savings

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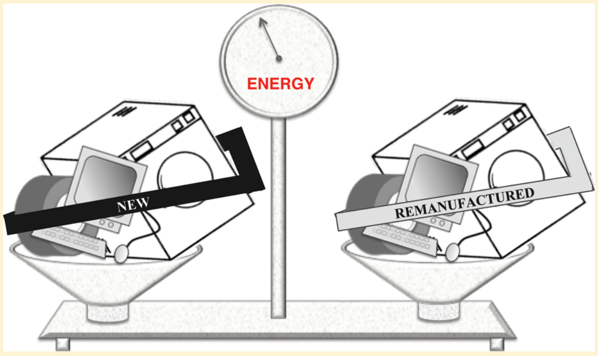
S *Supporting Information*



ABSTRACT: Remanufactured products that can substitute for new products are generally claimed to save energy. These claims are made from studies that look mainly at the differences in materials production and manufacturing. However, when the use phase is included, the situation can change radically. In this Article, 25 case studies for eight different product categories were studied, including: (1) furniture, (2) clothing, (3) computers, (4) electric motors, (5) tires, (6) appliances, (7) engines, and (8) toner cartridges. For most of these products, the use phase energy dominates that for materials production and manufacturing combined. As a result, small changes in use phase efficiency can overwhelm the claimed savings from materials production and manufacturing. These use phase energy changes are primarily due to efficiency improvements in new products, and efficiency degradation in remanufactured products. For those products with no, or an unchanging, use phase energy requirement, remanufacturing can save energy. For the 25 cases, we found that 8 cases clearly saved energy, 6 did not, and 11 were too close to call. In some cases, we could examine how the energy savings potential of remanufacturing has changed over time. Specifically, during times of significant improvements in energy efficiency, remanufacturing would often not save energy. A general design trend seems to be to add power to a previously unpowered product, and then to improve on the energy efficiency of the product over time. These trends tend to undermine the energy savings potential of remanufacturing.

1. INTRODUCTION TO REMANUFACTURING

Remanufacturing is generally seen as the most environmentally friendly of "end of life" treatments for a retired product. If the remanufactured product can be considered a substitute for a new product, then a credit is usually claimed for the avoided resource use and emissions associated with the new product production. The biggest savings is generally from the avoided new materials production, but the difference between new manufacturing and remanufacturing can also be significant. At the same time, remanufactured products generally sell for about 50−80% of the new product. Hence, remanufacturing can be seen as a win−win; it saves money (for the consumer), and it saves the environment.

In the United States, remanufacturing is at least a \$50 billion industry with direct employment of about 480 000 in 73 000 firms.[1] Remanufactured products include automotive and aircraft parts, compressors and electrical motors, office furniture, tires, toner cartridges, office equipment, machine tools, cameras, and still others.[1] One of the primary requirements for remanufacturing is that the retired products have significant residual value at the end of life. The second is that the remanufacturing firm can effectively capture the retired product. The third is that the product can be restored to like-new condition (in terms of product function) with only a modest investment. In terms of number of remanufacturing plants, the largest remanufacturing categories in the U.S. are tires, followed by motors and generators and motor vehicle parts.[2]

The fact that a product can have significant residual value at its end of life can present a dilemma for the original equipment manufacturer (OEM). For example, if the OEM decides to not remanufacture its own products, then it might find itself competing with its own products remanufactured by another firm. To avoid being placed in this situation, an OEM might employ a variety of strategies to defeat "third party" remanufacturing. These strategies might include making spent products inoperable, rapid (minor) design changes, using a "prebate" system, and buying back the spent products. All of these strategies have been employed by various printer OEMs with varying success in an effort to protect their ink cartridge business. For example, the prebate system employed by Lexmark attempts to enter into a contractual agreement with the buyer to return or throw away the spent ink cartridge in exchange for a discount. However, the U.S. District Court of Kentucky barred this practice recently citing a U.S. Supreme Court 2008 decision in Quanta versus LG

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Electronics,[3] interpreting it as an attempt to avoid the patent exhaustion doctrine.

