Life Cycle Comparison of Manual and Machine Dishwashing in Households

By

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Abstract

Machine dishwashers are a unique consumer appliance since they are often substituted with manual dishwashing. Although some studies indicate machine dishwashers use less energy and water than manual dishwashing, their scopes are limited to the use phase. Our study evaluates the full life cycle burdens for both manual and machine dishwashing following typical and recommended behaviors. Use phase behaviors are observed through a laboratory study and survey, while burdens are calculated using a life cycle assessment framework. We find that typical manual dishwashing behaviors result in the greatest greenhouse gas emissions (GHG). Even when recommended behaviors for machine dishwashers are not followed, they outperform typical manual dishwashing. Although manufacturers do not include typical behaviors like pre-rinsing when estimating their value-chain emissions profile, these activities can increase lifetime GHG emissions by 17%. The sustainability of the average American household can be significantly enhanced by following recommended machine dishwashing instead of typical manual dishwashing, thereby reducing GHG emissions by 72%.

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Table of Contents

List of Figures

List of Tables

INTRODUCTION

In 2013, the U.S Energy Information Administration (EIA) reported that 17.7% of energy consumed in the average American household is used for water heating with appliances, electronics, and lighting consuming 34.6%. The majority of residential electricity use is attributed to appliances, electronics, and lighting [1]. Common household appliances such as machine dishwashers and clothes washing machines require both energy and heated water to function. Appliances like clothes washing machines are hard to replace with manual alternatives. Machine dishwashers however, are unique because manual dishwashing behaviors can replace this appliance. The U.S. Department of Energy (DOE) estimates that a typical household washes 4 loads of dishes a week (215 annual loads) and the EIA reported that although dishwashers are owned by more than 80% of American households, 20% of those households use this appliance less than once a week [2, 3]. These findings suggest that machine dishwashers are underutilized appliances with dishes often being washed manually.

Both methods of washing dishes are assumed to achieve an adequate level of cleaning performance, but as noted in previous studies, there are potential time, energy, and water savings that result from using a machine dishwasher instead of manually dishwashing [4-6]. An ENERGY STAR Market Penetration Report indicated that 84% of dishwashers shipped in 2015 achieved ENERGY STAR standards [7]. The current ENERGY STAR Recognition criteria for standard sized dishwashers are less than 240 kWh of energy use per year and less than 3.2 gallons of water use per cycle [8]. Although energy and water savings are improving according to DOE and ENERGY STAR standards, users may not be utilizing machine dishwashers as recommended by manufacturers. In previous studies, typical manual dishwashing was compared to standard testing procedures for dishwashing machines; this is not an equivalent comparison. [4-6]. Therefore, results for machine dishwashers may not have been representative because typical user behaviors with the machines were not considered. Further, these European studies limited the system boundaries of their comparisons to only the use phase. Burdens associated with different types of machine dishwashers throughout their life cycles, from material production to disposal, were not included.

Here, we assess life cycle burdens associated with both typical and recommended best practices for machine use and manual dishwashing in American households. Scenario analyses showing the impacts of varying electricity grid, water heater type, method of manual dishwashing, and machine cycle selection are also included.

Literature Review

Energy and Water Use in Residential Buildings

Chini et al. quantified water, energy, and electricity demands in the average single-family US household, pointed out that appliances and fixtures directly and indirectly use these resources through the energy-water nexus; in this nexus, energy is necessary for the production of water and vice versa. A four-occupant home residence uses 100 gallons per day and the average citizen uses 13,000 kWh of electricity and 720 cubic feet of natural gas annually [9].

Cost abatement curves indicate that ENERGY STAR machine dishwashers are economically inefficient. While they offer significant cumulative annual savings in terms of energy (kWh/year) and water (gal/year) they have larger energy ($/kWh) and water ($/gal) costs than other appliances. Machine dishwashers ranked third highest on energy cost abatement and highest in water cost abatement potentially owing to their lower water and energy use than other household appliances. [9] While the cost abatement analysis indicates that it is unfavorable to invest in a machine to maximize household resource savings it did not factor in the potential savings from displaced manual dishwashing.

A European study tracked water consumption associated with different activities performed at the residential kitchen sink and indicated that dishwashing was the most water-intensive activity, account for 58% of the daily average water use per capita [10]. Dishwashing included manual dishwashing, pre-rinsing activities prior to loading a machine dishwasher, machine dishwasher use, and cleaning of the sink (if it was associated with dishwashing). Pre-rinsing activities used 14-25% of water in households with a dishwashing machine. Households with fewer people consumed more water per person than larger households. As indicated by the 2010 U.S. Census, the average American household size is 2.58 people [11]. If European trends of smaller households being more water intensive than larger households holds true in the United States, smaller households may be a favorable use case for machine dishwashers.

Machine Dishwashers and Manual Dishwashing

The University of Bonn has produced several papers comparing resource use of different manual dishwashing behaviors and machine dishwashers. These studies involved observing participants manually wash a set of soiled dishes in a laboratory. European manual dishwashing behavior is characterized by three different motives: “super dishwashers” who focused most on cleaning results, “economizers” who cared most about using as few resources as possible, and “carefree washers” who had no regard for cleaning results or resource use [4]. A similar study characterized three different manual dishwashing methods in Europe: dishwashing under running tap water, dishwashing in a water bath, and a combination of both methods[6]. If more than 80% of dishwashing was associated with a behavior, then it was categorized into one of the three manual dishwashing methods. Running tap washers scrub and rinse dishes with little to no shutting off of the water. Water bath washers often plug a sink or use a plastic tub to soak and scrub dishes. Rinsing of dishes may also occur in a water bath or with minimal washing under the tap. Combination washers run the tap at some point in the process dishwashing. These studies highlight distinct methods of manual dishwashing but do not directly compare them. A subsequent study expanded the scope to global consumer behaviors and found that Americans had the highest energy use and tend to use the combination method of washing [5]. In these manual dishwashing studies, it was found that acceptable cleaning results are possible with both high and low amounts of energy and detergent but that half of participants did not achieve an acceptable cleaning result [4, 6]. Most of these studies concluded that the machine dishwasher is superior to manual dishwashing in terms of water and energy use as well as cleaning performance. **Appendix A** summarizes results of previous studies. Although these studies show that there are different manual dishwashing methods in Europe and differences in resource consumption, they only focus on the use phase. A full life cycle assessment of the machine dishwasher compared to manual dishwashing in American households has not been done.

In the observational studies performed at Bonn, machines were evaluated following the EN 50242 procedure for soiling and testing dishes [4, 6]. In the U.S., dishwashing machines are similarly evaluated in accordance with the Uniform Test Method for Measuring the Energy Consumption of Dishwashers set by the DOE [12]. These standards are designed to test the machine dishwasher as if the user follows the manufacturer's recommended procedure best practices for optimal cleaning performance. However, these standardized procedures do not capture variability in actual behaviors such as loading patterns, pre-rinsing, or running a dishwasher at less than its full capacity. In the earlier Bonn studies, participants were asked to manually wash dishes as they typically would at home. These typical manual dishwashing behaviors were compared to the standard recommended procedure for machine dishwashers; which does not make for an equivalent comparison. Recommended machine dishwasher use should be compared to recommended manual dishwashing. Similarly, typical manual dishwashing behaviors should be compared to typical machine dishwasher use, including pretreatment and loading behaviors.

Recommended and typical manual dishwashing were compared in a dissertation that indicated Best Practice Tips (BPT) for manual dishwashing outperformed Everyday Behavior (EDB) in terms of energy and water consumption [13]. The dissertation cited several online sources for creating best practice tips for manual dishwashing and these will be the foundation for recommended behaviors used in this analysis.

Energetic impact, energy for human work, of labor-saving devices such as machine dishwashers was quantified in a study that indicated manual dishwashing requires approximately 1.83 kcal/min while machine dishwashing requires about 1.31 kcal/min. This human energy (calorific energy) for machine dishwashing included energy needed to pre-rinse dishes, load them, remain seated during the cycle time, and unload the dishwasher [14]. Overall, less calorific energy is required for a person to simply load a dishwasher than manually wash dishes since loading requires slightly less calorific energy as well as takes less time. In this analysis, the time needed for manual dishwashing and loading a machine dishwasher will be also be compared.

Behaviors and Beliefs about Dishwashing

Homeowners do not use machine dishwashers as often as they manually wash dishes. Previous surveys have explored the motivations behind this decision, the biases that people have against one method of dishwashing over the other, as well as why people choose to engage in pretreatment behaviors when using a machine dishwasher. A study of UK machine dishwasher owners surveyed why they choose to manually wash dishes; 53% of respondents indicated that the item took up too much space and 52% said that the item was needed immediately [15]. The same survey found that those who did not own machine dishwashers stated their main reasons for this were that they do not mind manual dishwashing (59%) or that they did not feel they had enough dirty dishes (54%). In the same survey, subjects stated that environmental reasons (water and energy savings) for owning a machine dishwasher are secondary to time and cleanliness considerations; 66% responded that time saving was a reason for buying a machine dishwasher, 48% said it cleans better that manual dishwashing, and 29% believed it uses less water. Another European survey found that 83% of respondents consider water and energy are the most important considerations when purchasing a machine dishwasher [16]. This survey confirmed that in houses with machine dishwashers, the main reasons dishes are still manually washed is because the item takes up too much space in the dishwasher or is needed immediately.

Pretreatment of dishware entails soaking, rinsing, scraping, scrubbing, and washing dishes prior to loading them into a machine dishwasher. When asked about pretreatment behaviors 39% of respondents indicated they scrape off leftovers, 39% pre-rinse or soak items, 14% do not pretreat at all, and the remainder wash heavily soiled items manually. It was also found that pretreatment does not improve satisfaction with cleaning results. In a survey of 500 Americans, it was found that 75% of machine dishwasher owners pre-rinse their dishes, 63% of who said that their main reason for doing so was because food sticks to the dishes [17]. It is notable that 31% reported that they were taught to pre-rinse. These surveys indicate that time considerations are an important factor for machine dishwasher ownership, barriers exist to using the machine for all items, and beliefs persist around pretreatment being necessary for achieving satisfactory machine performance.

Aside from motivations behind choosing between machine and manual dishwashing, some surveys also asked people what their typical everyday behaviors around washing dishes are. A survey of 2599 Germans showed that households that own a machine dishwasher are more likely to use the running tap method when manually dishwashing than households without a machine dishwasher [18]. However, it is unclear if there is a causal connection or merely a correlation between the two behaviors. The same survey also found that more than half of respondents would choose a normal cycle, instead of other cycle options, for running their machine dishwasher. Pretreatment question responses showed that between 40% and 70% of respondents would wipe food off plates, cups and bowls while 18% to 41% perform no pretreatment.

While these surveys indicate established behaviors and some underlying motivators, they do not consider influencing or changing consumer behavior. Another study set out to determine whether or not Europeans were willing to adjust their cleaning behaviors based on the soil level of the dishes [19]. Test subjects were found to use similar amounts of time, water, and detergent regardless of the amount of soiling on the dish and that only their cleaning performance (measured using a European standard) was significantly different. This suggests that manual dishwashing is a behavior that is a habitual response and also a result of parental influence. Therefore, it may be challenging to alter consumer habits or optimize manual dishwashing to minimize resource consumption while achieving minimal acceptable cleaning performance.

Kitchen Sponges and Microbes

The primary function of dishwashing is to clean dishes. Two types of residues on dishware are usually considered: microbiological and chemical [20]. Microbiological residue measured as total surface bacteria counts (colony forming units of bacteria per area) are reduced most when dishes are washed with a machine dishwasher rather than by hand. Kitchens have a high potential to serve as “microbial incubators” [21]. Kitchens host more microbes than toilets mainly due to the presence of porous sponges, which are ideal habitats for microbes to thrive. Laboratory testing revealed that kitchen sponges contained microbial species that can infect humans regardless of regular sanitation techniques (boiling or microwaving) which can increase certain species counts. The study concludes that sponges can spread bacteria from dishes to kitchens surfaces to humans and recommend weekly replacement of them. A study of 1029 Swedish children found that manual dishwashing reduces their risk of allergic disease possibly because of increased microbial exposure [22]. These studies indicate that the manual dishwashing can bolster children's health by exposing them to some microbes but that the sponges needed for this activity may be supporting infectious microbes. Due to their frequent replacement, the use of sponges will be included when calculating life cycle burdens in this analysis.

Machine Dishwashers in the United States

Machine dishwasher manufacturers offer a variety of built-in features and varying aesthetics in their products. Dishwashers come in different sizes: standard (24" X 24" X 35"), compact (18" X 35" X 24"), and countertop (18" X 18" X 18"). There are portable versions, single drawer, in-sink, and under-sink dishwashers. The majority of dishwashers sold are standard sized [23]. Some machines offer built-in water softeners that help reduce mineral deposits and spots on glassware and the dishwasher. Surfactants in rinse-aids are intended to reduce these mineral deposits as well. Filters can be self-cleaning or require occasional manual cleaning. The trade-off between the two types of filters is generally noise level, since the self-cleaning filter is in fact a hard food disposer that requires a motor to grind food waste, while meshed filters are manually rinsed. A common feature in dishwashers is noise reduction, generally achieved through sound-dampening insulation and mastic materials. Operating sound levels can range from 38 decibels (dB) (with noise reduction) up to 60 dB (without noise reduction) [24]. For context, a normal conversation is 60 dB. Manufacturers also offer different drying processes such as condensation drying, heating elements, and fans. Condensation drying works by heating water to high temperatures at the end of a cycle and increasing the temperature of the dishes to be hotter than the tub of the dishwasher walls. Since the walls are cooler, droplets will condense on them rather than on the dishes [25]. Heating elements are electric coils that heat air in the dishwasher. Fans can be used in conjunction with heating elements to force air out of the dishwasher vents or they can be used alone to cycle room-temperature air throughout the dishwasher. Prices for machine dishwashers range from $300 to $2000 [25, 26]. Machine dishwashers also have different exterior finishes including stainless steel, painted front panels, and wood panels. There are two materials used for manufacturing machine dishwasher tubs: plastic and stainless steel. While plastic tub dishwashers are generally cheaper and more likely to absorb odors and stains since they are porous, they do not permit the same high temperatures as stainless steel for heating water and drying. Stainless steel interiors aid in the drying process as they retain heat longer than plastic interiors. Stainless steel tub dishwashers are seen as more high-end, durable products, and are more expensive.

