Appliance Remanufacturing and Energy Savings

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1. Introduction

Appliances are major contributors to national energy consumption of the United States. Residential energy consumption accounts for nearly one third of U.S. energy-related consumption [Shorey]. Based on data from the U.S. department of energy (DOE), major home appliances account for nearly one third of the nation's residential energy consumption (equivalent to about 10% of total energy consumption) [Shorey]. 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, 1999]. Certain parts of the country in the residential sector also have room air conditioners. The distribution of electricity consumption for household appliances varies by type, size, and operational behavior of the appliance. Table 1 below reveals the saturation of major household appliances and its contribution to total U.S. electricity consumption [Shorey; DOE EIA, 1997].

Table 1 Inventory of Appliances and Residential Electricity Consumption in 1997

Appliances Type	Inventory of Units (Millions)	Saturation (percent of households)	Electricity Consumption per year (Thousand GWh)
Refrigerators	112	115%	151
Ranges	100	101%	34
Washer/Dryers	95	74%	81
Dishwashers	45	52%	40
Room air conditioners	42	41%	52
Electricity Consumption Major Home appliances			335
Total U.S. Residential Electricity consumption			1,000
Total U.S. electricity consumption			3,000

Source: U.S. Department of Energy, Appliance Magazine, Association of Home Appliance Manufacturers [Shorey].

It is evident that if just the production phase of an appliance were considered, remanufacturing would provide a distinct advantage over a similar new product because most production costs, including the highly energy intensive material energy costs, could be avoided. According to a survey of remanufacturers conducted by Lund et al. (2003), a majority of remanufacturing energy investment is in human labor whereas for new products, a majority of the production energy is consumed by making materials and conventional manufacturing processes, which are mostly automated. Remanufacturing extends the lifetime of a product, bringing parts that are prone to failure and are cheap to remanufacture out of retirement, hence, giving an old model of a product new life.

It is important to define the concept of a remanufactured appliance. For the most part, this does not refer to the entire appliance, but rather to a part that is integral to operation and can be prone to failure [Hauser]. For example, while it is not common to find a remanufactured refrigerator in the U.S., acquiring remanufactured compressors, valves, pumps, or control units is prevalent. Once these units are found and reinstalled into the appliance, the appliance has new life and can last until another component fails. Therefore, the definition of 'remanufactured' appliances as presented in this report may overlap with appliance 'repair', 'reuse', and 'refurbish.'

Buying a remanufactured appliance component may be desirable for the consumer from an economic standpoint: it is much cheaper to purchase a small but integral part of a refrigerator rather than an entirely new unit. Furthermore, the consumer may believe they are saving energy by reducing the demand for new goods. However, from a total lifecycle perspective, 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 use phase compared to a new model. As such, in this report, the evolution of energy efficiency trends for appliances is presented to provide a retrospective assessment of the viability of appliance remanufacturing in time.

In the past two and a half decades new appliances have been often built to higher efficiency standards than older comparable units due to technological advancements, rise in electricity cost, and series of federal and state policies standardizing minimum efficiency performance of appliances. Over their lifetimes, therefore, new units produced may save significantly more energy than older units, even though they necessitate material and manufacturing costs that remanufactured units do not. However, prior to standards, appliance efficiency had not been a crucial focus for manufacturers. As such, a refrigerator manufactured in 1970 consumed more energy during its lifetime 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, we have witnessed substantial improvements in appliances energy performance during operation, as shown in Figure 1 below.

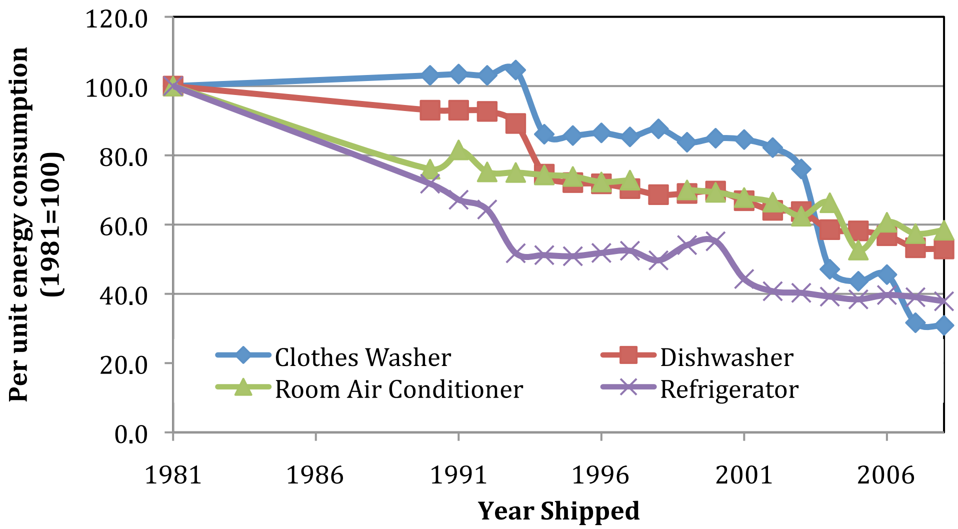


Figure 1 Change in energy consumption for major appliances [AHAM, 2008]

The appliance remanufacturing energy savings is evaluated in the following context:

Upon the appliance reaching its end-of-life (due to component failure, malfunctions, unit break-down, approaching physical limits etc) the consumer is facing a decision: (a) to purchase a new appliance (latest mode) or (b) remanufacture the appliance that has been used for one full lifetime. The analysis is conducted retrospectively to capture changes in appliance use-phase traits in time. The results of our analysis are shown mainly in three distinct plots:

1. Retrospective plot illustrating total life cycle energy of new appliances
2. Retrospective plot illustrating total life cycle energy comparison of a newly produced appliance and a remanufactured (1 lifetime/ generation older) appliance
3. Retrospective plot illustrating energy saved in manufacturing-phase versus energy expenditure during use-phase compared to new due to remanufacturing (normalized by new product use-phase)

Similar plots are generated for remanufacturing financial analysis.

There are several assumptions made 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. Remanufacturing will extend an appliance service life by one full lifetime.
4. Raw material processing and manufacturing for appliances are based on a single model (i.e. dynamic changes in product material compositions and/or changes in production energy intensity is not accounted for in this life cycle assessment).

5. 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.
6. For conservative analysis in favor of remanufacturing, the monetary cost of remanufacturing an appliance is assumed to be zero.
7. Constant energy consumption throughout the appliance service life ignoring the appliance decline in efficiency over time [Johnson].
8. 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).

The appliances presented in this report constitute major residential appliances: refrigerator, dishwasher, clothes washer, and residential air conditioner. As expressed in detail below, appliances lifetime energy consumption has considerably changed in the past decades mainly due to policy directives and technological changes. Our energy assessments conclude that appliances remanufacturing could be a net energy saving as well as net energy expending end-of-life option. Our second conclusion is that it is necessary to take into account not only the production phase in our system boundary, but also include subsequent phases, especially use phase, to accurately and holistically evaluate the environmental impacts of appliances remanufacturing. This requires accounting for several other prevailing drivers that influence use phase such as governmental policy interventions and pace of technological changes in time. The following sections will analyze life cycle energy and economic valuation of appliances in face of such changes.

2. Methodology

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is predominantly utilized for determining the potential environmental impacts of a product from 'cradle-to-grave.' LCA models encompass four main categories of analysis: (1) definition of the goal and scope of the LCA (2) the life cycle inventory analysis (LCI) (3) the life cycle impact assessment (4) improvements and interpretations [ISO, 2006].

This study utilizes life cycle inventory analysis, which quantifies cumulative material and energy inputs and outputs of all life cycle stages of a product from cradle-to-grave [Bole]. More specifically, this study focuses only on energy consumption in order to quantify the environmental impact of new and remanufactured products.

2.2 System boundary

The system boundary of our analysis is defined by a functional unit (e.g. refrigerator, clothes washer, dish washer, room air conditioner) undergoing raw material extraction, manufacturing, and use phase. Figure 2 below illustrates the life cycle inventory system boundary in model detail.

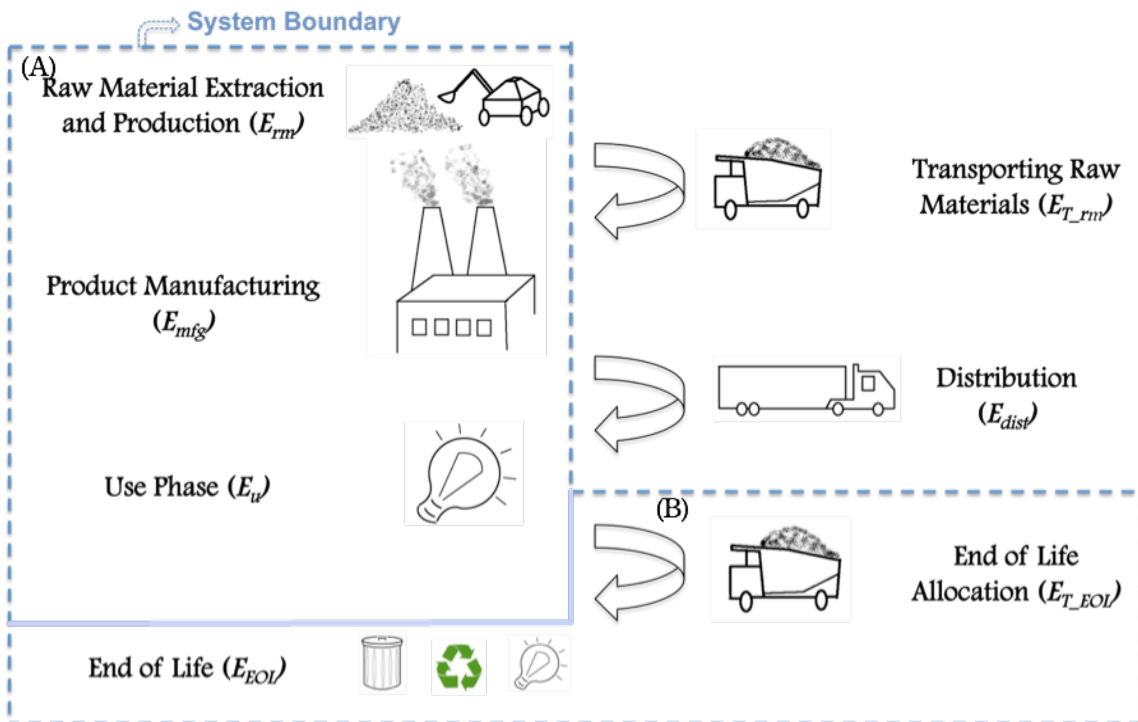


Figure 2 System Boundary for Life Cycle Energy Assessment

2.3 Raw material production and manufacturing phase

In order to perform lifecycle energy analysis, several pieces of information were gathered about the appliance, including a bill of materials, use-phase energy consumption, and appliance average useful lifetime. Using data about the typical energy cost of common materials found in Smil, 2008, the energy embedded in the product (based on bill of materials) was found. Smil gives a range for the energy values for materials. Upper bounds were used to make the most conservative estimate of remanufacturing's potential gains in manufacturing phase. Energy consumption by typical manufacturing processes used during the production of most appliances, such as machining and injection molding, fall between 1 and 20 MJ/kg [Gutowski]. To make the most conservative estimate, the 20 MJ/kg figure was multiplied by the total weight of an appliance to approximate energy used during manufacturing. The total estimated production energy use for an appliance, then, is the sum of the embedded material energy and manufacturing energy. Because most appliances are not remanufactured in whole and since most of the remanufacturing energy is human labor, we assume that, through remanufacturing, all of the production energy use for an appliance is saved (Assumption 5).

2.4 Use Phase

The trends for unit energy consumption, capacity, and efficiency of appliances studied in this report are mainly based on Association of Home Appliance Manufacturers (AHAM) report published in 2008, which provides trends from 1981 to 2008. For refrigerators, an additional source [Rosenfeld] 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 initiative [AHAM].