An alternative position is to embrace remanufacturing and to make it part of the OEM's business strategy. A variety of firms have done this, particularly for truck tires and heavy equipment (e.g., Caterpillar, Cummins, Goodyear, Michelin). This strategy can build a strong long-term relationship with customers. As a general method for supplying products to customers, however, remanufacturing presents some challenges. One challenge is to match supply and demand. The early steps in remanufacturing, which consist of recovering the spent product (sometimes called "the core"), cleaning it, and testing it, all represent an investment. To capture the value of that investment and to guard against fluctuations in core supply, a remanufacturer may have to maintain a large inventory of cleaned and tested cores. A second challenge is that remanufacturing is labor intensive. The condition and variety of incoming cores can vary significantly. This means that remanufacturing must be flexible. Hence, two conditions that favor remanufacturing are: (1) a relatively low wage, skilled labor market, and (2) modest inventory storage costs. In addition to this, the remanufacturer will need to have an effective way to recover spent cores.

2. RESEARCH QUESTIONS

The aim of this Article is to test the hypothesis "remanufacturing of products saves energy", as popularly claimed. The research questions that motivated this study were: (1) how big is the energy savings potential of remanufacturing, with a particular interest in identifying the products that represent the best opportunities for energy savings, and (2) how could this energy savings potential be expanded, both in terms of remanufacturing more of the usual category of products, and to expand to new product categories.

To address these issues, we studied eight different product categories: (1) furniture, (2) clothing, (3) computers, (4) electric motors, (5) tires, (6) appliances, (7) engines, and (8) toner cartridges, many with very high remanufacturing potential in the United States. The analysis was framed in terms of a product replacement decision for a consumer in the U.S. That is, we pose a scenario in which a consumer intends to replace a product, and we examine the normative question: to save energy, should the consumer acquire a remanufactured version of the retired product, or should the consumer buy new? The question is answered by using a life cycle energy analysis for the two product options. The analysis includes the energy requirements for materials production, manufacturing, and the product use phase. We perform a sensitivity analysis to consider elements that were not included in the analysis, as well as parameter variation. Variations on system boundaries and elements beyond the life cycle of a single product are discussed at the end of this Article.

3. LIFE CYCLE ENERGY ANALYSIS OF PRODUCTS

The life cycle energy analysis of products is now a well-established field of study. Many studies have already been performed, many software programs are available to help in this analysis, and international standards exist to guide the practitioner. In this study, we take advantage of the analyses by others for products that fit into the general categories for remanufacturable products. To double check these studies, and to resolve differences between multiple studies for similar products, we developed a life cycle energy estimation tool for materials production and manufacturing.[4] The tool only requires a bill of materials (BOM) for the product and uses well-known estimates both for the embodied energy in materials,[5,6] and for the energy requirements for various manufacturing processes.[4,7] Comparisons between the life cycle energy results from others and our model helped validate the accuracy of the data used in this study. The Supporting Information provides the model used to conduct the analyses.

Others have also addressed related questions in the literature such as in studies on the remanufacturing of specific products, optimum product replacement strategies, and product leasing.[8−16] An important and generally well-known result from product life cycle studies is that for most products the energy requirement for materials production dominates the energy requirements for manufacturing. In addition, observations from remanufacturing studies show that most of the original materials in the remanufactured product are saved, and the energy required for remanufacturing is almost always much less than that required for the original manufacturing.[1,17−19]

A second common observation from life cycle analysis (LCA) studies for "powered" products, which require an energy source, is that it is very common for the use phase to dominate energy use. That is, the energy requirements of the use phase can exceed the combined requirements of both materials production and manufacturing. As a result, as will be seen, even small changes in use phase energy can produce significantly different outcomes.

On the basis of these observations, for some products in this study we chose to ignore the energy requirements for remanufacturing. This, of course, will bias the results slightly in favor of remanufacturing; however, as will be seen, the effect is generally negligible. Furthermore, this simplification opens up the interpretation of these results to include several other categories of product restoration such as repairing, refurbishing, and even reselling if the product is still in like-new condition.

4. RESEARCH RESULTS

We start with two representative cases, refrigerators and heavy-duty truck tires, which illustrate the methodology, and point out special issues that can arise. The analysis that follows considers a product retired in year X after a first lifetime of L years. The comparison is between a like-new, but remanufactured product of model year $(X - L)$ versus a new product of model year X. For example, for a computer with a purchase-to-purchase life of 4 years (L), we compare a new device of 2005 (X) with a used one of 2001 $(X - L)$. Because of the magnitude of the use phase energy for powered products, we will pay particular attention to changes in usage patterns and changes in energy performance in the U.S. In addition, we normalize the analysis to account for improvements to the product that can be captured in the functional unit, for example, larger refrigerators and longer lasting tires.

