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Life-Cycle Optimization of Residential Clothes Washer Replacement

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Abstract

The energy efficiency of the average clothes washer in the United States improved by 88.4% from 1981 to 2003 (AHAM 2005). Replacement of old vertical-axis washers with new horizontal-axis washers results in decreased operating costs, both environmental and economic. But replacement also results in one-time financial and environmental impacts from purchasing, manufacturing and disposition. The purpose of this study is to quantify this trade-off and determine optimal replacement intervals for residential clothes washers.

The Life-Cycle Optimization (LCO) model employed to answer this fundamental research question uses as inputs separate Life-Cycle Inventory (LCI) and Life-Cycle Cost (LCC) profiles for each model year clothes washer from 1985-2020. These profiles represent four life-cycle phases of a washer: Material production, manufacturing and assembly, use, and end-of life management.

The results of the LCI and LCC studies showed that the use phase of the washer's life cycle accounts for 96-99% of energy, carbon dioxide emissions and water use, but just 61%-86% of total costs over an anticipated 20 year life. From an energy or carbon dioxide emissions perspective, *any* average washer, regardless of model year, should be replaced with a new horizontal-axis washer in 2006, 2011 and 2016. From a water use and cost minimization perspective an average washer should be immediately replaced with a horizontal-axis washer which should be held until the end of the study period.

In addition to a base case that seeks to model the typical American household, four alternative scenarios were examined. The first was a scenario where the consumer was assumed to have an electric water heater instead of gas. This did not substantially change the optimization routine. The second alternative assumed all clothes were washed

with cold water, causing replacement only twice in 2013 and 2020 when minimizing energy and carbon dioxide emissions. The third scenario assumed that all clothes were washed with cold water *and* line-dried. This magnified the differences highlighted in the second scenario and changed the optimal interval for carbon dioxide emissions and energy, eliminating the need for a second replacement in 2013. The fourth alternative was a scenario where energy prices were assumed to remain constant in 2006 dollars as opposed DOE projections which forecast a decline in real dollar terms. This had little impact on replacement intervals.

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I would like to thank my advisor Greg Keoleian. Dr. Keoleian, through the Center for Sustainable Systems and his relationship with Whirlpool Corporation, provided me with the opportunity to conduct this research. He provided great guidance throughout the project and always drove me to produce a high-quality product. In the final months he took a hands on approach, spending hours reading drafts and revisiting important modeling decisions.

I would also like to thank research associate David Spitzley whose management of the project involved months of modeling development and revision, draft reading and data searching. David's knowledge of life-cycle modeling helped me avoid dozens of pitfalls over the past year. His proofreading of the model and write-up have been invaluable in ensuring that the study results in a quality, error-free product.

This study would not have been possible without the assistance of Wayne Morris at the Association of Home Appliance Manufacturers (AHAM), who provided critical data and guidance.

Whirlpool Corporation, and Floyd Jackson in particular, deserve special recognition for partnering with the Center for Sustainable Systems to promote this research. Floyd's identification of relevant data from previous Whirlpool research and creation of new data using Whirlpool's testing facilities provided this study with critical information that it needed to be successful.

Finally I would like to thank Tom Gladwin for being a member of my thesis committee and for helping me navigate through three successful years as an Erb Institute Student.

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I. Introduction

Figure 1.1 – Vertical & Horizontal-Axis Clothes Washers

Vertical-Axis Washer　　Horizontal-Axis Washer

Approximately 35 billion loads of laundry are washed each year in the United States, consuming 2.6% of total household energy use (Home Energy 1996). The energy efficiency of the average clothes washer in the United States improved by 88.4% from 1981 to 2003 (AHAM 2005). Starting in 1997, horizontal-axis washers became commercially available in the American market. These washers were dramatically more efficient than their vertical-axis peers, causing the gap between the most efficient unit and the industry average unit to widen. By 2004 the most efficient full-sized, horizontal-axis washer on the market was 76.3% more efficient than the average washer (AHAM 2005; EPA 2005). This large efficiency gap is driven primarily by water use.

Market penetration of washers that qualify for the United States Environmental Protection Agency (EPA) Energy Star designation (primarily but not exclusively horizontal-axis washers) increased from 5% among new machines sold in 1997 to 28% at the end of 2004 (EPA 2005). As market penetration and affordability of horizontal-axis washers increases, consumers may be interested to know when it would be the most economically and environmentally efficient for them to replace their existing washer with a new horizontal-axis washer. This study seeks to provide consumers with this information. The life-cycle optimization (LCO) model developed for this study also informs consumers what purchasing decisions will be likely to allow them to minimize the economic and environmental costs of their washing needs from 2006-2020 going forward. Finally the study looks at the effect that other consumer decisions and external factors, such as whether to wash with warm or cold water, and the future of energy prices, have on these results.

In order to answer these questions the study first performs traditional life-cycle assessment (LCA) and life-cycle cost (LCC) calculations for all model years from 1985 to 2020 where data are available. The LCI analysis quantifies environmental impacts of all product life-cycle phases including material production, machine manufacturing and assembly, transport, machine use and machine disposal. The optimization criteria studied are limited to energy use, water use, air emissions of carbon dioxide and life cycle cost. Other greenhouse gas emissions were not considered but were expected to be relatively small compared to carbon dioxide. The LCC analysis considers all life-cycle phases where direct costs are incurred. The purchase price includes manufacturing, transport and disposal of the old machine. The use cost includes water and energy used in operation of the washer.

1.1 Review of Prior Research

Since the 1990s the life-cycle assessment (LCA) framework has been standardized by the International Organization for Standardization (ISO) through ISO 14040-14043 (ISO 1998). Studies have used this framework to analyze household appliances as part of complete homes (Blanchard & Reppe 1998) and individually. In May of 2000 the Department of Energy’s Technology Installation Review published an LCA of commercial clothes washers (used in residential settings) in “Assessment of High-Performance, Family-Sized Commercial Clothes Washers” (DOE 2000). In 2003 the Center for Sustainable Systems at the University of Michigan developed the concept of Life-Cycle Optimization (LCO), whereby LCA results from multiple model years are analyzed to find optimal replacement intervals. The Center first applied this concept to vehicles in “Life Cycle Optimization of Automobile Replacement: Model and Application” (Kim et al. 2003), “Shaping Sustainable Vehicle Fleet Conversion Policies Based on Life Cycle Optimization and Risk Analysis” (Kim 2003), “Optimal Fleet Conversion From a Life Cycle Perspective” (Kim et al. 2004), and “Automotive Life Cycle Economics and Life Cycle Replacement” (Spitzley et al. 2004). Most recently the concept was applied to refrigerators in “Life Cycle Optimization of Household Refrigerator-Freezer Replacement” (Horie 2004) and “Optimal Household Refrigerator Replacement Policy for Life Cycle Energy, Greenhouse Gas Emissions, and Cost” (Kim et al. 2005). This study extends the LCO method of analysis to residential clothes washers.

1.2 Consumer Behavior

Purchase price is becoming a larger portion of the LCC equation as consumers continue to purchase larger, more efficient, and more expensive clothes washers. Increased market penetration of Energy Star machines is one driver of this trend. Besides being more efficient, these machines do not typically have agitators taking up space in their cylinders. Whereas most clothes washers had capacities of 2.7 to 3.0 cubic feet in the 1990s, most full-sized horizontal axis washers now have capacities of about 3.3 cubic feet, with Whirlpool’s Duet brand washer representing the largest capacity residential model in the marketplace with 3.7 cubic feet of capacity (Whirlpool 2006), (AHAM 2005). The United States Department of Energy (DOE) has recently decreased its estimate of the average number of annual laundry loads washed in an American household from 416 to 392, possibly to reflect an increase in average machine volume (DOE 2003). Other trends in the marketplace include an increased emphasis on clothes washers that are quiet, stylish, stackable with matching clothes dryers, and less likely to damage fabrics during the washing process. Horizontal-axis machines outperform their vertical-axis peers in all of these areas (Consumer Reports 2006).

In a 1997 study, the Association of Home Appliance Manufacturers (AHAM) examined clothes washers being retired in the United States market. The average age of these machines was 20.1 years (AHAM 2005). A recent study completed in 2005 reinforced this finding, demonstrating an average retirement age of 20 years (AHAM 2005). This long average life data is a testament to the reliability of clothes washers sold in the United States market, and it also suggests that consumers are loath to replace their washers before they absolutely have too – when the machine breaks down and repair would be expensive or cumbersome.

DOE statistics suggest that 49% of clothes washing cycles are completed with warm water, while 37% are completed with cold water and 14% are completed with hot water (DOE 2004). Recently, Proctor and Gamble Corporation and other detergent manufacturers have introduced products designed to function best in cold wash cycles. These introductions have been supported by major advertising campaigns which may influence consumer behavior (Proctor and Gamble 2005).

85-90% of all clothes washers are recycled at the end of their life in the United States (Recycling Today 2004). This statistic is influenced by the availability of recycling facilities, consumer behavior and local regulations.

1.3 History of Federal Regulations

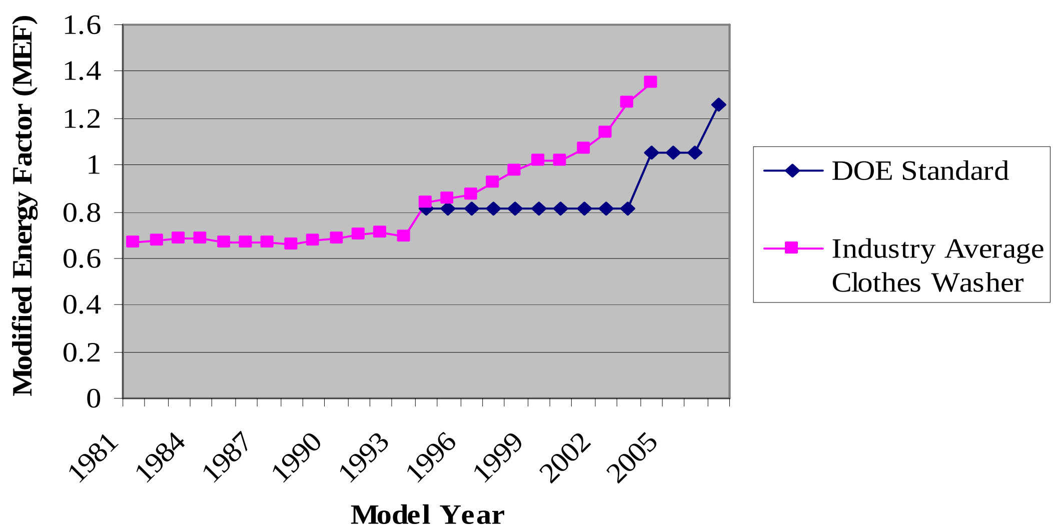
Federal attempts to regulate consumer appliance efficiency started with the Energy Policy and Conservation Act of 1975 (EPCA), which established appliance efficiency targets, but did not set efficiency standards. Several states, particularly California, did set standards, causing difficulty for manufacturers. Eventually manufacturers decided that compliance with a uniform federal standard would be easier than compliance with a variety of state standards. This resulted in their support of the National Appliance Energy Conservation Act of 1987 (NAECA), which established minimum efficiency standards for a variety of appliances including clothes washers and dryers. Except where states successfully petitioned DOE for an exemption, federal standards preempted state standards after NAECA. The original NAECA standard for most appliances was applied to models manufactured after January 1, 1990. The standard was updated for an approximate 30% efficiency improvement for models manufactured after January 1, 1993 (DOE 2004).

The first clothes washer standard, however, was not implemented until January 1, 1994 (DOE 2004). Initially, clothes washer efficiency was calculated using the clothes washer Efficiency Factor (EF) = C/(ME+HE), where C is the capacity of the washer in cubic feet, ME is the electricity drawn from an outlet by the machine for one wash cycle, and HE is the energy used to heat water for one wash cycle.

On January 1, 2004 DOE changed its method for calculating the standard from EF to Modified Energy Factor (MEF) = C/(ME+HE+DE) where DE is the dryer energy needed to dry a load based on residual moisture content (RMC) in the clothes and load size. DOE set the 1994 minimum EF at 1.18 (approximate MEF equivalent of 0.817

(Consortium for Energy Efficiency 2004)). This was not changed until 2004 when the calculation switch was implemented. At that time DOE raised the minimum standard MEF for all washers to 1.04, an approximate 27.3% increase. DOE also required that models achieve an MEF of 1.42 to be Energy Star qualified. On January 1, 2007 the department will again raise the minimum MEF standard to 1.26, a 21.2% increase. Figure 1.2 charts the industry average MEF, as documented by AHAM, against the DOE mandated minimum MEF from 1981-2003 (DOE 2004).

Figure 1.2 - Estimated Average Clothes Washer Efficiency vs. DOE Standard



Because MEF data were not available prior to 2004, conversions were made assuming that MEF values were always 69.2% of EF values going back to 1981. This estimate was drawn from estimates made by the Consortium For Energy Efficiency in 1996 and 2002.

Starting January 1, 2004 the DOE also began to evaluate the amount of water used as a critical determinant of clothes washer performance. At that time the department introduced the Water Factor (WF) =QT/C where QT is the gallons of water used in a load and C is the capacity of the machine in cubic feet. The department introduced this additional standard to reflect the observed imperfect correlation between decreased water use and increased MEF (DOE 2004).

1.4 Problem Statement

Consumers hold their clothes washers for 20 years on average (AHAM 2005). Are they wise to make such a choice? If consumers replaced their clothes washers more frequently would they be able to reduce the total financial and environmental impacts of their clothes washing needs? Now that dramatically more efficient horizontal-axis clothes washers are gaining a foothold in the marketplace, when should consumers replace their existing machine with a new, state-of-the-art model? This study seeks to better inform these important consumer choices.

