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Appliance Remanufacturing and Life Cycle Energy and Economic Savings

A. Boustani*, S. Sahni*, S. C. Graves, and T.G. Gutowski

Abstract- In this paper we evaluate the energy and economic consequences of appliance remanufacturing relative to purchasing new. The appliances presented in this report constitute major residential appliances: refrigerator, dishwasher, and clothes washer. The results show that, despite savings achieved in production, appliance remanufacturing is a net energy-expending end-of-life alternative. Moreover, we find that economic incentives can be an influential driver for consumers to remanufacture and re-use old appliances.

Index Terms- Appliances, Energy, Remanufacturing, Re-Use.

I. INTRODUCTION

In 2008, the U.S. residential sector consumed 21.6 quadrillion BTUs of energy [1]. This is equivalent to more than one fifth of the U.S. energy consumption [1]. According to the Energy Information Administration, total consumption by home appliances accounts for nearly one third of the nation's residential energy consumption and more than 6% of total national energy consumption [2]. This is largely due to appliances' high saturation rates in the residential sector [3]. With high penetration rates in the U.S. households, appliances draw considerable amounts of energy in use, and in turn, have a high potential for impacting the environment. The appliances presented in this report constitute major residential appliances: refrigerator, dishwasher, and clothes washer.

There is considerable amount of literature regarding policy, economics, and efficiency impacts on appliances. Relevant literature includes Kim et al., which discuss the optimal household refrigerator lifetime in the U.S. [4]. Similarly, Bole et al. present the optimal replacement intervals for residential clothes washers [5]. Dale et al. provide retrospective evaluation of appliance price trends [6]. Meyers et al. evaluate energy, environmental, and consumer impacts of U.S. federal residential energy efficiency standards for residential appliances [7]. Lindahl et al. convey general environmental costs and benefits associated with remanufacturing, focusing

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on multiple case studies including environmental assessment of the refurbishment of household appliances in Sweden [8].

At the end of the first ownership lifetime, some appliance units are re-used, hence, avoiding conventional end-of-life options: landfilling and recycling [3]. Re-use of an old unit may be prone to degraded performance and premature failure [9]. Remanufacturing the appliance is one way to restore the old appliances to 'like-new' conditions and to effectively mitigate the chances of pre-mature failure. Remanufacturing processes encompass unit inspection, disassembly, parts replacement or refurbishment, cleaning, reassembly, and final testing. Remanufacturing an old appliance may 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 demand for new goods.

Appliance remanufacturing can save energy and raw materials during the production process, hence, benefiting the environment in this regard. However, given that remanufacturing preserves the technological architecture of an old product, a remanufactured unit may consume more energy compared to a new, more efficient unit. Therefore, despite savings in production, utilizing a remanufactured appliance may lead to higher life-time energy consumption compared to purchasing a new unit. Indeed, policy interventions and technological improvements have led to substantial reductions in energy consumption of appliances since 1981, as shown in Figure 1 below.

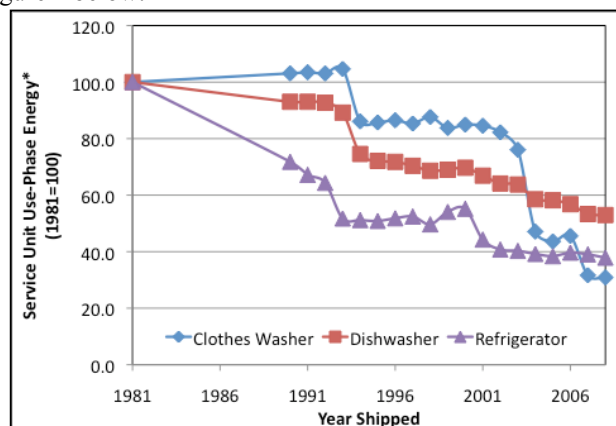


Fig. 1 Change in energy consumption for major appliances [13]. * Service unit for the clothes washer, the dishwasher, and the refrigerator, as shown in this plot, are energy consumption per cycle, energy consumption per cycle, and annual energy expenditure, respectively.

This paper addresses the total life cycle energy and economic savings potential of extending the service life of an old

appliance through remanufacturing. Life Cycle Assessment (LCA) as well as Life Cycle Costing (LCC) are utilized to capture the energy savings and economic feasibility of appliance remanufacturing.