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, the annual energy consumption of appliances was determined. Furthermore, the annual values were amortized over average useful lifetime to determine use-phase energy consumption of the appliance.

2.5 Energy Model

Given the system boundary above, the total life cycle inventory of a product from cradle-to-grave would give:

$$LCI_{Total} = E_{rm} + E_{T\_rm} + E_{mfg} + E_{dist} + E_{u} + E_{T\_EOL} + E_{EOL}$$
Equation 1

where LCI_{Total}, E_{rm}, E_{T_rm}, E_{mfg}, E_{dist}, E_{u}, E_{T_EOL}, E_{EOL} are total lifecycle, raw material processing, raw materials transportation, manufacturing, distribution, use, end-of-life transport and treatment energy consumptions, respectively.

The life cycle inventory constrained by system boundary eliminates raw material transportation as shown below,

$$LCI_{system} = E_{rm} + E_{mfg} + E_{u} + E_{T\_EOL} + E_{EOL} = LCI = E_{m} + E_{u} + E_{T\_EOL} + E_{EOL}$$
Equation 2

The life cycle energy assessment of products was determined by considering raw material extraction and production, product manufacturing, and use phase as shown in Figure 2 part (A). The values were normalized by the corresponding unit capacity of product to capture the change in size effects in energy consumption.

When comparing the energy saved in production-phase against energy expended in use-phase due to remanufacturing, Part (A) and Part (B) were considered in the system boundary (Figure 2). In order to determine the break-even point- where the customer would be in-different between new and remanufactured unit from energy standpoint- the life cycle inventory of new is set equal to life cycle inventory of a remanufactured product:

$$LCI_{new} = LCI_{reman}$$ **Equation 3**

$$E_{m,new} + E_{u,new} + E_{T\_EOL,new} + E_{EOL,new} = E_{m,reman} + E_{u,reman} + E_{T\_EOL,reman} + E_{EOL,reman}$$

This study assumes that end-of-life treatment for new and remanufactured products are similar. Therefore, the following expressions hold true:

$$\mathbf{E_{EOL,new} = E_{EOL,reman}}$$ Equation 4

$$\mathbf{E_{T\_EOL,new} = E_{T\_EOL,reman}}$$ Equation 5

By re-arranging Equation 3, and taking into account Equation 4 and Equation 5, and normalizing by $E_{use,\ new}$ the following expression is determined:

$$\frac{E_{m,new} - E_{m,reman}}{E_{u,new}} = \frac{E_{u,reman} - E_{u,new}}{E_{u,new}}$$

Equation 6

where the equal sign represents the break-even point between the amount of energy saved in production stage versus the amount of energy expended in use-phase (normalized by use phase) due to remanufacturing. In other words, the energy savings from using a more efficient appliance is the difference between the use-phase energy consumption of an older remanufactured product and a newer, more efficient equivalent product. If this saved energy is determined to be much greater than the energy used during production of the applianc then remanufacturing does not present a net benefit in terms of energy consumption. For simplistic presentation, Equation 6 is shown in plots in the following format:

$$\frac{\Delta E_{production}}{E_{u,new}} = \frac{\Delta E_{use}}{E_{u,new}}$$

2.6 Life Cycle Economic Cost Analysis

In addition to energy analysis, this study illustrates the economic feasibility of remanufacturing. In doing so, the purchase price and use-phase electricity cost 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]; market pricing for room air conditioner and clothes washer was found from Dale et al. The average retail price of electricity (adjusted for inflation) was used for determining the total electricity cost of a unit during its operational lifetime [EIA]. Finally, the values were normalized by the corresponding unit capacity of product to capture the change in size effects.

3. Refrigerator

3.1 Introduction

In this section, we present a conservative 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 Analysis

3.2.1 Raw material processing and Manufacturing Phase

The raw materials processing and manufacturing energy consumption is based on a 1997 model refrigerator model [Kim et al.]. Table 2 includes a bill of materials for this model.

Table 2 Production energy consumption of 1997 model refrigerator top-mount refrigerator (with freezer)

Raw Materials	Amount (Kg)	%
Steel	47.55	56.3
Iron	4.56	5.4
Subtotal: Ferrous Metal	52.11	61.7
Aluminum	2.11	2.5
Copper	2.7	3.2
Brass	0.17	0.2
Other Metals	0.25	0.3
Subtotal: Non-Ferrous Metal	5.24	6.2
Rubber	0.17	0.2
Fiber and Paper	0.08	0.1

Polypropylene	0.51	0.6
PS&HIPS	6.26	7.4
ABS	5.07	6
PVC	1.01	1.2
Polyurethane	5.57	6.6
Other Plastics	3.63	4.3
Asst. Mixed Plastics	1.44	1.7
Subtotal: Plastic	23.48	27.8
Fiberglass	0.08	0.1
Glass	2.87	3.4
Subtotal: Glass	2.96	3.5
Refrigerant	0.08	0.1
Oil	0.17	0.2
Subtotal: Materials removed before processing	0.25	0.3
Other	0.08	0.1
TOTAL	84.37	100

We used ranges of energy intensity provided by Smil et al. and Ashby et al. to determine the lower bound and the upper bound of energy expenditure associated to raw materials processing. More specifically, for embedded energies we used are: 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 [Tire Technical Report], 10 to 15 MJ/Kg for fiber and paper, 75 to 115 MJ/Kg for plastics, 15 to 30 MJ/Kg for glass [Smil; Ashby].

The manufacturing process of refrigerator consists of parts assembly, door assembly, cabinet assembly, refrigeration cycle assembly, plastic parts processing and assembly [Kim]. Our literature review indicates that the manufacturing energy intensity for refrigerators varies from 12 MJ/Kg [Kim] to 22 MJ/Kg [MEEUP] depending on boundary conditions, assumptions, and methodologies taken into account.

Therefore, we estimate the energy consumed during the raw materials processing to be 3,432 to 4,983 MJ. Moreover, 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 Kim et al., Baldwin et al., Trutmann et al., MEEUP study 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.

According to AHAM, average length of ownership of currently owned refrigerators is 9 years while average useful lifetime of refrigerators is 14 years [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.

As mentioned earlier, 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 for 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:

Table 3 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

The change in energy consumption of refrigerators in time is influenced by change in unit capacity. Rosenfeld et al. and AHAM provides average volume size of a refrigerator from 1947 to 2008, as shown in Figure 3 below. More specifically, the unit capacity of the refrigerator models as well as % change from prior version is shown in

Table 4:

Table 4 Change in refrigerator size 1947-2008

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, which will also consume more electricity due to greater service offering. As such, we have performed our analysis by normalizing the results by corresponding unit of service (e.g. m^3 refrigerator capacity) for realistic and accurate comparison.

3.2.2 Use Phase

Refrigerators annual energy consumption trends have been collected from California Energy Commission (1947-1990) [Rosenfeld] and Association of Home Appliance Manufacturers (1990-2008) [AHAM, 2008]. Figure 3 below illustrates the change in average annual energy consumption and volume capacity of a refrigerator.

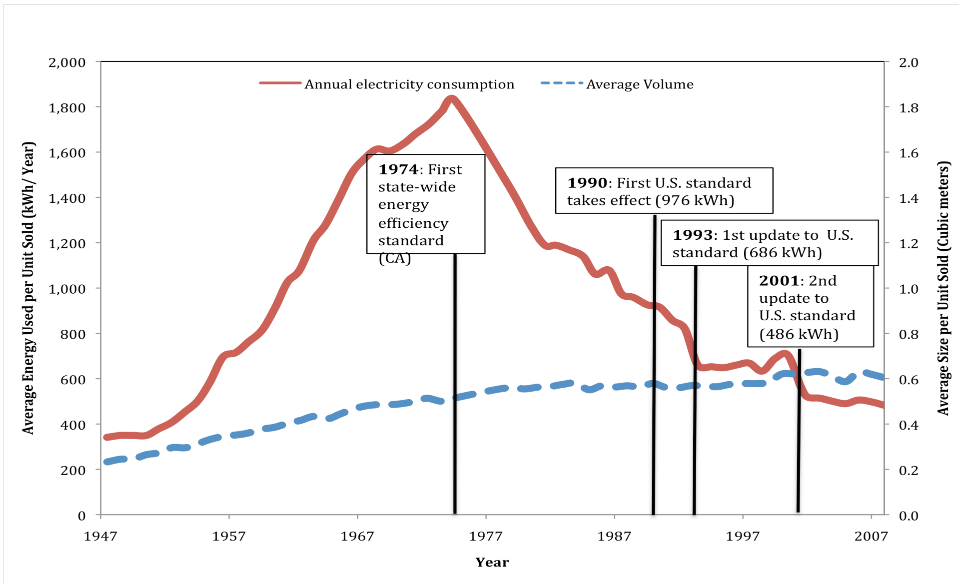


Figure 3 Average energy consumption of refrigerator sold in the U.S. 1947-2008

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 Figure 3 above). 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; AHAM, 2008].

According to our analysis, the total energy consumption of refrigerator has varied from roughly 70 GJ for a 1956 model, rising to 180 GJ for a 1974 model, then declining to 50 GJ for a 2008 model. Figure 4 below illustrates a retrospective life cycle energy assessment of refrigerators per unit volume capacity from 1956 to 2008.

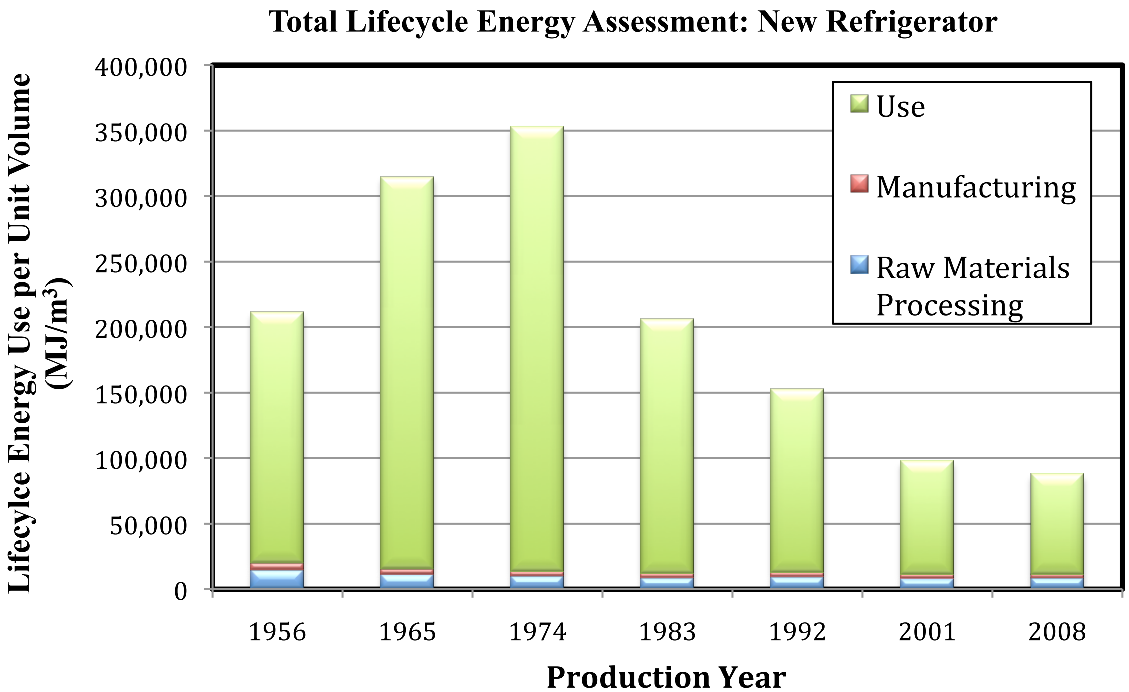
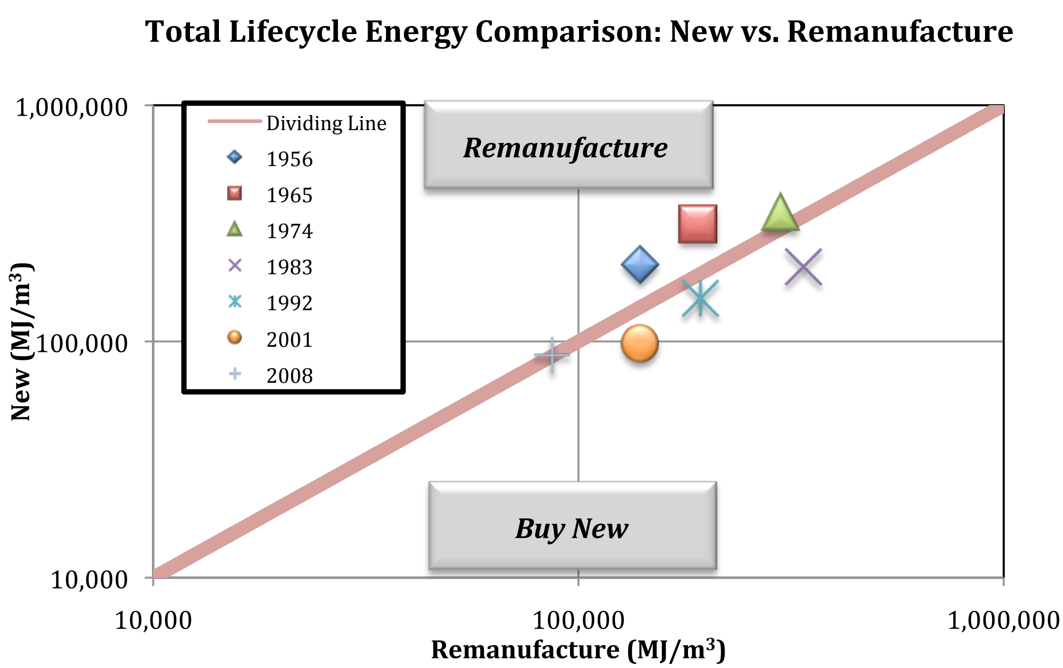