In addition to all of these features and characteristics, machine dishwasher manufacturers generally offer similar cycle options that use varying amounts of water and energy. Common cycles include normal, express, and sensor cycles. The normal cycle is the default on most dishwashers and assumes a full load of 8 places settings with average food soil. Express wash cycles can have several other names (1 hour Wash, Quick Wash, etc.) and are meant to quickly wash a load, often in as little as an hour. Sensor cycles (Auto Wash, Smart Wash, etc.) utilize optical waster indicators (OWI) that adjust water usage to the amount of soil in the load being washed. OWIs are turbidity meters that work by shining light through a sample of water in the tub, with the fraction of light transmitted through the sample being dependent on the amount of soil in the wash water [27]. OWIs take measurements throughout the cycle to adjust operation. The machine dishwashers in this study have OWIs. In addition to these cycles, additional options such as high temperature washing or drying can be added to cycles, which will increase energy and water use.

METHODS

Whirlpool Corporation

This project is a joint effort between the Whirlpool Corporation and the University of Michigan's Center for Sustainable Systems. Whirlpool provided data, laboratory space, and industry insight throughout the project. Whirlpool's Findlay, Ohio facility manufactured the dishwashers modeled in this study.

Life Cycle Assessments (LCA)

Life cycle assessments commonly break the life of a product into four distinct phases: material production, manufacturing, use, and end-of-life. This assessment is a cradle-to-grave analysis that evaluates methods of dishwashing throughout these four phases by modelling them on GaBi, a common LCA software [28]. For this study, two general models are created on GaBi: one for manual dishwashing and one for machine dishwashers. The models incorporate data from available databases, literature review, and laboratory data. Each of these models is structured to allow for a sensitivity analysis of various parameters (type of water heater, electrical grid, end-of-life option, etc.)

Metrics Used to Quantify Impacts

We evaluate primary energy, greenhouse gas (GHG) emission, water consumption, and solid waste production metrics. Primary energy is a common metric used for measuring the raw energy from nature needed for a product or process and is reported here in megajoules (MJ). GHG production is characterized using EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1) and is reported in kg CO_2 equivalents (kg CO_2e) on a 100-year global warming potential basis based on the 2001 Intergovernmental Panel on Climate Change (IPCC) calculations [29]. Water consumption has three major components according to the Water Footprint Network: green, blue, and grey water [30]. In this analysis, blue water consumption will be the metric used as it is water from ground and surface sources that is incorporated into a product. Solid waste production captures the mass of input materials that is not converted into product or into other forms of waste (such as emissions) and is measured in kilograms (kg).

Selected Machine Dishwashers

The two machine dishwasher models analyzed in this study are the Kitchen Aid KDTM354 and Whirlpool WDF330. These were selected because they are representative of machine dishwashers that are most commonly purchased. **Table 1** summarizes the differences between the two machines. A key difference being compared in this study is that the Whirlpool model is a plastic tub machine whereas the Kitchen Aid model is a stainless steel tub machine. Hereafter, the WDF330 Whirlpool machine will be referred to as the plastic machine dishwasher and the KDTM354 Kitchen Aid model will be referred to as the stainless steel machine dishwasher.

Table 1-*Comparison of Selected Dishwasher Models*

	WDF330PAH (Whirlpool)	KDTM354ESS (Kitchen Aid)
Tub Material	Plastic	Stainless Steel
Filtration System	Filter Cup	Microfiltration System
Spray Arm	1 pressurized lower spray arm	3 spray nozzles on dynamic lower spray arm
Jets	Target Clean Jets	ProScrub Jets
Cycles	Normal, Heavy, Hour Wash	Normal, Light, Express, Rinse Only
Features	Heat Dry, Hi Temp	Heat Dry, Hi-Temp, ProScrub, Sani Rinse
Size	Standard	Standard
Weight (lb.)	67	104
MSRP ($)	479	1199

System Boundary

A system boundary is a common way of visualizing the scope of a product's life cycle and the processes that are (or are not) considered in an LCA. It is important to clearly define the system boundary and at what point a flow crosses this imaginary line, thereby no longer considered part of the system being analyzed**. Figures 1** and **2** illustrate the life cycle of machine dishwashers and manual dishwashing, with the system boundary indicated as a dashed line. A sink and a water heater are required for both machine dishwashers and manual dishwashing. Since these elements are common to both systems, the production and disposal of these elements is outside the system boundary. This reduces the scope of the life cycle of manual dishwashing to the use phase only. For the machine dishwasher, all phases of the life cycle (material production, manufacturing, use, and end-of-life) are included.

As shown in **Figure 1**, the life cycle for a machine dishwasher begins with material production. Materials are manufactured into parts of the dishwasher by suppliers and assembled at the Findlay factory. **Figure 1** also shows the waste produced in each phase. In general, this waste is sent to the landfill or water treatment plant and is included as a burden for the system. Recycled material generated during manufacturing is assumed to be used by other product systems and no credits for displacing virgin materials are given. Recycled materials produced at end-of-life are assumed to leave the system boundary and continue to other product systems and are addressed in a similar manner. Burdens associated with recycling processes undertaken to turn these materials into useable form (shredding) are included in the system boundary.

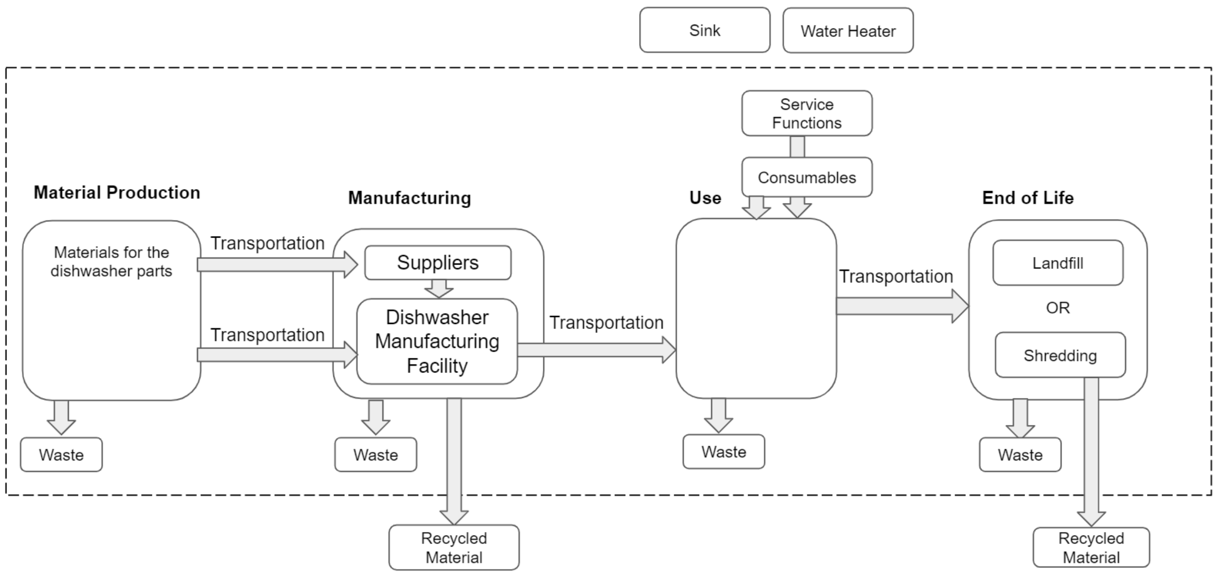

Figure 1-*Life Cycle of a Machine Dishwasher*

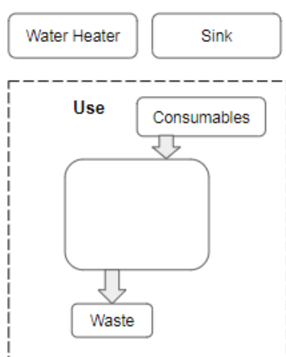

Figure 2-*Life Cycle for Manual Dishwashing*

Figure 1 and **Figure 2** show similar use phases. In both systems, a constant supply of consumables such as detergent and sponges are necessary for dishwashing. Machine dishwashers also need service functions including occasional cleaning cycles and replacement of aged parts during their lifetime. Commonly replaced parts include rack adjusters, spray arm hubs, and inlet valves. These are assumed to be replaced once during the lifetime of the product. In both systems, scenarios for use-phase behaviors are evaluated to compare how they result in different outcomes.

Functional Unit

The lifetime of a dishwasher is approximately 10-13 years [31, 32]. A standard size residential dishwasher holds the equivalent of 8 place settings where each place setting is a cup, saucer, plate, small plate, bowl, glass, and accompanying cutlery. Energy Guide labels assume four wash loads a week (208 annual uses) while the DOE testing procedures assume 215 annual uses [2, 12]. The functional unit in our study is washing a full load of soiled dishes (8 place settings) 215 times a year for a lifetime of 10 years. One fully-loaded dishwasher running 2150 cycles throughout its life is the basis of comparison to manually washing the same amount of dishes. This functional unit assumes cleaning performance equivalency between machine dishwashers and manual dishwashing, an assumption validated by our findings. (See results section **Figure 16** for details.)

Material Production and Manufacturing Phases

Life Cycle Inventory

Whirlpool Corporation provided the Bill of Materials (BOMs) for the two machine dishwashers analyzed here. The BOM lists the name, description, and quantity of parts needed to manufacture the machine dishwasher. BOMs are structured as assemblies of parts that create major features of the machine dishwasher such as the dish rack, tub, mainline, door, and packaging. Parts go into subassemblies which go into bigger subassemblies that go into the final product. Material production burdens can be estimated if the masses of different material types within a machine dishwasher are known. The smallest part of the assembly is the basis for modelling; the stainless steel machine dishwasher has approximately 464 parts and the plastic tub machine dishwasher has 330. While the masses of all these parts are not directly available from the BOM, their volume and type of material are listed. While some parts are classified as a single material, others are an aggregate of different components. For example, mastic (a dampening material) is a single material whereas a motor pole contains a plastic housing unit as well as metal components. Using the type of material described in the BOM, and material densities from documentation or literature review, the total mass for each part is calculated using

Equation 1. Parts are sorted by type of material and totaled. The aggregate mass of all the parts in the machine dishwashers are checked with the gross machine masses provided by Whirlpool.

$$Mass_{part} = (quantity)(density)(volume) \qquad \textit{Equation 1}$$

Each part listed in the BOM is itself a finished product that is the result of a manufacturing a process on a raw material. For example, a dish rack adjuster is polypropylene plastic that has undergone the process of injection molding. The processes to create each part were assumed and parts were grouped by material type and process in order to be input into the GaBi model. As described earlier, parts like the motor pole were divided into different material types and appropriate processes were modelled.

BOMs provide the mass of the finished product but not the mass of raw materials needed to make each part, so they provide no insight into manufacturing scrap rates. Manufacturing processes in GaBi databases based on industry averages are available that model the inputs and outputs needed to create one unit of product. GaBi processes can be scaled according to the unit of product produced. A manufacturing process such as injection molding tracks the required amounts of raw materials (plastic resin) and auxiliary materials (electricity, transportation, natural gas, etc.) to produce one kilogram of injection molded part. Auxiliary inputs are those that are necessary for the process to happen but do not become part of the final product. Outputs such as wastes, emissions, and byproducts are tracked by GaBi as well.

Only by using calculated masses for each part and manufacturing processes available in GaBi databases can the amount of raw material needed to make a machine dishwasher be determined. This process-level approach also captures manufacturing burdens by suppliers and the Whirlpool machine dishwasher factory. Manufacturing done by suppliers is modelled using these calculated masses and GaBi processes. Manufacturing at the Whirlpool factory can be modelled using this process-level approach or alternatively with factory-level data.

Process-level approach

Machine dishwashers are produced at a Whirlpool manufacturing factory in Findlay, Ohio. This plant produces only machine dishwashers and incorporates renewable energy into its operations by sourcing from a nearby wind farm. Approximately 22% of the annual energy requirement needed by the plant is attributed to wind turbines [33]. Gabi modelling accounted for electricity generation from renewables as well as from the Ohio electrical grid. The Findlay plant employs 2,200 workers over an area of 1,086,400 square feet. Different manufacturing processes are involved for making plastic and stainless steel machine dishwashers. Proprietary process diagrams describing the distinct series of steps are used as an outline for modelling the manufacturing phase. A tour of the plant informed the types of machinery, what materials undergo which specific processes, and additional details about manufacturing steps. Annual water use for non-manufacturing purposes at the plant was estimated from the Green Globes Water Calculator for nonresidential buildings and resulted in 19,500,000 gallons of annual water use in the facility [34]. See **Appendix B** for details. Modelling the Findlay factory was possible using the inventory of parts from the BOMs and knowledge about processes for their production. **Appendix C** lists the processes and data sources for modelling machine dishwasher manufacturing at Findlay.

Facility-Level (Black Box) Approach

Manufacturing at the Findlay plant can also be modelled using a facility-level approach, quantifying only inflows and outflow from the plant as a whole. Whirlpool provided input and output data for the Findlay plant in 2017 [35]. This summary describes volumetric outputs of different classifications of waste including nonhazardous wastes, hazardous wastes, and wastewater. The summary also quantifies inputs for the plant including water, renewable energy, electric power, natural gas, etc. Whirlpool also provided machine dishwasher production volumes for 2017. Findlay produced 1.84 million plastic and 1.71 million stainless steel machine dishwashers in 2017 [36]. All plastic machine dishwashers produced at Findlay are modelled as the Whirlpool WDF330 model and all stainless steel machine dishwashers are modelled as the Kitchen Aid KDTM354 model. Facility-level modelling is also known as top-down modelling because only high-level information is known about the facility. In our facility-level analysis, the Findlay plant can be referred to as a "black box" model because only input and output information is provided without any more details about how these inputs are being used within the plant.