To determine optimal life-cycles, the study first conducts life-cycle inventory (LCI) and life-cycle cost (LCC) analyses for industry average models manufactured from 1985-2005. The same analyses are then conducted for average horizontal-axis models manufactured from 2006-2020. All phases of the machines' life-cycles are considered: assembly, manufacturing and assembly, transport, use, and disposal. These data provide the necessary inputs for a life-cycle optimization (LCO) model derived from a similar model previously applied to automobiles and refrigerator-freezers (Kim 2003), (Kim et al. 2003), (Kim et al 2004), (Spitzley et al. 2004), (Horie 2004). The outputs of the LCO model answer two primary research questions (1) What model year machines should be replaced with a horizontal-axis machine today? (2) What are likely to be the optimal years for consumers to replace their clothes washers in order to minimize financial and environmental impacts of their clothes washing needs from 2006-2020 going forward?

This study also addresses the following four secondary research questions (1) How would the results change if the consumer is assumed to have an electric (rather than the more common gas) powered hot water heater (2) How would the results of the LCO model change if consumers washed their clothes exclusively with cold water? (3) How do the results of the LCO model change for the 16% of consumers who elect not to use a dryer and hang their clothes on a line to dry instead? (DOE 2005) (4) How do these results change if energy prices are assumed to remain constant in 2006 dollars from the end of 2005 to 2020 (as opposed to the significant decrease forecasted by the Department of Energy and employed in the base case of this study).

1.5 Thesis Outline

Chapter two describes the method and basic concepts of life cycle inventory (LCI) and life cycle optimization (LCO). First, the LCI, a collection of materials, energy and waste inputs and outputs within a system boundary encompassing the entire life cycle of a clothes washer, is explained. Next, a dynamic life cycle inventory that accounts for the annual introduction of increasingly efficient machines each year is explained. Factors that determine energy and water consumption during the various life-cycle stages are also described.

In chapter three, the life cycle inventory for a clothes washer is presented. Life cycle energy and water consumption is estimated for the entire life of clothes washers including material production, manufacturing and assembly, use, and end-of-life phases. An LCI software tool, SimaPro 5.1, is combined with other data sources to complete the inventory.

Chapter four models the dynamic life cycle inventory variables of efficiency improvement and price variation. Analysis of price variation relates both to purchase price of clothes washers and ongoing actual and projected energy costs of electricity and natural gas.

Chapter five presents the results of simulations for energy optimization, carbon dioxide emissions optimization and cost optimization in the use of residential clothes washers. After findings based on a national average "base case" which assumes use of a gas hot water heater and electric dryer are presented, alternative results are presented for those who have electric hot water heaters, and those who wash their clothes with cold water and/or do not use a clothes dryer. A final scenario assumes higher than expected energy prices in the future.

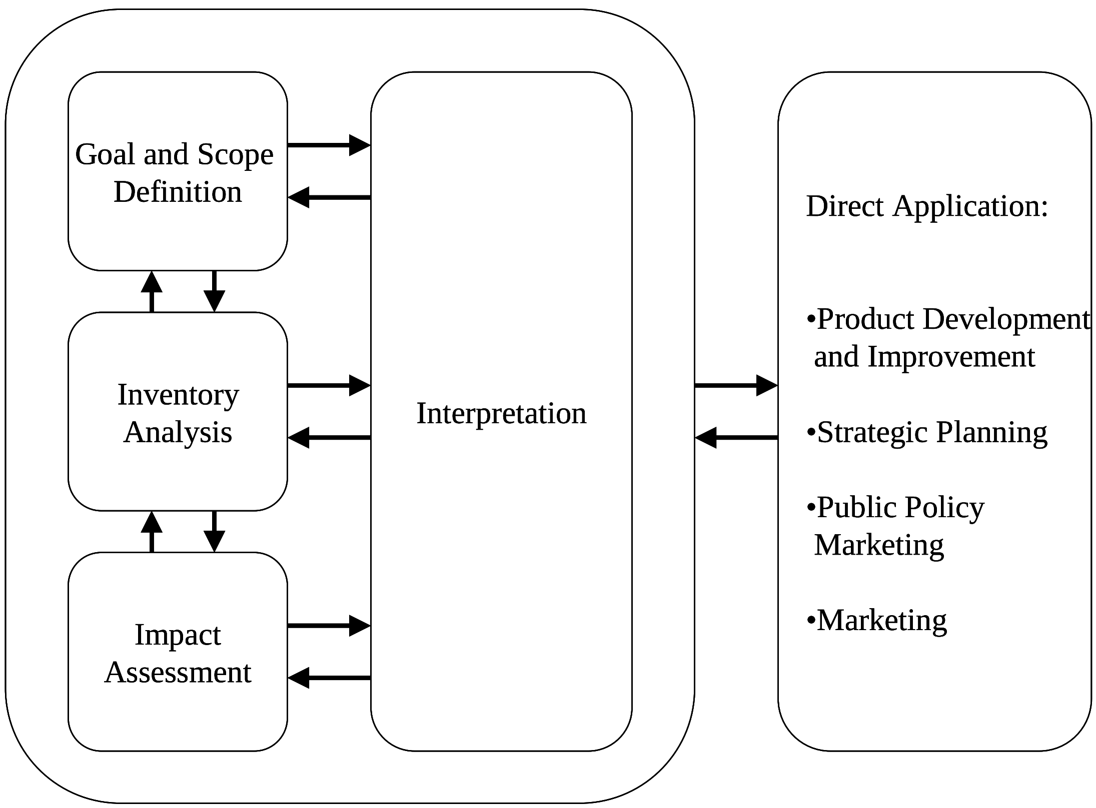
Chapter six concludes with overall results and key findings, presents policy implications, and suggests potential topics for further study.

II. Methodology

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) models potential environmental impacts of a product from "cradle to grave." The International Organization for Standardization (ISO) describes three objectives of LCA analyses for a product (1) identify and quantify energy and materials used and wastes released to the environment (2) assess the impact of the energy and materials used and released into the environment (3) identify and evaluate opportunities for environmental improvement (ISO 2002). ISO also defines the four-phases of an LCA (1) goal and scope definition (2) inventory analysis (3) impact assessment (4) interpretation. This study includes phases (1), (2) and (4). The goal and scope phase defines the purpose and intended audience as well as the boundaries of the system being analyzed. Inventory analysis is the data collection and analysis phase where material and energy inputs and outputs are quantified. The impact assessment phase takes data from the inventory analysis phase and assesses the significance of environmental impacts. In the interpretation phase conclusions are drawn and recommendations for further study are made (ISO 1998).

Figure 2.1 – Life-cycle Assessment Framework



(ISO, 1997)

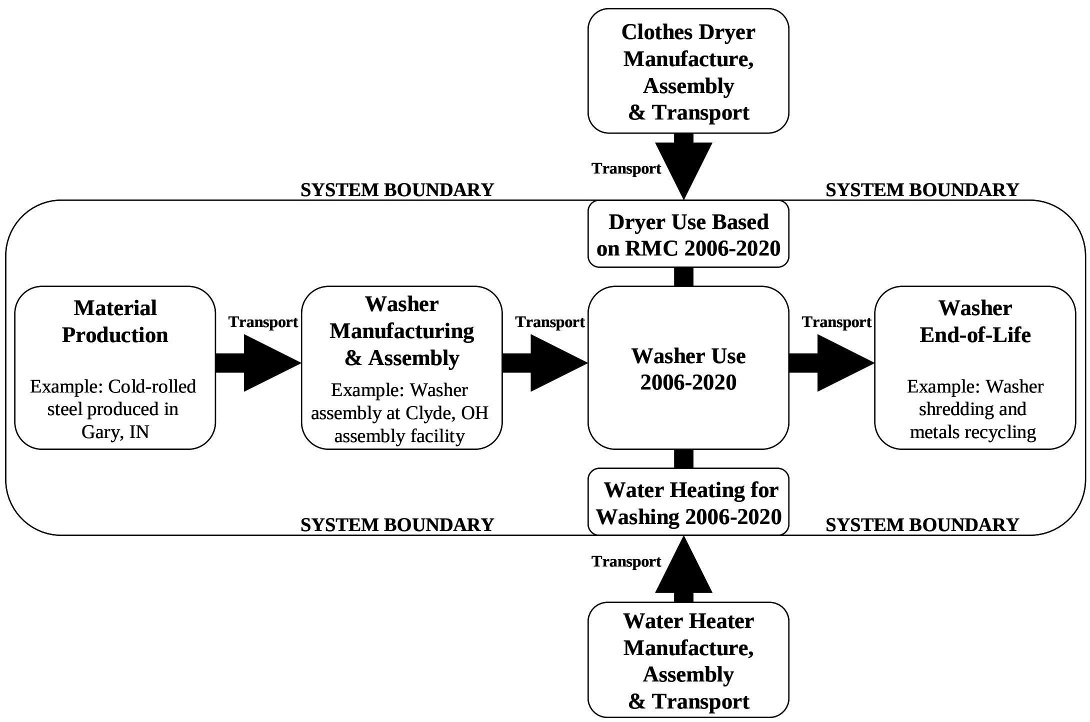
2.2 Scope and System Boundary

A product system is defined by the "functional unit." In this study the functional unit is "the laundering and drying of 1,195.6 cubic feet of clothing per year from 2006-2020." This excludes laundry detergent, which is assumed to be relatively constant across different washers. The system includes unit processes, elementary flows and product flows across and within the system's boundary. The system boundary defines which processes will be included and excluded in the system that is being modeled. The goal is to be as comprehensive as possible. Figure 2.2 is a representation of the system boundary for this study. The accounting of the burdens of the clothes washer itself is very comprehensive, with all life-cycle phases contained within the system boundary. The functional unit in this study calls for more than a washer, however – it also requires warm water for washing and the removal of moisture at the end of the wash for drying. These functions require a hot water heater and a clothes dryer, whose production is not modeled. Rather we include only the use phase component of those machines that is applicable to clothes washing and drying within the system boundary. It is expected that the use phase will dominate the relevant life cycle burdens for these machines.

2.3 Dynamic Life Cycle Inventory

LCI analyses often assume that a machine such as a clothes washer has constant performance over time. Further, they may assume that the cost and efficiency of a replacement machine will be constant over time if a time period is defined in the functional unit. Dynamic LCI analysis accounts for changes over time. These changes can be both machine specific and external to the machine. In this study the efficiency of new clothes washers, both in terms of energy and water use, changes over time. The actual performance of each individual machine, however, is assumed constant over time. Material composition of machines from different model years also changes. External changes modeled include the value of money over time, energy prices over time, and energy intensity of different materials and processes over time.

Figure 2.2 – Washer Life-Cycle Assessment (LCA) System Boundary



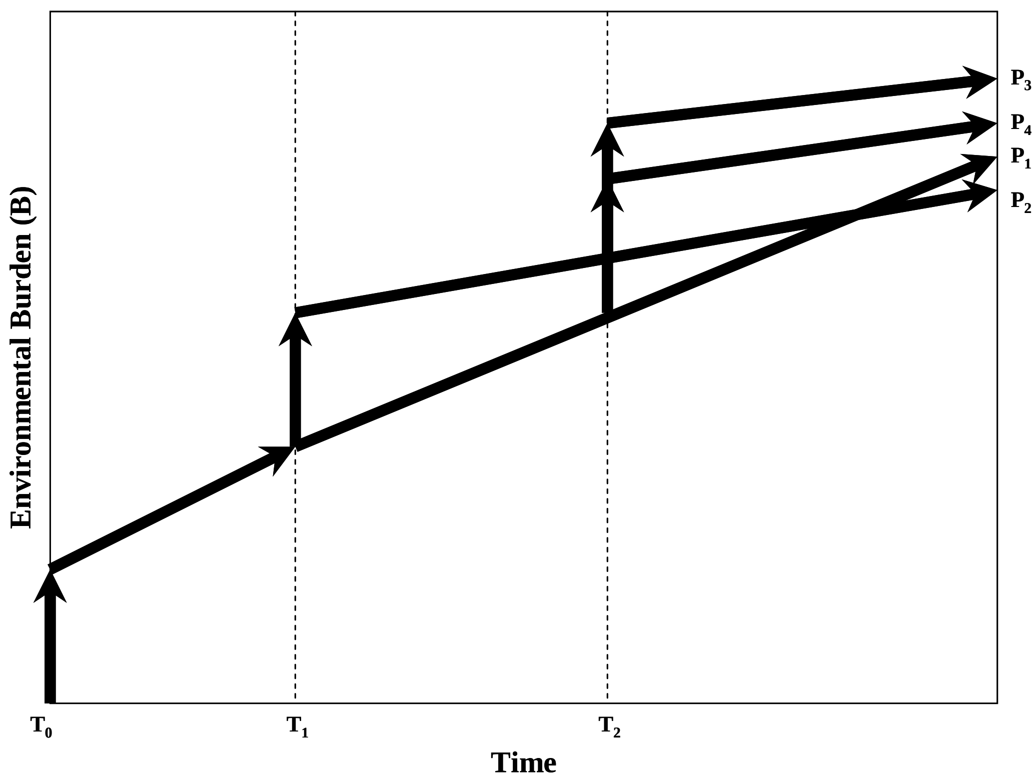
2.4 Life Cycle Optimization Model

Significant environmental and financial impacts result from the replacement of clothes washers. On the other hand, aging machines may use significantly more energy and water than new machines available in the market today, indicating that replacement would result in ongoing reductions in financial and environmental costs during the use phase of the product. Life cycle optimization (LCO) models quantify this trade off.