Figure 4 Refrigerator: Retrospective life cycle energy assessment of new model (normalized by refrigerator adjusted volume).

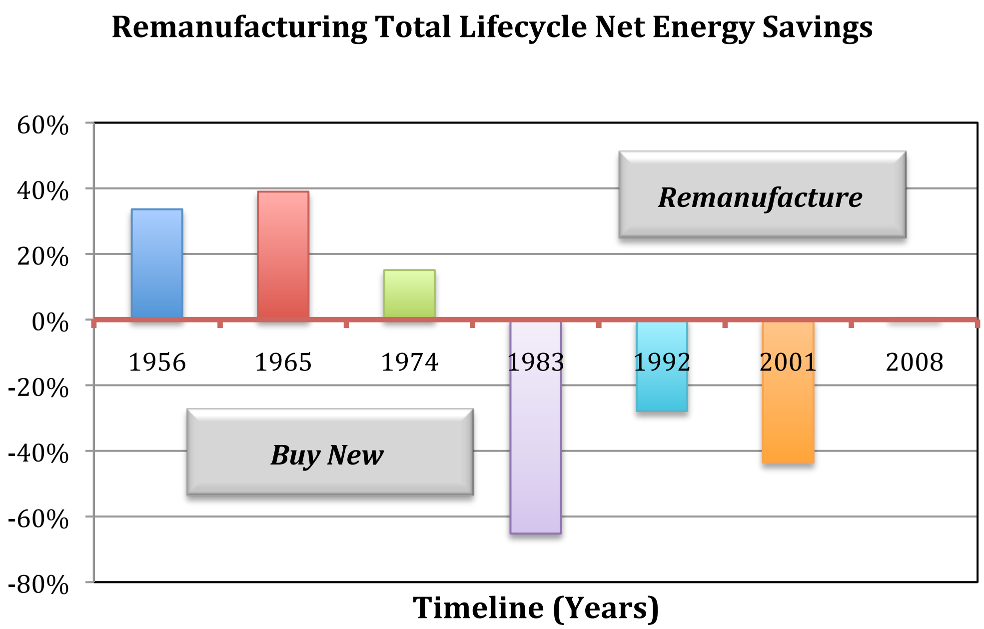
The raw materials processing and manufacturing energy consumption are 4,983 MJ and 1,864 MJ per unit, respectively (refer to 'raw materials processing and manufacturing' section above). Due to scarcity of data, these values are taken as fixed from 1956 to 2008. The change in contribution of raw materials processing and manufacturing phase observed in Figure 4 is due to normalizing the energy values by corresponding unit volume of conventional refrigerators sold in a particular year (refer to Table 4). Taking the raw materials processing and manufacturing energy consumption as fixed in time has considerable limitations. For example, there are considerable sources that indicate the dynamic changes in raw materials processing and manufacturing energy intensities in time. In addition, there has been substantial changes in the raw materials used for refrigerators due to change in construction, design, service offerings, performance, etc. However, the purpose of our study is to indicate the relative contribution of each lifecycle stage of the product from cradle to grave. As shown in Figure 4 we can conclude that use phase of refrigerator is the largest contributing phase in regards to energy consumption.

3.3 Remanufacturing and Energy Savings

The retrospective life cycle assessment above concludes 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. Figure 5 below illustrates the total lifecycle energy comparison between a new and a remanufactured refrigerator more directly. 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 labeled ‘Remanufacture’ indicates the region where the decision to remanufacture is an energy savings opportunity. The top triangle in the plot labeled ‘Remanufacture’ indicates the region where the decision to remanufacture is an energy savings opportunity. In the ‘Buy New’ region, in order to save energy from a total life cycle perspective, the consumer should buy a new appliance and discard the old unit.



(a)



(b)

Figure 5 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 generator (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

Figure 5 above reveals that in years 1956, 1965, and 1974, remanufacturing an older generation refrigerator would lead to 34%, 39%, 15% savings in life cycle energy consumption, 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 5). 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 use phase, which exceeds the energy savings during manufacturing phase, hence, making 'buying new' the energy savings decision.

The comparison between 2001 and 2008 models in year 2008 reveals a unique story where the additional energy expenditure of a remanufactured unit breaks even with the savings in production phase. This is due to a slow pace in energy efficiency improvements in the past few years and successful progress from OEMs in achieving federal standards in the past 9 years (refer to Figure 3). 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. This leads us to the next section, that discusses the political and technological changes, the main driving forces affecting remanufacturing energy savings.

3.4 Technological Changes and Policy Implications

The substantial reduction in energy consumption of refrigerators since 1974 can be explained by establishment of statewide and federal standards. This movement began in 1974 by the establishment of Warren-Alquist Act in California that enforced a statewide appliance standard [Nadel]. These initiatives taking place at the state level generated interest for a federal level standard, which led to the establishment of The Energy Policy and Conservation Act (EPCA) in 1975 [Greening].

Since establishment of EPCA, there have been three critical national regulatory milestones for enforcing restrictions on refrigerator energy consumption [Bole]. Energy standards for refrigerators depends on the configuration of refrigerator/freezer as listed below:

1. Configuration (top freezer, bottom freezer, single door refrigerator and freezer, side-by-side, single door refrigerator, chest freezer, upright freezer)
2. Automatic or manual defrost
3. For refrigerators, whether or not it has through-the-door ice service

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) [DOE EERE 10 CFR Part 430]. For each class, an energy standards equation for maximum energy use (in kWh/year) is illustrated. All equations are dependent on one variable and that is the total adjusted volume of the product [DOE EERE 10 CFR Part 430]. By 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 less energy per year on average [DOE EERE, 2005].

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 used for increasing the energy consumption of refrigerator-freezer, which OEM have followed [DOE EERE, 2005]:

1. High efficiency compressors
2. Variable-capacity compressors
3. High-efficiency evaporator and condenser fans
4. High-efficiency evaporator and condenser fan motors
5. Improved door face frame and casket design
6. Smart defrost technology
7. Added cabinet insulation

8. Lower-conductivity insulation
9. Vacuum panel insulation

Therefore, the statewide and federal minimum efficiency standards for refrigerators have pushed the manufacturers to reduce energy consumption of units produced. This has led to a technological innovation progress 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. As shown in **Error! Reference source not found.** this leads to making refrigerator remanufacturing an energy-neutral end-of-life option. Energy Independence and Security Act in 2007 asks DOE for publication of updated standards by December 31, 2010, which will take effect January 1, 2014 [DOE EERE]. Depending on stringency limits, remanufacturing may or may not be an energy savings option in the future. The next section assesses another driving factor in remanufacturing, which is financial savings.

3.5 Remanufacturing and Financial Savings

The total life cycle cost of refrigerator was determined by utilizing the Life Cycle Cost assessment (refer to section above). Figure 6 below reveals the results:

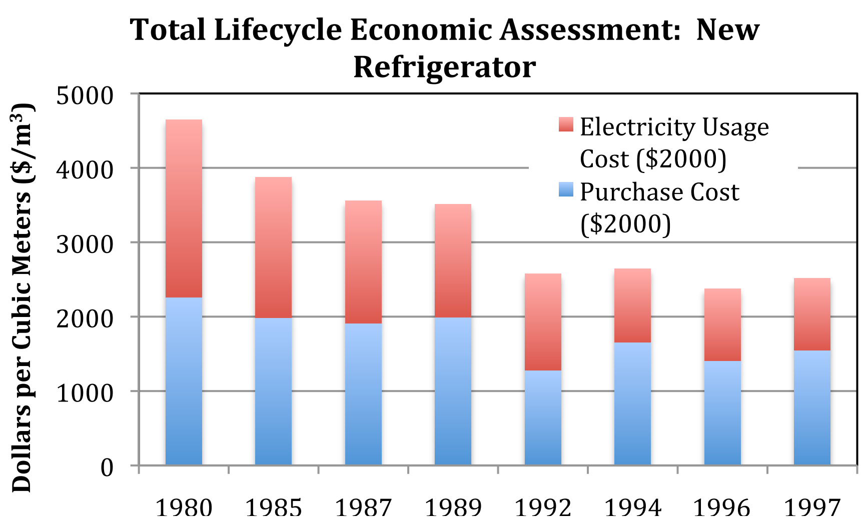


Figure 6 Refrigerator: retrospective total life cycle cost

According to figure 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 because the refrigerators have become more energy efficient and the price of electricity has been reduced by more than 10% in real value (refer to appendix). **Error! Reference source not found.** Table below conveys total lifetime financial savings due to remanufacturing a used-refrigerator as opposed to purchasing a new model. The results convey two distinct scenarios: (1) the cost of remanufacturing a refrigerator is zero, hence, total lifecycle economic cost is equivalent to total use-phase electricity cost, (2) cost of purchasing remanufactured parts and refurbishing the refrigerator is about 50% of the cost of a new unit (Hauser). This table 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 5 Retrospective life cycle economic comparison of newly produced and remanufacture refrigerators

SCENARIO (1)	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 (2)	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 (1). 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 (2), the economic savings of refrigerator remanufacturing gets reduced.

To further assess remanufacturing economic savings potential, Figure 7 illustrates a comparison between monetary savings in initial investment on vertical axis (M=monetary value) and additional electricity cost by re-using an older less efficient refrigerator on horizontal axis. Both values are expressed as a fraction of lifetime usage cost. The comparison is between purchasing a new refrigerator (e.g. 1994, 1996, 1997 models) versus remanufacturing a used model (e.g. 1985, 1987, 1988).