Differences in the Process and Facility-Level Approaches

The process-level approach using GaBi databases allows determination of raw material amounts necessary for producing machine dishwashers while the facility-level approach is an exact representation of inputs and outputs occurring at Findlay. Although the facility-level approach is an exact annual representation of flows, burdens cannot be allocated to a specific process or between different types of machine dishwasher production as with the process-level approach.

These two approaches can be used together to see how accurately GaBi databases model actual production processes at Findlay. Three main resources are highlighted in this comparison between the process and facility-level approach: water, electricity, and natural gas. The process-level approach allows determination of specific amounts of a resource necessary for discrete processes. These are totaled to find resource requirements for the process-level approach. These resource requirements can be scaled from production of one machine dishwasher to the annual production of machine dishwashers. On the other hand, the facility-level approach only has the total amount of a resource needed by Findlay for the entire year to produce a certain number of dishwashers. This approach does not permit us to allocate the total resource use to individual processes. A rough estimate of how much of a resource is needed per machine can be calculated by dividing the total amount of resource use by the total number of dishwashers. This estimate is crude since it does not reflect what processes are actually requiring this resource.

The process-level approach is used to model discrete manufacturing steps. The amount of resources required by these steps are totaled. For both the plastic and stainless steel models, these totals are scaled to annual production volumes. The stainless steel and plastic resource requirements are summed. The summed total for the process-level approach is compared to the facility-level total for the same resource. The total differences between the two approaches are divided by the total number of annual dishwashers produced. No weighted average is calculated due to lack of knowledge about where this difference should be allocated.

This comparison is done in order to validate the model and ensure that there is a comprehensive characterization of the manufacturing phase. The process-level approach is a bottom-up approach that is incomplete and relies on industry databases. However, it is necessary to determine raw materials needed for machine dishwasher production. The top-down facility-level approach is a complete representation of process material flows but makes allocating burdens between the two types of machine dishwashers difficult.

Use Phase

Laboratory Study

Observational laboratory assessments were conducted as part of this study, which was designed to compare use of machine dishwashers to manual dishwashing across recommended and typical behaviors, similar to studies conducted at the University of Bonn [4-6]. Testing of machine dishwashers already has standardized procedure and this is the basis from which to evaluate manual dishwashing.

We explicitly make a distinction between recommended (ideal, best practices) and typical (realistic, everyday) behaviors for both machine dishwasher use and manual dishwashing. This results in four scenarios: best practices for machine dishwasher use, best practices for manual dishwashing, typical machine dishwasher use, and typical manual dishwashing. In the case of the machine dishwasher, the recommended behaviors are those set out in the DOE standard procedure and suggested by the manufacturer, while typical behaviors capture specific loading and pretreatment behaviors. In the case of manual dishwashing, typical behaviors are observed and categorized into one of the three different categories described in research (running tap, water bath, combination) while recommended behaviors are guided by literature [6, 13].

DOE Testing Procedures for Machine Dishwashers

Machine dishwasher manufacturers must comply with the Department of Energy (DOE) provisions for consumer products, which are outlined in the electronic Code of Federal Regulations (eCFR) [12]. Dishwashers are normally tested following the Uniform

Test Method for Measuring the Energy Consumption of Dishwashers (Appendix C1 to Subpart B of Part 430 of the eCFR). The method indicates specific test conditions, instrumentation, procedure for testing cycles with differently soiled and sized loads, as well as an evaluation method for measuring machine dishwasher energy and water use performance. Further, it specifies how different machine dishwashers should be tested depending on whether or not they are soil-sensing, water heating, and/or water softening. The code also distinguishes how calculations should be done in test facilities with natural gas or electric water heaters.

ANSI/AHAM DW-1-2010

Incorporated within the DOE testing procedure are the American National Standards Institute/Association of Home Appliance Manufacturers (ANSI/AHAM) standards for a test load (described in **Table 2**). These standards are meant to create uniform and repeatable procedures for dish soiling. The typical test load includes plates, cups, bowls, platters, glasses, and flatware that are soiled according to ANSI/AHAM DW-1-2010 standards. The standards describe different levels of soil ranging from light to heavy soil. Soil consists of varying food types including eggs, mashed potatoes, coffee, tomato juice, and raspberry preserves. These are all prepared following a specified procedure using a specific brand and are spread in defined amounts on a portion of a dish's surface. A normally soiled plate, for example, could have ¼ of its surface covered with 1 tablespoon of mashed potatoes. Furthermore, these soils are applied to test loads two hours before they are washed; this allows for soils to dry onto dishes.

For the purposes of this laboratory study, a few modifications were made to the soiling and selection of dishes to be washed. In addition to the standard soils and plates, Whirlpool has developed other soils and dishes in response to user concerns. A cheesy spaghetti dish and apple sauce on plastic bowls represent tougher soils. These soils are baked on instead of air dried as in the ANSI/AHAM standard. **Figure 3** shows the normally soiled 8 place setting load used in the laboratory testing, and the additional Whirlpool tougher soils items.

Figure 3-*Normally Soiled Load of Dishes*

Table 2-*Description of Normally Soiled Load of Dishes*

Amount	**Type of Dish**	**Soil**
8	Coffee Cups	Coffee
8	Saucers	Coffee
8	Glasses	Lipstick and tomato juice
8	Small Bowls	Oatmeal
8	Large Plates	¼ of plate covered with eggs, mashed potatoes, meat, or jam
8	Small Plates	
8	Knives	Peanut Butter
16	Forks and Spoons	Eggs or tomato
1	Medium Bowl	
1	Spatula	Baked Egg
2	Plastic Bowls	Applesauce baked for 10 minutes
1	Baking Dish	Cheesy Spaghetti baked for 10 minutes
2	Platters	Used to hold soiled cutlery
79	**Total**	

Cleaning Performance

Apart from soiling procedures, the ANSI/AHAM standards also describe evaluation of plates cleaned by machine dishwashers. After a cycle is completed, dishes are allowed to air dry before they are graded. Dishes in a load are classified into the following categories: dishware, glassware, and flatware. A laboratory technician inspects these in a room with a specified lamp illuminance, grading each item with score from 0 to 9 that reflects how clean it is. The lowest score (0) indicates a clean dish. For dishware and flatware, only particles are counted while for glassware, particles, spots, rack contact marks, and streaks are counted. Next the total number of items that received the same score are grouped (number of 1's, etc.) and the category cleaning index (CI) is calculated per **Equation 2**.

$$CI_{category} = 100 - \frac{[12.5\,(number\ \ of\ 1's) + 25(number\ \ of\ 2's + 3's)\ + 50(number\ of\ 4's + 5's + 6's) + 75(number\ of\ 7's + 8's) + 100(number\ \ of\ 9's)]}{total\ number\ of\ items\ in\ category}$$

Equation 2

Subsequently, a total cleaning index is calculated for the entire load using **Equation 3** below. The ANSI/AHAM standard recommends running a minimum of three tests and applying statistical methods in order to produce more reliable results. Three tests were run for each dishwasher and the average Total Cleaning Index are reported here.

$$Total\ Cleaning\ Index = \frac{CI_{Dishes}\,N_{Dishes} + CI_{Glasses}\,N_{Glasses} + CI_{Flatware}\,N_{Flatware}}{N_{Dishes} + N_{Glassware} + N_{Flatware}}$$ *Equation 3*

ENERGY STAR

Both machine dishwashers in our analysis are ENERGY STAR certified. ENERGY STAR released the most recent recognition criteria for dishwashers in 2017 [8]. To verify that a machine meets these requirements, energy and water performance is measured using the DOE uniform test procedure. To receive the ENERGY STAR Most Efficient product label, a machine dishwasher must also have a cleaning index greater than 70 for heavy, medium, and light cycles as determined by the AHAM/ANSI evaluation method embedded within the DOE uniform test procedure. **Table 3** compares DOE and ENERGY STAR standards for standard-size dishwashers.

Table 3-*Standards for Standard-Size Dishwashers*

	Energy	**Water**
	(kWh/year)	(gal/cycle)
DOE (2013)	307	5
ENERGY STAR (2017)	240	3.2

Recommended (Best Practices) for Machine Dishwashers

Manufacturers provide a manual describing how to use the machine for optimal performance. The manual includes a diagram that demonstrates optimal loading of the machine, as well as recommending using rinse aid, high-quality detergent packs, and periodic cleaning of the machine interior. A normal cycle with the heat dry option is the recommended cycle and is often the default setting on machines. The DOE Uniform Testing Procedures are performed using standard consumables and cycle selection. Therefore, recommended machine use for both the stainless steel and plastic machine dishwasher models can be evaluated as they normally would under the DOE testing procedures. These standardized procedures do not account for pre-rinsing with water; the ENERGY STAR website advises to avoid this behavior [37]. For both the plastic and stainless steel machine dishwashers, the normal and heavy/tough cycle is tested three times each. Water consumed (gallons), electric energy used (kWh), detergent used (grams), time taken (minutes), and cleaning score for the load are recorded for each test cycle.

Recommended (Best Practices) for Manual Dishwashing

Recommended manual dishwashing behaviors are sourced from existing literature. Best practices include soaking and scrubbing soiled dishes in a hot-water bath and rinsing dishes in a cold-water bath [13]. Air drying of dishes is recommended. In order to capture resource use by manual dishwashers who follow recommended behaviors, an in-house observational study was conducted by Whirlpool. Three participants were trained on best practices for manual dishwashing. Next, they were asked to wash the load of normally soiled dishes. A small summary page with a diagram of best practices for manual dishwashing was posted at the washing station to remind participants of the steps (**Appendix D**). Resource consumption and cleaning scores were evaluated. Participants also answered subsequent survey questions.

Typical Machine Dishwasher Loading, Typical Manual Dishwashing, & Survey Questions

Machine dishwashers may not be optimally loaded as recommended by manufacturers. The only pretreatment recommended in the manual is scraping leftover food off dishes without pre-rinsing [38]. However, some still choose to pretreat by rinsing or soaking their dishes before loading. Manual dishwashing behaviors can be categorized into running tap, water bath, and combination methods [5]. In order to observe typical behaviors, an observational laboratory study was conducted using forty participants recruited from within the Benton Harbor Whirlpool campus. The majority of participants were male, over the age of 35, and the majority lived in households with four people.

Further demographics for this group are summarized in **Appendix E**. In order to minimize bias, only employees who were not from the Sustainability or Dishwasher Teams were allowed to participate. These participants were asked to complete three different tasks: load a machine dishwasher, manually wash dishes, and answer survey questions. **Figure 4** shows the laboratory set-up. The testing room was intended to replicate a common kitchen sink area in the average household. The installation included a double sink and counter space. Before beginning the three tasks, participants were asked to set up the test station to resemble their kitchen sink at home as much as possible. An assortment of tools shown in **Figure 5** were offered to participants including dish racks, sponges, drying mats, towels, cleaning rags, scrubber brushes, gloves, and other items.

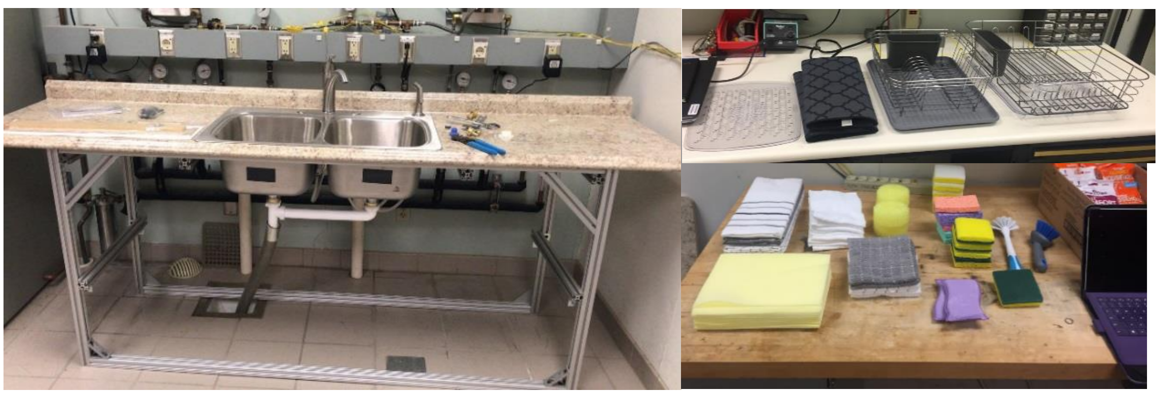

Figure 4-*Laboratory set-up*

For the first task, participants were asked to load the 8 place settings of normally soiled dishes into a machine dishwasher just as they typically would at home. Photos of the loaded machine were taken after each participant had completed the tasks. For the second task, participants were asked to manually wash a set of soiled dishes just as they typically would at home. Cleaning scores for manual dishwashing were calculated by the dishwashing team graders. Resource consumption (water volume consumed, soap consumed, water temperature, and time taken) was recorded for both the loading and manual dishwashing task. For manual dishwashing, observers characterized participants and their behaviors into the three broad categories (running tap, water bath, and combination) and noted their preferred method of drying. For the third task, participants were asked to answer survey questions related to their general dishwashing habits and the motivations behind them.