4.1. Refrigerators. Consider the case of a refrigerator that breaks down in year X after a first life of L years of service because of a failed compressor. All other functions for the refrigerator perform at their like-new level corresponding to their original model year $(X - L)$. (This of course is an optimistic statement favoring remanufacturing.) The options considered in this analysis are to replace the failed compressor with one that has been remanufactured and use the refrigerator for another L years, or to buy new. The analysis calculates the life cycle energy requirements per cubic meter of cooled space for the materials, manufacturing, and use phases. In this case, we assume that the materials and manufacturing energy requirements to remanufacture the product are zero. The analysis is performed for four cases corresponding to new model years in 1966, 1980, 1994, and 2008. The key assumptions used in this study pertain to the use phase energy requirements, which have already been well documented for medium-sized residential refrigerators used in the U.S. over the time period 1947−2008. See in particular Rosenfeld[20] and AHAM;[21] also Kim et al.[11] gives a good review of this topic. The data show that over this time period, the electricity requirements per unit go from about 350 kWh/yr in 1947, to a peak of about 1850 kWh/yr in 1974, to about 450 kWh/yr in 2008. The early rise is due to added features (e.g., defrosting, larger freezer) and increases in size, while the decrease is due to energy efficiency mandates first in California in 1974 and later at the federal level. During this time period, refrigerators grew from about 0.23 m^3 cooled volume in 1947 to 0.61 m^3 in 2008. The U.S. Department of Energy (DOE) sets the typical service lifetime for a refrigerator in the range of 10−16 years. In this study, we assume a lifetime of L = 14 years (also used in refs 22, 23). Using these values means that a 2008 new refrigerator will use 6300 kWh electricity or (using a grid efficiency of 1/3) about 68 GJ of primary energy over its lifetime. To estimate the primary energy requirements for the materials and manufacturing of a modern refrigerator, we reviewed the studies of others[11,24− 26] and using the bill of materials provided by ref 11 applied our model.[4] The results give a range of 4442−6847 MJ for a late 1990s era model with 0.59 m^3 of cooled space. Again, to be conservative (in favor of remanufacturing), we used the higher value of about 6.9 GJ and assumed that it is applicable to 2008, which is argued below. Comparing this with 68 GJ, one sees that the use phase energy is larger by about a factor of 10. In the 1974 case (the peak year for energy use per refrigerator), the ratio is over 40, and in the 1952 case (the remanufactured model year for the 1966 new comparison), the ratio is about 9. The upshot of this is that materials and manufacturing energy play a relatively small role in the life cycle energy requirements of a refrigerator. During the 56 years examined here, it is true that materials and manufacturing energy would have changed, but we argue that these changes were probably not much different from the original range given earlier (4.4−6.9 GJ). This case can be made based upon the observation that among the various changes, the two most important probably canceled each other out. That is, among design changes one would expect more optimized use of materials (e.g., thinner sections), materials substitution (mostly plastics for ferrous metals), and most importantly larger size (a factor of 2.1 from 1952 to 2008). The size change, however, would probably be offset by increased efficiency in materials production. Trends given by Smil,[5] Chapman and Roberts,[27] and Dahmus and Gutowski[28] suggest that a reasonable estimate for efficiency improvements for ferrous metal production (the dominant material in refrigerators) would be about 1.5% per year. At this rate, over 56 years, yields a factor of improvement of about 2.3. Overall, then it appears that increases in energy due to (1) the substitution of plastics for ferrous metals and (2) an increase in size would be offset by improvements in design and materials production efficiency. Improvement in parts manufacturing would also have increases (injection molding and thermoforming of plastics vs sheet forming) and decreases due to efficiency improvements, but overall would be insignificant.