An LCO model identifies the optimal years in which a product should be replaced to minimize a particular impact over a fixed time period. Each impact requires a separate LCO model. In this study four separate LCO models are used to optimize replacement intervals for cost, energy, carbon dioxide emissions, and water. The inputs for an LCO model consist of fixed impacts associated with purchase and disposal and variable impacts associated with use.

Figure 2.3 is a schematic representation of a simple LCO model with two replacement opportunities and four possible outcomes. The horizontal axis represents time and the vertical axis represents the cumulative environmental or financial burden. T_1, and T_2 represent opportunities to replace the current model with a new model. The vertical increases at T_1, and T_2 represent upfront costs due to replacement (the fixed burdens). The sloped increases between intervals represent ongoing (variable) impacts from the use phase. The steeper the slope, the less efficient the machine. Like an LCO model, the schematic charts each possible outcome. The LCO model, however, identifies the lowest cumulative impact and then outputs the optimal replacement path.

Figure 2.3 – Hypothetical Life-Cycle Optimization



In this example P_2 is the optimal path, indicating that the consumer should replace the washer once at T_1 to minimize environmental impacts over the study period. The inputs for the LCO model that is the subject of this study include 14 potential replacement dates and therefore 2^{14} or about 16,384 possible outcomes. Therefore the model depends on a programming algorithm rather than a graphical representation to find the optimal path.

III. Washer Life Cycle Inventory

Washer environmental impacts can be divided into two categories; fixed and variable. Fixed impacts are those that are automatically incurred when a decision to purchase is made. These include impacts from manufacturing, assembly, transport and end-of-life management. Impacts incurred in the use phase are variable because they depend on the use patterns of the individual owner. The sections that follow highlight each phase of the washer's life-cycle.

3.1 Life-Cycle Phases

3.1.1 Material Production

Two materials composition data sources are used for the purpose of this study. The primary source is composition data generated by the Association of Home Appliance Manufacturers (AHAM), which conducted breakdown studies of vertical axis machines being retired and vertical axis machines currently on the market in 1997. AHAM did materials composition analysis again in 2005, this time comparing 1997 material composition findings for average vertical and horizontal-axis machines to breakdowns of new models in the marketplace in 2005, both vertical and horizontal-axis. The secondary source of data used was a complete list of all parts in a standard Whirlpool Corporation vertical-axis washer being produced in Clyde, OH in 2005. This secondary data is more comprehensive, providing estimates of the actual sub-categories of materials being used. For instance, the AHAM study provides industry-wide estimates for the amount of steel in washers, but the Whirlpool data actually states what percentage of that steel is cold-rolled, hot-dipped or galvanized.

AHAM stated that the machines being retired in 1997 were on average 1977 models (because they had an average age of 20.1 years). In this study it was assumed that there was a straight-line trend in material use from the 1977 vertical-axis machine to the 1997 vertical-axis machine. For example, if there were 160 pounds of steel in the 1977 machine and 140 pounds of steel in the 1997 model, this study assumes that the machines lost one pound of steel each year from 1977 to 1997. The study repeats this straight-line trend assumption for vertical-axis machines from 1997 to 2005, and then uses a straight-line trend observed from 1997 to 2005 for horizontal-axis machines to make estimates for material composition of horizontal-axis machines going forward from 2006 to 2020. The study then uses the actual Whirlpool data to make more detailed estimates about the specific types of metals being used in production. This Whirlpool data demonstrated that approximately 67.8% of all steel in a washer is corrosion resistant, hot-dipped steel. 22.0% is cold-rolled coil, while the other 10% of steel in the machine is split amongst hot-rolled coil (3.4%), electrogalvanized (3.4%), stainless(1.0%), welded pipe (1.2%), and wire rod (1.2%) (Whirlpool 2005). This steel breakdown is assumed constant for all machines in this study.

The average 1977 vertical-axis washer weighed 185.7 pounds, of which 73% was steel (as broken-down above) and 11% was cast-iron. Other significant materials included copper (3.2%), aluminum (2.5%), polypropylene (2.5%), and rubber (2.0%). By 1997 the average vertical-axis machine weighed only 147 pounds, with steel representing just 64% of the mass. Other significant materials included polypropylene (13.8%), aluminum (8.5%), copper (3.9%), and cast iron (3.2%). The industry average 2005 machine had similar percentages of materials to 1997, but weighed only 130 pounds. By contrast, the average horizontal-axis machine was much heavier, weighing 196 pounds in 2005, of which 50.4% was steel and 15.6% was polypropylene. Other significant materials included fiber and paper (3.9%) and aluminum (3.2%). A significant percentage of the mass of the clothes washers, ranging from 0.1% for a 2005 industry average machine to 23.9% for a 2006 horizontal-axis machine, was made of unknown materials. In order to get an estimate of the burdens associated with those materials it was assumed that all unknown materials had the same impacts as the average material in that particular washer. Complete material composition data for selected clothes washers is contained in Table 3.1 (AHAM 2005).

There are three key findings from analysis of this data: first, that steel weight is declining while lighter-weight materials such as polypropylene and aluminum are increasing; second, that there is a trend towards lighter-weight machines; third, that horizontal-axis machines are considerably heavier than their vertical-axis peers. All of these findings influence the environmental impacts associated with material production.

To get the best possible estimates of the impacts associated with each material used in clothes washers, this study relies on data from the International Iron and Steel Institute (IISI), the Association of Plastics Manufacturers in Europe (APME), Franklin Associates and other sources contained in the SimaPro 5.1 impacts database. Material inventory data used in the study are included in Appendix A. Combined, these data sources led to estimates of total environmental impacts (measured in emissions of carbon dioxide, primary energy consumption and water use) for the materials in clothes washers.

Table 3.1 - Material Composition Data for Selected Clothes Washers

	1977 Industry Average Washer		1997 Industry Average Washer		2005 Industry Average Washer		1997 Horizontal-Axis Washer		2005 Horizontal-Axis Washer	
	% of Total	Mass (lbs.)	% of Total	Mass (lbs.)	% of Total	Mass (lbs.)	% of Total	Mass (lbs.)	% of Total	Mass (lbs.)
Steel	73.2%	135.9	63.0%	92.5	73.0%	94.7	49.5%	100.8	50.4%	98.6
Iron (gray Cast)	10.7%	19.9	3.2%	4.7	0.7%	0.9	0.0%	0.0	0.1%	0.1
Aluminum (cans)	2.5%	4.6	8.5%	12.5	4.5%	5.9	1.6%	3.2	3.2%	6.3
Copper	3.2%	5.9	3.9%	5.7	2.0%	2.6	1.7%	3.5	1.3%	2.5
Brass	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.1%	0.2	0.0%	0.0
Other Metal	0.2%	0.4	0.0%	0.0	0.0%	0.0	1.7%	3.5	0.2%	0.3
Rubber	2.0%	3.7	1.4%	2.1	1.9%	2.4	1.8%	3.7	1.7%	3.4
Fiber & Paper	0.1%	0.2	0.0%	0.0	0.0%	0.0	0.0%	0.0	3.9%	7.6
Polypropylene (caps)	2.5%	4.6	13.8%	20.3	15.4%	20.0	12.9%	26.3	15.6%	30.5
PS & HIPS	0.1%	0.2	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0
ABS	0.1%	0.2	0.0%	0.0	0.1%	0.1	0.1%	0.2	1.3%	2.6
PVC	0.1%	0.2	0.4%	0.6	0.9%	1.2	2.7%	5.5	1.0%	1.9
Polyurethane	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0
Other Plastics	0.2%	0.4	0.3%	0.4	1.4%	1.8	2.2%	4.4	2.6%	5.0
Asst. Mixed Plastics	1.1%	2.0	1.3%	1.9	0.0%	0.0	0.0%	0.0	0.0%	0.0
Fiberglass	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0
Glass	0.0%	0.0	0.0%	0.0	0.0%	0.0	1.9%	3.8	1.9%	3.8
Refrigerant	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0
Oil	0.7%	1.3	0.6%	0.9	0.0%	0.0	0.0%	0.0	0.0%	0.0
Other	3.1%	5.8	3.5%	5.1	0.1%	0.1	23.9%	48.6	16.9%	33.1
Total	**99.8%**	**185.3**	**99.9%**	**146.7**	**100.0%**	**129.7**	**100.0%**	**203.7**	**100.0%**	**195.7**

3.1.2 Manufacturing and Assembly

Where available, materials data sets that included fabrication were used. For instance, data for aluminum cans and polypropylene caps was preferred to general aluminum and polypropylene. Materials data in Appendix A accounts for parts fabrication for 16-37% of the washer's mass, depending on the model year of the washer. This decision was made because of a lack of data available for parts manufacturing in Whirlpool Corporation's supply chain. Whirlpool indicated that a large percentage of parts are not manufactured in their assembly facilities, but did not have data for energy and water use of their suppliers. Therefore, the total energy use of their assembly facility sited below does not capture most of the impacts from parts manufacturing. Although material production data sets are comprehensive for energy and emissions of carbon dioxide, they are less comprehensive for water, where data were only available for steel, aluminum, copper and some specified polymers (See Appendix A).

To get an estimate for the energy, carbon dioxide emissions and water impacts attributable to each clothes washer for assembly by the manufacturer, the study uses actual utility data from Whirlpool Corporation's Clyde, Ohio washer production facility for the calendar year 2004. In that year 4,845,947 units were produced, consuming 574,156 thousand cubic feet of natural gas and 103,464,337 kilowatt hours of electricity. This equates to 118 cubic feet of natural gas and 21.35 kilowatt hours of electricity per washer (Whirlpool 2005). No data was available for water use during assembly. Absent gas and electricity data for different years these assembly impacts per washer were assumed constant for the life of the study and then adjusted to reflect the average energy intensity of manufacturing in the United States generally (see section 4.2), both for vertical-axis and horizontal-axis washers, even though the Clyde facility manufactures vertical-axis washers exclusively.

This approach has significant limitations. By assuming that assembly impacts change at the same rate as manufacturing in general (see Appendix B), the study ignores specific changes to the clothes washer industry. Technology and efficiency improvements might lead to a trend of lower impacts per unit produced. On the other hand the well publicized mechanization of washer assembly might lead to higher impacts per unit (NY Times 2005). Further, it is logical to assume that relatively massive, horizontal-axis machines might have higher energy consumption in assembly than their vertical-axis peers. A final clear limitation is the lack of water use data from the assembly process.

3.1.3 Use

As with material composition analysis, this study uses a combination of data from Whirlpool Corporation and the Association of Home Appliance Manufacturers to estimate past and present energy use data.

AHAM provided average EF data for clothes washers in the U.S. market from 1981 to 2003. This data demonstrated an 88.4% efficiency improvement during that time period. It also showed average machine capacity increasing from 2.52 cubic feet in 1981 to 3.05 cubic feet in 2004. Whirlpool provided data for a 1980 clothes washer tested using MEF procedures, as well as MEF data for the company's current Duet brand horizontal-axis model. All data on washer capacity and average washer efficiency are included in Appendix C of the study (AHAM 2005) (Whirlpool 2006).

The study assumes that the percentage of energy attributed to residual moisture content (the third component of the denominator in the MEF equation and only component not included in the EF equation) in the 1980 Whirlpool machine was equal to the percentage attributable to residual moisture content (RMC) in the 1981 industry average machine, the study makes MEF estimates from AHAM actual industry average EF data. Because the percentage attributable to RMC was different in the 2005 vertical-axis machine (48.5%) than it was in the 1980 vertical-axis machine (41.9%), it was assumed that a straight-line trend from the 1980 value to the 2005 value occurred. Once the study switched to examination of the horizontal-axis machine in 2006, it was assumed that the percentage of energy attributed to RMC remained constant at 2006 levels (72.9%) through the end of the study period in 2020. Water heating and agitation (the energy drawn from an outlet by the washer) were allocated the remaining energy from the

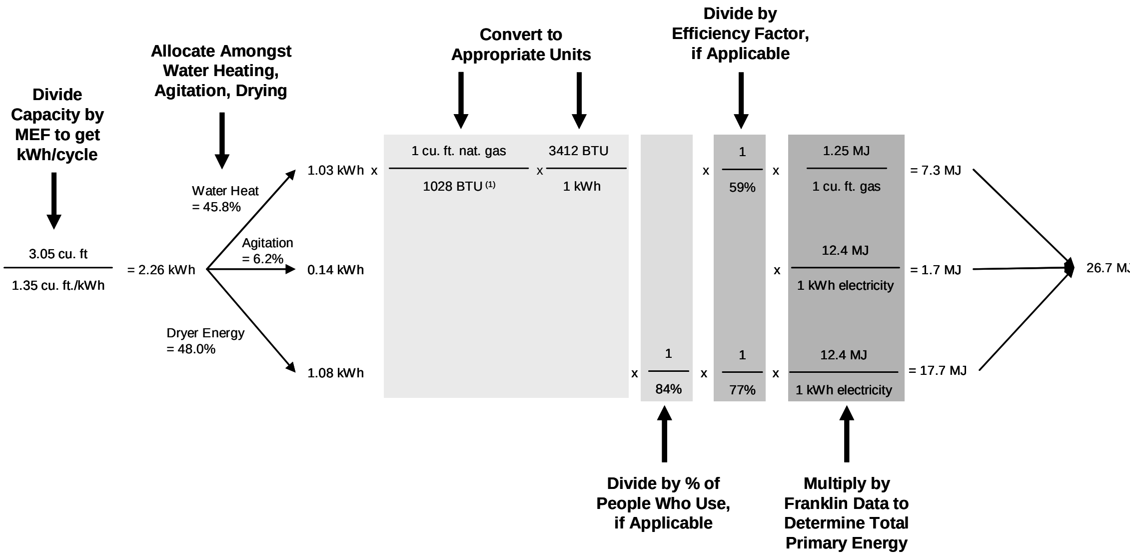
MEF, with 88% of what remained being assigned to water heating and 12% of what remained allocated to agitation. This ratio is based on actual 2005 vertical-axis data, but also closely approximates percentages observed in all models for which data were available.