Energy Calculations

The system boundary for determining energy consumption during manual dishwashing only considers water heating. **Equation 4** is the general equation for energy consumed to heat water, where C is the specific heat capacity of water, V is the volume of water heated, ΔT is the temperature change, and e is the heater recovery efficiency. The eCFR assumes that the initial temperature of incoming water is 50˚F. Depending on the type of water heater used, energy to heat water can be calculated by using **Equation 5** for electric water heaters or **Equation 6** for natural gas water heaters. Heater recovery efficiency is the amount of energy that is used to heat a specified volume of water to a specified temperature over an hour-long period. The heater recovery efficiency of natural gas is assumed from the eCFR to be 75%. Similarly, the heater recovery efficiency for electric water heaters is assumed to be 100%. It should be noted that no efficiency in a natural system is ever 100% and that usually electric water heaters are said to be 99% efficient [39]. **Equation 5** uses a specific heat, C, of 0.0024 kWh/gal-˚F while **Equation 6** uses a specific heat of 8.2 BTU/gal-˚F and includes a conversion from kWh to BTU. As shown in **Equation 5**, the eCFR assumes 100% heater recovery efficiency for electric water efficiency. The St. Joseph Tech Center, where the laboratory experiments were conducted, has natural gas water heating.

$$Energy\ Consumption\ to\ heat\ water = (V)(\Delta T)\left(\frac{C}{e}\right) \qquad Equation\ 4$$

$$E_{Heat\ Electric} = (V)(\Delta T)\left(0.0024\frac{kWh}{gal-°F}\right) \qquad Equation\ 5$$

$$E_{Heat\ Natural\ Gas} = (V)(\Delta T)\left(\frac{\left(8.2\frac{BTU}{gal-°F}\right)}{.75}\right)\left(0.00029307\frac{kWh}{BTU}\right) \qquad Equation\ 6$$

In the eCFR, total energy measured for a machine dishwasher is the sum of energy to heat water, energy to run the machine in the wash cycle, energy to run the machine in the dry cycle, and energy to standby between uses. **Equation 8** shows energy to heat water used by the machine. The machine dishwashers in this study both use water that is heated to 120˚F. The water volume, V, input into the model depend on the cycle being run. Standby energy per cycle is calculated by **Equation 9.** Standby electric power, P, was provided for both dishwashers by Whirlpool; the stainless steel model uses 0.563W and the plastic model uses 0.316W. Standby time associated with running the machine dishwasher for only one cycle is calculated with **Equation 10** where X depends on the cycle duration. The eCFR assumes 215 annual washes. **Equation 11** shows the total energy use per load. The aggregate of energy to run and energy to dry is recorded by instrumentation in the laboratory experiments. Standby time energy and energy to heat water are calculated separately using data recorded during the experiment.

$$E_{Heat\ Machine} = (V)(120°\text{F} - 50°\text{F})\left(\frac{8.2\frac{BTU}{gal-°\text{F}}}{.075}\right)\left(0.00029307\frac{kWh}{BTU}\right) \qquad \textit{Equation 7}$$

$$E_{Standby} = (\ P\ kW)\left(\frac{Standby\ time}{load}\right)\left(\frac{hour}{60\ min}\right) \qquad \textit{Equation 8}$$

$$\frac{Standby\ time}{load} = \left(525600\frac{min}{year} - \left(X\frac{min}{cycle} * \ 215\frac{cycles}{year}\right)\right) * \left(\frac{1}{215\frac{cycles}{year}}\right) \qquad \textit{Equation 9}$$

$$E_{Total} = \ E_{Heat\ Machine} + E_{Standby} + E_{Run} \ + E_{Dry} \qquad \textit{Equation 10}$$

Laboratory Data to GaBi

Laboratory data was captured in GaBi by creating generic processes for manual dishwashing and machine dishwashing as shown in **Figure 5** and **Figure 6** respectively. Process boxes like water heating and electricity from the grid allow selection of appropriate inputs; for example, water can be heated using either electricity or natural gas. Electricity from region-specific grids (with varying carbon intensities and fuel mixes) as defined by eGRID, are available in the GaBi databases. Water inputs are assumed to be tap water from surface water sources. Soap for manual dishwashing and detergent used for machine dishwashers are modelled as tensides (alcohol ethoxy sulfates) which is a common class of detergent with high solubility and low sensitivity to water hardness. Cascade Phosphate Free Tabs (15.4 g) are used in the DOE testing procedures and is the detergent used in this model. Sponges (18.7 g) are modelled as flexible foam polyolether and are assumed to be disposed of monthly. Consumables like rinse aid, vinegar, and cleaning tablets that are recommended by the manufacturer are also included in the model. Rinse aid reduces surface tension of water allowing for better drying; it is modeled as ethylene oxide (3 g) which is assumed to be used with every cycle. A vinegar rinse is recommended for removing odor in the machine dishwasher. It is modeled as acetic acid and is assumed to be used once a year. Cleaning tabs (20 g) are recommended to be used once a month to remove hard water and filming stains. These tabs are modeled as citric acid.

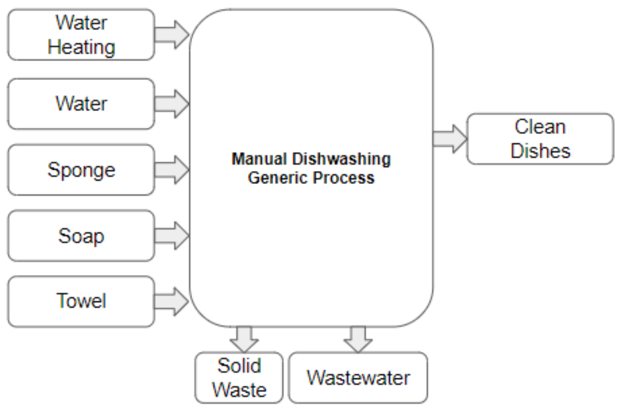

Figure 5-*Use Phase Generic Process Manual Dishwashing*

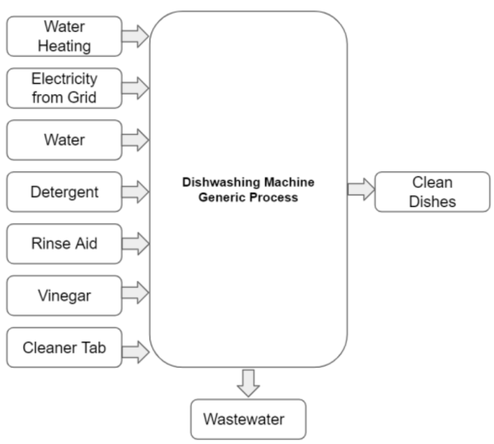

Figure 6-*Use Phase Generic Process Machine Dishwashing*

After developing this general framework, the processes can be parameterized. Inputs for water, temperature, and consumables can be adjusted to match the dishwashing machine cycle and options as well as the archetypes of manual dishwashers observed in the laboratory study.

Other Parameters

Towels (15” X 25” X 0.25”) are modelled with cotton fiber. Water and energy use associated with cleaning towels and disposing of them are accounted for by assuming the average volume (4.8 ft^3) and water (32 gallons) consumption of an ENERGY STAR clothes washer [40, 41]. Towels are assumed to weigh 0.174 pounds and be washed once a week and ENERGY STAR assumes 6 wash loads a week (or 312 cycles/year). This means that to wash a towel every week, it takes 0.229 additional gallons used in the clothes washing machine for every dish load as shown in **Equation 12**. A similar calculation for energy required to wash the towel results in a small additional amount of kWh to clean a towel for every dish load washed as shown in **Equation 13**. Drying of the dishtowels after washing is included as clothes dryers account for the majority of household energy use of standard household appliances [42]. It is assumed that an electric, standard volume (4.4 ft^3) clothes dryer has an average annual energy consumption (957 kWh/year) and use (416 cycles/year) [43]. **Equation 14** calculates the additional energy needed to dry a towel for every dish load washed.

$$\left(\frac{14\frac{gal}{cycle}}{4.8\,ft^3}\right)\left(\frac{0.0542\,ft^3}{towel}\right)\left(\frac{312\,cycles}{year}\right)\left(\frac{year}{215\,dish\,loads}\right)=\frac{0.229\,gal}{dish\,load-towel} \qquad \text{Equation 11}$$

$$\left(\frac{212\,kWh}{year}\right)\left(\frac{year}{312\,wash\,loads}\right)\left(\frac{wash\,load}{4.8\,ft^3}\right)\left(\frac{0.0542\,ft^3}{towel}\right)\left(\frac{1}{215\,dish\,load}\right)=\frac{3.57\,x\,10^{-5}\,kWh}{dish\,load-towel} \qquad \text{Equation 12}$$

$$\left(\frac{967\,kWh}{year}\right)\left(\frac{year}{416\,dryer\,loads}\right)\left(\frac{dryer\,load}{4.4\,ft^3}\right)\left(\frac{0.0542\,ft^3}{towel}\right)\left(\frac{1}{215\,dish\,load}\right)=\frac{1.33\,x\,10^{-4}\,kWh}{dish\,load-towel} \qquad \text{Equation 13}$$

End-of-life (EOL)

Owner’s manuals do not give recommendations for disposal of machine dishwashers. White goods like machine dishwashers are typically recycled but can also end up in a landfill. The end-of-life for a machine dishwasher depends on the availability and access to recycling facilities. Two recycling facilities in southeast Michigan were asked how they process dishwashing machines [44, 45]. Typically, the machines are shredded and then a magnetic separator is used to separate ferrous metals. Steel tub dishwashing machines are more profitable since they contain more metals that can be sold to material processors. Plastic, nonferrous metals, and other separated materials are sent to the landfill.

The following assumptions are made for recycling and landfilling. The appliance shredder is assumed to be have a 149 kW power rating and take 25 seconds to shred a dishwashing machine. [46] The magnetic current separator is assumed to require 16.2 kW of power and 60 seconds to process all the material through [47-49]. It is unclear if recycling centers or landfills would actually be closer to use-phase locations. Therefore, the same distance will be assumed for both as is commonly done [50, 51]. The default setting in GaBi for transport distances is 100 miles taken from EPA SmartWay fleet data. This distance will be assumed for distance from home to landfill, distance from home to recycling center, and distance from recycling center to landfill.

RESULTS

Material Production

Table 4 summarizes the amount and type of material found in the stainless steel and plastic machine dishwashers as calculated using the estimation technique described in the Methods section. Whirlpool reports the gross weight of a stainless steel machine as 47.2 kg (104 lb.), however **Table 4** totals 45.4 kg (100 lb.). ISO 14044 describes cut-off criteria for modelling by mass; typically, 95% of the total mass of a product is modelled while the rest can be excluded [52]. It should be noted that the excluded portions are not expected to have a significant environmental impact. For the stainless steel machine dishwasher, 96.2% of the total mass is captured in the estimation. The plastic machine dishwasher has a gross weight of 30.4 kg (67 lb.) and 95.7% of this total mass is captured in the model.

Table 4-*Material by Mass for Machine Dishwasher Models*

Stainless Steel Dishwasher			Plastic Dishwasher		
Material	**Mass (kg)**	**%**	**Material**	**Mass (kg)**	**%**
Plastics			**Plastics**		
PP	4.34	9.57%	PP	8.94	30.7%
LDPE Film	2.19	4.82%	LDPE	2.44	8.4%
PET	1.02	2.26%	PVC	0.89	3.0%
Nylon	0.70	1.55%	Nylon	0.43	1.5%
LDPE resin	0.67	1.47%	PET	0.32	1.1%
Polystyrene	0.51	1.13%	PP/EPDM	0.15	0.5%
POM	0.34	0.75%	POM	0.14	0.5%
EPDM/Rubber	0.48	1.06%	Polystyrene	0.13	0.4%
PP/EPDM	0.22	0.48%	PPO/PS	0.02	0.1%
PPO/PS	0.18	0.39%	PC	0.01	0.04%
PVC	0.12	0.26%	ABS	0.001	0.003%
HDPE	0.12	0.25%	E/VA	0.001	0.002%
ABS	0.05	0.12%	HDPE	0.0004	0.001%
TPU	0.04	0.08%	**Total**	13.45	46.2%
PC-ABS	0.03	0.07%			
PC	0.01	0.02%			
Vinyl	0.001	0.002%			
Total	11.01	24.26%			
Metal			**Metal**		
Stainless Steel	19.35	42.63%	Stainless Steel	10.33	35.5%
Galvanized Steel	4.34	9.57%	Galvanized Steel	2.01	6.9%
Zinc	0.22	0.49%	Aluminum	0.01	0.04%
Aluminum	0.17	0.36%	**Total**	12.35	42.4%
Copper	0.15	0.33%			
Total	24.23	53.39%			
Other			**Other**		
Mastic	6.96	15.33%	Cardboard	1.38	4.8%
Cardboard	1.43	3.14%	Wood	0.86	3.0%
Wood	0.86	1.89%	Wiring Harness	0.43	1.5%
Wiring Harness	0.43	0.94%	Rubber	0.31	1.1%
Pulp	0.25	0.54%	Pulp	0.20	0.7%
PCB	0.23	0.51%	PCB	0.12	0.4%
Total	10.14	22.35%	**Total**	3.30	11.3%
TOTAL	45.39	100.00%	**TOTAL**	29.10	100.0%

Process-level & Facility-level Approaches to Manufacturing

Figure 7 illustrates water use at the dishwasher manufacturing factory in Findlay, Ohio. This figure describes the water requirements for producing one machine dishwasher following the bottom-up process-level approach. Water required for processes like injection molding and painting are shown. Unaccounted water is the difference between the facility-level total and process-level approach water totals as described in the methods section. Similar figures for natural gas and electricity consumption for the Findlay facility are shown in **Appendix F**.

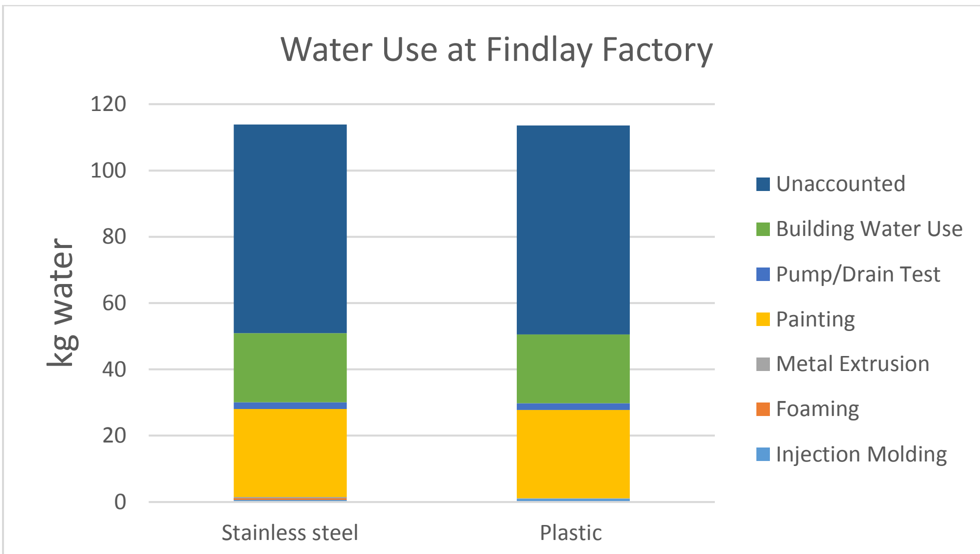

Figure 7-*Water Use at Findlay factory to produce one machine dishwasher following the process-level approach where unaccounted water is the difference between the facility-level and process-level approach total*

Differences in GHG emissions (in kg CO_2e) between the process-level approach and facility-level approach are shown in **Figure 8**. The facility-level approach divides burdens equally between the total number of machine dishwashers produced in a year. The process-level approach allocates burdens between the stainless steel and plastic machines by annual production volume. In this figure, the process-level approach excludes the correction term (unaccounted resources).