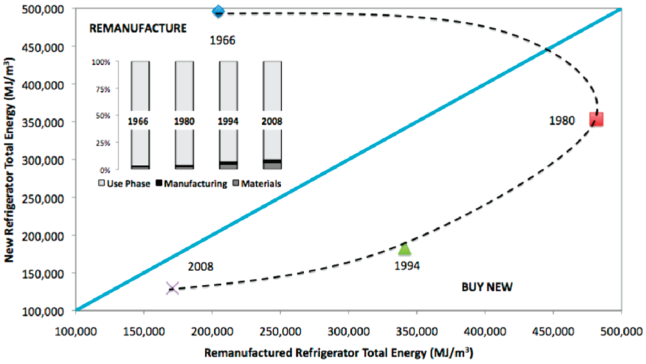

Figure 1. Total life cycle energy consumption of new and remanufactured refrigerators for the decision analysis of years 1966, 1980, 1994, and 2008. The inset shows the breakdown into different life cycle phases for the new refrigerators.

Putting this all together, we show in Figure 1 the new-product life cycle energy plotted on the Y axis, and the remanufactured-product life cycle energy plotted on the X axis. Points above the dividing line favor remanufacturing, while points below the line favor buying new. Following the points around the figure shows that in the early years when use energy was increasing, remanufacturing is favored; however, after 1974, improvements in use phase efficiency favored buying new. In the inset, one can see the resulting life cycle energy for the four new model years (1966, 1980, 1994, and 2008). The life cycle energy for the remanufacturing case is essentially the earlier model year (e.g., 1966 for the 1980 comparison) minus the materials and manufacturing contribution. The figure clearly shows how small the materials and manufacturing energy is as compared to the use phase energy.

4.2. Heavy-Duty Truck Tires. For a second illustrative example, consider the decision to replace a spent truck tire with a new or an "equivalent" retreaded tire. Retreading truck tires is a big business in the United States. According to Michelin, about 44% of all replacement tires are retreaded.[29] From a life cycle analysis perspective, there are several important differences between this example and the previous example for refrigerators. The first difference is that we found fewer life cycle studies in the literature for tires and far more variation in the available data, in particular concerning rolling resistance and the tire use phase. Second, the life span of a truck tire is far shorter than that of a home refrigerator. Driving at 50 mph for 8 h a day, 5 days a week for 50 weeks adds up to 100 000 miles in one year, equal to the tire lifetime. Hence, historical changes in use phase efficiency are far less important than the technology options a decision maker has when he or she goes to replace a tire. Additionally, retreading adds significant new material to the old casing and is in itself an energy intensive process. As a result, the energy requirements for materials and manufacturing for the remanufacturing of tires are included in this example.

The base case considered for this study is a class 8 tractor trailer truck (gross vehicle weight greater than 33 000 lb or 14 969 kg) with a fuel mileage of 5.5 mpg[30] and 18 radial tires. The life cycle inventory (LCI) for the materials and manufacturing for the radial tires relied on available data in the literature[31−34] and our estimation method.[4] We estimate the materials production and manufacturing for a new 55 kg radial tire to be 3622 + 643 = 4265 MJ.[34] The estimate for the remanufactured tire is 1365 MJ. Hence, there is a 68% energy savings if only these two phases of the life cycle are considered.

To estimate the use phase, we assume that the use phase energy of a tire is equivalent to the fraction of the fuel required to overcome the rolling resistance divided by the number of tires. Rolling resistance as a fraction of total fuel consumed for trucks, however, depends on many factors including driving and roadway conditions, speed, tire pressure, tire wear, and more. As a consequence, values given in the literature for the fraction of fuel required to overcome rolling resistance vary enormously from 13% to 47% of the total fuel used.[34] The U.S. DOE, however, suggests a smaller range from 13% to 33%.[35] To manage this variation, we identify a midpoint fraction (24%) with a specific measured rolling resistance coefficient of 0.0068 and then make comparisons to this reference case. We do this because rolling resistance coefficients can be directly measured in the laboratory under highly controlled conditions. The key assumption is that changes in the fuel required to overcome tire rolling resistance are proportional to the coefficient of rolling resistance.[34] To make comparisons with other tire technologies then, we use the following values of the coefficient of rolling resistance: for conventional bias ply tires 0.0097, for new improved radials (sometimes called low rolling resistance tires) 0.0061, and for new single-wide tires 0.0054.[33,35] New single-wide tires are now offered by a number of tire companies. They can replace a pair of conventional tires when mounted together on the axle.