The study assumes that the total annual volume of clothes washed in the average American household remained constant throughout the duration of the study period. This was based on Department of Energy J and J1 test procedures, which indicated that the average number of laundry cycles per annum have declined from 416 to 392 from 1997 to 2003. If these average annual cycles data are assumed to be correct they suggest that total annual volume washed is actually very close to constant over time. (416 cycles x 2.83 average cubic feet = 1,177 average cubic feet of volume washed in 1997, 392 cycles x 3.05 average cubic feet = 1,196 average cubic feet of volume washed in 2004). Therefore this study held annual volume washed constant at the 2004 level of 1,196 average cubic feet per annum (DOE 2004) (AHAM 2005).

Together the adapted MEF data and assumption about volume allow for estimates of average total annual energy consumption for models from 1985 to 2003. As AHAM began compiling industry average MEF data in 2004, actual MEF data can be used for that year. In order to estimate an MEF value for 2005 the study simply assumes that the average rate of efficiency improvement for the previous years in the study continued from 2004 to 2005.

Once estimates for total annual on-site energy and the percentages of energy allocated to each of the three components of the MEF equation are made, two steps remain to get actual energy estimates for models in each year. First, losses due to efficiency of the related appliances (the hot water heater and dryer) must be considered. Second, losses due to the efficiency of the electricity grid and natural gas delivery system must be accounted for. For the hot water heater we take the on-site energy allocated to water heating, which assumes that 14% of consumers wash with hot water (an increase of 75 degrees farenheit from a supply temperature of 60 degrees), 49% wash with warm water (an increase of 38 degrees) and 37% wash with cold water (no increase). We then divide that site energy by 59%, the efficiency of an average natural gas powered hot water heater in the market today (DOE 2006). Then we multiply the resulting value by the burdens (energy, carbon dioxide and water use) per cubic foot of natural gas delivered as reported by Franklin Associates (See Appendix D), which includes upstream impacts. For agitation we multiply energy allocated to agitation by the burdens per kilowatt hour delivered, also as reported by Franklin Associates. Finally for dryer energy we take the annual allocation to RMC for the average washer, divide by 84% (to add back the 16% of consumers assumed not to use a dryer by DOE given that the base case of this study assumes that all consumers *do have* a dryer), and compare the resulting value in kilowatt hours to the known average kilowatt hours consumed by electric dryers in the marketplace today of 824, to find an efficiency factor (77%) by which to divide the dryer energy of all model year dryers. The resulting values are then multiplied by the burdens per kilowatt hour delivered as reported by Franklin Associates. Figure 3.1 illustrates the calculation of total use phase primary energy from the actual use phase MEF value for the average 2004 machine used in the study.

Figure 3.1 Calculating Use Phase Energy Impacts/Cycle with 2004 MEF



(1) Natural Gas Heat Content as taken from EIA Annual Energy Review Appendix A

Starting in 2006 the study focused exclusively on horizontal-axis washers. Whirlpool Corporation provided actual MEF data for the 2006 Duet horizontal-axis machine. The company also provided its projected fleet average MEF improvements for 2006 through 2009. This average was 3.53% per year. For the purpose of this study it is assumed that the Duet brand washer will increase its efficiency from 2006-2020 at the same rate as the Whirlpool fleet average is projected to improve from 2006-2009.

AHAM has not historically tracked industry average Water Factor (WF) data. Therefore this study relies on data from the Whirlpool 1980 washer, a 2005 Whirlpool Gold vertical-axis washer and the 2006 Whirlpool Duet horizontal-axis washer. The WF values in gallons per cubic foot of capacity, for those three machines are 12.5, 12.0, and 4.4 respectively (Whirlpool 2006). Appendix E demonstrates complete WF data for all model years.

3.1.4 Transport

In this study all transport impacts are attributed to a machine at the date of purchase, even though some of those impacts will not be realized until the machine is transported from the consumer's house to a scrap metals processor or landfill. The study charts the hypothetical path of a Whirlpool vertical-axis washer whose steel is produced in Gary, Indiana. The steel is then transported from Gary to Whirlpool's Clyde, Ohio assembly facility, a distance of 247.1 miles (100% by diesel truck). The machine then travels a distance of 1,102 miles to a US distributor (also 100% by diesel truck), 50 miles from the distributor to the consumer's home (100% by diesel truck), and an additional 50 miles from the consumer's home to a scrap metals processing center or landfill (100% by diesel truck). The 1,102 mile distance from Clyde to a distributor is estimated using a population weighted average of the distance from Clyde, OH to the 20 largest metropolitan areas in the United States. Average 50 mile distances from distribution centers to consumers home and from home to scrap yards or landfills are the midpoint of a 25-75 mile delivery distance range calculated in a previous Center for Sustainable Systems study of Aveda Corporation's product distribution (Arbitman et al. 2005).

As described above, the study examines a vertical-axis machine from 1985 to 2005 and a horizontal-axis machine from 2006 to 2020. The horizontal axis machine is assumed to travel from Germany, where Whirlpool currently manufactures its horizontal-axis washers for the US market, a distance of approximately 3,965 miles (100% by diesel boat). Next the horizontal-axis machine is transported 1,217 miles to a hypothetical US distribution facility (100% diesel truck) from the United States' largest eastern sea port in Elizabeth, New Jersey. The 3,965 sea travel distance was estimated using actual air travel distances between Berlin and New York. The distance from manufacturer to distribution is a population-weighted average from Elizabeth, New Jersey to the same 20 largest metropolitan areas in the United States. From the distribution center the horizontal-axis machine is assumed to have the same per pound transit energy as the vertical-axis machine detailed above. Appendix F lists the distances from Clyde, Ohio and Elizabeth, New Jersey to the 20 largest metropolitan areas. It also shows the populations of those areas and their contribution to the weighted average shipping distance. Appendix G shows all distances used in the transport calculation.

3.1.5 End-of-Life

As with transport, all end-of-life impacts are assumed to be incurred at the time that the machine is purchased. 85-90% of all white goods are recycled in the United States, and the only materials recaptured are generally metals (Recycling Today 2004). Previous studies have estimated the energy use of scrap metal grinders that process white goods, automobiles and other large, predominantly metal, goods to be 32 British thermal units per pound (Kim et al. 2003). Therefore, the average recycled clothes washer in this study is assumed to have an 87.5% chance of getting recycled and require between 1.25 and 1.75 kilowatt hours of electricity to shred for recycling (based on the 32 Btu estimate and machine weights). Because only metal is recycled, only the metal weight is assumed to avoid the landfill. All other mass from the recycled machines, plus the full mass of the 12.5% of machines that are not recycled, is then assumed to be land-filled. The carbon dioxide emissions from land-filling are estimated to be 0.0043 kilograms per pound of material. The estimated energy consumption per pound of land-filled material is estimated to be 0.069 mega joules per pound of material (Ecobalance and National Polution Prevention Center 1997).

This method for calculating the impacts associated with a washer's end-of-life has clear limitations. First, it is unknown whether washers are recycled at the same rate as other appliances. Refrigerator-freezers might weigh down the overall recycling rate, for instance, because they require removal of Freon, typically for a financial cost. Clothes washers, having no such burden, might be recycled at a rate higher than the overall 85-90% range attributed to white goods generally. A second limitation is the lack of adequate credit given for recycling. High appliance recycling rates lead to more recycled content in the steel stock in the United States. Even though this leads to lower embodied energy and carbon dioxide emissions for the steel stock as a whole, the appliances that are recycled at high rates do not get any energy or carbon dioxide emissions credits in this study.

IV. Dynamic Life Cycle Inventory

4.1 Material Contents

Materials composition data for clothes washers over time indicates a strong shift from ferrous metals to lighter weight non-ferrous metals and polymers. The average washer weighed 185.7 pounds in 1977, approximately 84% of which was steel and cast iron. By contrast, the average washer manufactured in 2005 weighed 129.7 pounds, 73.7% of which was steel or cast iron. The average 1977 washer had 4.6 pounds of aluminum and 4.6 pounds of polyester. By 2005 the average washer had 5.9 pounds of aluminum and 20 pounds of polyester.

As noted above, horizontal-axis machines are more massive. The average horizontal-axis washer manufactured in 2005 weighed 195.7 pounds. In these machines as well there is a decreasing emphasis on steel. The average 2005 horizontal-axis machine only contained 50.4% steel. All of these material composition trends have been incorporated into the life-cycle analysis conducted in this study.

4.2 Energy Intensity

The amount of energy required to produce certain materials or complete certain processes changes over time. It is particularly important to model these changes in this study because of the dramatic improvements in energy per unit of output that have been realized in steel production since the beginning of the time period under examination. From 1985 to 2006 energy per unit of output of steel decreased by approximately 35%. This trend is projected to continue such that energy per unit of steel produced will improve by an additional 14% by the year 2020. The energy profiles of other materials modeled in this study have also improved over time. Polymers produced in 2020 are expected to require 5.7% less energy than polymers produced in 1985. Over that same time period aluminum is projected to improve its energy intensity by 25%. The average material, including those mentioned above is projected to improve its energy intensity by 26% (Kim et al. 2003).

The changes in energy intensity for several processes including manufacturing, transport and end-of-life management are also modeled in this study. Both transport and end-of-life management are projected to increase in energy intensity by about 4.5% over the study period. General manufacturing has fluctuated since 1985, but is projected to improve by approximately 22% from 2006 to 2020. Appendix B shows energy intensities modeled in this study, indexed to 2006 values (Kim et al 2003).

4.3 Maintenance and Repairs

Previous life-cycle optimization studies have looked at the impacts that maintenance and repairs have on life-cycle optimization outcomes (Kim et al 2003) (Horie 2004). While these were considered to be a significant factor in a study of vehicles, they were judged to be negligible in a study of refrigerators. Given that clothes washers, like refrigerators, are stationary with long histories of maintenance-free operation, this study assumes that maintenance and repair also has a negligible impact on the life-cycle analysis of clothes washers.

4.4 Life-Cycle Cost Analysis

All unit operating costs (calculated by multiplying the amount of energy consumed by the DOE recorded average energy costs for that year (DOE 2004)) are inflated or deflated so that they may be stated in 2006 dollars rather than the 2004 dollars that DOE uses to report them. Unit purchase prices as reported in Consumer Reports are adjusted by historical inflation rates to be stated in 2006 dollars. Where available, prices are based on actual data. Refer to Appendix H for a full list of purchase price assumptions (in 2006 dollars). The rate used to inflate or deflate data is the U.S. Bureau of Labor Statistics historical inflation rate of 3.1% since 1926 (Wall Street Journal, 1996). Refer to Appendix I for the cost of natural gas and electricity in each year as reported or projected by DOE and adjusted to 2006 dollars. DOE forecasted declining energy prices. This study also examines a scenario where energy prices are held constant in real dollar terms. Water use costs are assumed constant throughout the study period at $4.16 per one thousand gallons (EPA 2006).

V. Results

5.1 Life-Cycle Inventory

Separate LCI models were generated for each clothes washer model from 1986-2020. From 2006-2020 inventories focused exclusively on horizontal-axis washers. A base case plus four alternative scenarios were examined. The base case examines the best possible estimation of what happens in the average US home. It takes MEF and WCF values as they are reported by the company. These reporting criteria based on DOE's JI test procedure estimate the percentage of consumers who wash their clothes with hot warm and cold water. The criteria also specify that 16% of consumers use no clothes dryer. Because the reporting criteria only report site energy, with no allowance for the efficiency of water heaters or dryers, this study makes further assumptions about those two machines. The base case assumes that the consumer has a natural gas powered, storage hot water heater with 59% efficiency, the mid-point of the range of common efficiencies in the US market today as reported by DOE (DOE 2001). This assumption is due to natural gas powered water heaters having a 53% market share in the United States. The base case further assumes that the consumer has an electric clothes dryer because these dryers have 79% market share in the United States (Energyguide.com 2006). The efficiency of the electric dryer is assumed to be 77%. This efficiency level makes the industry average RMC site energy allocation from the MEF convert to the efficiency of the average electric dryer in the marketplace (824 kilowatt hours per annum) (Natural Resources Canada 2004). Although it is likely that the efficiency of these water heaters and dryers have changed and will continue to change over time, those changes are excluded due to lack of data.

The first alternative scenario assumes that the consumer has an electric water heater with 90.5% efficiency (again the midpoint of models common in the marketplace today (DOE 2001)) instead of the gas water heater. Here again the efficiency level is assumed constant over time. The second alternative excludes water heating energy, implying that all clothes are washed and rinsed with cold water. This is accomplished in the life cycle models by taking the base case and setting the water heating component of the MEF calculations equal to zero for all model years. A third alternative scenario excludes water heating energy *and* dryer energy, assuming that clothes are washed with cold water and dried on clothes lines rather than in mechanical dryers, accomplished by setting both water heating energy and dryer energy equal to zero when adapting the base case model. The final alternative scenario alters the base case so that energy prices are held constant from 2006-2020 in 2006 dollars. In each of these cases the total impacts of models for various years of production were different. A list of the key differences between the base case and the alternative cases is included in table 5.1.