The results depict that the life cycle energy cost of appliances is dominated by the use phase. Furthermore, the results indicate that appliance remanufacturing is a net energy-expending alternative. Moreover, the retrospective energy analysis reveals that the conclusions regarding appliance remanufacturing and energy saving are strictly correlated with pace of efficiency improvements in time. In addition, the results from the life cycle economic costing reveal that economic and energy analyses may provide different outcomes regarding the feasibility of appliance remanufacturing. Furthermore, we investigate the macroscopic influences on the feasibility of remanufacturing and reusing old appliances. For this, we address two important system factors, namely, the impact of technology progress and the impact of regulatory policies on appliance remanufacturing¹.

II. RESEARCH METHODS

We utilize Life Cycle Assessment (LCA) as the methodology for determining the potential environmental impacts of a product from cradle-to-grave. More specifically, we consider Life Cycle Inventory (LCI) analysis to quantify cumulative material and energy inputs and outputs for all life cycle stages. This study focuses on energy consumption in order to quantify the environmental impacts.

A. Life Cycle Energy Analysis

The LCI system boundary for this study entails raw material extraction, manufacturing, and use phase for a functional appliance unit. Other phases such as the transportation phase and the end-of-life phase are ignored in the main analysis, but discussed in detail in the sensitivity analysis.

Raw Material Acquisition and Processing Phase

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. We begin with a bill of materials of the product (in kg of raw materials). The bill of materials for refrigerator (1997 model), clothes washer (2005 model), and dishwasher (1995 model) are taken from [4], [5], [10], respectively. We find the raw materials energy intensity in each appliance by using the data on the energy cost of common materials found in [11] and [12]. We utilize the raw materials energy requirements in order to quantify energy demands.

Manufacturing and Assembly Phase

We rely on literature values for quantifying manufacturing energy demands. The manufacturing process of a refrigerator consists of parts assembly, door assembly, cabinet assembly,

refrigeration cycle assembly, plastic parts processing, and assembly [4]. We use the manufacturing energy intensity (MJ/kg) provided in [10] and multiply it by unit mass [4]. Due to scarcity of data, we assume that the manufacturing energy intensity (MJ/kg) of a clothes washer is similar to a refrigerator as provided in [10]; the unit mass of the clothes washer is taken from [5]. For a dishwasher the manufacturing energy consumption is taken from [10]. Though changes across manufacturing practices, product architecture, and production efficiency would change the embodied energy value for the appliance, we will use the same raw materials and manufacturing energy values for all models due to lack of available data.

Use Phase

The annual energy consumption is determined by relying on the trends for unit energy consumption, capacity, and efficiency of appliances from 1981 to 2008 provided by the Association of Home Appliance Manufacturers (AHAM) [13]. The annual values are summed over average useful lifetime to determine the use-phase energy consumptions. The average length of ownership for refrigerator, clothes washer, and dishwasher are taken as 14 years [3,14], 11 years [15], and 10 years [16], respectively. The average number of washing loads per year is estimated to be 392 cycles for residential clothes washers [15,17] while for dishwasher, the average number of cycles per year is taken as 215 cycles [16,17].

Appliance Remanufacturing

Appliance refurbishing and remanufacturing are common industrial practices in the EU [8]. This study, however, focuses on appliance remanufacturing in the U.S. 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 the operation and that can be prone to failure such as compressors, valves, pumps, or control units [9]. Once these units are repaired and reinstalled, 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.

We evaluate the 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) purchase a new appliance (latest model) or (b) bring the old appliance to ‘like-new’ conditions by replacing the malfunctioned components with remanufactured parts.

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.

As depicted in (1) and (2), for new appliances the life cycle inventory (LCI) includes raw material processing ($E_{rm,new}$), manufacturing ($E_{m,new}$), and use ($E_{u,new}$). Similarly, for remanufactured appliances the life cycle energy impacts encompass remanufacturing ($E_{reman,old}$) for old product, and use ($E_{u,old}$).