An additional complication for tire remanufacturing is that because these operations can take place at many small companies, there can be significant variation in the quality of the retreading job. While it is true that a tire retreading operation can restore a tire to near original performance, from the available data there is evidence that retreading can sometimes fail to achieve like-new product performance. For example, measurements by Michelin show that the rolling resistance for retreaded radial tires can increase between 7% and 9% as compared to new radials.[36]

Putting this all together requires a series of assumptions often for variables that can have a large range of values. We tried to select values that represented central tendencies, or to slightly bias the calculation in favor of remanufacturing. For example, our assumption that both the new radials and the retreaded radials have the same mileage lifetime of 100 000 miles favors retreading.

For the overall use phase calculation, we assume 100 000 miles traveled at 5.5 mpg with 24% of the fuel used to overcome rolling resistance; this gives an energy value per tire of 35 640 MJ.[34] If the retreaded tire has an 8% increase in rolling resistance, this adds an additional 2851 MJ for the use phase of the remanufactured tire. Now if we compare this to the savings from the difference in the materials production and manufacturing phases (4265 − 1365 = 2900 MJ), we see a potential savings of 49 MJ for the retreading option. Yet this is only about 0.1% of the life cycle energy for the new tire. This difference is clearly within the margin of error for the life cycle energy methodology. There is no measurable increase, nor decrease, in the total energy consumed between the two options. If the lifetime of the retreaded tire is less, then more than one retreaded tire will be needed, and this will favor buying new. If we assume the rolling resistance fraction is larger, say 33% instead of 24% (less starting and stopping, driving continuously at a slightly reduced speed to decrease aerodynamic drag), then this will favor buying new. If one can show that the performance of the retreaded tire is equal to the new tire, then retreading can produce a maximum savings of 2900 MJ (about 7.6% reduction in life cycle energy as compared to the new tire, also probably within the margin of error for the methodology). Yet this would be the exceptional case, not the rule. Using the coefficients of rolling resistance given earlier, one can calculate that choosing a retreaded radial ply (0.0068) instead of a retreaded bias ply tire (0.0097) will save 15 199 MJ. (This is about 28% of the bias ply tire life cycle energy, and clearly significant.) In this calculation, we assumed that the material and manufacturing energy for the bias tire were the same as those for the radial. Other significant energy savings can be calculated by using the new lower rolling resistance tires listed above.

4.3. Twenty-Five Case Studies. The results from the two previous cases, although quite different in details, lead to rather similar conclusions. In both cases, the life cycle energy is dominated by the use phase, and in both cases no clear answer can be given to the simple question, does remanufacturing save energy? The answer is nuanced and depends upon many details. When we opened this study up to still more products, we found this situation occurred quite often. In fact, the answer to the question of does remanufacturing save energy is conditional and highly dependent upon current product development trends. Furthermore, when there was a clear answer, it was just as likely that the answer was "no" as it was "yes".

The details for these case studies are given in Table 1, with relevant product and scenario data, literature references, and a reference number system (1−25) that is carried through to the graphical representations of the results in Figures 2 and 3 (extra literature references (labeled "SI") are provided in the Supporting Information). Figure 2 is a log−log plot of the absolute values for the life cycle energy for the new (*Y*-axis) and remanufactured products (*X*-axis). Figure 3 is the percent energy savings for remanufacturing relative to the new product option in order 1−25.

Figure 3 clearly reveals that the answers to our question are split; there is a group of products that can provide large relative energy savings (products numbered 1−8), and there is a group of products that strongly favor buying new (products numbered 20−25), and then there is a group in the middle that are more nuanced (products number 9−19). The products in the first group (1−8) include office furniture (2 cases), clothing (2 cases), and computer equipment (4 cases). They all save energy when remanufactured, resold, or upgraded because there have been insignificant changes in the use phase energy over the time period considered. For the office furniture, there is no use phase energy. For the computer equipment, energy efficiency improvements within the same kind of devices over the time period (2001−2005) are not large enough to overcome the manufacturing phase savings achieved by reusing. Similarly (although not included in this study), the refurbishing of returned new products would fall into this category.

At the other end of the figure, products 20−25 are cases where the use phase energy has changed significantly due to efficiency mandates and/or the introduction of new efficient technologies. Case 20 compares a remanufactured 1998 dishwasher with a much more energy efficient 2008, case 21 compares a CRT to a LCD monitor, case 22 compares a retreaded bias ply truck tire to a new radial truck tire, case 23 compares a 1994 refrigerator to a 2008 model, case 24 compares a used desktop computer to a new laptop, and case 25 compares a rebuilt top loader clothes washing machine to a new front loader. In each case, choosing the remanufactured product over a new will result in a significant additional energy requirement as indicated in Figure 3.