Table 5.1 - List of Scenarios Examined

Scenario	Water Heat	Dryer	Energy Prices
Base Case	Gas, 59% Efficient	Electric, 77% Efficient	DOE, 2006$
Electric Water Heat	Electric, 90.5% Efficient	Electric, 77% Efficient	DOE, 2006$
No Water Heat	None	Electric, 77% Efficient	DOE, 2006$
No Water Heat or Dryer	None	None	DOE, 2006$
Higher Cost Energy	Gas, 59% Efficient	Electric, 77% Efficient	Flat at 2006 Levels, 2006$

Key LCI findings from the base case analysis are demonstrated in tables 5.2 – 5.4 and figures 5.1-5.3. Table 5.2 shows estimated energy profiles, with energy used in each life-cycle phase, for industry average (predominantly vertical-axis) clothes washers manufactured in 1985, 1990, 1995, 2000 and 2005. It also shows projected energy profiles for horizontal-axis clothes washers manufactured in 2006, 2010, 2015 and 2020.[1] All data in this figure assumes a 20-year life for all washers. In all model years the use phase of the product is dominant, accounting for 99% of total primary energy use in industry average washers prior to 2005 and 96-97% of total primary energy for horizontal-axis washers manufactured in 2006 or after. Figure 5.1 is a graphical representation of total life-cycle energy use for all phases combined. This figure brings to light an accelerated rate of efficiency improvement that began in the mid-1990s. It also demonstrates the extent to which horizontal-axis machines are environmentally preferable to their vertical-axis peers.

Table 5.2 Base Case Energy Profiles of Selected Washers (MJ)

	Industry Average Washer					Horizontal-Axis Washer			
	1985	1990	1995	2000	2005	2006	2010	2015	2020
Assembly	439	442	471	447	420	412	386	356	328
Manufacturing	4,697	4,348	4,049	3,488	2,894	4,393	4,218	4,088	3,987
Transport	190	178	167	151	137	301	292	286	284
Use	558,221	565,620	472,644	410,625	240,177	194,425	169,669	143,185	120,919
End-of-Life	21	20	19	18	16	26	25	24	23

[1] Data for each model year from 1985 to 2020 are available as part of the excel model that accompanies this study, submitted by CD to the School of Natural Resources at the University of Michigan in April 2006.

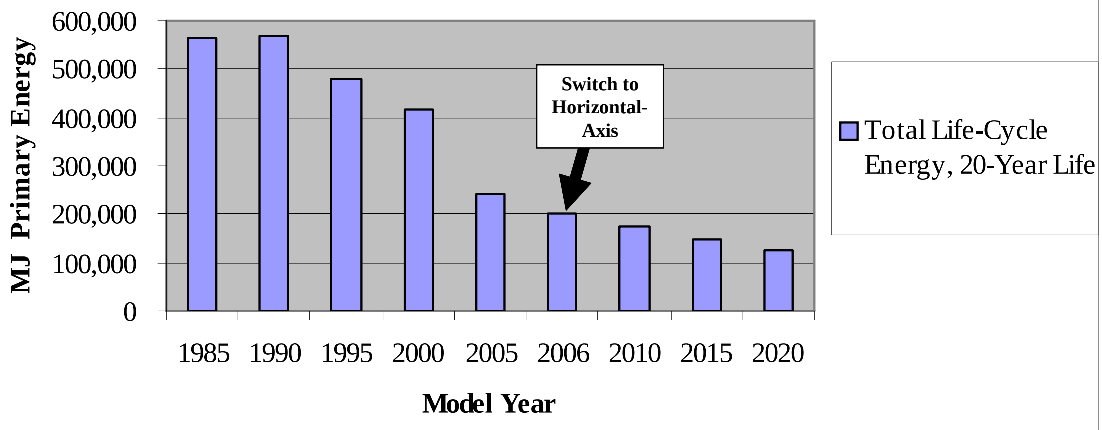


Figure 5.1 - Base Case Energy Profiles of Clothes Washers

Table 5.3 and Figure 5.2 demonstrate a similar trend for emissions of carbon dioxide. In this case the use phase accounts for 98-99% of carbon dioxide emissions for industry average washers and 96-97% of carbon dioxide emissions for horizontal-axis washers. A 2006 horizontal-axis washer emits only 34.4% as much carbon dioxide over its 20-year life as a 1985 vertical-axis washer did.

Table 5.3 Base Case Emissions Profiles of Selected Washers (kg CO2)

	Industry Average Washer					Horizontal-Axis Washer			
	1985	1990	1995	2000	2005	2006	2010	2015	2020
Assembly	24	24	26	25	23	23	21	20	18
Manufacturing	325	289	258	217	179	250	236	222	210
Transport	14	13	12	11	10	22	22	22	21
Use	31,227	31,682	26,511	23,064	13,517	11,144	9,725	8,208	6,932
End-of-Life	1.2	1.2	1.1	1.0	0.9	1.5	1.4	1.4	1.4

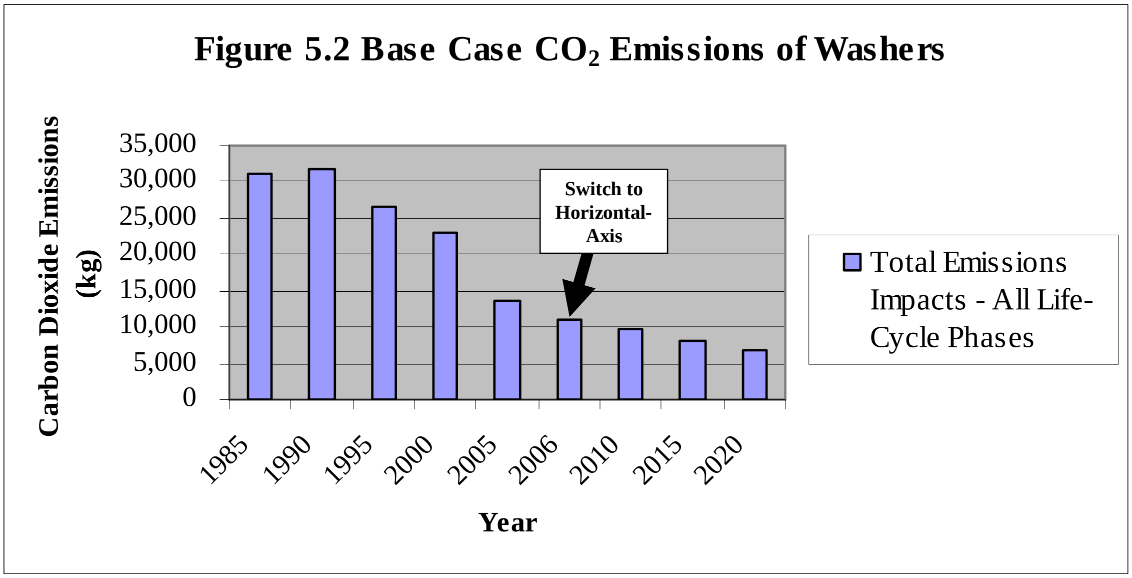
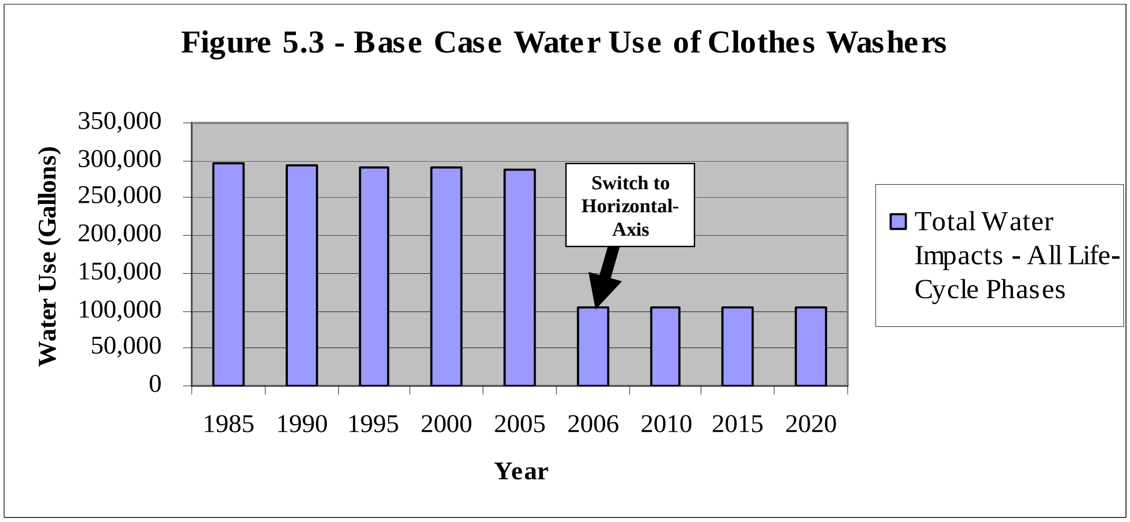


Table 5.4 and figure 5.3 show the water use of selected clothes washers from 1985 to 2020. No data was available for water use in assembly, transport and end-of-life management, so these results are less complete than the carbon dioxide emissions and energy findings. Another shortcoming of the results was a lack of data that would support projections of water use in future machines (forcing this study to assume that water use per volume of clothes washed remains constant from 2006 to 2020). The results suggest that virtually all water demand in a washer's life-cycle occurs during the use phase, meaning that even small technology improvements will cause the LCO model to output a replacement.

Table 5.4 Base Case Water Use Profiles of Selected Washers (gallons)

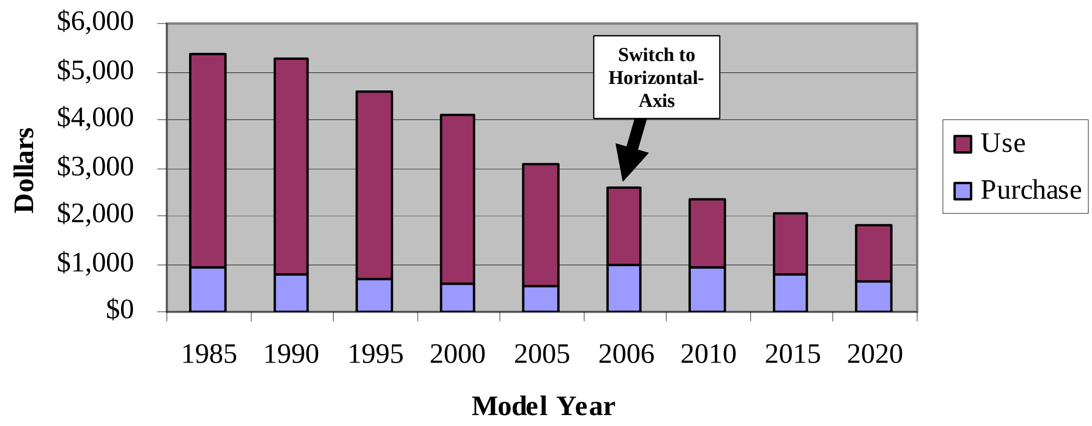
	Industry Average Washer					Horizontal-Axis Washer			
	1985	**1990**	**1995**	**2000**	**2005**	**2006**	**2010**	**2015**	**2020**
Assembly	NA	NA	NA	NA	NA	NA	NA	NA	NA
Manufacturing	352	322	293	284	289	335	339	355	370
Transport	NA	NA	NA	NA	NA	NA	NA	NA	NA
Use	296,977	294,337	291,697	289,056	286,944	105,213	105,213	105,213	105,213
End-of-Life	NA	NA	NA	NA	NA	NA	NA	NA	NA



5.2 Life-Cycle Cost

The life-cycle cost results of this study also show the use phase of the clothes washer to cause the highest impact. The financial costs incurred by the consumer are 1.) Water and sewerage costs from the use phase 2.) Energy costs from all three components of the MEF calculation, also in the use phase 3.) Washer purchase costs. The 2005 Whirlpool Gold vertical-axis washer examined in our study retailed for $500. The projected 20-year operating cost (in 2006 dollars) of this machine was $3,062, meaning that 83% of total costs were projected to be incurred in the use phase of the product. The 2006 to 2020 horizontal-axis washers show the increasing importance of the purchase cost of washers over time. In 2020 approximately 64% of total cost will be attributed to the 20-year use costs. Figure 5.4 illustrates the relative importance of use costs and purchase costs for selected clothes washers over time.

Figure 5.4 - Base Case Washer Life-Cycle Cost



5.3 Alternative Scenario Inventory Results

The four alternative scenarios outlined above only have impacts on the use phase of the LCI results and the use phase of the LCC results. Those use phase changes are outlined in table 5.5. Actual use phase impacts are demonstrated at the top of the table. Next a summary of the use phase impacts in the base case of the study is repeated for reference. Finally percentage values at the bottom of the table demonstrate the percentage of original use phase impacts that are still incurred under the alternative scenarios.

Use of an electric hot water heater (alternative scenario 1) increases total use phase costs by 8-10% for horizontal-axis washers manufactured after 2006. In the past it increased use phase costs for industry average machines manufactured before 2005 by 17-39%. The electric water heater will also result in increased energy and carbon dioxide emissions profiles for horizontal-axis washers manufactured after 2006. There the increase in carbon dioxide emissions is greater (approximately 11%) than the increase in energy use (approximately 10%) because of the carbon dioxide intensive nature of the fuels used in the electricity grid, particularly coal. The same trend can be seen for past industry average washers, where electric water heaters raised the overall energy and carbon dioxide emissions profiles by 22-32%.