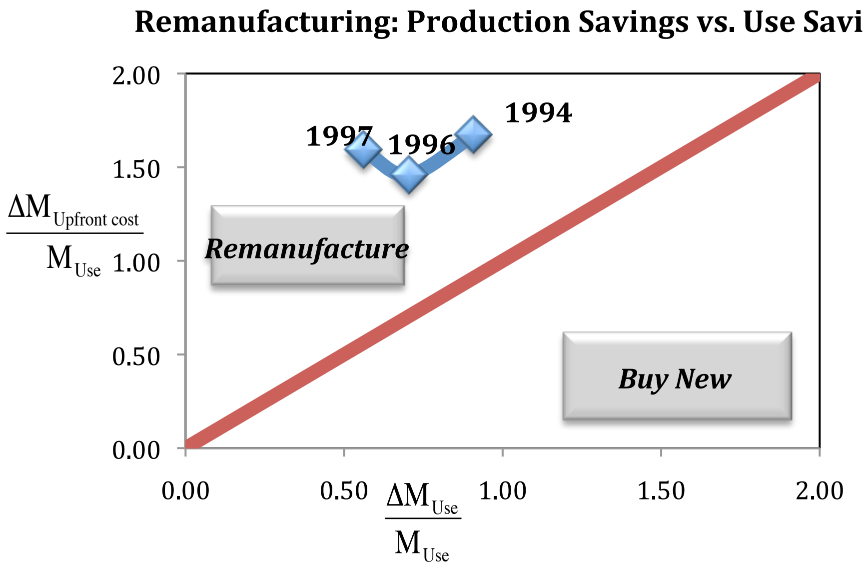


Figure 7 Refrigerator: Retrospective assessment of financial savings in production-phase against financial expenditure in use-phase due to remanufacturing

Figure 7 above illustrates that the consumer will be spending 50 to 90 per cent more in lifetime 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 6). Note that our 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 in-different to buying new versus remanufacturing from an economic standpoint.

4. Clothes Washer

4.1 Introduction

It is estimated that 87 million households in the U.S. (74-79% of U.S. households) have clothes washers (U.S. Census Bureau). This translates to 34 Billion loads of laundry washed each year in the U.S. consuming less than 5% of household energy use [Home Energy, 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]. The following sections will evaluate the impact of these efficiency improvements on clothes washer remanufacturing.

4.2 Life Cycle Inventory Analysis

4.2.1 Raw material processing and Manufacturing Phase

The applications of clothes washer are eminent in both household and commercial sector. 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 ruled out.

A report by University of Michigan's Center for Sustainable Systems provides a compilation of data for industry average washer bill of material produced in 1977, 1997, 2005 [Bole; 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; AHAM, 2005]. We utilized a methodology for computing raw materials energy consumption similar to the refrigerator (refer to 'Raw Materials Processing and Manufacturing' section for refrigerators). Similar to refrigerator analysis, we rely on literature data for manufacturing energy consumption. Bole et al. provides energy consumption for assembly process of clothes washers, which is 420 MJ. This translates to 7.1 MJ/Kg. Given that this value does not take into account total manufacturing process, we assume that the manufacturing energy consumption of clothes washer is similar to refrigerate (12 to 22 MJ/Kg). As such, we choose, 22 MJ/Kg as the manufacturing energy consumption for this analysis.

Table 6 Clothes washer material composition

Materials	Mass (Kg)	%
Steel	43.0	73.00%
Iron (Gray Cast)	0.4	0.70%
Aluminum (Cans)	2.7	4.50%
Copper	1.2	2.00%
Brass	0.0	0.00%
Other Metals	0.0	0.00%
Rubber	1.1	1.90%
Fiber & Paper	0.0	0.00%
Polypropylene (caps)	9.1	15.40%
PS & HIP	0.0	0.00%
ABS	0.0	0.10%
PVC	0.5	0.90%
Polyurethane	0.0	0.00%
Other Plastics	0.8	1.40%
Asst. Mixed Plastics	0.0	0.00%
Fiberglass	0.0	0.00%
Glass	0.0	0.00%
Refrigerant	0.0	0.00%
Oil	0.0	0.00%
Other	0.0	0.10%
Total	58.8	100%

The analysis results in raw materials processing to be between 2,301 to 3,118 MJ. For this study we take the upper bound value, namely 3,118 MJ as the energy value for raw materials processing. Moreover, we estimate the manufacturing energy consumption of clothes washer to be 1,294 MJ. Therefore, the total raw materials processing and manufacturing energy consumption is 4,412 MJ on average for producing a clothes washer.

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]. Therefore, the following models of clothes washers are compared in this analysis:

Table 7 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

4.2.2 Use Phase

The yearly lifetime of household clothes washers used in the U.S. are taken as 11 years [Appliance Magazine, 2008]. The average numbers of washing loads per year are estimated to be 392 cycles for residential applications [DOE EERE, 2009].

Error! Reference source not found. below reveals the annual energy consumption and volume capacity trend per a conventional clothes washer.

According to figure above, the energy consumption of a conventional clothes washers have dropped by almost 70 percent while tub volumes have increased by 27% from 1981 to 2008.

The sharp drop in efficiency in 2004 is due to change in efficiency measure by DOE from energy factor to modified energy factor. Prior to 2004, clothes washer efficiency was expressed in energy factor (EF), which is the energy performance metric for clothes washers. EF is the ratio of the capacity of the clothes container volume, V, divided by the sum of the water heating energy demanded for each cycle, $E_{water\ heating}$, and the machine electrical energy for the mechanical motion (agitation) for each cycle, $E_{electricity}$, as shown in equation below [Energy Star]:

$$EF = \frac{V}{E_{water\ heating} + E_{electricity}} \qquad \text{Equation 7}$$

Water heating consumes the larger share of energy consumption (about 88 per cent) while agitation would consume about 12% of the energy drawn for the clothes washer

[Bole]. A gas or electric water heater may provide the water heating energy (Energy Star). The efficiency of an average natural gas powered water heater and an electric water heater is 59% and 90.5%, respectively [Bole]. The EF units are cubic feet per kWh per cycle, [$\frac{ft^3}{kWh/Cycle}$]. The higher the EF value, the more efficient the clothes washer would perform.

On January 1,2004 the DOE updated the standard calculation from EF to Modified Efficiency Factor (MEF) [Bole]. The MEF entails an additional contributing factor DE, which takes into account the dryer energy needed for extracting the residual moisture content (RMC) from the clothes as shown in figure below [Bole]:

$$MEF = \frac{V}{ME + HE + DE} \qquad \text{Equation 8}$$

where ME, HE, DE are energy consumption for mechanical motion, water heating, and drying energy [Bole]. Similar to EF, the units are cubic feet per kWh per cycle.

Given the above information, the life cycle energy assessment of household clothes washer was computed as shown in Figure 8 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].

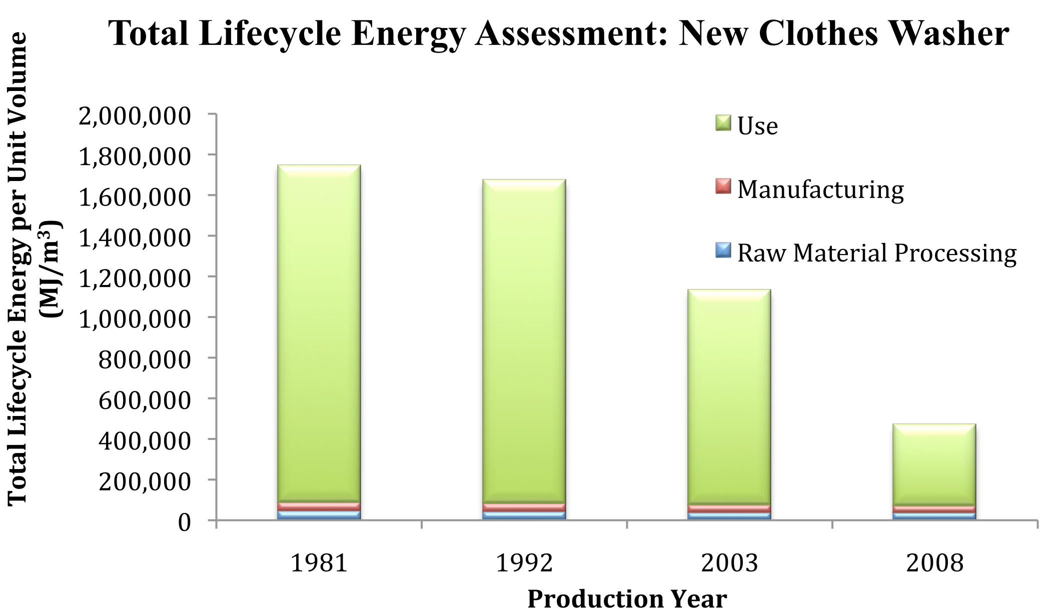


Figure 8 Residential Clothes Washer: Retrospective life cycle energy assessment of new model

4.3 Remanufacturing and Energy Savings

According to Figure 8 above, the total life cycle energy assessment for clothes washers have been substantially reduced in the past two and a half decades. In addition, the plots reveal the dominance of use phase amongst life cycle stages (97 to 99 percent of total energy). Furthermore, figure above reveals 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 pace of improvement in energy efficiency despite increase in capacity, it is more energy savings to purchase a new clothes washer than to extend the life of an older clothes washer. Table 8 below illustrates this phenomenon more clearly.

Table 8 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)	Total Lifetime % Economics 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 above, remanufacturing is not a viable energy savings strategy due to steep enhancements in energy efficiency of clothes washers. In other words, the savings in production phase due to remanufacturing are overshadowed by extra energy expenditure in use phase. According to our analysis, by extending the life of a used 1997 model clothes washer that has reached end-of-life in 2008, production phase energy savings sum up to 0.12 (or 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 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 (due to 1994 and 2004 standards), which made clothes washer remanufacturing an energy-expending option. The next section provides the main driving factors influencing clothes washer remanufacturing energy savings: technological progress in efficiency, and enforcement of policy standards.

4.4 Technological Changes

The main explanation behind large improvements in clothes washers is the technological transformation from top-load-vertical-axis washers to front-load-horizontal-axis washers

[Bole]. The figure below depicts both vertical-axis washer as well as horizontal-axis washer:


Vertical-Axis Clothes Washer Horizontal-Axis Clothes Washer

Figure 9 Conventional residential clothes washers sold in the U.S. and worldwide

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 [Washington State University].

Technological advancements in clothes washers led to the creation of horizontal-axis washers, which became commercially available in 1997 [Bole]. The horizontal-axis washers (shown above) were predominately more efficient than vertical-axis counterparts, widening the efficiency gap between the most efficient washer and conventional washers in the market [Bole]. By 2004, the most efficient horizontal-axis washer was more than 76% more efficient than the average washer [AHAM, 2005; EPA, 2005]. The predominant impact on efficiency has been due to water resource management [Bole].

Horizontal-axis washers (front-load) wash clothes by repeatedly tumbling (instead of agitation) while consuming considerably less water as an input source. There are advantages as well as disadvantages to utilizing horizontal-axis washers as listed below [BC Hydro]:

Advantages:

- Reduced water consumption
  - Horizontal-axis washing cycles significantly reduce water volume usage and the energy required to heat the water
- Reduced Energy Consumption
  - 88% of energy of clothes washer is consumed in heating water [Bole]
  - By consuming less water the amount of energy required to heat the water is also reduced by 50%
- Reduced drying time
  - Typically horizontal-axis spins around 1,500 rounds per minute (RPM), which is nearly twice as fast as a conventional vertical-axis washer

    - This causes increased moisture removal reducing the energy and time demanded for drying
- Less detergent consumption
    - Reduced detergent consumption due to tumbling less amount of water instead of agitating clothes immersed in larger water volume

Disadvantages:

- Cost
    - Front-loading washer typically cost more than conventional vertical-load wash
- Longer wash time
    - Washing times are particularly longer especially if the washer has an internal water heater
    - The total cycle may take 35 to 50 minutes for a typical horizontal load whereas for a conventional vertical-load washer it would be 35 minutes

The technological advancement in clothes washers in combination with standard enforcements make clothes washers highly advanced from resources and energy savings perspective.