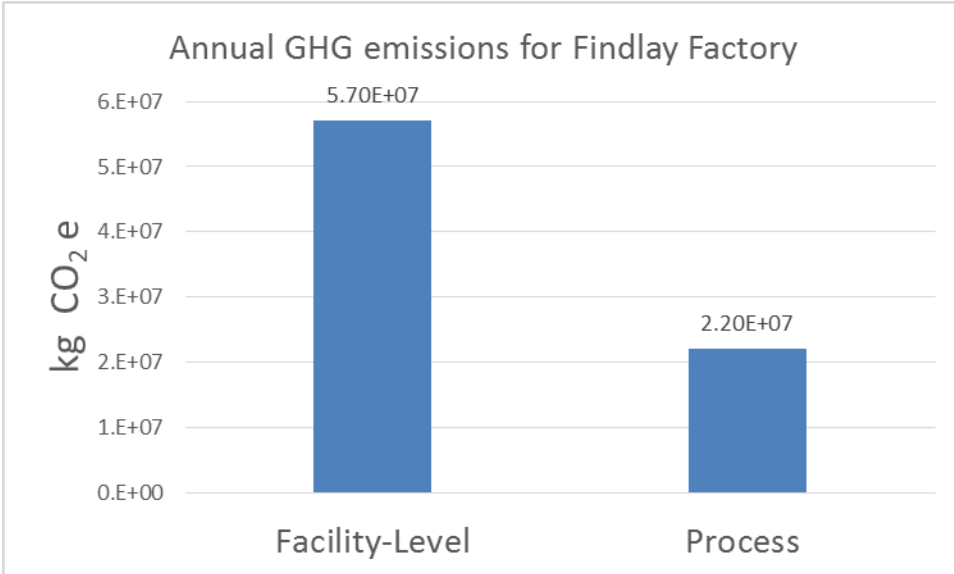

Figure 8-*Facility-level vs. process-level approach comparison where GHG emissions from manufacturing at the Findlay factory are shown.*

As shown in **Figure 7** and **Figures 26** and **27** in **Appendix F**, GaBi processes significantly underestimate water, electricity, and natural gas inputs needed for production-the unaccounted difference between the process-level approach and facility-level data is the largest portion of each bar graph. This may be due to the overhead that is not measured separately here. Comparison of the facility-level and process-level approaches to modelling the Findlay factory (**Figure 8**) demonstrate that GaBi process models may not fully represent the actual annual burdens associated with manufacturing. The annual kg CO_2e production for Findlay factory is only half the amount estimated by the facility-level approach. The significant portion of unaccounted resources on a per dishwasher basis translates to significant underestimation of annual burdens by the process-level approach. This happens because the raw material and auxiliary inputs for GaBi processes are based on industry averages. Since these inputs are fixed values, there is a mismatch between raw and auxiliary inputs demanded by the process-level approach and the auxiliary inputs listed in the facility-level data.

Cradle-To-Gate

The cradle-to-gate GHG (kg CO_2e) impacts for producing a machine dishwasher are shown in **Figure 9** which utilizes the process-level approach to modelling. (This includes a correction term that adds in the unaccounted differences for natural gas, water, and electricity.) Material production includes all materials needed for producing a machine dishwasher, excluding the printed wiring board. The printed wiring board is shown separately, as material production and manufacturing of this item cannot be separated on the GaBi database. Manufacturing includes processes performed by suppliers and at the Findlay factory. Replacement parts are produced by the manufacturer and included in this life cycle phase.

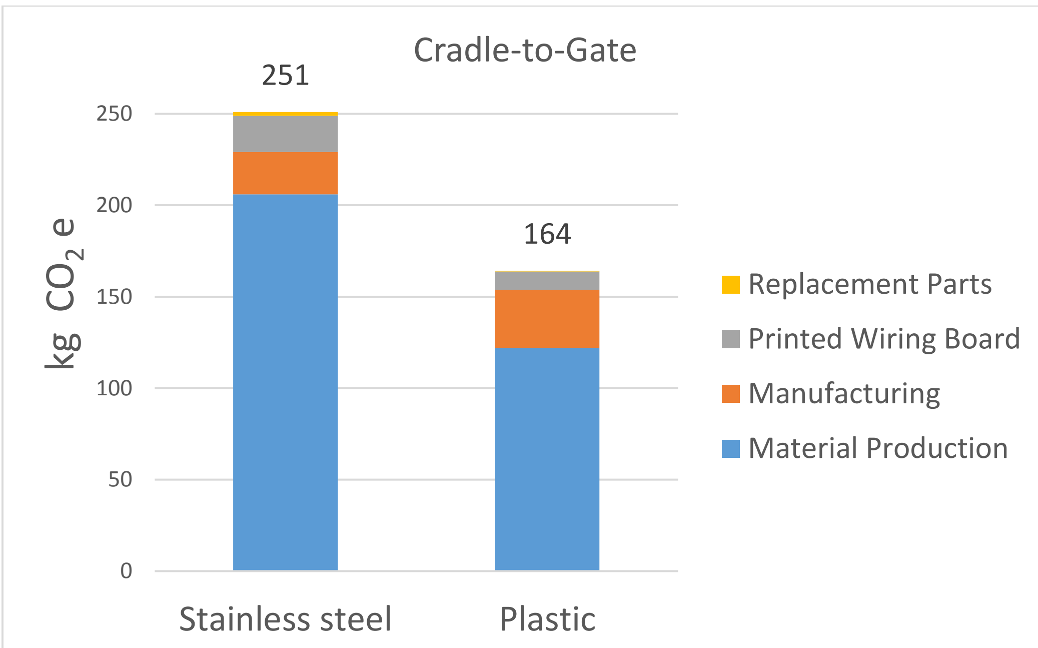

Figure 9-*Cradle-to-gate impacts of producing one dishwasher using the process-level approach. Printed wiring board includes both material production and manufacturing stages.*

The stainless steel machine dishwasher has 53% higher cradle-to-gate emissions than the plastic machine dishwasher. When considering only the cradle-to-gate phases, material production is responsible for the majority of emissions. Not only does the stainless steel model weigh more than the plastic model, stainless steel material production has higher impacts than plastic resin material production on a mass basis. However, plastic machine dishwashers have twice the amount of manufacturing burdens due to processes involved in their production.

Use Phase Results from Observational Laboratory Study

Recommended Machine Use Observations

Table 5 summarizes the resource consumption and cleaning scores for the normal and heavy/tough cycles run for each machine. Energy includes water heated with a natural gas water heater. All cycles used the same 15.4 g detergent tablet.

Table 5-*Average Recommended Machine Use Resource Consumption*

Machine Dishwasher	**Cycle**	**Time (minutes)**	**Water (gallons)**	**Energy (kWh)**	**Cleaning Score**
Stainless Steel	Normal	118	3.54	1.56	87.5
	Tough	148	5.52	2.26	89.7
Plastic	Normal	134	2.96	1.44	83.0
	Heavy	155	7.46	2.46	87.3

Recommended (Best Practices) Manual Dishwashing Observations

Participants who manually washed dishes following the best practice techniques were asked whether or not they would be willing to adopt these recommendations. Two participants responded that they had already established their own habits and stated that they did not like rinsing dishes with cold water. On average, these participants took 44 minutes to wash the test load, using 9.5 gallons of water and 0.68 kWh of energy from the natural gas water heater at the St. Joseph Tech center.

Typical Manual Dishwashing Observations

Of the forty participants, one outlier was found in the manual washing test and two others were found in the machine loading test. These outliers were more than three standard deviations greater than the calculated medians for water, energy, or time. Outliers were excluded from further calculations. Further, two other participants were unable to be identified in any category for manual dishwashing (running tap, combination, water bath) but were included in the machine-loading results. **Figure 10** summarizes how the 37 participants for manual dishwashing were distributed between running tap, water bath, and the combination method. About an equal number of participants ran the tap or used the combination method, while the water bath method was less common. Resource use to wash one load of normally soiled dishes for each category of manual dishwashing is summarized in **Table 6** where energy is assumed to include water heated by a natural gas water heater as well as machine standby energy.

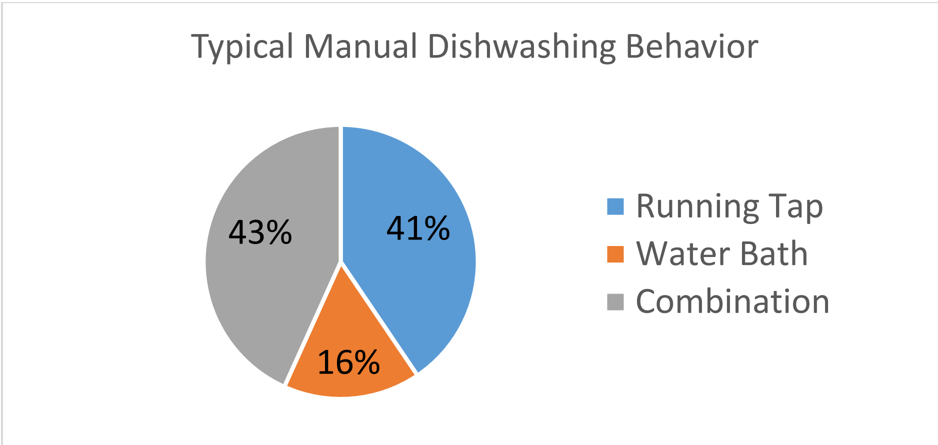

Figure 10-*Method of Manual Washing for 37 participants who were not outliers and were able to be identified.*

Table 6- *Average Observed Typical Manual Dishwashing Resource Use and Cleaning Scores*

Manual Dishwashing Behavior	Time (minutes)	Water (gallons)	Energy (kWh)	Soap (g)	Cleaning Score
Combination	33.2	12.84	1.84	26.75	87.7
Running Tap	44.7	22.8	2.26	20.9	86.6
Water Bath	38.7	6.85	0.89	13	94.1

Typical Machine Loading Observations

Of the 38 participants who loaded dishes into a dishwasher, 68% of them pretreated their dishes using water, while 28% did no pretreatment (**Figure 11**). Of those who did perform some sort of dish pretreatment using water, the average amount of water they used was 3.45 gallons. **Appendix G** shows how loading of the dishware into the machine varies from the manufacturer's recommended arrangement. Participants who loaded with no pretreatment took (on average) 8.8 minutes to load, while those who spent time pretreating and pre-rinsing took an additional 4.5 minutes to load the same set of dishes.

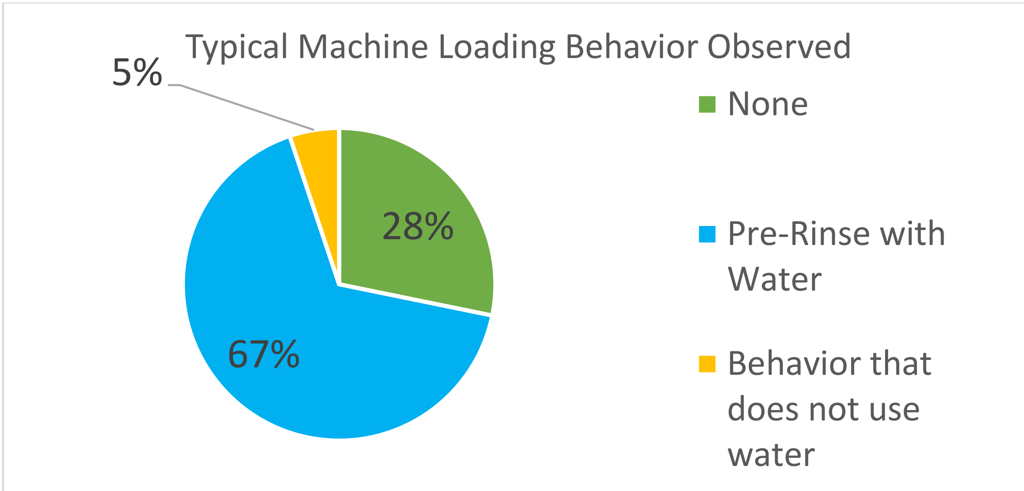

Figure 11-*Typical Machine loading behavior for 38 participants who were not outliers*

Laboratory Results Summary

Figure 12 compares the amount of time a person spends performing physical work in the process of manually washing dishes or loading a machine dishwasher. This figure excludes time required to put away dishes, since it is the same in both cases. For typical manual dishwashing behaviors, the reported time includes time to wash, as well as time used to towel dry (if applicable). The plastic dishwasher's normal and heavy load take (on average) 143 and 155 minutes respectively. The stainless steel dishwasher's normal and tough load take (on average) 118 and 148 minutes respectively. The times spent for machine operation are not shown in **Figure 12** because a person is not performing this work and is free to pursue an alternative activity.