Table 5.5 - Use Phase Impacts Under Alternative Scenarios

	Industry Average Washer					Horizontal-Axis Washer			
Electric Water Heat Scenario	**1985**	**1990**	**1995**	**2000**	**2005**	**2006**	**2010**	**2015**	**2020**
Use Cost	$6,177	$5,965	$4,971	$4,375	$2,989	$1,759	$1,577	$1,405	$1,261
Use Energy (MJ)	702,973	707,447	586,798	506,141	292,874	213,380	186,169	157,057	132,582
Use Emissions (kg/CO2)	40,874	41,135	34,119	29,430	17,881	12,407	10,825	9,132	7,709
Cold Wash Only Scenario	**1985**	**1990**	**1995**	**2000**	**2005**	**2006**	**2010**	**2015**	**2020**
Use Cost	$4,058	$3,986	$3,445	$3,122	$2,304	$1,514	$1,366	$1,226	$1,108
Use Energy (MJ)	405,609	416,090	352,291	309,921	184,619	174,440	152,273	128,560	108,622
Use Emissions (kg/CO_2)	23,584	24,194	20,484	18,020	10,735	10,143	8,854	7,475	6,316
Cold Wash/No Dryer Scenario	**1985**	**1990**	**1995**	**2000**	**2005**	**2006**	**2010**	**2015**	**2020**
Use Cost	$1,495	$1,467	$1,401	$1,356	$1,277	$468	$463	$460	$456
Use Energy (MJ)	46,033	45,210	38,136	33,344	22,460	8,143	7,522	6,859	6,301
Use Emissions (kg/CO_2)	2,677	2,629	2,217	1,939	1,306	473	437	399	366
High Cost Energy Scenario	**1985**	**1990**	**1995**	**2000**	**2005**	**2006**	**2010**	**2015**	**2020**
Use Cost	$4,432	$4,516	$4,062	$3,805	$2,749	$1,756	$1,585	$1,403	$1,249
Base Case	**1985**	**1990**	**1995**	**2000**	**2005**	**2006**	**2010**	**2015**	**2020**
Use Cost	**$4,432**	**$4,463**	**$3,893**	**$3,545**	**$2,546**	**$1,599**	**$1,439**	**$1,291**	**$1,166**
Use Energy (MJ)	**558,221**	**565,620**	**472,644**	**410,625**	**240,177**	**194,425**	**169,669**	**143,185**	**120,919**
Use Emissions (kg/CO_2)	**31,227**	**31,682**	**26,511**	**23,064**	**13,517**	**11,144**	**9,725**	**8,208**	**6,932**
Electric Water Heat % Base	**1985**	**1990**	**1995**	**2000**	**2005**	**2006**	**2010**	**2015**	**2020**
Use Cost	139.4%	133.6%	127.7%	123.4%	117.4%	110.0%	109.6%	108.9%	108.1%
Use Energy (MJ)	125.9%	125.1%	124.2%	123.3%	121.9%	109.7%	109.7%	109.7%	109.6%
Use Emissions (kg/CO_2)	130.9%	129.8%	128.7%	127.6%	132.3%	111.3%	111.3%	111.3%	111.2%
Cold Wash % of Base	**1985**	**1990**	**1995**	**2000**	**2005**	**2006**	**2010**	**2015**	**2020**
Use Cost	91.6%	89.3%	88.5%	88.1%	90.5%	94.7%	94.9%	95.0%	95.0%
Use Energy (MJ)	72.7%	73.6%	74.5%	75.5%	76.9%	89.7%	89.7%	89.8%	89.8%
Use Emissions (kg/CO_2)	75.5%	76.4%	77.3%	78.1%	79.4%	91.0%	91.0%	91.1%	91.1%
Cold Wash/No Dryer % of Base	**1985**	**1990**	**1995**	**2000**	**2005**	**2006**	**2010**	**2015**	**2020**
Use Cost	33.7%	32.9%	36.0%	38.2%	50.2%	29.2%	32.2%	35.6%	39.1%
Use Energy (MJ)	8.2%	8.0%	8.1%	8.1%	9.4%	4.2%	4.4%	4.8%	5.2%
Use Emissions (kg/CO_2)	8.6%	8.3%	8.4%	8.4%	9.7%	4.2%	4.5%	4.9%	5.3%
High Cost Energy % of Base	**1985**	**1990**	**1995**	**2000**	**2005**	**2006**	**2010**	**2015**	**2020**
Use Cost	100.0%	101.2%	104.3%	107.3%	108.0%	109.8%	110.2%	108.7%	107.1%

Elimination of water heat (scenario 2) will reduce total use phase costs of the washer by 5% for future horizontal-axis washers and 8-11% for industry average machines manufactured prior to 2005. The effects on energy and carbon dioxide emissions are greater. For horizontal-axis washers manufactured after 2006 the use phase savings will be approximately 9-10% and for industry-average washers manufactured prior to 2005 the savings were 21-27%.

The third alternative scenario, which eliminates dryer energy in addition to water heating energy, causes even greater impact reductions. Cost savings will be 61-71% for future horizontal-axis washers, while they were 50-67% for industry average machines manufactured prior to 2005. Energy and carbon dioxide emissions savings were much greater still, as mechanical energy (the only component of the MEF equation still present in this scenario) represents only 4-10% of total washer energy use, depending on the model year. Appendix C shows the relative weights of the three components of the MEF equation over time.

The final alternative scenario increased energy prices from the DOE projected values in the base case of the study to constant values (in 2006 dollars) of 8.213 cents per kilowatt hour and .00673 cents per cubic foot of natural gas. This raised use phase costs by 7-10% for horizontal-axis washers manufactured in the future.

5.4 Life-Cycle Optimization

Table 5.6 shows the results of the base case life-cycle optimization. In order to minimize cost, the model instructs owners of industry average clothes washers older than 2005 model years to replace with a 2006 horizontal-axis washer. “Never” outputs indicate that the machine never gets replaced in the study period. For energy and carbon dioxide emissions minimization the results call for replacement of all industry average models immediately with a 2006 horizontal-axis washer, and then again with a 2011 model and a 2016 model (indicating that the optimal replacement interval is approximately 5 years). Finally, if the goal is to minimize water use, the model mandates immediate replacement of all average efficiency washers with a 2006 horizontal-axis washer. Unlike with energy and carbon dioxide emissions, water optimization never calls for a second or third replacement during the study period. As mentioned above, this is due to a lack of projected water efficiency improvements.

Table 5.6 LCO Base Case Results

Cost		Energy		Emissions		Water	
Currently Own	Replace In …	Currently Own	Replace In …	Currently Own	Replace In …	Currently Own	Replace In …
1986	2006	1986	06, '11,'16	1986	06, '11,'16	1986	2006
1987	2006	1987	06, '11,'16	1987	06, '11,'16	1987	2006
1988	2006	1988	06, '11,'16	1988	06, '11,'16	1988	2006
1989	2006	1989	06, '11,'16	1989	06, '11,'16	1989	2006
1990	2006	1990	06, '11,'16	1990	06, '11,'16	1990	2006
1991	2006	1991	06, '11,'16	1991	06, '11,'16	1991	2006
1992	2006	1992	06, '11,'16	1992	06, '11,'16	1992	2006
1993	2006	1993	06, '11,'16	1993	06, '11,'16	1993	2006
1994	2006	1994	06, '11,'16	1994	06, '11,'16	1994	2006
1995	2006	1995	06, '11,'16	1995	06, '11,'16	1995	2006
1996	2006	1996	06, '11,'16	1996	06, '11,'16	1996	2006
1997	2006	1997	06, '11,'16	1997	06, '11,'16	1997	2006
1998	2006	1998	06, '11,'16	1998	06, '11,'16	1998	2006
1999	2006	1999	06, '11,'16	1999	06, '11,'16	1999	2006
2000	2006	2000	06, '11,'16	2000	06, '11,'16	2000	2006
2001	2006	2001	06, '11,'16	2001	06, '11,'16	2001	2006
2002	2006	2002	06, '11,'16	2002	06, '11,'16	2002	2006
2003	2006	2003	06, '11,'16	2003	06, '11,'16	2003	2006
2004	2006	2004	06, '11,'16	2004	06, '11,'16	2004	2006
2005	Never	2005	06, '11,'16	2005	06, '11,'16	2005	2006

Table 5.7 assumes that the consumer has an electric water heater. Like the final alternative scenario discussed below, this causes even the most recent models to be replaced by a 2006 horizontal-axis model. Otherwise the financial results are unchanged, with 2006 washers held to the end of the study period. High electricity use in this scenario does not change replacement intervals (optimally five years) when energy and carbon dioxide emissions are optimized. This scenario has no impact on water use.

Table 5.7 Electric Heat LCO Results							
Cost		Energy		Emissions		Water	
Currently Own	Replace In …	Currently Own	Replace In …	Currently Own	Replace In …	Currently Own	Replace In …
1986	2006	1986	06,'11,'16	1986	06,'11,'16	1986	2006
1987	2006	1987	06,'11,'16	1987	06,'11,'16	1987	2006
1988	2006	1988	06,'11,'16	1988	06,'11,'16	1988	2006
1989	2006	1989	06,'11,'16	1989	06,'11,'16	1989	2006
1990	2006	1990	06,'11,'16	1990	06,'11,'16	1990	2006
1991	2006	1991	06,'11,'16	1991	06,'11,'16	1991	2006
1992	2006	1992	06,'11,'16	1992	06,'11,'16	1992	2006
1993	2006	1993	06,'11,'16	1993	06,'11,'16	1993	2006
1994	2006	1994	06,'11,'16	1994	06,'11,'16	1994	2006
1995	2006	1995	06,'11,'16	1995	06,'11,'16	1995	2006
1996	2006	1996	06,'11,'16	1996	06,'11,'16	1996	2006
1997	2006	1997	06,'11,'16	1997	06,'11,'16	1997	2006
1998	2006	1998	06,'11,'16	1998	06,'11,'16	1998	2006
1999	2006	1999	06,'11,'16	1999	06,'11,'16	1999	2006
2000	2006	2000	06,'11,'16	2000	06,'11,'16	2000	2006
2001	2006	2001	06,'11,'16	2001	06,'11,'16	2001	2006
2002	2006	2002	06,'11,'16	2002	06,'11,'16	2002	2006
2003	2006	2003	06,'11,'16	2003	06,'11,'16	2003	2006
2004	2006	2004	06,'11,'16	2004	06,'11,'16	2004	2006
2005	2006	2005	06,'11,'16	2005	06,'11,'16	2005	2006

Tables 5.8 examines the cold water wash scenario, and finds results which are substantially similar to the base case, with cost optimization calling for only one replacement (for models older than 2003). This is because the purchase cost becomes an even larger percentage of the total cost equation with no water heating bills, meaning that upfront costs become an even larger percentage of the total cost and therefore an even larger hurdle to clear for replacement. When the goal is to minimize energy and carbon dioxide emissions, the replacement pattern from the LCO model calls for two rather than three replacements in 2006 and 2013. Water use minimization is unchanged by this model, which only changes water temperature, not water volume.

Table 5.8 Cold Wash LCO Results							
Cost		Energy		Emissions		Water	
Currently Own	Replace In …	Currently Own	Replace In …	Currently Own	Replace In …	Currently Own	Replace In …
1986	2006	1986	2006, 2013	1986	2006, 2013	1986	2006
1987	2006	1987	2006, 2013	1987	2006, 2013	1987	2006
1988	2006	1988	2006, 2013	1988	2006, 2013	1988	2006
1989	2006	1989	2006, 2013	1989	2006, 2013	1989	2006
1990	2006	1990	2006, 2013	1990	2006, 2013	1990	2006
1991	2006	1991	2006, 2013	1991	2006, 2013	1991	2006
1992	2006	1992	2006, 2013	1992	2006, 2013	1992	2006
1993	2006	1993	2006, 2013	1993	2006, 2013	1993	2006
1994	2006	1994	2006, 2013	1994	2006, 2013	1994	2006
1995	2006	1995	2006, 2013	1995	2006, 2013	1995	2006
1996	2006	1996	2006, 2013	1996	2006, 2013	1996	2006
1997	2006	1997	2006, 2013	1997	2006, 2013	1997	2006
1998	2006	1998	2006, 2013	1998	2006, 2013	1998	2006
1999	2006	1999	2006, 2013	1999	2006, 2013	1999	2006
2000	2006	2000	2006, 2013	2000	2006, 2013	2000	2006
2001	2006	2001	2006, 2013	2001	2006, 2013	2001	2006
2002	2006	2002	2006, 2013	2002	2006, 2013	2002	2006
2003	Never	2003	2006, 2013	2003	2006, 2013	2003	2006
2004	Never	2004	2006, 2013	2004	2006, 2013	2004	2006
2005	Never	2005	2006, 2013	2005	2006, 2013	2005	2006

The scenario reported in table 5.9 goes one step farther than that in table 5.8 by eliminating both water heating energy *and* dryer energy. This once again increases the desirability of hanging onto the 2006 machine from a cost perspective and does not change anything from a water use perspective. Major overall use phase energy and carbon dioxide emissions savings cause the LCO model to call for only one replacement in 2006 for all industry average washers. This reflects the extent to which the use phase is still very dominant in total overall environmental impacts.

Table 5.9 Cold Wash, No Dryer LCO Results

Cost		Energy		Emissions		Water	
Currently Own	Replace In …	Currently Own	Replace In …	Currently Own	Replace In …	Currently Own	Replace In …
1986	2006	1986	2006	1986	2006	1986	2006
1987	2006	1987	2006	1987	2006	1987	2006
1988	2006	1988	2006	1988	2006	1988	2006
1989	2006	1989	2006	1989	2006	1989	2006
1990	2006	1990	2006	1990	2006	1990	2006
1991	2006	1991	2006	1991	2006	1991	2006
1992	2006	1992	2006	1992	2006	1992	2006
1993	2006	1993	2006	1993	2006	1993	2006
1994	2006	1994	2006	1994	2006	1994	2006
1995	2006	1995	2006	1995	2006	1995	2006
1996	2006	1996	2006	1996	2006	1996	2006
1997	2006	1997	2006	1997	2006	1997	2006
1998	2006	1998	2006	1998	2006	1998	2006
1999	2006	1999	2006	1999	2006	1999	2006
2000	2006	2000	2006	2000	2006	2000	2006
2001	Never	2001	2006	2001	2006	2001	2006
2002	Never	2002	2006	2002	2006	2002	2006
2003	Never	2003	2006	2003	2006	2003	2006
2004	Never	2004	2006	2004	2006	2004	2006
2005	Never	2005	2006	2005	2006	2005	2006

The final scenario in table 5.10 seeks to determine whether energy prices higher than DOE projects (held constant in 2006 dollars at 2006 levels), would increase the frequency of optimal replacements from a cost perspective. As table 5.8 demonstrates, this change is only slight, with the results calling for replacement of all industry average washers with a 2006 horizontal-axis washer (this is different from the base case which only replaces models older than 2005) and then holding of that 2006 washer through the end of the study period.