4.5 Policy implications

The department of energy has established the standards for clothes washers as follows [DOE EERE, 2009].

1. Clothes washers manufactured prior to January 1, 2004 shall have **energy factor** no less than:
    a. 0.9 for compact top-loading clothes washer (capacity less than 1.6 cubic feet)
    b. 1.18 for standard top-loading clothes washer (1.6 cubic feet or great capacity)

2. Clothes washers produced on of after January 1, 2004 and prior to January 1, 2007 shall have a **modified energy factor** no less than:
    a. In this year, DOE modified the measure of energy efficiency for clothes washers from 'energy factor' to 'modified energy factor'
    b. 0.65 for compact top-loading clothes washer (capacity less than 1.6 cubic feet)
    c. 1.04 for standard top-loading clothes washer (1.6 cubic feet or great capacity)
    d. 1.04 for front-loading clothes washer
3. Clothes washers produced on of after January 1, 2007 shall have a modified energy factor no less than:
    a. 0.65 for compact top-loading clothes washer (capacity less than 1.6 cubic feet)

b. 1.26 for standard top-loading clothes washer (1.6 cubic feet or great capacity)
c. 1.26 for front-loading clothes washer

Energy Star requirements for residential clothes washers are as follows [Energy Star]:

Table 9 Current and future Energy Star efficiency performance requirements for top and front loading clothes washers

Criteria/Product Type	Current Criteria Levels (as of July 1, 2009)	January 1, 2011
ENERGY STAR top and front loading	MEF >= 1.8 WF <= 7.5	MEF >= 2.0 WF <= 6.0

According to table above, the energy requirements for clothes washers will become more stringent till 2011 increasing modified energy factor by 59% from current federal standard (MEF=1.26). Also Energy Star has a restrictive requirement for water consumption that enables a comparison between clothes washers independent of capacity. As of 2009, manufacturers must submit a water performance metric, water factor (WF), to qualify for Energy Star labeling. WF is the total-weighted water consumption per cycle (Q) divided by capacity of clothes washer (C) as shown below [Energy Star].

$$WF = \frac{Q}{C} \qquad \text{Equation 9}$$

the lower the value the more efficient the clothes washer performs with respect to water consumption.

According to AHAM, 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 washer were to continue growing, then it is evident that remanufacturing less efficient non-Energy Star clothes washers will continue to be an energy expending strategy.

4.6 Market Analysis

The residential clothes washer shipments by year have increased from 6.8 million unit to 8.9 million units during 1998 to 2007 (except 2007) [Energy Star]. With the establishment Energy Star labeling in 1992, market penetration of highly efficient washers (predominantly horizontal-axis units) have grown from 4% to 38% during 1997 to 2006 [Energy Star].

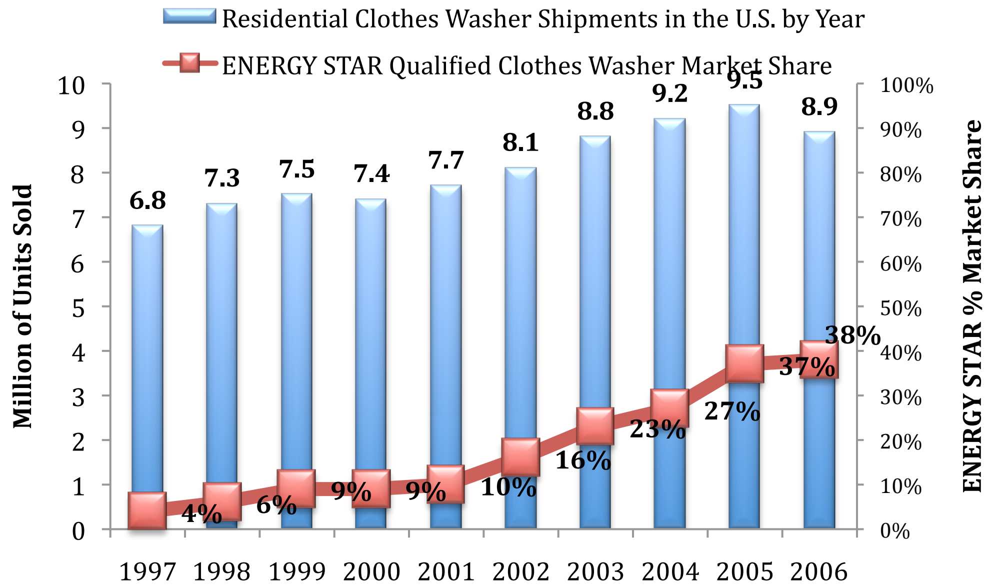


Figure 10 Residential clothes washer shipments in the U.S. 1997-2006 and Energy Star qualified clothes washer market share

Energy Star units consume 31% less energy and 55% less water than standard unit [Energy Star]. There are two consequent implementation phases that will generate further stringency on Energy Star units:

Phase I: Increase in energy and water efficiency by 5%, which has taken effect in July, 2009
Phase II: Increase energy and water efficiency another 10% beyond 2009 stringent limits; will take effect in January 2011

Energy Star analysis concludes that if all conventional units were replaced with Energy Star qualified units, the U.S. consumers in total would save [Energy Star]:

- 11 billion kWh
- 290 million therms of natural gas
- 550 billion gallons of water
- $4 billion annually

4.7 Remanufacturing and Financial Savings

The total lifecycle economic cost of clothes washers normalized by cubic meters of volume has dropped by close to 40% as illustrated in Figure 11 below. Note that the shorter time span in retrospective evaluation (compared to energy assessments) is due to scarcity of data for market price of clothes washers prior to 1981.

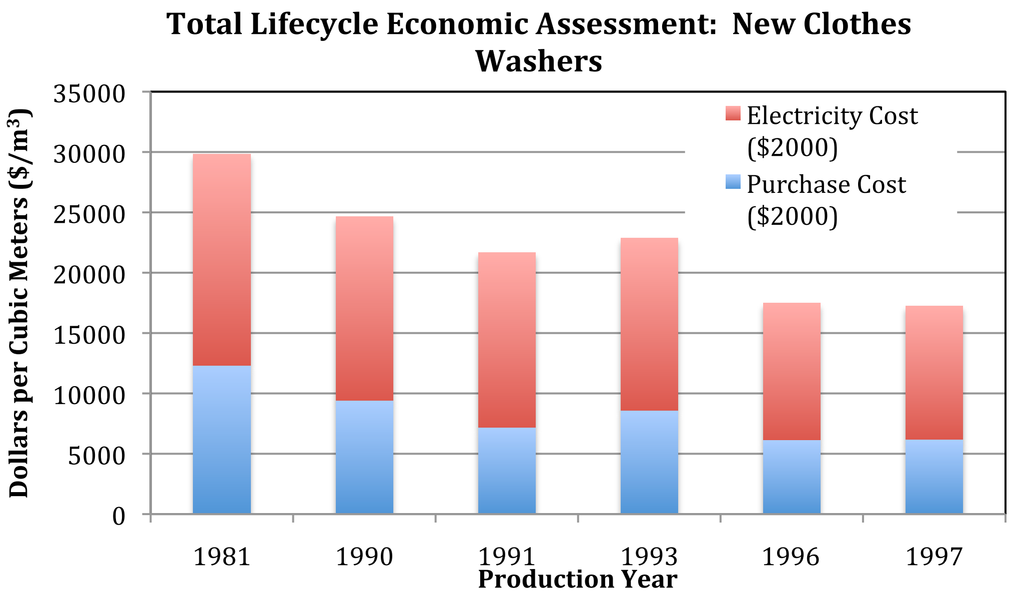


Figure 11 Clothes Washer: retrospective total life cycle cost 1981-1997

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 to about $1300 in 1997.

By comparing the total life cycle financial cost of a newly built 1993 model and a remanufactured/re-used 1981 model (assuming no upfront cost) will lead to total lifecycle economic cost of $22,870 per Cubic Meters and $17,517 per Cubic Meters, respectively. This leads to total lifecycle economic savings of 23% by remanufacturing a clothes washer. Our sensitivity analysis concludes that if the cost of purchasing a remanufactured appliance is 50% of new [Hauser] then the economic savings in purchasing breaks even with additional electricity cost; in this case, the user would be in-different between purchasing new and remanufacturing from a financial standpoint.

5. Dish Washer

5.1 Introduction

The first ever dishwasher machine was patented as a hand-operated device in 1850 [Koeller]. In 1947, the dishwashers were produced for the household residential sector and were progressively demanded by household owners [Koeller]. The market usage of dishwashers has been growing from 42% in 1985 to about 58% in 2003 [Koeller].

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].

The U.S. market for dishwashers is dominated by 17 manufacturers producing a total of 565 different dishwasher models. 486 of the models, or 86% of the total market-share, are compliant to Energy Star standards and protocols. 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 in spite of dynamic changes in use-phase energy trends for dishwashers.

5.2 Life Cycle Inventory Analysis

5.2.1 Raw material Production and Manufacturing

Table 10 below provides the bill of material for a conventional dishwasher produced in 1995 [Truttmann]. The energy intensity for each substance is taken from Smil et al. to determine the raw material processing energy costs.

Table 10 Dish Washer Material composition

	Material	Mass (Kg)	%
Metals			
Non ferrous	Aluminium	0.39	0.66%
	Copper	0.92	1.57%
	Nickel		0.00%
	Lead		0.00%
	Tin		0.00%
	Zinc	0.02	0.03%
ferrous	Iron		0.00%
	Stainless steel	7.42	12.64%
	Steel	15.4	26.24%
Plastics	**Aggregated**	23.207	39.54%
	ABS	0.87	1.48%
	PVC	0.66	1.12%
	PP	8.81	15.01%
	PE	0.02	0.03%
	PS	1	1.70%
	PA	0.2	0.34%

	Bitumen	9.5	16.18%
	Elastomer (as ABS)	0.57	0.97%
	Other plastics (as PP)	0.39	0.66%
	EPS	1.018	1.73%
	PE-foil	0.169	0.29%
	Epoxy		0.00%
Ceramics	Silicon		0.00%
	Glass		0.00%
	Other ceramics		0.00%
Electronics	Electronic parts (PWB)	0.41	0.70%
Other	e.g. wood, cardboard	2.93	4.99%
	paper, packaging	0.431	0.73%
	Gravel	6.31	10.75%
	felt/recycled cotton	1.04	1.77%
	other	0.22	0.37%
	Total Mass (Kg)	58.698	

In order to compute the energy expenditure for raw materials processing we used range of energy intensity values from Smil et al. and Ashby et al. (refer to Appendix C). Based on this, we estimate that the raw materials energy consumption is between 2,856 MJ and 3,971 MJ per dishwasher unit. This value is in agreement with the MEEuP study energy estimation for raw materials processing of domestic dishwasher [MEEuP].

Manufacturing energy consumption is taken from MEEuP study, which convey that it takes 14.4 MJ/Kg to produce dishwasher [MEEuP]. This translates to 847 MJ for the aforementioned dishwasher. Therefore, it costs between 3,703 MJ and 4,818 MJ to produce a dishwasher. Though changes in appliances 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.

5.2.2 Use phase

Figure below, illustrates change in energy consumption and efficiency trends for dishwashers between 1981 and 2008 [AHAM, 2008]. According to Figure 12 , the 2nd Federal Standard (discussed in detail in later sections) implemented in 1994, caused a considerable change in energy efficiency and consumption of dishwashers.