¹ Detailed information about calculations, assessments, and discussions regarding appliance remanufacturing and energy saving are provided in [20].

$$LCI_{NEW} = E_{rm,new} + E_{m,new} + E_{u,new} \quad (1)$$

$$LCI_{REMAN} = E_{reman,old} + E_{u,old} \quad (2)$$

The customer would be indifferent between new and remanufactured units from an energy standpoint when $LCI_{NEW} = LCI_{REMAN}$. For this study we assume the same lifetime and the same end-of-life disposal mechanisms for both new and remanufactured appliances. Remanufactured products may be prone to degraded performance. For this study, we assume that the remanufactured product will operate like-new. In this study, re-using an old appliance is based on replacing the worn parts with remanufactured parts and components. As a very conservative assumption, favoring remanufacturing, we assume that the energy cost for producing and incorporating the remanufacturing parts is negligible. We perform sensitivity analysis to examine this assumption (see Sensitivity Analysis).

Also, we assume that for a particular appliance, the product lifetime is the same regardless of the year it was manufactured. In addition, raw material processing and manufacturing for each appliance are based on a single model. Therefore, we do not account for the dynamic changes in the production material compositions as well as changes in the production energy intensity over time. We assume that there is consistent energy consumption throughout the appliance service life ignoring potential decline in efficiency over time [18]. Due to the existing complexities in reverse logistics, we ignore the transportation energy in retrieving the used appliance. These assumptions favor remanufacturing and hence, we view them as being conservative. We perform sensitivity analysis to examine these assumptions (see Sensitivity Analysis).

Given the system boundary above, we determine the total life cycle energy demands of new and remanufactured appliances by utilizing (1) and (2). The analysis is conducted retrospectively to capture changes in appliance use-phase performance in time.

B. Life Cycle Economic Analysis

In addition to energy analysis, we conduct the economic feasibility of remanufacturing for appliances. In this paper, we provide Life Cycle Costing results for refrigerators focusing on cost valuation from a consumer's perspective. In doing so, the purchase price and the use phase electricity costs were computed for refrigerators produced in different years. All economic valuations were performed in real dollar values in the year 2000, adjusting for inflation. The market value of a refrigerator was determined by [6]. The average retail price of the electricity for the residential sector (adjusted for inflation) was used for determining the total electricity cost of a unit during its operational lifetime [1]. Due to unavailability of data, the electricity pricing for years after 2008 was assumed to be same as year 2008 (9.28 cents per kWh) [1]. Finally, the values were normalized by the corresponding unit capacity of the refrigerator to filter-out the energy impacts due to changes in volume. As a conservative assumption favoring remanufacturing, we assume that the economic cost of remanufacturing an old unit is negligible. We perform sensitivity analysis to examine this assumption (see Sensitivity Analysis).

We present the results of our energy and economic analyses in three main forms:

1. Total life cycle energy cost of new refrigerator, new clothes washer, and new dishwasher.
2. Retrospective life cycle energy comparison of a newly produced dishwasher and a remanufactured dishwasher (one lifetime [10 years] older) between 1991 and 2008.
3. Retrospective life cycle economic comparison of a newly produced refrigerator and a remanufactured refrigerator (1 lifetime/ generation older) between 1994 and 2000.

III. RESULTS

A. Life Cycle Energy Results

Figure 2 illustrates the life cycle energy demands of new appliances: clothes washer, refrigerator, and dishwasher.

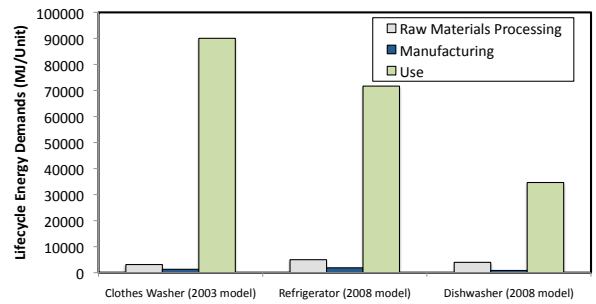


Fig. 2. Life cycle energy assessment of new appliances.

According to Figure 2, the use phase dominates by consuming between 88 to 95 percent of the life cycle energy of the appliances; as such, it is critical to consider the use-phase impacts while evaluating the energy savings potential of appliance remanufacturing.

Table 1 shows the life cycle energy savings (in percentages) by remanufacturing an old (1 generation prior) appliance versus purchasing new.