Table 5.10 Higher Energy Cost LCO Results							
Cost		Energy		Emissions		Water	
Currently Own	Replace In …	Currently Own	Replace In …	Currently Own	Replace In …	Currently Own	Replace In …
1986	2006	1986	06,'11,'16	1986	06,'11,'16	1986	2006
1987	2006	1987	06,'11,'16	1987	06,'11,'16	1987	2006
1988	2006	1988	06,'11,'16	1988	06,'11,'16	1988	2006
1989	2006	1989	06,'11,'16	1989	06,'11,'16	1989	2006
1990	2006	1990	06,'11,'16	1990	06,'11,'16	1990	2006
1991	2006	1991	06,'11,'16	1991	06,'11,'16	1991	2006
1992	2006	1992	06,'11,'16	1992	06,'11,'16	1992	2006
1993	2006	1993	06,'11,'16	1993	06,'11,'16	1993	2006
1994	2006	1994	06,'11,'16	1994	06,'11,'16	1994	2006
1995	2006	1995	06,'11,'16	1995	06,'11,'16	1995	2006
1996	2006	1996	06,'11,'16	1996	06,'11,'16	1996	2006
1997	2006	1997	06,'11,'16	1997	06,'11,'16	1997	2006
1998	2006	1998	06,'11,'16	1998	06,'11,'16	1998	2006
1999	2006	1999	06,'11,'16	1999	06,'11,'16	1999	2006
2000	2006	2000	06,'11,'16	2000	06,'11,'16	2000	2006
2001	2006	2001	06,'11,'16	2001	06,'11,'16	2001	2006
2002	2006	2002	06,'11,'16	2002	06,'11,'16	2002	2006
2003	2006	2003	06,'11,'16	2003	06,'11,'16	2003	2006
2004	2006	2004	06,'11,'16	2004	06,'11,'16	2004	2006
2005	2006	2005	06,'11,'16	2005	06,'11,'16	2005	2006

A related question not discussed previously is which machine the consumer who currently has no washer should buy. In this case the answer is clearly the horizontal-axis machine, which will have a significantly better environmental profile in all three categories and will also save the consumer money. The total 20-year life-cycle cost of a current horizontal-axis washer in 2006 dollars is $2,559, a savings of $463 over a current industry average washer, whose life-cycle 2006 dollar cost is $3,062.

What would be the financial ramifications of replacing according to an optimal environmental schedule and vice versa? This depends on what model year the consumer currently owns and what scenario is being analyzed, but a typical case might be an owner of a 1995 industry average machine under base case settings (gas water heater, electric dryer, DOE projected energy prices). No matter what his objective, this consumer would replace his machine with a horizontal-axis machine in 2006 and incur use phase costs from 2006 to 2011. This is where the optimal environmental path (excepting water) strays from the optimal financial path. From an energy or carbon dioxide emissions perspective, the consumer replaces a second time in 2011 and a third time in 2016, incurring purchase costs of $858 and $737, respectively. Ongoing operating costs from 2006 to 2020 would then be $1,071, for a 2006 to 2020 total including the 2006 purchase of $3,666. Economically the consumer holds the 2006 machine to 2020, incurring only one purchase cost of $1,000 in 2006 and operating costs of $1,199 from 2006 to 2020, for a total of $2,199. This causes a savings of 61%. The consumer that optimizes energy incurs primary energy impacts of 5,132 mega joules (MJ) from purchase of the 2006 model, 4,884 MJ from purchase of the 2011 model, and 4,719 MJ from purchase of the 2016 model. Primary use phase energy impacts in the optimal scenario from 2006 to 2020 are then 124,172 MJ, for a 2006 to 2020 total of 138,945 MJ. By holding his 2006 washer, which optimizes cost, he incurs total impacts from 2006-2020 of 150,950 MJ. Thus the energy optimization policy leads to an 8% energy savings over the cost optimization policy.

VI. Conclusions, Policy Recommendations and Areas for Study

6.1 Conclusions

In this study a LCO model was developed to evaluate optimal replacement for washers from 2006-2020. The critical importance of the use phase in the life-cycle analysis (both in terms of energy and carbon dioxide emissions) suggest that, from an environmental perspective, clothes washers should be replaced frequently. The optimization results for the base case and most alternative scenarios confirm this hypothesis, calling for three replacements every five years in most cases, and two in the second alternative scenario that assumes no water heating. The third alternative scenario that assumes no water heating and no drying reduces the use phase impacts significantly, causing the consumer to only replace once, migrating to a horizontal-axis machine as soon as possible and then holding that machine.

Life-cycle costs are generally minimized by migrating to a 2006 horizontal-axis washer and holding that machine until the end of the study period, regardless of what industry average model the consumer currently has. The exception to this rule is the lower use cost alternative scenarios of no water heat and no water heat/no dryer, which do not advocate switching at all if the consumer owns a model that is a 2003 or newer. The base case also does not replace model years 2005 or newer. Energy and carbon dioxide emissions impacts, on the other hand, are minimized by migrating to a horizontal-axis washer as soon as possible and replacing twice more before the end of the study period. The exceptions here are the cold wash scenario, which did not mandate a third replacement and the cold wash/no dryer scenario, whose low use phase impacts did not even justify a second replacement.

In the base case as in all of the alternative scenarios save one, there is a disconnect between the optimal replacement interval from an environmental perspective and the optimal replacement interval from a financial perspective. If the consumer wishes to minimize economic costs he should replace all but the most recently manufactured industry average washer and then hold that 2006 model until the end of the study period. By contrast, if the consumer wishes to minimize his environmental impacts he should replace his washer every five years.

What causes environmental goals to clash with economic goals? Many costs not directly correlated with increasing environmental impacts contribute to the overall purchase price of a washer. Labor, instrument and machine maintenance, and general overhead are all examples.

It is also important to recall that new purchasers with no current washer would do well to buy the more environmentally efficient horizontal-axis washer. This means that, in the long term, all wise economic decision makers will end up also making a wise environmental choice. This study proves, however, that the date at which they make that choice depends on whether they prefer to minimize environmental or economic impacts.

6.2 Policy Recommendations

When their current inefficient clothes washers reach the end of their useful life, rational economic decision makers will purchase more efficient replacement models to save money. Many government entities may prefer to wait for this market-based solution to occur without interference. The drawback to such a strategy is the additional environmental burdens that will be incurred while this transition takes place over the coming decades. Other governments may decide to attempt to hurry the transition to more efficient washers. In this case financial incentives such as tax credits might be attractive because they would help consumers offset the additional upfront costs of an efficient model.

There may be good reason for different local governments to take different approaches. Arid regions of the country, for instance, may view water savings to be critical and therefore choose to provide incentives to upgrade sooner. Regions with plentiful water and power, on the other hand, may not find such incentives to be best placed.

The efforts of policy makers and advocates may be better focused on influencing consumers to make rational economic choices in the first place. The 72% of machines sold in the marketplace today that are not Energy Star qualified are financially inefficient for their owners. Governments and advocates could reach out to consumers to ensure that they understand the savings that they could realize from paying more upfront for efficiency. They could also make sure that consumers are aware of financing options that may allow them to spread higher purchase costs over a longer period. The alternative LCA results also highlight the significant economic advantages of washing with cold water and line drying clothes. Policy makers may wish to promote these approaches for their environmental benefits, once again through outreach to consumers.

6.3 Areas for Further Study

The relationship between regulation and efficiency improvements is a potential area for further study; in particular scholars interested in this area may wish to use average efficiency data calculated this study to statistically analyze correlations between regulations and improved efficiency.

Another interesting question is how LCO analyses can influence the durability targets of manufacturers. If environmental impact minimization suggests optimal replacement of machines every seven years, is it logical to for manufacturers to continue building washers that last twenty years on average?

Further research also could increase the complexity of the model used in this study to include optimization of hot water heater replacement and clothes dryer replacement.

LCO studies must also continue to be conducted for different appliances, at least until clear patterns emerge. To date optimal replacement intervals have been significantly different across vehicles, refrigerators and washers. Finally, it is important to examine the best ways for scholars to communicate complex LCO findings to consumers in an understandable format.

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Appendix A - Material Impacts Data

(per **Pound** of Material)

	Emissions (Kg CO2)	Energy (MJ)	Water (Gallons)	
Steel (weighted average of below)	1.194	14.580	2.915	
Iron (Gray Cast)(1)	1.020	13.400		
Auminum (Cans)(1)	2.970	54.000	0.699	
Copper (2)	3.407	43.046	0.015	
Brass				
Other Metal				
Rubber(1)	1.120	43.300		
Fiber & Paper				
Polypropylene (Caps)(1)	1.620	45.100		
PS & HIPS(1)	1.350	46.500		
ABS(3)	1.429	43.200	12.136	
PVC(3)	0.859	26.852	5.872	
Polyurethane				
Other Plastics				
Asst. Mixed Plastics				
Fiberglass				
Glass				
Refrigerant				
Oil(1)	0.176	23.067		
Other Removed Materials				
Other (weighted average of all others)	1.454	25.259		
Steel Breakdown	Emissions	Energy	Water	% of Overall Steel
Cold Rolled Coil(4)	1.108	12.771	2.466	22.0%
Electrogalvanized(4)	1.329	16.412	2.521	3.4%
Hot Rolled Coil(4)	1.006	11.237	2.010	3.4%
Hot Dipped(4)	1.228	15.333	3.149	67.8%
Stainless Steel(4)	1.108	12.771	2.466	1.0%
Welded Pipe(4)	1.108	12.771	2.466	1.2%
Wire Rod(4)	1.108	12.771	2.466	1.2%
Total Washer Steel	**1.194**	**14.580**	**2.915**	100.0%

(1) Source: Franklin Associates 2006

(2) Source: Delft University of Technology (IDEMAT) 2001

(3) Source: Association of Plastics Manufacturers in Europe 2002

(4) Source: International Iron and Steel Institute 2002

Appendix B - Intensities of Materials and Processes

(Indexed to 2006)

Year	Ferrous	Aluminum	Polymers	Average Other	Manufacturing	Transport/ End of Life
1985	1.531	1.217	1.025	1.241	1.065	0.923
1986	1.518	1.196	1.025	1.230	1.060	0.923
1987	1.503	1.174	1.025	1.219	1.056	0.923
1988	1.489	1.153	1.025	1.207	1.051	0.923
1989	1.443	1.146	1.025	1.192	1.061	0.923
1990	1.399	1.137	1.025	1.176	1.073	0.923
1991	1.355	1.131	1.025	1.160	1.083	0.923
1992	1.338	1.128	1.025	1.155	1.106	0.923
1993	1.323	1.126	1.025	1.149	1.128	0.923
1994	1.306	1.124	1.025	1.144	1.151	0.923
1995	1.264	1.109	1.025	1.125	1.143	0.923
1996	1.220	1.093	1.025	1.108	1.142	0.923
1997	1.178	1.079	1.025	1.089	1.116	0.923
1998	1.137	1.064	1.025	1.073	1.115	0.923
1999	1.137	1.061	1.025	1.071	1.102	0.946
2000	1.111	1.053	1.019	1.059	1.085	0.952
2001	1.088	1.043	1.016	1.048	1.084	0.976
2002	1.064	1.035	1.013	1.036	1.063	0.973
2003	1.046	1.025	1.010	1.027	1.051	0.984
2004	1.032	1.015	1.005	1.017	1.039	0.984
2005	1.014	1.008	1.002	1.010	1.018	0.984
2006	1.000	1.000	1.000	1.000	1.000	1.000
2007	0.985	0.992	0.997	0.992	0.984	1.011
2008	0.973	0.985	0.994	0.986	0.967	1.004
2009	0.962	0.977	0.992	0.979	0.952	1.001
2010	0.949	0.970	0.989	0.973	0.936	0.996
2011	0.939	0.963	0.986	0.965	0.922	0.994
2012	0.926	0.958	0.983	0.959	0.907	0.986
2013	0.918	0.951	0.983	0.954	0.893	0.992
2014	0.907	0.945	0.981	0.948	0.878	0.988
2015	0.900	0.940	0.977	0.943	0.864	0.986
2016	0.890	0.933	0.974	0.938	0.852	0.983
2017	0.883	0.929	0.972	0.932	0.837	0.976
2018	0.878	0.924	0.972	0.928	0.823	0.972
2019	0.868	0.920	0.969	0.924	0.809	0.967
2020	0.862	0.916	0.966	0.919	0.796	0.963

Source: Kim 2003

Appendix C - Use Phase Energy Calculation Drivers

(site energy only, before allowance for efficiency of water heater and clothes)