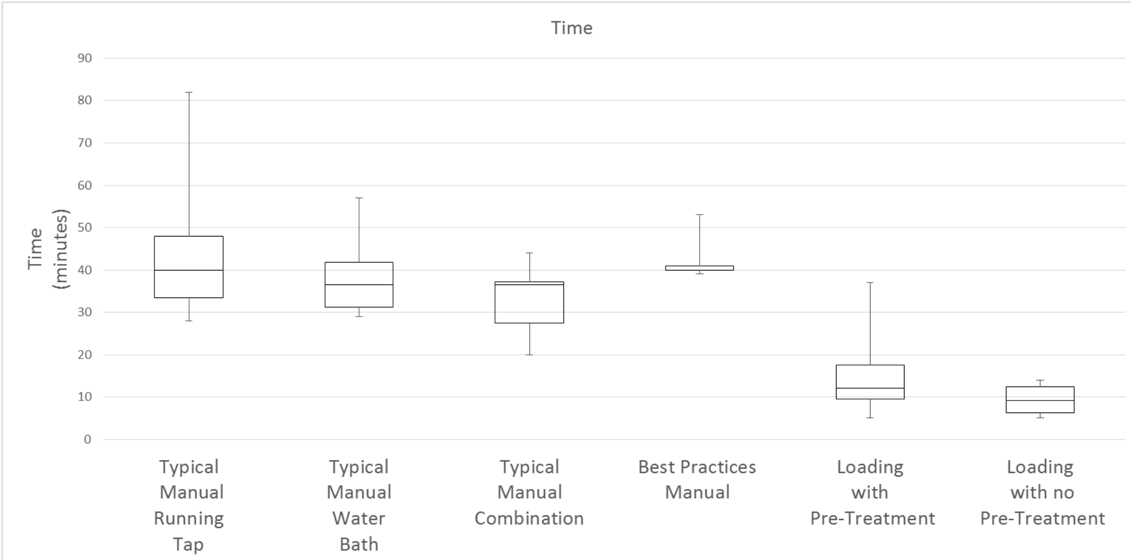

Figure 12-*Time used for washing one load of normally soiled dishes*

In **Figure 13**, energy for manual washing only includes energy to heat the water. Energy used by the machine dishwashers includes electricity to run the machine, energy to heat the water, energy to dry dishes, and energy to standby for one cycle. In both cases, water was heated using a natural gas water heater. Manual dishwashing behaviors show high variability in energy requirements whereas machines used a consistent amount. Running tap washers used more energy than any other method of dishwashing.

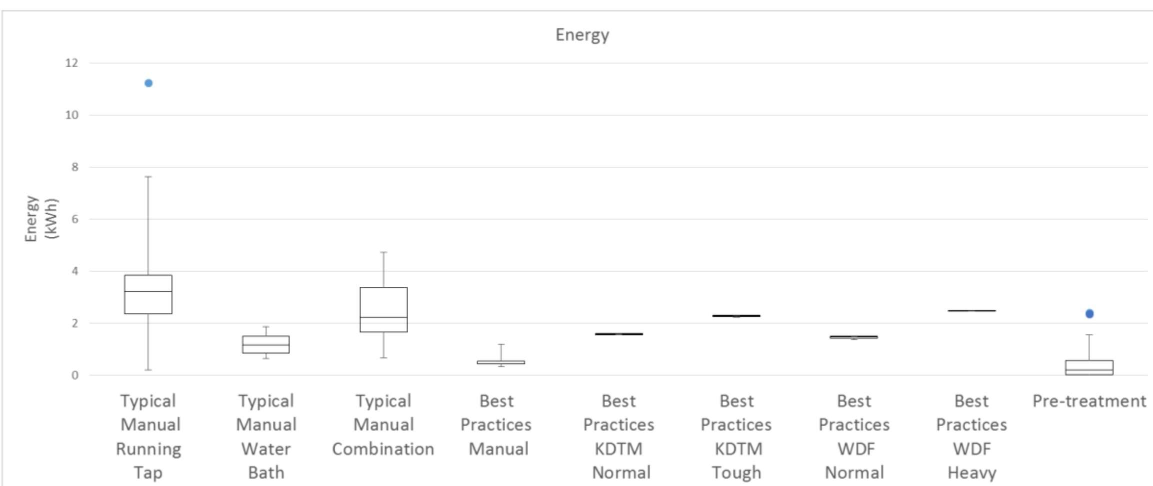

Figure 13-*Energy used for washing one load of normally soiled dishes assuming a natural gas water heater including energy needed by dishwasher to run, heat water, dry, and standby for one cycle.*

Figure 14 shows the water observed to wash one load of normally soiled dishes with outliers being excluded as described previously. Running tap washers used more water than any other method of dishwashing. Again, manual dishwashers exhibit more variability than machines. Soap used by different dishwashing methods are summarized in **Figure 15** and show similar trends.

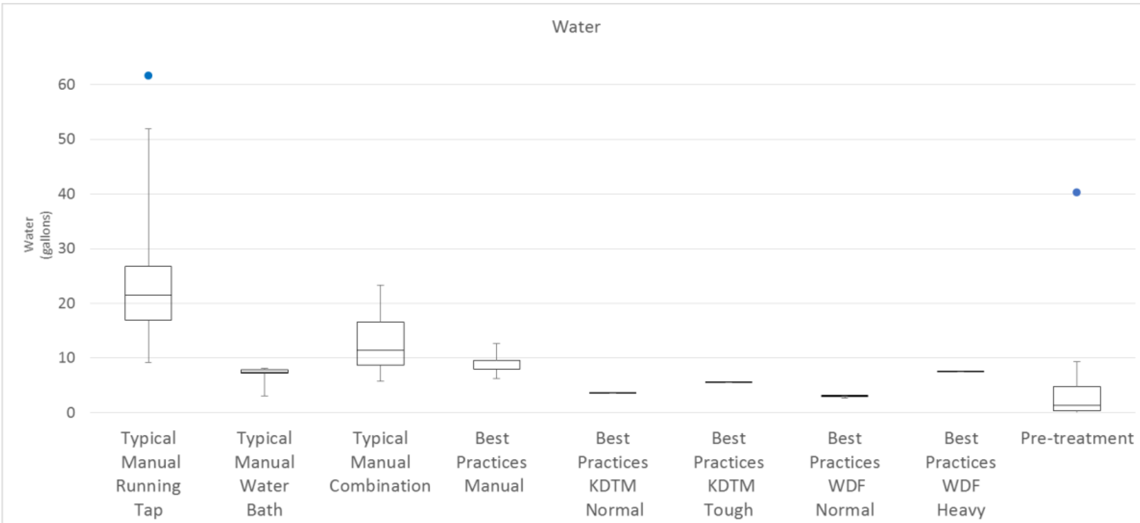

Figure 14-*Water used for washing one load of normally soiled dishes*

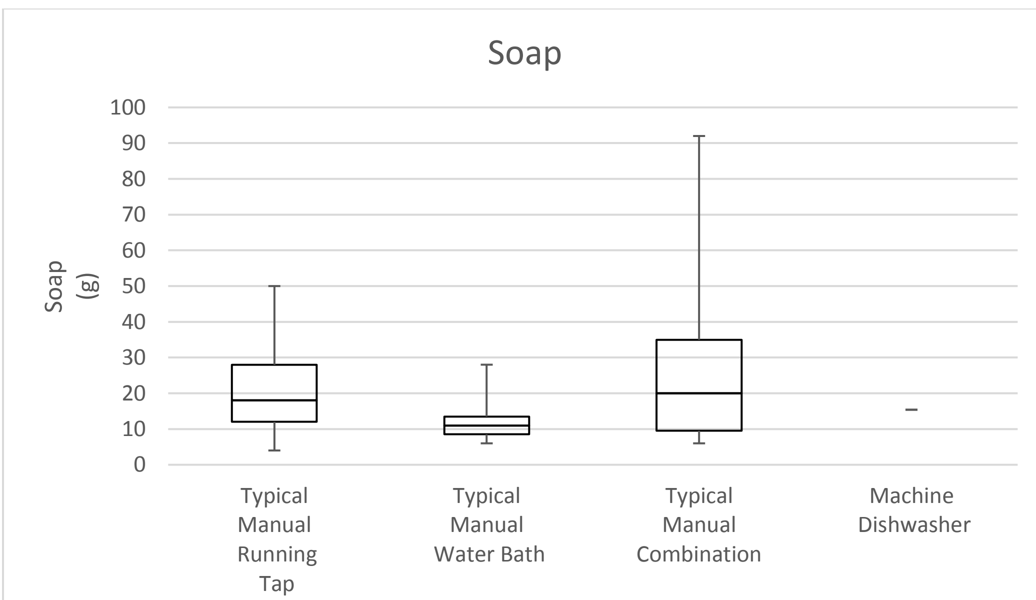

Figure 15-*Soap used for washing one load of normally soiled dishes*

Figure 16 shows the cleaning results from this study. The tested machine dishwashers and manual dishwashing participants scored above the DOE acceptable standard of 70 AHAM Cleaning Index. Therefore, machines and manual dishwashing can be compared since they both provide adequate cleaning and can be assumed to be functionally equivalent. However, the cleaning scores illustrated here demonstrate that manual dishwashing has much more variability in the range of scores received while machine dishwashers had less variability.

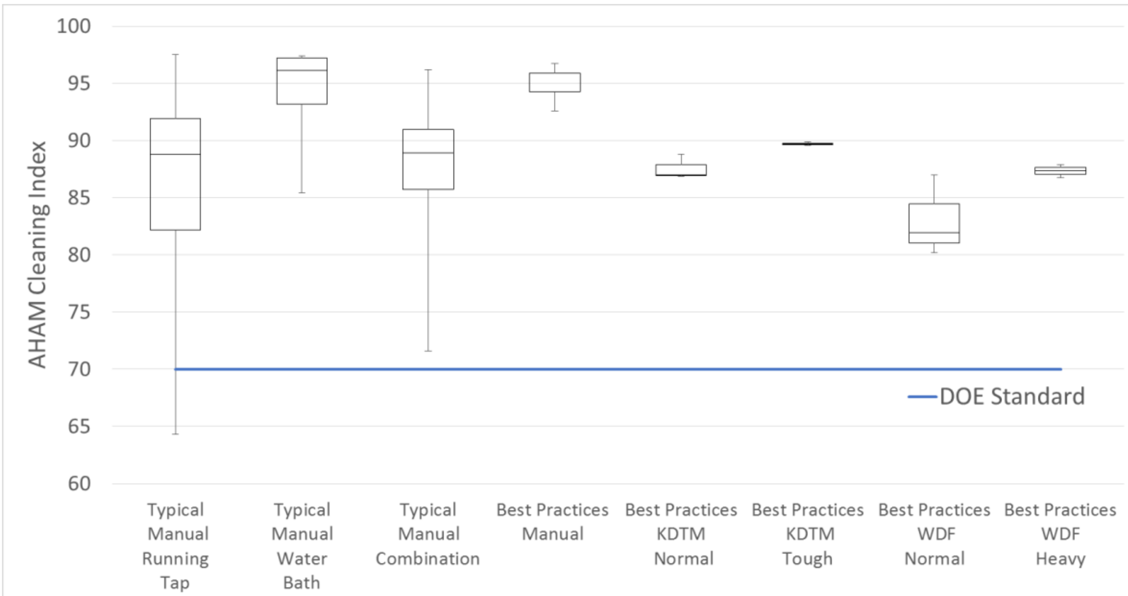

Figure 16-*Summary of Cleaning Results for dishwashing a normally soiled load of 8 place settings. Manual and Machine dishwashing are scored using the AHAM Cleaning Index.*

Survey Results

The majority of participants (82%) in this study stated that they are from the Midwest or have lived in the region for more than five consecutive years. None of the respondents stated that they never use a machine dishwasher at home; the majority (59%) stated that they both manually and machine wash dishes but mostly use the machine (**Figure 17**). When asked what cycle they typically run on their machine dishwashers, participants responded that they mostly select the normal cycle (**Figure 17**). (Additional survey responses are shown in **Appendix E**).

Figure 17-*Survey Study results*

End-of-life

Figure 18 shows the GHG emissions from recycling or landfilling plastic and stainless steel dishwashers. For recycling burdens, **Figure 19** shows drivers of these burdens. The recycling burdens account for shredding and sorting processes. The stainless steel machine dishwasher has a higher proportion of "other" materials going to the landfill due to the large amount of mastic.

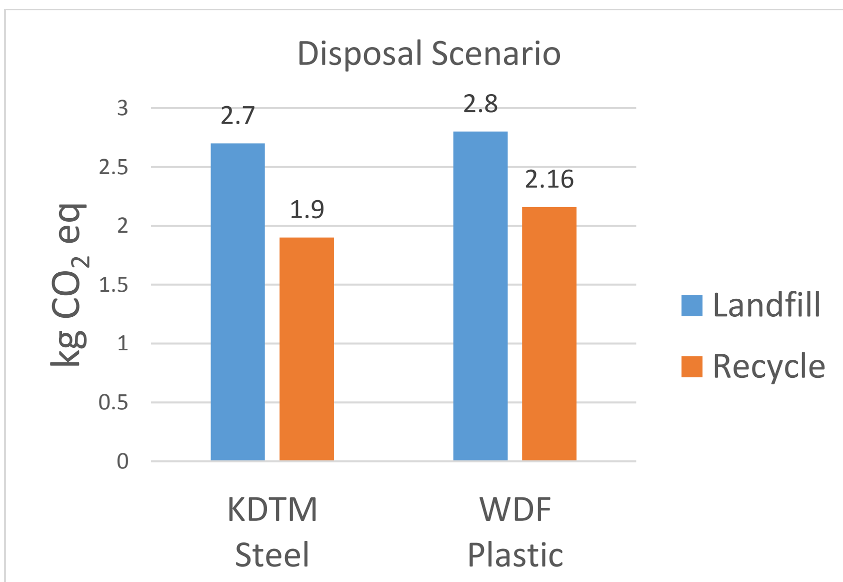

Figure 18-*End-of-life Options. kg CO2e following TRACI 2.1 Impacts*

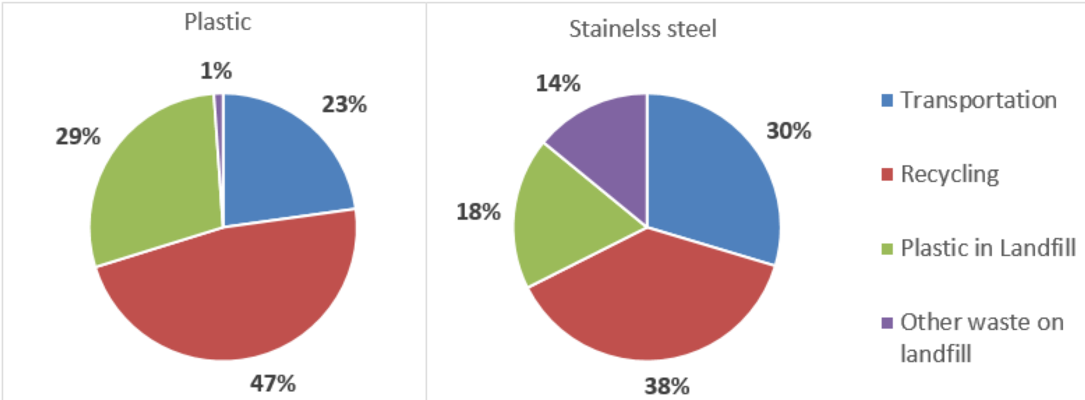

Figure 19-*Recycling burdens for plastic and stainless steel machine dishwashers as kg CO2e following TRACI 2.1 Impacts*

Comparison of Machine and Manual Life Cycles

Figure 20 illustrates life cycle primary energy burdens of different cycles for the stainless steel and plastic dishwasher, assuming 2150 lifetime uses. **Figure 21** shows similar burdens for an equivalent lifetime of different manual dishwashing methods.