TABLE I
APPLIANCE REMANUFACTURING
LIFE CYCLE ENERGY SAVINGS

	Energy New Unit (MJ/Unit Service ^a)	Energy Remanufactured Unit (MJ/Unit Service ^a)	Energy Savings ^b (%)
Clothes Washer (2003 model versus 1992 model)	1,108,194	1,590,310	- 44%
Refrigerator (2008 model versus 1994 model)	129,886	170,852	-32%
Dishwasher (2008 model versus 1998 model)	39,459	44,896	- 14%

^a Unit service for clothes washer and refrigerator are cubic meters while for dishwasher is a unit product. Dishwashers are not normalized by unit volume because their volumes have not changed substantially.

^b Remanufacturing lifecycle energy saving = $\frac{LCI_{NEW} - LCI_{REMAN}}{LCI_{NEW}} \times 100$

As depicted in Table 1, by remanufacturing an old clothes washer, an old refrigerator, and an old dishwasher, 44%, 32%, and 14% more life cycle energy is expended. The results in Table 1 provide a static representation of appliance remanufacturing by performing the comparison only for one specific year. We use the recent evolution of energy efficiency to provide a retrospective assessment of the feasibility of appliance remanufacturing over time. Figure 3 illustrates the life cycle energy comparisons (per unit) between new and remanufactured dishwashers retrospectively, from years 1991 to 2008. Each data point represents the life cycle energy comparison of a new dishwasher (produced in the year depicted in Figure 3) against a 1 generation (10 years) older remanufactured dishwasher.

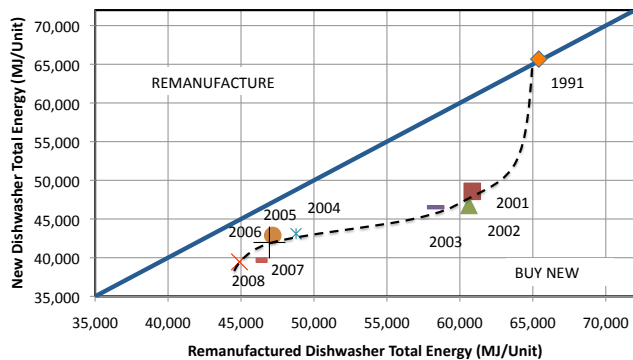


Fig. 3. Retrospective life cycle energy comparison of new and remanufactured dishwashers. This plot illustrates the total life cycle energy comparison (per unit) of a newly produced dishwasher against 1 generation (10 years) older remanufactured dishwasher. The dividing line shows the break-even points where $LCC_{NEW} = LCC_{REMAN}$. The labels on the plot represent the year for which the comparison analysis is conducted (e.g. 1991 refers to the energy comparison analysis in year 1991 between purchasing a new 1991 model dishwasher versus remanufacturing a 1981 dishwasher). ‘REMANUFACTURE’ and ‘BUY NEW’ indicate the optimal decision for saving energy for data points positioned above dividing-line and below dividing-line, respectively.

As shown in Figure 3 the life cycle energy savings of dishwasher remanufacturing depends on the level of efficiency improvements (see Figure 1). Figure 3 is discussed in detail in section IV.

B. Life Cycle Economic Results

In addition to LCA, LCC is conducted for determining economic feasibility of appliance remanufacturing. Moreover, retrospective assessments are performed to capture the dynamic changes in appliance capital cost and use characteristics. Figure 4 illustrates the retrospective assessment of the total life cycle economic comparison in dollars (normalized by unit volume) of a newly produced refrigerator against 1 generation (one lifetime) older remanufactured refrigerator from 1994 to 2000.