	EF	MEF	Kwh/ Cycle	% Site Energy Allocation: Water Heating	Agitation	Dryer	Capacity (cu.ft.)	Cycles/ Year	Annual Capacity (cu.ft.)
1980		0.83	3.53	51.1%	6.9%	41.9%	2.93	408	1195.6
1981	0.97		4.49	50.9%	6.9%	42.2%	2.52	474	1195.6
1982	0.98		4.49	50.7%	6.9%	42.5%	2.53	473	1195.6
1983	0.99		4.48	50.4%	6.9%	42.7%	2.54	471	1195.6
1984	0.99		4.44	50.2%	6.8%	43.0%	2.51	476	1195.6
1985	0.97		4.57	50.0%	6.8%	43.2%	2.52	474	1195.6
1986	0.97		4.63	49.8%	6.8%	43.5%	2.54	471	1195.6
1987	0.96		4.79	49.6%	6.7%	43.7%	2.59	462	1195.6
1988	0.95		4.90	49.3%	6.7%	44.0%	2.61	458	1195.6
1989	0.98		4.79	49.1%	6.7%	44.2%	2.62	456	1195.6
1990	0.99		4.78	48.9%	6.6%	44.5%	2.63	455	1195.6
1991	1.01		4.87	48.7%	6.6%	44.7%	2.72	440	1195.6
1992	1.02		4.83	48.4%	6.6%	45.0%	2.71	441	1195.6
1993	1.00		4.95	48.2%	6.6%	45.2%	2.71	441	1195.6
1994	1.21		4.08	48.0%	6.5%	45.5%	2.69	444	1195.6
1995	1.23		4.08	47.8%	6.5%	45.7%	2.72	440	1195.6
1996	1.26		4.11	47.5%	6.5%	46.0%	2.80	427	1195.6
1997	1.34		3.93	47.3%	6.4%	46.2%	2.83	422	1195.6
1998	1.41		3.78	47.1%	6.4%	46.5%	2.85	420	1195.6
1999	1.47		3.69	46.9%	6.4%	46.7%	2.89	414	1195.6
2000	1.47		3.75	46.7%	6.3%	47.0%	2.92	409	1195.6
2001	1.55		3.62	46.4%	6.3%	47.3%	2.96	404	1195.6
2002	1.64		3.44	46.2%	6.3%	47.5%	2.96	404	1195.6
2003	1.83		3.15	46.0%	6.2%	47.8%	3.01	397	1195.6
2004		1.35	2.26	45.8%	6.2%	48.0%	3.05	392	1195.6
2005		1.37	2.23	45.3%	6.2%	48.5%	3.06	391	1195.6
2006(1)		2.01	1.64	23.9%	3.2%	72.9%	3.30	362	1195.6
2007		2.13	1.55	23.9%	3.2%	72.9%	3.31	362	1195.6
2008		2.20	1.50	23.9%	3.2%	72.9%	3.31	361	1195.6
2009		2.23	1.49	23.9%	3.2%	72.9%	3.32	361	1195.6
2010		2.31	1.44	23.9%	3.2%	72.9%	3.32	360	1195.6
2011		2.39	1.39	23.9%	3.2%	72.9%	3.33	360	1195.6
2012		2.47	1.35	23.9%	3.2%	72.9%	3.33	359	1195.6
2013		2.56	1.30	23.9%	3.2%	72.9%	3.34	359	1195.6
2014		2.65	1.26	23.9%	3.2%	72.9%	3.34	358	1195.6
2015		2.75	1.22	23.9%	3.2%	72.9%	3.35	357	1195.6
2016		2.84	1.18	23.9%	3.2%	72.9%	3.35	357	1195.6
2017		2.94	1.14	23.9%	3.2%	72.9%	3.36	356	1195.6
2018		3.05	1.10	23.9%	3.2%	72.9%	3.36	356	1195.6
2019		3.15	1.07	23.9%	3.2%	72.9%	3.37	355	1195.6
2020		3.27	1.03	23.9%	3.2%	72.9%	3.37	355	1195.6

(1) Switch to Horizontal-Axis Washer

Source: Whirpool Corporation 2005, Association of Home Appliance Manufacturers 2005

Appendix D - Other Impacts Data

Energy (Impacts per kWh, cubic foot of gas)

	Emissions ($Kg\ CO_2$)	Energy (MJ)	Water (Gallons)
Grid Electricity (per kWh)(1)	0.721	12.400	
Natural Gas (per cubic foot)(1)	0.063	1.250	

Scrap Processing and Landfilling

	Emissions	Energy	Water
Shredding(2)		0.009	
Landfilling(3)	0.004	0.069	

Water (Impacts per Gallon Used)

	Emissions	Energy	Water
Produced Potable Water(4)	0.001	0.017	
Waste Water Treatment(4)	0.001	0.015	

Transport (Impacts per Pound/Mile)

	Emissions	Energy	Water
Diesel Truck(1)	0.109	1.490	
Diesel Rail(1)	0.028	0.381	
Diesel Boat(1)	0.024	0.327	

(1) Source: Franklin Associates 2006
(2) Source: Kim et al. 2003
(3) Source: Ecobalance and National Polution Prevention Center 1997
(4) Source EPRI 2004

Appendix E
Water Use Calculation Drivers

Model Year	Gallons/ Cycle	Average Capacity (cu.ft.)	Cycles/ Year	Capacity Water (gallons)	WCF
1980	36.7	2.93	408	14,981	12.5
1981	31.5	2.52	474	14,954	12.5
1982	31.6	2.53	473	14,928	12.5
1983	31.7	2.54	471	14,902	12.5
1984	31.2	2.51	476	14,875	12.4
1985	31.3	2.52	474	14,849	12.4
1986	31.5	2.54	471	14,822	12.4
1987	32.1	2.59	462	14,796	12.4
1988	32.2	2.61	458	14,770	12.4
1989	32.3	2.62	456	14,743	12.3
1990	32.4	2.63	455	14,717	12.3
1991	33.4	2.72	440	14,690	12.3
1992	33.2	2.71	441	14,664	12.3
1993	33.2	2.71	441	14,638	12.2
1994	32.9	2.69	444	14,611	12.2
1995	33.2	2.72	440	14,585	12.2
1996	34.1	2.80	427	14,558	12.2
1997	34.4	2.83	422	14,532	12.2
1998	34.6	2.85	420	14,506	12.1
1999	35.0	2.89	414	14,479	12.1
2000	35.3	2.92	409	14,453	12.1
2001	35.7	2.96	404	14,426	12.1
2002	35.7	2.96	404	14,400	12.0
2003	36.2	3.01	397	14,374	12.0
2004	36.6	3.05	392	14,347	12.0
2005	36.7	3.06	391	14,347	12.0
2006(1)	14.5	3.30	362	5,261	4.4
2007	14.5	3.31	362	5,261	4.4
2008	14.6	3.31	361	5,261	4.4
2009	14.6	3.32	361	5,261	4.4
2010	14.6	3.32	360	5,261	4.4
2011	14.6	3.33	360	5,261	4.4
2012	14.7	3.33	359	5,261	4.4
2013	14.7	3.34	359	5,261	4.4
2014	14.7	3.34	358	5,261	4.4
2015	14.7	3.35	357	5,261	4.4
2016	14.7	3.35	357	5,261	4.4
2017	14.8	3.36	356	5,261	4.4
2018	14.8	3.36	356	5,261	4.4
2019	14.8	3.37	355	5,261	4.4
2020	14.8	3.37	355	5,261	4.4

(1) Switch to Horizontal-Axis Washer

Source: Whirlpool 2005, EPA 2005

Appendix F
Calculation of Distance to US Distribution

Metropolitan Area	Population (millions)	Weight	Distance to Clyde (miles)	Distance to NJ Port (miles)
New York	22.0	18.2%	523	15
Los Angeles	16.4	13.6%	2,337	2,822
Chicago	9.2	7.6%	274	782
Washington	7.6	6.3%	436	218
San Francisco	7.0	5.8%	2,434	2,896
Philadelphia	6.2	5.1%	514	86
Boston	5.8	4.8%	724	231
Detroit	5.5	4.6%	100	607
Dallas	5.2	4.3%	1,152	1,608
Houston	4.7	3.9%	1,331	1,628
Atlanta	4.1	3.4%	679	872
Miami	3.9	3.2%	1,307	1,280
Seattle	3.6	3.0%	2,403	2,910
Phoenix	3.3	2.7%	2,172	2,487
Minneapolis	3.0	2.5%	691	1,199
Cleveland	2.9	2.4%	79	455
San Diego	2.8	2.3%	2,405	2,833
St. Louis	2.6	2.2%	552	962
Denver	2.6	2.2%	1,264	1,819
Tampa	2.4	2.0%	1,139	1,154
	120.8			
Clyde Average	**1,102**			
NJ Port	**1,217**			

Source: US Census Bureau 2000

Appendix G Transport Assumptions

(miles)	
Gary, IN to Clyde (diesel truck)	247
Clyde to Average US Dist. (diesel rail)	0
Clyde to Average US Dist. (diesel truck, see Appendix D)	1,102
Distribution to home (diesel truck)	50
Germany to US Port (diesel boat)	4,000
NJ Port to US Dist. (diesel truck, see Appendix D)	1,217
Consumer to White Goods Recycler (diesel truck)(1)	50
Consumer/Recycler to Landfill (diesel truck)(1)	50

(1) source: Arbitman et al. 2005

Appendix H

Purchase Prices

Year	2006$
1985	$911
1986	$884
1987	$857
1988	$832
1989	$807
1990	$782
1991	$759
1992	$736
1993	$714
1994	$692
1995	$672
1996	$651
1997	$632
1998	$613
1999	$594
2000	$576
2001	$582
2002	$565
2003	$548
2004	$531
2005	$516
2006(1)	$1,000
2007	$970
2008	$941
2009	$912
2010	$885
2011	$858
2012	$833
2013	$808
2014	$783
2015	$760
2016	$737
2017	$715
2018	$693
2019	$672
2020	$652

(1) Horizontal-Axis

source: Consumer Reports 2000-2006

Appendix I - Use Cost Drivers

Year	EIA Gas 2004$/cu.ft.	Gas Inflation 2006$/cu.ft.	EIA Electric 2004$/kWh	Electric Inflation 2006$/kWh	Inflation Adjuster
1980	$0.0031	$0.0033	$0.0941	$0.1001	94.1%
1981	$0.0036	$0.0038	$0.1007	$0.1070	94.1%
1982	$0.0042	$0.0044	$0.1051	$0.1117	94.1%
1983	$0.0042	$0.0045	$0.1048	$0.1114	94.1%
1984	$0.0042	$0.0044	$0.1000	$0.1063	94.1%
1985	$0.0038	$0.0041	$0.1000	$0.1063	94.1%
1986	$0.0029	$0.0031	$0.0978	$0.1040	94.1%
1987	$0.0024	$0.0026	$0.0942	$0.1001	94.1%
1988	$0.0024	$0.0025	$0.0908	$0.0965	94.1%
1989	$0.0023	$0.0024	$0.0889	$0.0945	94.1%
1990	$0.0022	$0.0024	$0.0871	$0.0926	94.1%
1991	$0.0021	$0.0022	$0.0865	$0.0919	94.1%
1992	$0.0021	$0.0023	$0.0854	$0.0908	94.1%
1993	$0.0025	$0.0026	$0.0849	$0.0902	94.1%
1994	$0.0022	$0.0023	$0.0829	$0.0881	94.1%
1995	$0.0018	$0.0019	$0.0810	$0.0861	94.1%
1996	$0.0025	$0.0026	$0.0791	$0.0841	94.1%
1997	$0.0026	$0.0028	$0.0777	$0.0826	94.1%
1998	$0.0022	$0.0023	$0.0756	$0.0804	94.1%
1999	$0.0024	$0.0025	$0.0734	$0.0780	94.1%
2000	$0.0039	$0.0042	$0.0737	$0.0783	94.1%
2001	$0.0042	$0.0044	$0.0774	$0.0822	94.1%
2002	$0.0030	$0.0032	$0.0750	$0.0797	94.1%
2003	$0.0049	$0.0052	$0.0758	$0.0805	94.1%
2004	$0.0054	$0.0057	$0.0757	$0.0804	94.1%
2005	$0.0075	$0.0080	$0.0834	$0.0886	94.1%
2006	$0.0067	$0.0072	$0.0821	$0.0873	94.1%
2007	$0.0060	$0.0064	$0.0782	$0.0831	94.1%
2008	$0.0057	$0.0060	$0.0755	$0.0803	94.1%
2009	$0.0053	$0.0056	$0.0742	$0.0789	94.1%
2010	$0.0049	$0.0052	$0.0731	$0.0777	94.1%
2011	$0.0047	$0.0050	$0.0718	$0.0764	94.1%
2012	$0.0046	$0.0049	$0.0714	$0.0759	94.1%
2013	$0.0047	$0.0050	$0.0721	$0.0767	94.1%
2014	$0.0046	$0.0049	$0.0719	$0.0764	94.1%
2015	$0.0044	$0.0047	$0.0712	$0.0757	94.1%
2016	$0.0044	$0.0047	$0.0713	$0.0757	94.1%
2017	$0.0044	$0.0047	$0.0714	$0.0759	94.1%
2018	$0.0046	$0.0049	$0.0718	$0.0764	94.1%
2019	$0.0048	$0.0051	$0.0725	$0.0771	94.1%
2020	$0.0048	$0.0051	$0.0724	$0.0770	94.1%
2021	$0.0049	$0.0053	$0.0729	$0.0775	94.1%
2022	$0.0050	$0.0053	$0.0731	$0.0777	94.1%
2023	$0.0051	$0.0054	$0.0730	$0.0776	94.1%
2024	$0.0052	$0.0055	$0.0734	$0.0780	94.1%
2025	$0.0053	$0.0057	$0.0740	$0.0787	94.1%
2026	$0.0054	$0.0058	$0.0740	$0.0787	94.1%
2027	$0.0055	$0.0059	$0.0742	$0.0789	94.1%
2028	$0.0056	$0.0059	$0.0742	$0.0789	94.1%
2029	$0.0057	$0.0060	$0.0743	$0.0790	94.1%
2030	$0.0058	$0.0062	$0.0751	$0.0798	94.1%

Source: EIA 2006, Bureau of Labor Statistics 2006