Table 1. Summary for 25 Case Studies[a]

	new							remanufactured							
category	ref no. for Figures 2 and 3	product details	mass new; mass reman (kg)	year of mfg (X)	service life	Emfg	Euse	product details	year of mfg	service life (L)	Emfg	Euse	scenario	normalized unit for energy	references
appliances	20	dishwasher	59; 59	2008	10 years	4818	34 641	dishwasher	1998	10 years	0	44 896	remanufacture	MJ/unit product	21,24,26 SI.1
	23	refrigerator	84; 84	2008	14 years	11 326	118 560	refrigerator	1994	14 years	0	170 852	remanufacture	MJ/m^3	11,20,21,26 SI.1
	25	washing machine (front-load)	59; 59	2008	11 years	48 391	401 027	washing machine (top-load)	1997	11 years	0	1 260 508	remanufacture	MJ/m^3	21,26, SI.1, SI.2
computers	7	desktop control unit	10; 10	2005	4 years	2193	6008	desktop control unit	2001	4 years	0	6341	reuse/upgrade	MJ/unit product	SI.3
	4	laptop	2.8; 2.8	2005	4 years	1201	2537	laptop	2001	4 years	0	1867	reuse/upgrade	MJ/unit	
	6	CRT monitor	14; 14	2005	4 years	910	4275	CRT monitor	2001	4 years	0	3763	reuse	MJ/unit product	
	8	LCD monitor	6; 6	2005	4 years	963	1981	LCD monitor	2001	4 years	0	2547	reuse	MJ/unit product	
	24	laptop	2.8; 24	2005	4 years	1201	2537	desktop w/ CRT monitor	2001	4 years	0	10 104	reuse/upgrade	MJ/unit product	
	21	LCD monitor	6; 14	2005	4 years	963	1981	CRT monitor	2001	4 years	0	3763	reuse	MJ/unit product	
furniture	2	Office desk	122; 122			3290	0	office desk			0	0	reuse	MJ/unit product	SI.4
	1	office chair	29; 29			1350	0	office chair			0	0	reuse	MJ/unit product	
textiles	5	cotton t-shirt	0.25; 0.25			47	65	cotton t-shirt			1	65	reuse	MJ/unit product	SI.5, SI.6
	3	viscose blouse	0.2; 0.2			47	7	viscose blouse			1	7	reuse	MJ/unit product	
toner cartridge	10	toner cartridge			6000 pages	73	978	toner cartridge		6000 pages	6	978	refill	MJ/fraction of usable pages	37, SI.7
engines	12	passenger car gasoline engine	151; 151	1999	120 000 miles	11 901	556 121	passenger car gasoline engine	1987	120 000 miles	2795	553 924	remanufacture	MJ/unit product	18,30
	11	combination truck diesel engine	1349; 1349	1999	750 000 miles	86 673	20 342 257	combination truck diesel engine	1987	750 000 miles	1850	19 309 871	remanufacture	MJ/unit product	17,18,30, SI.8
electric motors	19	22 kW electric motor energy efficient	190; 166		6 years	18 216	4 579 302	22 kW electric motor standard efficiency		6 years	2222	4 784 652	rewind	MJ/unit product	38 , SI.9, SI.10
	14	22 kW electric motor energy efficient	190; 190		6 years	18 216	4 579 302	22 kW electric motor energy efficient		6 years	3080	4 628 969	rewind	MJ/unit product	
	15	22 kW electric motor NEMA	238; 190		6 years	19 942	4 535 505	22 kW electric motor energy efficient		6 years	3080	4 628 969	rewind	MJ/unit product	
	18	22 kW electric motor NEMA premium	238; 238		6 years	19 942	4 535 505	22 kW electric motor NEMA		6 years	3674	4 584 221	rewind	MJ/unit product	
	17	200 kW electric motor NEMA	1758; 1512		6 years	123 767	60 746 916	200 kW electric motor standard efficiency		6 years	16 400	62 499 231	rewind	MJ/unit product	
	13	200 kWelectric motor NEMA premium	1758; 1758		6 years	123 767	60 746 916	200 kW electric motor NEMA		6 years	21 200	61 063 967	rewind	MJ/unit product	