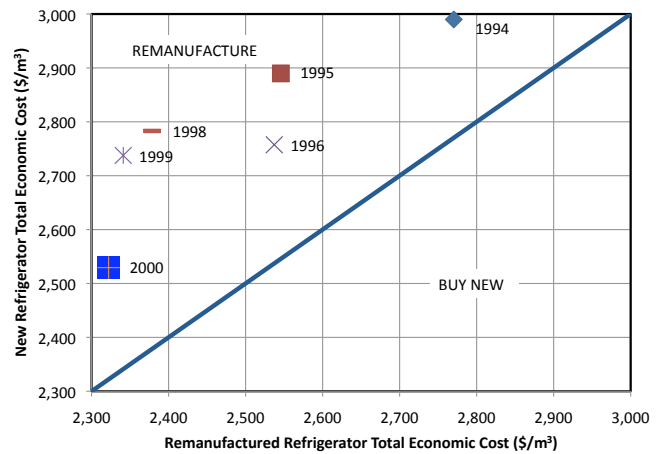


Fig. 4. Retrospective life cycle economic comparison of new and remanufactured refrigerators. This plot illustrates the total life cycle economic comparison (normalized by adjusted volume) of a newly produced refrigerator against 1 generation (14 years) older remanufactured refrigerator. The dividing line shows the break-even points where $LCC_{NEW} = LCC_{REMAN}$. The labels on the plot represent the year for which the comparison analysis is conducted (e.g. 2000 refers to the economic comparison analysis in year 2000 between purchasing a new 2000 model refrigerator versus remanufacturing a 1986 refrigerator). ‘REMANUFACTURE’ and ‘BUY NEW’ indicate the optimal decision for economic saving for data points positioned above dividing-line and below dividing-line, respectively.

IV. DISCUSSIONS

A. Appliance Remanufacturing and Energy Savings

Remanufacturing can save considerable energy in the production phase of appliances. Our analysis shows that the use phase constitutes 88% to 95% of the total life cycle energy use of the appliances (see Figure 2). Therefore, it is critical to consider the use-phase when investigating the environmental impacts of appliance re-use. Based on the improvements in energy consumption of new units (see Figure 1), appliance remanufacturing is net energy expending. For example, the efficiency improvements in clothes washers (see Figure 1), makes remanufacturing an old unit (1992 model) a net energy-expending end-of-life option by expending 44% more energy per cubic meter compared to a new 2003 unit (see Table 1). Similarly, by remanufacturing an old refrigerator in 2008, 32% more energy is expended from a total life cycle perspective compared to a new refrigerator.

As depicted in Figure 3, the efficiency improvements have reduced the life cycle energy demands for dishwashers from 65,668 MJ per unit in 1991 to 39,459 MJ per unit in 2008 (40% reduction). The retrospective analysis shows that the life cycle energy impacts of new and remanufactured dishwashers break-even in 1991 ($LCC_{NEW} = LCC_{REMAN}$). Due to efficiency improvements, re-using an old dishwasher instead of purchasing new leads to 25% and 14% more life cycle energy use in 2001 and 2008, respectively. The retrospective assessment (see Figure 3) illustrates that dishwasher life cycle energy was reduced greatly between 1991 and 2001. Following this period (2001 to 2008), the continued improvements in efficiency led to more energy saving in new dishwashers. If the trend for dishwashers continues as shown in Figure 3, then

remanufacturing a dishwasher will be net energy expending. On the other hand, if the efficiency improvement stops, then remanufacturing would be preferred since it would save both materials and energy during the entire life cycle.

Assuming 10% margin of error due to the approximations and inaccuracies inherent in LCA models, remanufacturing energy savings potential for results that fall in this range demand further investigations in order to draw insightful conclusions.

B. Appliance Remanufacturing and Economic Savings

As shown in Figure 4, the total life cycle economic cost of new refrigerators has dropped by 15% between 1994 and 2000. Contrary to the energy impacts, the dominant phase of the life cycle economic costing for appliances is the purchase cost. For example, the capital investment of a new conventional refrigerator in 2008 is nearly 60% of its total life cycle economic cost. The retrospective analysis reveals that the consumer will spend 52% to 96% (depending on the comparison year) more on electricity by re-using an older, less efficient refrigerator; however, this is still less significant than savings in capital cost. As a result, re-using an old refrigerator could lead to 6 to 15% percent savings on average in total lifetime cost of a refrigerator during years 1994 and 2000 (see Figure 4). Given the LCA 10% error margin, remanufacturing economic savings for some years may be unclear and demands further investigation to draw insightful conclusions.

The next section addresses the two main drivers in improvements observed in appliances, namely, policy interventions and technological progress.