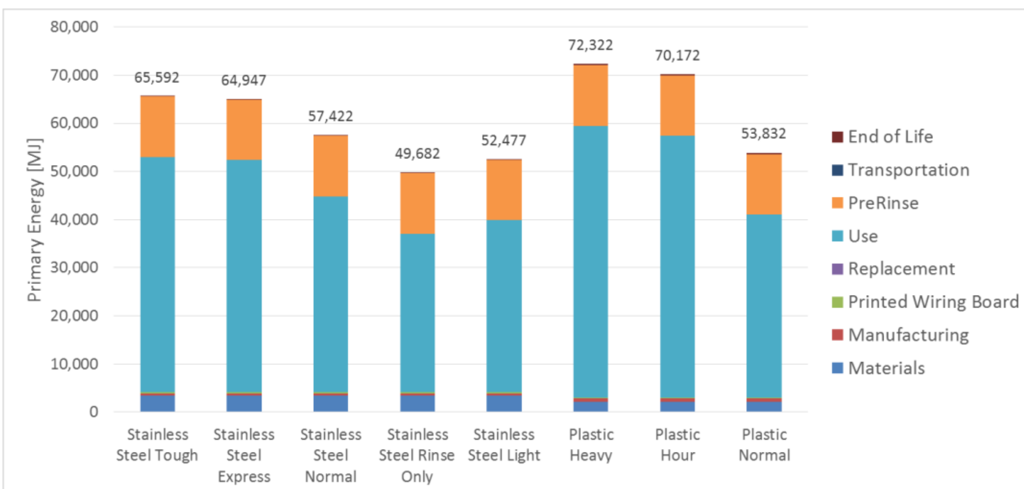

Figure 20-*Lifetime Primary Energy Demand for Different Machine Cycles*

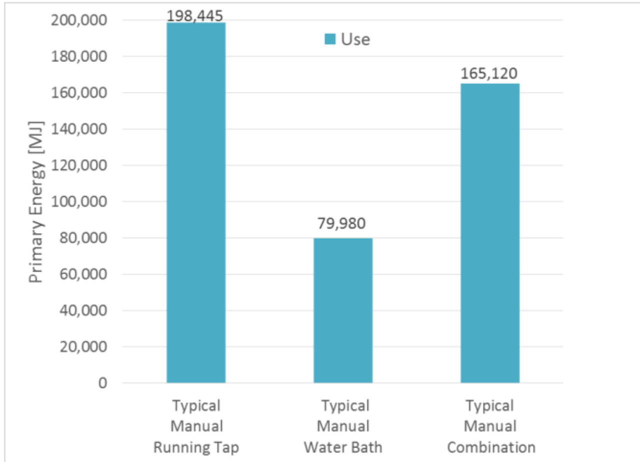

Figure 21-*Lifetime Primary Energy Demand for Different Manual Dishwashing Methods*

Life cycle environmental burdens were calculated in GaBi using the system boundaries discussed in the methods section. The base case for this analysis is a household with an electric water heater connected to the Michigan electricity grid. An electric water heater is selected because this will result in a more conservative estimate of GHG emissions in Michigan due to the carbon intensity of the electrical grid as described later. In our base case, typical and best practice behaviors will assume that all of the 2150 lifetime loads are washed using the same method or cycle. For the machine dishwashers in this base case, no additional features (high temperature water heating, etc.) are added to the cycle. As a conservative estimate, machine dishwashers are assumed to be landfilled since this produces more GHG emissions than recycling. For best practices using machines, a normal cycle is used for every wash. For manual dishwashing, dishes are assumed to be air dried, while machine dishwashing includes heated drying. **Table 7** summarizes the base case across all scenarios being explored.

Table 7-*Base Case Assumptions*

	Typical		Recommended	
	Manual Dishwashing	**Machine Use**	**Manual Dishwashing**	**Machine Use**
Water heater	Electric			
Electrical Grid	Michigan (RFCM)			
Lifetime Uses	2150			
Washing Method	Weighted average from observation	Weighted average from survey	Best Practices	Normal cycle
Pre-rinsing	--	Weighted average from observation	--	None
Replacement Parts	--	Rack adjusters, spray arm hubs, and inlet valve replaced once during lifetime	--	Rack adjusters, spray arm hubs, and inlet valve replaced once during lifetime
Vinegar for Odor Control	--	Once a year	--	Once a year
Cleaning Tab	--	Monthly	--	Monthly
Drying	Air dry	Heated dry	Air dry	Heated dry
End-of-life	--	Landfill	--	Landfill

Using the proportions of behaviors observed in the use phase laboratory study (**Figures 10** and **17**), the consolidated graph **in Figure 22** shows the base case primary energy between typical and recommended behaviors for machine dishwashers and manual dishwashing. Similar trends for the base case occur when evaluating GHG emissions, blue water consumption, and solid waste deposition as shown in **Appendix H**. Evidently, the use phase drives impacts across the entire life cycle of manual and machine dishwashing.

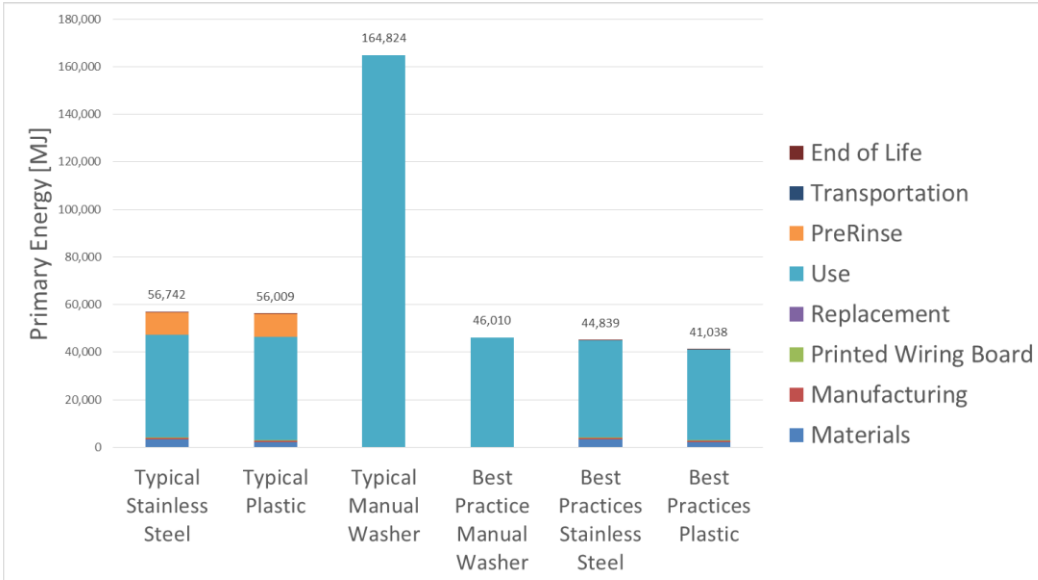

Figure 22-*Consolidated Graph of Base Case Scenario*

Figure 22 demonstrates that under typical behaviors, machine dishwashers use significantly less primary energy over their lifetime than manual dishwashing. Pre-rinsing can account for about 17% or burdens as primary energy while use (excluding pre-rinsing) accounts for 76-93% of life cycle burdens. When considering only best practices, machines are slightly better than manual dishwashers. For manual dishwashing, best practices use 72% less primary energy as the typical manual dishwasher. If a household were to make the switch from typical manual dishwashing to best practices for machine dishwashers, primary energy demand would be reduced by about 124,000 MJ.

Sensitivity Analysis

Although base-case parameters reflect the results for typical manual and machine dishwasher us, it is important to capture the variability in behaviors and operational domains. Using a sensitivity analysis, we consider here how changing several use-phase assumptions summarized in **Table 7** impacts results.

Optimizing Machine Dishwasher GHG Reductions

Machine dishwasher use-phase parameters can be changed to optimize GHG reductions. The base case for machine dishwashers assumes that the cycle is run with the default heat dry option. Users may opt to disable this setting when washing their dishes. **Figure 23** shows the distribution of energy needed by machine dishwashers to wash one load. If the dry cycle is de-selected for every run of a machine dishwasher, between 399 and 494 kWh of energy can be saved over its lifetime. Powered from the Michigan grid, this can result in reduced emissions between 81.5 and 362 kg CO_2e. **Figure 23** indicates that the majority of energy involved with machine dishwashing is associated with the energy required to heat water. The water heater type, therefore, has a large influence on energy requirements.

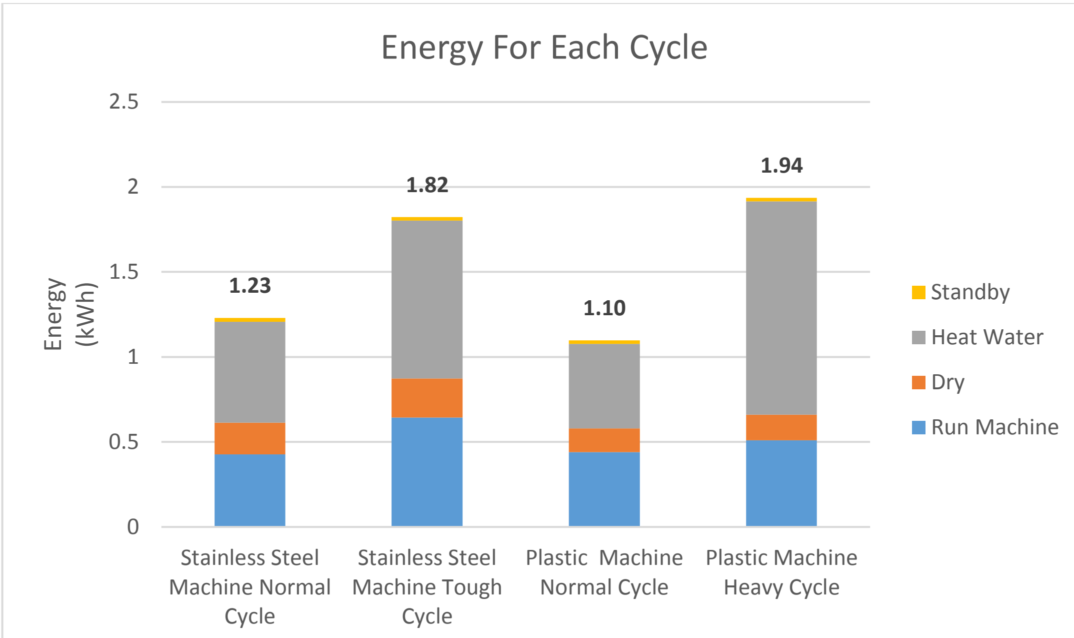

Figure 23-*Energy Consumed in Per Cycle*

As shown in **Figure 24**, we observe reductions in GHG emissions produced by machine dishwasher use (blue bars) from the typical machine dishwasher use (orange line) by changing three observed behaviors. Eliminating pre-rinsing results in the largest reduction of emissions (18%), followed by removing the heat dry option (10%), and selecting the normal cycle for every wash cycle (4%). These results indicate that best practices for machine dishwashing (grey line) are still the most optimal compared to any of these behavior changes. It was shown that pre-rinsing is not necessary to achieve minimal acceptable cleaning performance and that a normal cycle selection also results in adequate cleaning. Note that the cleaning performance of machine dishwashers was not tested when removing the heated dry option.