Table 1. Continued

		new						remanufactured							
category	ref no. for Figures 2 and 3	product details	mass new; mass reman (kg)	year of mfg (X)	service life	Emfg	Euse	product details	year of mfg	service life (L)	Emfg	Euse	scenario	normalized unit for energy	references
tires	22	heavy-duty Ttruck tires radial	55; 55		100 000 miles	4265	35 640	heavy-duty truck tires bias-ply		100 000 miles	1365	50 839	retread	MJ/unit product	12,31–33,35, SI.11, SI.12, SI.13, SI.14, SI.15, SI.16
	9	heavy-duty truck tires Rradial	55; 55		100 000 miles	4265	35 640	heavy-duty truck tires radial		100 000 miles	1365	35 640	retread	MJ/unit product	
	16	heavy-duty truck tires advanced radial	55; 55		100 000 miles	4265	31 971	heavy-duty truck tires radial		100 000 miles	1365	35 640	retread	MJ/unit product	

[a] See the Supporting Information for further details and references.

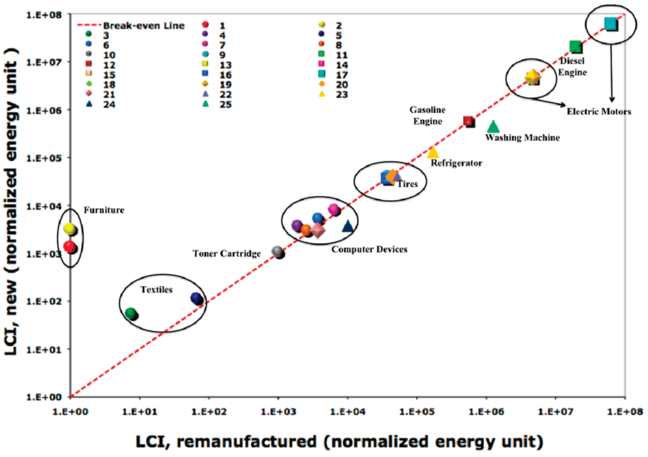

Figure 2. Life cycle energy consumption (normalized units) for new and remanufactured versions of all 25 product case studies. For the reference number, refer to Table 1. Note both axes are in logarithmic scale.

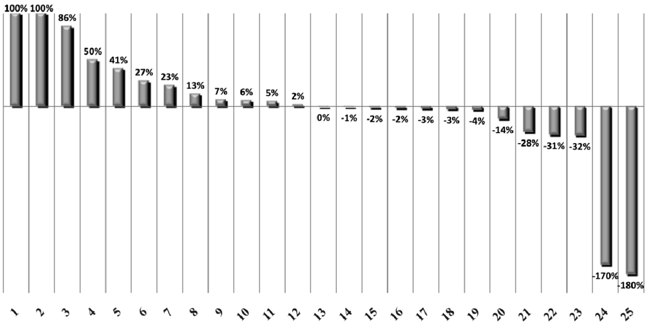

Figure 3. Percentage life cycle energy savings by choosing to remanufacture over replace with new for the 25 different product cases. The reference numbers and normalized units can be referred from Table 1.

In the middle of this figure are a number of products (9–19) that require more explanation. It should first be pointed out, however, that all of these cases lie between +7% and −4% of the new product energy requirement, and we are not sure the LCI methodology can make accurate statements in this range. Nevertheless, starting with case 9, we compare a retreaded radial truck tire to a new radial truck tire. A savings is indicated here because we have not included the potential loss in performance for the retreaded tire. As discussed earlier, this loss can be substantial, with the result that the potential savings shown would be reduced to zero.

Case 10 is for the refilling of a toner ink cartridge. The projected savings would be 6% provided the refilled cartridge functioned as new. In this area, there is very little data on the performance of refilled cartridges and nothing we have found from the remanufacturing industry. However, one report, commissioned by HP, suggests that it takes 101 sheets of paper to print 100 good copies with a new cartridge and 114 to print 100 with a refilled cartridge.[37] If these data were correct, the embodied energy in the extra paper and electricity needed to print the additional 13 pages would be enough to offset the projected savings. However, to make all assumptions in favor of remanufacturing, data and results presented in the tables and figures, for cartridges as well as other products, assume that the remanufactured products perform like-new and do not experience such degradation in performance.