C. Technology and Policy Impacts on Life Cycle Energy Requirements of Appliances

Appliance standards have been an effective catalyst in promoting technological progress in the appliance industry to produce products that serve consumer needs with less energy requirements. Prior to the establishment of the Energy Policy and Conservation Act in 1975, efficiency of appliances was not a crucial focus for appliance manufacturers. Mandatory energy conservation standards for residential appliances were first legislated as part of the National Appliance Energy Conservation Act (NAECA) in 1987 [6]. Additional standards were written into law with the establishment of the Energy Policy Act of 1992. For example, the first mandatory standard for dishwashers was put-forth in 1988 following an update in 1994. As depicted in Figure 3, these standards led to substantial improvements in new dishwashers between 1991 and 2001, causing appliance remanufacturing to be an energy-expending end-of-life option in 2001.

The policy interventions have been influential in promoting technological improvements and efficiency enhancements for appliances. The efficiency improvements have been driven by step-wise (transitional) technological progress. In addition, technological advancements have led to transformational (architectural) changes in the fixtures of some appliances. For example, the architectural design changes in clothes washer from vertical-axis to horizontal-axis in the late 1990s have led

to considerable improvements in water and energy consumptions.

The technological advancement in appliances in combination with policy intervention makes new appliances highly advanced from a resources and energy savings perspective.

V. SENSITIVITY ANALYSIS

A. Transportation Phase

The objective of this sensitivity analysis is to examine the impact of transportation phases on life cycle energy demands for appliances. The transportation phases taken into account are: (1) transport of processed raw materials to manufacturing plant and (2) transport of the assembled product from manufacturing along the distribution channels to the consumer.

For transportation distances and modes of transportation for appliances we rely on data provided by [5], which provides a hypothetical transportation path of a Whirlpool vertical-axis washer. We assume that the transportation distances apply to refrigerator and dishwasher as well. The transportation modes for these phases take place domestically and are by heavy tractor-trailer diesel trucks. From [19] the typical transportation energy of a diesel-operated tractor-trailer is about 2.05 MJ per ton-miles of transport. Therefore, for the clothes washer, the refrigerator, and the dishwasher the energy estimates for the supply chain transport is 171.8 MJ, 245.6 MJ, and 172.5 MJ, respectively. This translates to less than 0.5% of life cycle energy demands. As a result, due to the minimal energy impacts of transportation, the transportation phase was neglected in the main life cycle analysis.

B. End-of-Life Treatments

In this section the energy impacts of landfilling and recycling are discussed. The transportation distance from the disposal location to a local landfill is assumed to be around 50 miles [5]. Similar to above, the typical transportation energy was taken from [19]. We assume that the energy requirement for end-of-life processes for landfill is negligible. Therefore, the energy demands for landfilling for clothes washer, refrigerator, and dishwasher is computed as 6.03 MJ, 8.61 MJ, 6.05 MJ, respectively. Landfilling as an end-of-life option leads to energy impacts that are less than 0.02% of the total life cycle energy.

An alternative end-of-life option is appliance recycling. One can assume that recycling is only conducted when it leads to a net energy saving. Thus by choosing to purchase a new unit and recycling the old unit, the net life cycle energy for the new unit would be less than the estimated values in Table 1. This further strengthens the conclusions about dishwasher, refrigerator, and clothes washer remanufacturing as net energy-expending end-of-life option in recent years. Therefore, this sensitivity analysis reveals that including recycling in the life cycle energy analysis does not change the conclusions.

C. Life Cycle Economic Analysis

In the main analysis, the conservative assumption is that the cost to remanufacturing is null. In reality, the repair/replacement/remanufacturing costs may be considerable. Our sensitivity analysis indicates that if the cost of remanufactured appliance is 10% to 30% of the market value of a new refrigerator, then economic savings in investment phase would break-even with the additional lifetime electricity cost. This makes the consumer financially indifferent between buying new and remanufacturing old. Furthermore, this sensitivity analysis reveals that economic saving associated with appliance remanufacturing depends on the market value of new and remanufactured appliances. As a result, we conclude that economic analysis can be highly sensitive to market prices for repair and remanufacture and should be performed on a case-by-case basis in order to draw insightful conclusions.

D. Life Cycle Energy Analysis

In the main analysis, we assume that the energy requirements for remanufacturing are null. The LCA results indicate that the raw materials processing and manufacturing constitute 5 to 12% of appliance life cycle energy (see Figure 2). As such, if the remanufacturing energy required as much energy as the production of new appliances (due to energy requirements in replacement, repair, inspection, reverse-logistics) then total life cycle energy savings in Table 1 would be reduced to -49%, -41%, and -26% for the clothes washer, the refrigerator, and the dishwasher, respectively. This would result in making the clothes washer, the refrigerator, and the dishwasher remanufacturing even more energy expending (see TABLE I). Therefore, this sensitivity analysis depicts that our assumption about remanufacturing energy requirements as being negligible does not have a strong impact on the conclusions drawn from the life cycle energy analysis.