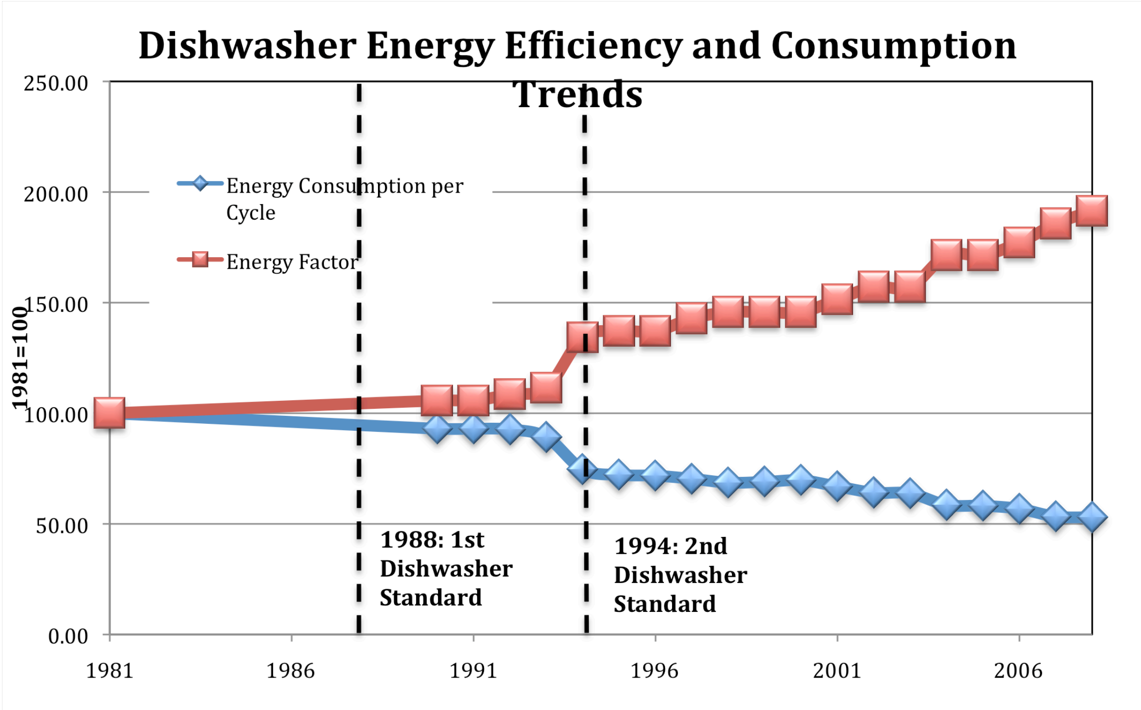


Figure 12 Energy consumption and energy factor per cycle of new dish washer sold in the U.S. 1981-2008 (shipment-weighted average)

5.3 Efficiency Measures

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

$$EF = \frac{1}{M + W} \qquad \text{Equation 10}$$

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 11, the efficiency of dishwasher is only a function of unit energy consumption and not capacity; therefore, for this analysis, it is assumed that the capacity of dishwashers 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 dishwasher per cycle by average numbers of washing cycles per year (215) and 10 years of service [Appliance magazine, 2008; DOE EERE, 2009]. Figure 13 below illustrates the total life cycle energy assessment of a newly produced dishwasher in years 1981,1991, 2001, and 2008.

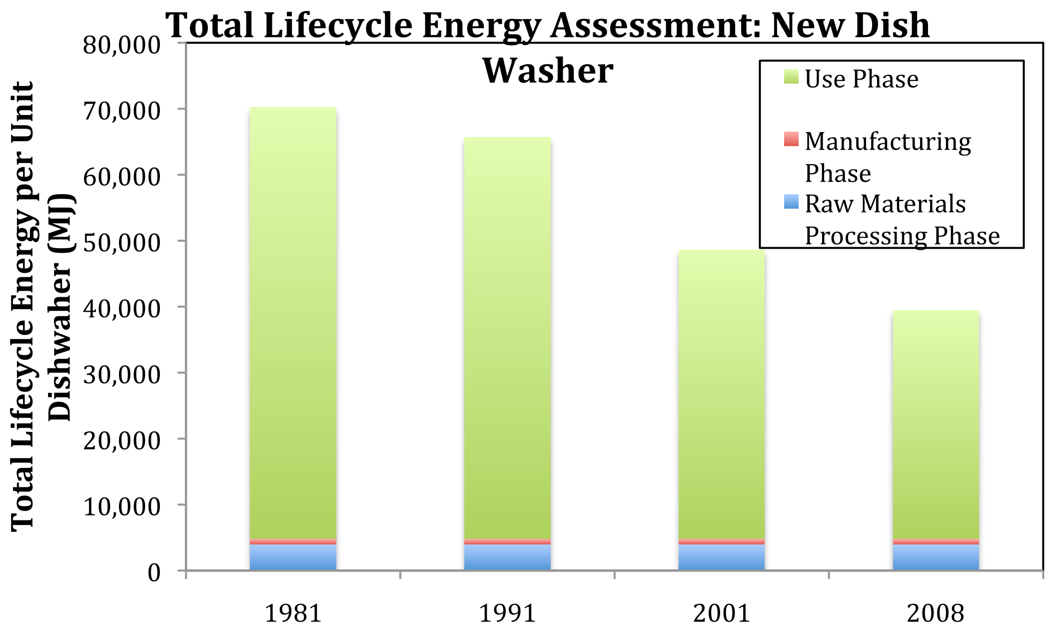


Figure 13 Dishwasher: Retrospective life cycle energy analysis of new model

5.4 Remanufacturing and Energy Savings

The remanufacturing comparison scenario is based on choosing to purchase a new dishwasher versus remanufacturing a unit that has reached end-of-life after 10 years of service use.

Table 11 Comparison year and model between purchasing new dish washer 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

Table 12 Dishwasher: Retrospective life cycle energy comparison of new and remanufactured.

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

According to the table 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 enforced 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 use phase due to remanufacturing. Our analysis concludes that the savings associated with dishwasher remanufacturing causes savings in 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 use-phase energy consumption. As a result, the over-expenditure in use-phase of a remanufactured unit supersedes savings in production-phase. The following section discusses the reasons behind such results.

5.5 Technological Changes

Since the origination of Energy Star in 1 997, dishwasher technology has improved substantially. Main technology improvement in relation to reduction of energy and water consumption are listed below [Energy Star]:

1. Improved water filtration
    a. Effective removal of food items from the water cycle enabling efficient water and detergent usage
2. More efficient jets
    a. Less energy usage for supplying detergent and water during dish washing
3. Disk rack design
    a. Strategically situating the dish location for maximized cleaning
4. Soil sensors

a. Effective testing mechanism that assess the dirtiness of dishes all throughout the washing cycle, accordingly adjusting the water and energy usage

5.6 Policy Implications

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 12), 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]. These two initiatives have led to the following minimum efficiency factors EF:

Federal Standard (NAECA)- Mandatory:	0.46 (standard) and 0.62(compact) (1994)
Energy Star (DOE)- Voluntary	0.53 (1997-2000)
	0.58 (2001 to today)
	0.65 (standard) and 0.88 (compact) (starting 2007)

According to AHAM, in 2008 the shipment-weighted average energy consumption of dish washers per cycle and EF were 1.52 kWh/cycle and 0.67, respectively [AHAM, 2008]. Assuming 215 washing cycles annually [DOE EERE], 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 (refer to appendix). 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 remanufacturing would remain to be an energy expending option from a total life cycle perspective.

6. Room Air Conditioner

6.1 Introduction

Room air conditioner, also referred to as window air conditioner, provide cool air to a room as opposed to the entire house. The room air conditioners are produced for the purpose of being utilized when needed and are less expensive to use than central air conditioners, though the operation efficiency is not as efficient as central air conditioner. Room air conditioners can be small enough to operate on 15 or 20 amps, 115-volt household circuit to as large as units that would require a stand-alone 230-volt circuit [DOE EERE]. In the past two decades, room air conditioners have become more efficient utilizing higher efficiency compressors, fan motors, and heat transfer surfaces than previous models [NRDC]. Next section explores remanufacturing energy savings in light of improvements in cooling efficiency of room air conditioning.

6.2 Life Cycle Inventory Analysis

6.2.1 Raw material processing and Manufacturing Phase

Table 13 below reveals raw materials composition of a 2.1 kW single duct room air conditioner with cooling capacity of 7,000 BTU per hour [MEEuP]. We determined the range of embedded energy values by utilizing Smil et al. and Ashby et al. (refer to Appendix C).

Table 13 Room Air Conditioner Material Composition

	Material	Mass (Kg)	%
Metals			
Non ferrous	Aluminium	1.795	6.21%
	Copper (tube)	4.212	14.56%
	Cooper (wire)	0.706	2.44%
	Nickel		0.00%
	Lead		0.00%
	Tin		0.00%
	Zinc		0.00%
ferrous	Iron	2.062	7.13%
	Stainless steel	0.424	1.47%
	Steel	10.155	35.11%
Plastics	Aggregated	9.015	31.17%
	HDPE	0.021	0.07%
	PP	0.237	0.82%
	PS	1.894	6.55%
	EPS	0.114	0.39%
	HiPS	4.678	16.17%
	PVC	1.17	4.04%
	PA-6	0.366	1.27%
	PBT	0.174	0.60%
	ABS	0.062	0.21%
	lacquer	0.25	0.86%

	Rubber EPDM	0.006 0.043	0.02% 0.15%
Ceramics	Epoxy Silicon Glass		0.00% 0.00% 0.00%
Other	Other ceramics	0.065	0.22%
	e.g. wood, cardboard		0.00%
	paper, packaging	0.052	0.18%
	other	0.44	1.52%
	Total Mass (Kg)	28.926	

Our energy analysis reveals that energy consumption for raw materials processing is between 1,595 MJ to 2,538 MJ. We use the manufacturing energy intensity provided by the MEEuP study, which is 19.7 MJ/Kg. This translates to 586 MJ per unit 2.1 kW room AC produced. As a result, the total raw materials processing and manufacturing energy ranges between 2,164 MJ to 3,107 MJ for 2.1 kW single duct room AC (7,000 BTU/Hr cooling capacity). Note that 2.1 kW room AC is one of the smaller models of room air conditioners; the size of room AC can range widely between 2.1 kW (29 Kg mass) to 12.5 kW split duct (179 Kg), for example [MEEuP]. The subjectivity of our energy analysis is due to scarcity of data. This adds limitations to our analysis, since the utilized use-phase values are for room AC models with cooling capacities greater than the room AC analyzed in production phase (cooling capacity of 8,760 BTU/hr to 10,607 BTU/hr).

6.2.2 Use Phase

Figure below illustrates the capacity, energy consumption, and efficiency of a conventional room AC from 1980 to 2008.