Case 11 represents the remanufacturing of diesel engines. This product has been studied by Sutherland and co-workers, who indicate a large potential savings due to avoided materials production and manufacturing.[17] Furthermore, the energy efficiency of diesel trucks has been essentially flat at about 5.5 mpg over the time period 1975–2006.[30] Hence, we have calculated a potential 5% energy savings. At the same time, it is clear that even a small reduction in the fuel economy of a rebuilt engine or improvement in the new could offset this gain. For example, a change of only 0.025 mpg would be enough to undo this savings.

Cases 12–19 are dominated by two different sizes of electric motors. The smaller (22 kW) comes under the EPAct regulation of 1992, while the larger (200 kW) does not. The cases essentially compare different new motor efficiency ratings, with various rewound motors. The key piece of information included in these calculations is that we used the DOE recommendation to reduce the efficiency of the rewound 22 kW motors by 0.5% and for the rewound 200 kW motors by 1%.[38,39] This difference is enough to shift the result, in terms of energy usage, in favor of buying new. Again, we state our doubts whether the LCI methodology can really make meaningful statements when the differences are so small.

All of these cases are plotted in terms of absolute energy requirements in Figure 2. Points that lie above the dividing line favor remanufacturing, while those below favor buying new. Note that the energy resources used by motors and engines are large, and so small performance improvements, if they can be substantiated, could represent significant savings in magnitude. They would, however, be small relative to the total energy resources used.

5. DISCUSSION

When taken as a whole, it seems that making general energy savings claims for remanufacturing is not advisible. It happens that, historically, remanufacturing did save energy (and materials too) when products were unpowered. Yet current design trends of powering up products appear to have altered the energy resources usage substantially. That is, products that used to have no use phase are now powered. For example, rakes, snow shovels, and hammers are now leaf blowers, snow blowers, and power tools. This trend brings convenience and reduces human toil, but at the same time subsequent improvements in energy efficiency could work to reduce the potential energy savings promised by remanufacturing. (In Figure 2, this phenomena would be represented by products moving from on, or very near to the *Y*-axis, where remanufacturing would clearly save, to the dividing line, where the outcome involve small differences between large numbers.) It has often been proposed to design using a modular platform to incorporate new features in used products. This could be a significant advancement for remanufacturing. For the purpose of this Article, this would mean incorporating energy efficiency improvements. However, it was also observed in this study that many of the major efficiency improvements in products are not incremental but radical, with major transformations in the product architecture, inhibiting such upgrades. Examples include desktop to laptop computers, top-load to front-load washing machines, and bias-ply to radial tires. On the other hand, the upgrading of components could be accomplished if they were standardized.

At the same time, other old benefits still accrue. Remanufacturing does provide local skilled jobs, generally reduces transportation when the primary materials come from far away, and may displace some primary production if the remanufactured product is truly a substitute for a new product. Concerning transportation, in the sensitivity analysis, it became apparent that transportation could become an issue for some extreme cases such as the air transport of new laptop and notebook computers from Asia to the United States. This can add substantially to the energy requirements of new products. Under these conditions, remanufacturing can appear energy saving. The case for laptops presented in this paper (no. 4 as per Table 1) does not include transportation and shows energy savings from reusing the old laptop can be close to 50% of the manufacturing plus use phase energy requirements of the new laptop. Adding international transport will increase these relative energy savings to 58% making reuse even more favorable (details are available in the Supporting Information). Among other case studies, results in Table 1 include transportation for textiles, toner cartridges, and furniture, while for appliances and engines a sensitivity test showed the transportation contribution to be negligible (more information in the Supporting Information). In closing, we point out that, while there are many additional aspects of remanufacturing that could be explored, one that strikes us as particularly important is the degree to which the remanufactured products actually substitute for new. This is a research issue unto itself. Past work indicates that the relationship can be quite complex, and in some cases the two products can end up being more like complements than substitutes.[40,41]

ASSOCIATED CONTENT

Ⓢ **Supporting Information.** Additional assumptions, references for Table 1, and Technical Reports. This material is available free of charge via the Internet at http://pubs.acs.org.

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