VI. CONCLUSIONS

The life cycle energy analysis sheds light on the importance of considering use phase while evaluating the energy saving potential of remanufacturing appliances upon reaching end-of-life. We conclude that from a total life cycle perspective, remanufacturing is a net-energy-expending end-of-life option. The economic assessments indicate that if the cost of re-use/remanufacturing is minimal compared to the purchase cost, then appliance remanufacturing may provide an economic incentive for consumers. Our retrospective approach demonstrates the criticality to study macroscopic factors such as technological improvements, policy impacts, economic incentives in order to draw insights about energy and economic saving potential of appliance remanufacturing.

- [1] Energy Information Administration, "Annual Energy Review," 2009.
- [2] Energy Information Administration, "Residential Energy Consumption Survey," 2005.
- [3] Association of Home Appliance Manufacturers, "Major home appliance saturation and length of first ownership," Appliance Recycling Information Center, 2001.
<http://www.aham.org/ht/a/GetDocumentAction/i/1477>
- [4] H.C Kim, G.A. Keoleian, and Y.A. Horie, "Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost," *Energy Policy*, vol. 34, pp. 2310-2323, 2006.
- [5] R. Bole, "Life-cycle optimization of residential clothes washer replacement," M.S. Thesis, Dep. Natural Resources and Environment, Univ. of Michigan, Ann Arbor, MI, *Center for Sustainable systems, University of Michigan*, Report No. CSS06-03, 2006.
- [6] L. Dale, C. Antinori, M. McNeil, J.E. McMahon, K.S. Fujita, "Retrospective evaluation of appliance price trends," *Energy Policy*, vol. 37, pp. 597-605, 2009.
- [7] S. Meyers, J.E. McMahon, M. McNeil, X. Liu, "Impacts of U.S. federal energy efficiency standards for residential appliances," *Energy*, vol. 28, pp. 755-67, 2003.
- [8] M. Lindahl, E. Sundin, J. Oslin, "Environmental issues within the remanufacturing industry, "Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses, pp.447-452, 2006.
- [9] W. Hauser and R.T. Lund, "Remanufacturing: Operating Practices and Strategies," Boston, MA, 2008.
- [10] R. Kemna, M. V. Elburg, W. Li, R.V. Holsteijn, "Methodology Study Eco-Design of Energy Using-Products." *Van Holsteijn en Kemna BV and European Commission*.
- [11] V. Smil, *Energy in Nature and Society*: ed: MIT Press, 2008.
- [12] M. Ashby, *Materials and the Environment: Eco-informed Material Choice*: Butterworth-Heinemann, 2009.
- [13] Association of Home Appliance Manufacturers, "Energy efficiency and consumption trends," 2008.
- [14] Department of Energy, Energy Efficiency and Renewable Energy, "Buildings energy data book," 2009.
- [15] Appliance Magazine, 2008. Retrieved from Energy Star Life Cycle Cost Estimate for Energy Star Qualified Residential Clothes Washer.
- [16] Appliance Magazine, 2008. Retrieved from Energy Star Life Cycle Cost Estimate for Energy Star Qualified Residential Dishwasher.
- [17] DOE Federal Test Procedure 10 CFR 430, Appendix J1. "Energy Conservation Program for Consumer Products," 2007.
http://www1.eere.energy.gov/buildings/appliance_standards/residential/pdfs/dryer_roomac_framework.pdf
- [18] R.W. Johnson, "The effect of blowing agent on refrigerator/freezer Total Equivalent Warming Impact (TEWI)," *Polyurethanes Conference, Boston, Massachusetts*, 2000.
- [19] G. Keoleian, K. Kar, M. Manion, J.W. Bulkley, *Industrial ecology of the automobile: A life cycle perspective*: Society of Automotive Engineers, 1997.
- [20] A. Boustani, "Remanufacturing and Energy Savings," S.M. Thesis, Dept. Mechanical Engineering, Massachusetts Institute of Technology, 2010.