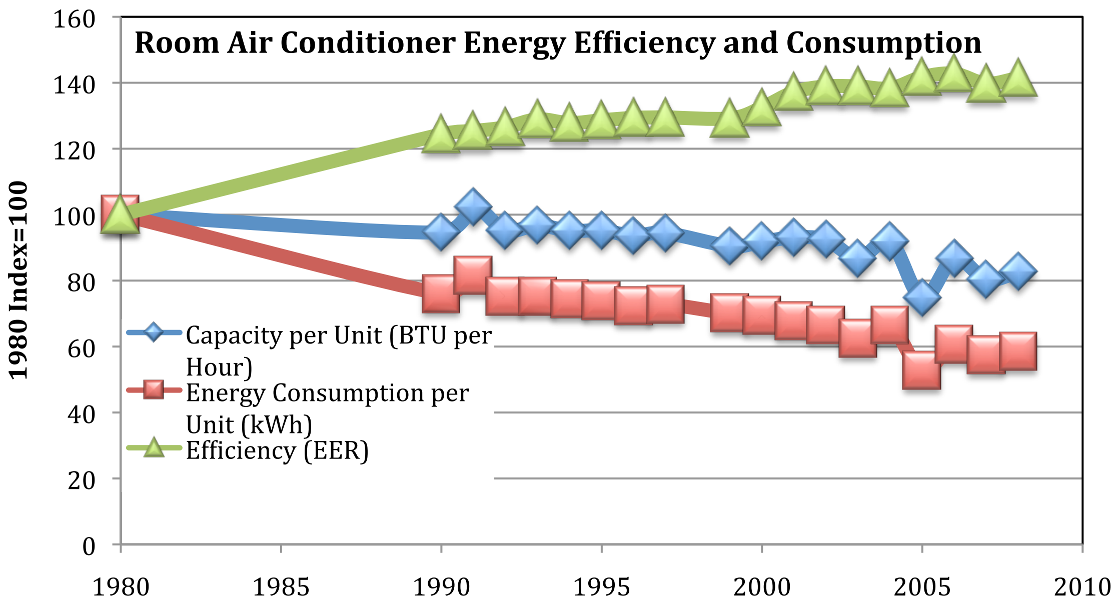


Figure 14 Efficiency, energy consumption, and cooling capacity per unit of new room air conditioner sold in the U.S. 1980-2008 (shipment-weighted average)

The energy consumption of the room air conditioner depends on various factors including operation hours. In this study, the analysis is computed based on 750 hours of operation annually [AHAM]. This value is smaller than 1,120 hours of average national cooling hours reported by Energy Star for selected locations (Energy Star). As shown in Figure 14 above, since 1980, the average energy consumption of room AC has declined by 42%. This is due to technological advancement in energy performance of room AC coupled with the presence of appliance standards, which has caused room AC to become more energy efficient in the past 20 years. According to Figure 14 above, sales-weighted cooling capacity of room AC models have decreased by about 18% since 1980.The lifetime of a conventional room air conditioner is assumed to be 9 years [Energy Star; Appliance Magazine, 2008].

6.2.3 Room Air Conditioner Energy Efficiency Measures

The efficiency metric for room air conditioners is the energy efficiency ratio (EER), measured as BTU/h/W, which reveals the cooling capacity output (BTU heat removed per hour) of the air conditioner for a given input power (Watts of power expended). The cooling capacity in BTU/Hour is the amount of heat that the room AC can extract per hour basis. The higher the EER the more efficient the room air conditioner. The federal regulations enforced a minimum efficiency performance of 8.0 or greater for units produced after January 1, 1990. The Association of Home Appliance Manufacturers reports that from 1980 to 2008 the EER rose by 13.7% [AHAM, 2008]. According to AHAM, "if you own a 1970's vintage room air conditioner with an EER of 5 and you replace it with a new one with an EER of 10, you will cut your air conditioning energy costs in half."

The capacity (sizing) of the room air conditioner varies based on the size of the room being cooled. The typical range for cooling capacity of Room AC is 5,500 to 14,000 BTU per hour. The room AC model showcased above (7,000 BTU per hour cooling capacity) lies within the range of conventional room AC. Note that user choice for proper capacity factor is crucial for using the unit most efficiently. More specifically, a unit that is much larger in capacity than the room it is put in will not cool the area homogenously. Also, a smaller unit that would run for an extended period of time would provide a more efficient and consistent cooling mechanism in addition to being more effective for dehumidifying.

A general rule of thumb is that 20 BTU of capacity can efficiently cool a square footage of living space. The life cycle assessment of room air conditioner is challenging since there are dynamic factors such as local climate, window size, shading, humidity that affect use-phase energy consumption of room air conditioners [DOE EERE].

We determined the use-phase energy consumption of room AC by utilizing energy efficiency and consumption trends provided by Association of Home Appliance Manufacturers from 1980 to 2008 [AHAM, 2008]. More specifically, AHAM provides shipment-weighted annual energy consumption values (based on 750 hours of operation per year) per unit of Room AC from 1980 to 2009. We choose use-phase values for year 1980, 1990, 1999, and 2008. The corresponding cooling capacities of these room AC models are 10,607, 10,034, 9,596, and 8,760 BTU/Hr, respectively. Note that the cooling capacities for use-phase are distinct and different from cooling capacity of the room AC analyzed in production phase (7,000 BTU/Hr cooling capacity). This leads to limitation of our assessments and is a source of error. Total lifecycle energy assessment for a newly produced room air conditioner is as shown in Figure 15.

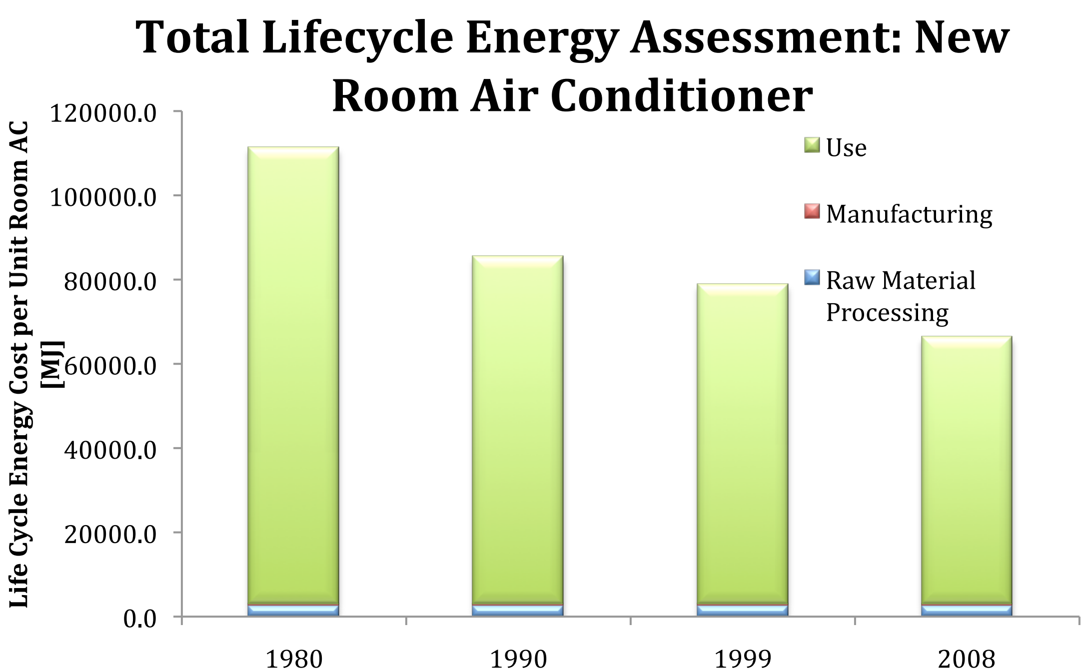


Figure 15 Room air conditioner: Retrospective life cycle energy assessment of new model

Note that the energy analysis for new room air conditioner is performed based on the new unit capacity of room AC (BTU cooling per hour). As such, the unit capacity of remanufactured room air conditioner is adjusted to the capacity of the corresponding new model. For example, in 2008 the unit capacity of room air conditioners produced were 8,760 BTU per hour, which is 9% smaller in capacity than a room air conditioner produced in 1999. As a result the total life cycle energy of the remanufactured 1999 model is reduced by 9% for appropriate capacity adjustments and accurate comparison.

6.3 Remanufacturing and Energy Savings

Given the availability of energy consumption trend and lifetime of room air conditioners, the comparison between new and remanufactured room air conditioner was performed for the following years:

Table 14 Comparison year and model between purchasing new room air conditioner and remanufacturing and re-using an older model

Comparison Year	New Model (Year Made)	Remanufactured Model (Year Made)
1990	1990	1980
1999	1999	1990
2008	2008	1999

Table 15 below reveals the comparison of total life cycle energy use of new versus remanufactured.

Table 15 Room air conditioner: Retrospective life cycle energy comparison of new and remanufactured.

	Year	Lifetime Energy Consumption New (MJ)	Energy Consumption Reman (MJ)
1980	111,290		
1990	85,341	102,339.42	-19.92%
1999	78,854	78,645.12	0.27%
2008	66,261	69,148.50	-4.36%

According to our retrospective evaluation, remanufacturing room air conditioner is an energy saving and/or energy expending option. The first DOE standard for room air conditioner was implemented in 1990 (refer below). The mandated reduction in energy consumption for models produced in 1990, has led to making remanufacturing a net energy-expending strategy. The next standard was implemented in 2000, which is not reflected upon in 1999 and 2008 data points since one comparison scenario occurs prior (1999 new versus 1990 remanufactured) and the other occurs after (2008 new versus 2000 remanufactured) the implementation of the 2000 standard.

Our analysis concludes that the energy savings during production phase is about 4% of total use phase energy of the new unit. In 1990 decision scenario, by remanufacturing a 1980 model the use phase increases by 24%. This number changes to 4% and 9% energy over-expenditure in use-phase in 1999 and 2008, respectively. Clearly, the results indicate that the energy savings potential of remanufactured room air conditioner is nuance in 2008.

6.4 Technological Changes

The technological improvements monitored and recorded by DOE for room air conditioners are [DOE EERE]:

Increased heat transfer surface area

1. Increased fin density
2. Increased depth of coil
3. Addition of sub-cooler to condenser coil
4. Increased frontal coil area

Increased heat transfer coefficients

1. Improved fin design
2. Improved micro-channel heat exchangers
3. Improved tube modeling

Component Improvements

1. Improved fan/blower efficiency
2. Improved compressor efficiency
3. Improved indoor blower efficiency

Part-Load Technology Improvements

1. Improved thermostatic cyclic controls
2. Two-speed, varialble-speed, or modularity capacity compressors

6.5 Policy Implications

The federal standards put forth for room air conditioners were in Jan 1,1990 and Oct 1, 2000. According to AHAM report, the industry shipment-weighted average in 2008 has an E.E.R. of 9.93, which is greater than the most stringent E.E.R. minimum performance standard for an average room air conditioner.

6.6 Remanufacturing and Financial Savings

The total lifecycle economic cost of new room AC is shown below. The values have been determined using the same methodology as for refrigerator and clothes washers.

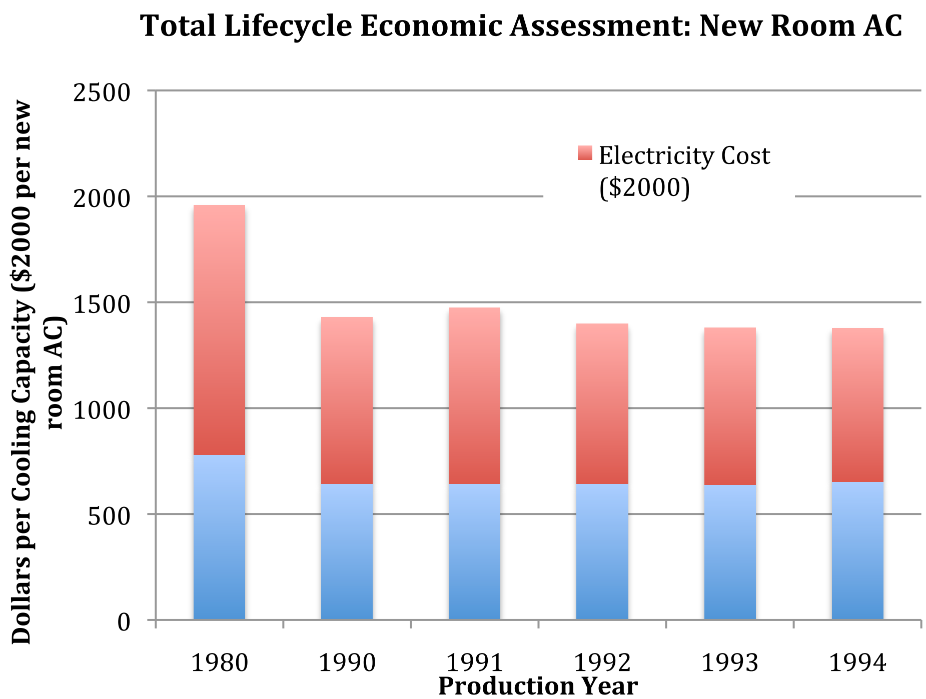


Figure 16 Room air conditioner: retrospective total life cycle cost

According to the above figure, between 1990 and 1994 the total financial cost has remained steady. Our analysis reveals that the total life cycle cost savings by remanufacturing an old 1980 model instead of purchasing a new 1990 model (assuming no cost associated to remanufacturing) is around 22% . Our sensitivity analysis reveals that the break-even point is when the cost of remanufacturing is 50% the market price of a new room air conditioner.

As mentioned above state-level and federal policies have served a critical role in promoting technological changes in order to increase energy efficiency of appliances to comply with minimum efficiency performance standards. Next section provides deeper insight about the historical, political, and technological context of these policies.

7. Energy Efficiency Standards and Voluntary Efficiency Programs for Residential Appliances

7.1 Introduction

History of standards in the U.S. goes back to 1960s where policy advocates were negotiating their interest in standards to help mitigate a series of consistent multi-state blackouts in northeast states in 1965 [Nadel]. In 1970, concerns about environmental impacts of power plants in west coast led to energy policy assessments including standards [Nadel]. 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]. California was the only state with a state-wide appliance standards directive until New York began to adopt standards in 1976. These initiatives taking place at the state level generated interest for a federal level standard, which led to the establishment of The Energy Policy and Conservation Act in 1975 [Greening].

This section addresses federal energy efficiency standards for residential appliances. 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]. 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]. These legislations combined with the National Appliance Energy Conservation Amendment of 1988 enforce energy conservation standards for main classes of consumer appliances [Greening]. 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 [Damnics]. Energy Star is a joint-program between DOE and U.S. Environmental Protection Agency (EPA), which identifies highly efficient products as well as low standby power consumption [Damnics]. Furthermore, a presidential executive order in 2001 passed an order as part of Federal Energy Management Program (FEMP) requiring all purchases by the governmental agencies to be Energy Star labeled [Damnics].

Most of the energy standards have been performance based, and not prescriptive type of regulation. As such, 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].

The standards rulemakings are led by the DOE’s Energy Efficiency Standards Group (EES), which perform in-depth analysis at Lawrence Berkeley National Laboratory (LBNL). Accompanying each standard rulemaking, DOE issues a technical support document (TSD) that includes the details of the analysis leading to the final regulatory action. The analysis typically includes engineering-economic study assessing current appliance market in relation to the relevant efficiency technologies. Economic analyses are carried for determining consumer life cycle cost and national net present value estimates of several possible efficiency trends [Dale]. Moreover, DOE takes into account a variety of factors such as modifications in product traits, technical feasibility, net energy savings, and usefulness of the standard for lifetime consumer use benefits

[Greening]. All the analyses are carried out to evaluate the technical feasibility and cost-effectiveness of the directive [Damnics]. Minimum energy performance standards for each appliance are defined for various product classes specified by functionality, system performance, etc.

The standard rulemaking is provided in the Notice of Proposed Rulemaking (NOPR) and the Notice of Final Rulemaking (NOFR), which prescribes the standard level [Damnics]. In general, manufacturers are given a few years between NOFR and the standard implementation date to improve the efficiency of their manufactured items. By the year the standard is effective, manufacturers must have fully transitioned to supplying appliances that meet minimum efficiency performance. By implementation date, the supply of less-efficient designs is strictly prohibited. A list of federal energy efficiency standards for residential appliances is shown below [Meyers]:

Table 16. Appliances standards

Federal Energy Efficiency Standards for Residential Appliances

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	

Source: Meyers et al.

Appliance standards have been an effective catalyst in promoting technological progress in appliances manufacturing industry to produce products that serve consumer needs with lesser energy consumption [Bole]. As shown in Table 16 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.

7.2 Efficiency Trends in the Absence of Standards

Even though the energy standards have been largely benefiting the energy reduction of appliances, in general, the energy efficiency improvement would have improved without standards due to technological progress and presence of governmental voluntary groups such as Energy Star [Wenzel]. However, the unit energy savings would be lower than the savings under standards.

8. Conclusions and Recommendations

This appliance case study sheds light on the importance of considering use-phase while assessing the energy savings potential of remanufacturing. Our analysis concludes that by remanufacturing/re-using/repairing/refurbishing considerable energy is saved in production. Moreover, it concludes that from a total life cycle perspective, remanufacturing may be a net energy-savings as well as net energy expending option.

Our retrospective approach conveys the criticality to study other factors such as technological improvements, policy impacts, rebound effects, economic incentives in order to draw inferences about energy savings potential of remanufacturing now as well as in the future. In accordance with this, Figure 17 below illustrates cumulative energy savings in lifetime use-phase by replacing a dishwasher, clothes washer, refrigerator, and room AC produced in 1981 with newer models.

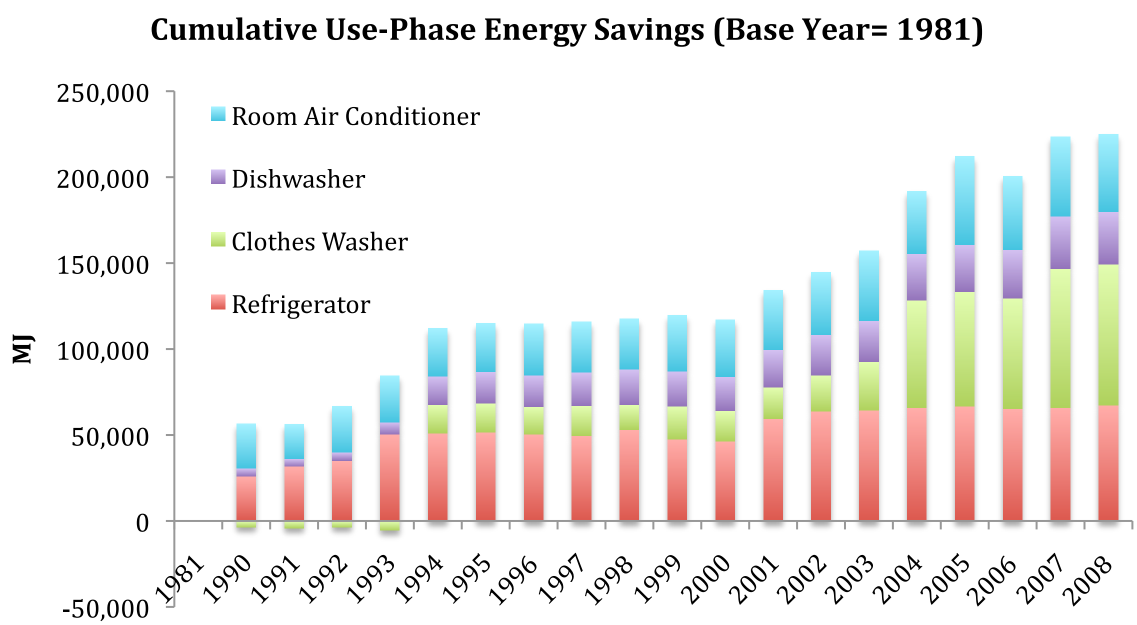


Figure 17 Cumulative use-phase energy savings by replacing 1981 appliance models (refrigerator, clothes washer, dishwasher, room AC) with a newer model

If this trend continues to grow in the future, 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 production phase.

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Abbreviations

AHAM	Association of Home Appliance Manufacturers
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
NRDC	National Resources Defense Council

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Appendix

Appendix A- Energy Star Requirements for Dish Washers

Equipment	**Capacity**	**ENERGY STAR Criteria (August 11, 2009)**
Standard Sized Models	>= 8 place settings + six serving pieces	<= 324 kWh/year <= 5.8 gallons/cycle
Compact Sized Models	< 8 place settings + six serving pieces	<= 234 kWh/year <= 4.0 gallons/cycle

Standardized Sized Model	**Current Criteria Levels**	**January 1, 2010**	**July 1, 2011**

ENERGY STAR	<= 324 kWh/year <= 5.8 gallons/cycle		<= 307 kWh/year <= 5.0 gallons/cycle
Federal Standard	EF >= 0.46	<= 355 kWh/year <= 6.5 gallons/cycle	
Compact Sized Model	**Current Criteria Levels**	**January 1, 2010**	**July 1, 2011**
ENERGY STAR	<= 234 kWh/year <= 4.0 gallons/cycle		<= 222 kWh/year <= 3.5 gallons/cycle
Federal Standard	EF >= 0.62		<= 260 kWh/year <= 4.5 gallons/cycle

Appendix B- Average Retail Prices of Electricity, 1960-2008 (Cents per Kilowatt-hour, including taxes)

	Residential ($2000 dollars)	
Year	**Nominal**	**Real**
1960	2.6	12.4
1961	2.6	12.2
1962	2.6	12.1
1963	2.5	11.5
1964	2.5	11.3
1965	2.4	10.7
1966	2.3	9.9
1967	2.3	9.6
1968	2.3	9.2
1969	2.2	8.4
1970	2.2	8
1971	2.3	8

1972	2.4		8	
1973	2.5		7.9	
1974	3.1		8.9	
1975	3.5		9.2	
1976	3.7		9.2	
1977	4.1		9.6	
1978	4.3		9.4	
1979	4.6		9.3	
1980	5.4		10	
1981	6.2		10.5	
1982	6.9		11	
1983	7.2		11	
1984	7.15		10.57	
1985	7.39		10.6	
1986	7.42		10.41	
1987	7.45		10.18	
1988	7.48		9.88	
1989	7.65		9.74	
1990	7.83		9.6	
1991	8.04		9.52	
1992	8.21		9.5	
1993	8.32		9.41	
1994	8.38		9.28	
1995	8.4		9.12	
1996	8.36		8.91	
1997	8.43		8.84	
1998	8.26		8.56	
1999	8.16		8.34	
2000	8.24		8.24	
2001	8.58		8.38	
2002	8.44		8.1	
2003	8.72		8.2	
2004	8.95		8.18	
2005	9.45		8.36	
2006	10.4		8.91	

2007	10.65		8.89	
2008	11.36		9.28	

Source: EIA Annual Energy Review.

Appendix C- Embodied Energies of Raw Materials

Abbreviation	Material	Energy cost (MJ/Kg)	Source:
Ag	Silver	2000 - 2000	Ashby
Al	Aluminium	190 - 230	Smil
As	Arsenic		
Au	Gold	70000 - 70000	Ashby
Be	Beryllium		
Bi	Bismuth		
Br	Bromine		
Cd	Cadmium		
Ceramics	Ceramics	3 - 7	Smil
Cl	Chlorine		
Cu	**Copper**	60 - 150	Smil
Cr	Chromium		
Epoxy	**Epoxy**	95 - 130	Ashby
Fe	**Iron**	20 - 25	Smil
Glass	**Glass**	15 - 30	Smil
Hg	Mercury		

Liquid Crystals	Liquid Crystals				
Ni	Nickel	140	-	150	Ashby
Pb	Lead	30	-	50	Smil
Pd	Palladium	35000	-	50000	Ashby
Plastics	**Aggregated, excl. PVC**	75	-	115	Smil
Pt	Platinum	117000	-	117000	Ashby
PVC	**PVC**	75	-	100	Smil
Sb	Antimony				
Si	Silicon	1400	-	4100	Smil
Sn	Tin	38	-	40	Ashby
Stainless	Stainless steel	80	-	90	Ashby
Steel	Steel	20	-	25	smil
Zn	Zinc	65	-	70	Ashby
Timber	e.g. wood, cardboard	1	-	3	Smil
Paper, Packaging	paper, packaging	10	-	15	Smil

Approximate embodied energies for Electronic components (Ashby, 2009)

			Energy cost (MJ)/given unit		
Small (handheld) electronic devices	Per Kg		2000	-	4000
Displays	Per m^2		2950	-	3750
Assembly of printed wired boards	per Kg		120	-	140
Batteries (Ni- Cd rechargeable)	per Kg		180	-	220