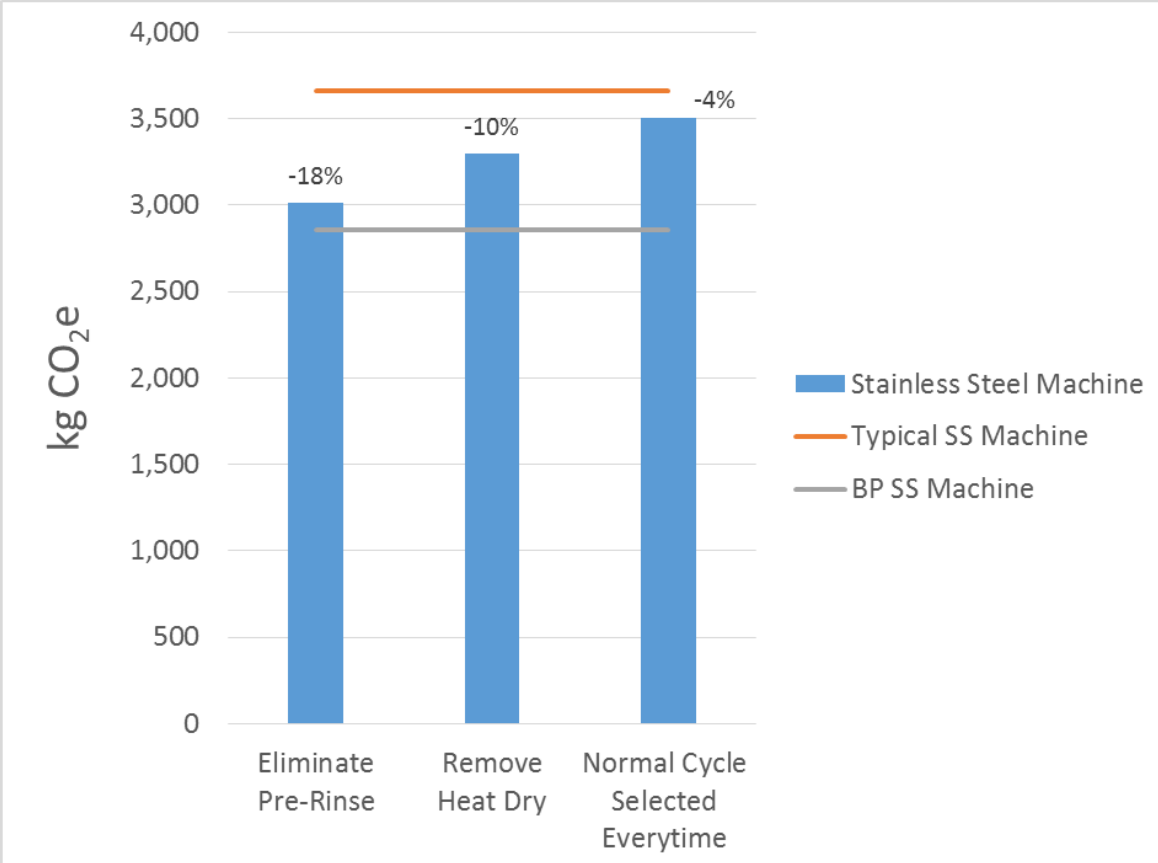

Figure 24-*Optimizing Machine Dishwasher Use for reduced GHG emissions*

Manual Dishwashing GHG Reductions

Figure 25 summarizes how the GHG emissions produced from manual dishwashing (blue bars) change by altering one use phase assumption at a time. Typical manual dishwashing (represented by the orange line) follows base case assumptions. Base case parameters that are changed include grid carbon intensity, towel drying instead of air drying dishes, and using a natural gas water heater instead of an electric water heater. The base case scenarios for the machine dishwashers and best practices for manual dishwashing are also shown.

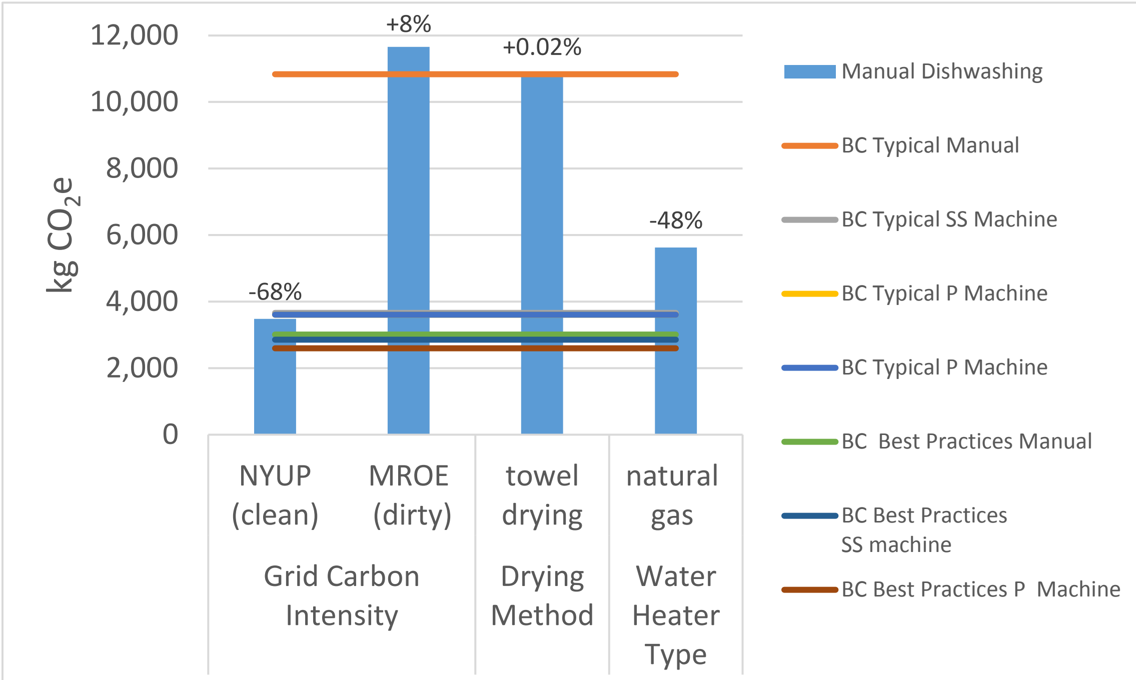

Figure 25-*Sensitivity Analysis for Manual Dishwashing*

The base case assumes that the household has an electric water heater and is connected to the Michigan electricity grid. On a carbon intensity basis (GHG per unit energy produced), the North American Electricity Reliability Corporation (NERC) sub-region containing the Michigan electricity grid (RFCM) is a relatively "dirty" grid (1279 lb. CO_2e/MWh) [53]. The Midwest Reliability Organization East (MROE) electricity grid, which covers a territory west of Lake Michigan, has the dirtiest grid (1679 lb. CO_2e/MWh). Cleaner grids include the Northeast Power Coordinating Council Upstate New York (NYUP) (296 lb. CO_2e/MWh). **Appendix I** shows differences between kg CO_2e emissions produced by the RFCM, NYUP, and MROE electricity grids for a lifetime of manual and machine dishwashing under the base case scenario. **Figure 25** illustrates these results as well, showing that by switching the base case to a less carbon intensive grid, GHG emissions are reduced by 68% and by switching the base case to the most carbon intensive electrical grid, emissions are increased by 8%.

In the base case manual dishwashing scenario, people are assumed to air dry dishes. If they were to towel dry instead of air dry dishes, over the life cycle, an additional 136 kg of blue water are used, 2.67 kg CO_2e are produced, and 33.1 MJ of primary energy are needed. **Figure 25** demonstrates that there is only 0.02% increase in GHG emissions from the base case if towel drying is used.

The majority of US households have a natural gas water heater [54]. By changing the base case water heater from electric to natural gas, the typical manual washer in Michigan can reduce lifetime GHG emissions by 48%. **Appendix J** shows that when a natural gas water heater is used, machine dishwashers produce less GHG emissions than manual dishwashing in most cases. However, when considering best practices as seen in **Appendix J**, the machines produce slightly more GHG emissions than manual dishwashing. While both methods of dishwashing have lower GHG emissions for water heating when natural gas is used, machines still require electricity from the Michigan electrical grid.

LIMITATIONS

We assume that machine dishwashers are run while fully loaded, consistent with the Uniform Test Method from the eCFR. However, it is important to acknowledge that users do not always wash a full load of dishes. Future work should consider the relative impacts of dishwashing for partial loads. A dishwasher that is run half loaded will have twice the environmental burdens per functional unit as one that is always run fully loaded (basis for this study).

We also assume constant efficiencies in our analysis. Like any appliance, machine dishwashers will have reduced electrical and water use efficiency over their lifetime [55]. Efficiency degradation of these machines over their lifetime is assumed to be negligible in our analysis. Several studies, including life cycle optimization for similar household appliances, assume constant performance efficiencies over their useful life [56-58]. Similarly, the efficiency of household water heaters is assumed to be constant over the period analyzed in our study. Both system models for machine use and manual dishwashing both include water heating. Even if degrading water heater efficiencies are considered, the relative difference in environmental burdens that come from heating water in the use phase between machines and manual dishwashing will remain the same. In cases where there is hard water, water heater efficiency will be significantly reduced, and the machine dishwasher lifespan will be reduced [59].

Loading patterns and pretreatment behaviors can impact cleaning performance but this is not evaluated in this analysis. Machine dishwashers are normally tested without considering pretreatment. If pre-rinsing is done, it remains unclear whether the OWI used in the sensor cycles will be able to detect any turbidity. No conclusions can be made about whether or not pre-rinsing actually has the intended effect on cleaning performance that users believe it does. Without pre-rinsing, dishes were already able to reach acceptable cleaning scores as shown in this study. Future work can evaluate this might impact operating energy and water inputs and how much cleaner (AHAM Cleaning Index) dishes get per unit of water used to pre-rinse.

The participants in this survey were Whirlpool employees and were considered to exhibit behaviors characteristic to Michigan. Most were males over the age of 35 living in households with four people. This study can be expanded beyond Michigan and to other demographics for observing whether dishwashing behaviors are regionally dependent or vary by across different groups. Further, adoption of best practices can have a larger benefit in water-stressed regions with electrical grids fueled mostly by non-renewables.

We used GaBi databases for modelling materials and processes needed for machine dishwasher manufacturing and production. These have default industry estimates for transportation of materials, resources use, and other data. However, an in-depth study of the actual machine dishwasher value chain could be conducted. In the actual value chain, sustainability can also be assessed from a social lens.

CONCLUSION

This study is a comprehensive life cycle assessment of machine dishwashers and manual dishwashing under various scenarios. Although machine dishwashers are not being used optimally, typical machine use produces fewer GHG emissions than typical manual dishwashing. The following major conclusions result from this assessment.

Key Findings

Of the typical manual dishwashing behaviors observed in the study, it is found that the water bath has the least lifetime primary energy demand (80,000 MJ), while the running tap method uses approximately 60% less primary energy (198,000 MJ). The most prevalent typical manual dishwashing behaviors (running tap and combination) are also those with the most burdens. Further, participants stated behavioral barriers exist to adoption of best practices for manual dishwashing.

The majority of the energy used in machine dishwashing is attributed to heating water. Although a natural gas water heater is preferable in a region with a highly carbon-intense electrical grid (like Michigan), this may not be true for all electrical grids. For example, in a grid that has a high penetration of renewables, it would not be preferable to use a natural gas instead of an electrical water heater.

Here, we discuss the similarities and differences with previous studies that machine dishwashers consume less energy and water than manual dishwashing. Our analysis provides more clarity about what drives energy use in machines and what scenarios result in the least environmental burdens. Finally, we conclude that the scenario that would result in the least GHG emissions is the machine dishwasher following recommended use (no pre-rinsing, normal cycle selection, heat dry option selected).

A major opportunity for reducing GHG emissions from dishwashing in the American residential sector exists in households that already own but do not use their machine dishwasher, about 16 million households [3]. If typical manual dishwashing was substituted by the recommended use of a steel machine dishwasher, approximately 89.2 metric tons CO_2e and 7.07 X 10^{11} kg (1.82 X 10^{11} gal) blue water could be reduced over an 10 year period (2150 uses). Even more savings are possible if the 24 million households that do not own a dishwasher were able to switch from typical manual to recommended machine dishwashing.

Future Work

Process-level modeling approaches underestimate facility-level burdens. Sub-metering within the Findlay manufacturing plant is recommended to determine the actual amount of resources (electricity, water, natural gas) used for each manufacturing process.

Subsequent values can be compared against GaBi databases to verify whether or not they adequately model the factory's actual operations. This may improve the accuracy and completeness of Scope 2 reporting.

Survey responses indicated that there are items that users are unwilling to load into the machine dishwasher (**Appendix E**). This may be because these items have soils that are more difficult to remove or they take up too much space in the machine. It remains unclear if these items are responsible for a higher fraction of manual dishwashing burdens. Experiments excluding the more heavily soiled items such as the baked spaghetti dish might result in less burdens from manual dishwashing.

ANSI/AHAM standards grade cleaning ability of machine dishwashers based on how many spots and stains are left on dishes. Since machine dishwashers can reach higher temperatures than manual dishwashing methods, they could potentially have a higher ability to sanitize dishes. If cleaning ability was measured using microbial counts, manual dishwashing methods might not achieve acceptable cleaning performance.

The LCA can be further refined by addressing limitations highlighted above. However, we expect our conclusion that machine dishwashing (following recommended procedures) will outperform manual dishwashing is robust.

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APPENDIX A.1- Summary of Previous Studies Testing Conditions

Study	Method	Summary of Test	Participants & Machines	Test Condition	Soiling Method	Dishes Washed
1	Manual	Laboratory observation	113	EN 50242	EN 50242	140
	Machine	Laboratory testing	2	EN 50242	EN 50242	140
2	Manual	Laboratory observation	(289 total) 80 US Americans	IEC	IEC ; ANSI/AHAM	140
	Machine	Laboratory testing	(6 total) 1 for US Americans	IEC	IEC; ANSI/AHAM	140
3	Manual	Laboratory observation	113	EN 50242	EN 50242	140
	Machine	Laboratory testing	2	EN 50242	EN 50242	140
4	Manual	Laboratory observation	60	EN 50242	EN 50242	140
	Manual	Best Practice Tips in the laboratory	53	EN 50242	EN 50242	140
	Manual	Observation of Everyday Behaviors before Best Practice Tips for manual washing training.	16-20 German households; 18-20 Spanish households	In-house	In-house	1
	Manual	Observation after Best Practice Tips for manual washing training.	16-20 German households; 18-20 Spanish households	In-house	In-House	1
5	Manual	Laboratory observations	150	EN 50242	EN 50242	140
	Machine	Laboratory testing	5	EN 50242	EN 50242	140
	Machine Loading	Laboratory observations of loading/unloading.	20	Not Reported	Not Reported	140

APPENDIX A.2- Summary of Previous Studies Results

Study	Method	Time [min]	Energy [kWh]	Water [gal]	Cleanser Consumption [g]	Cleaning Index [0-5]
1	Manual	79	2.5	27.2	35	3.3
	Machine	15 to load/ unload. 100-150 for cycle	1-2	3.96-5.81	30	3.3-4.3
2	Manual	Not reported	3.5	37.0	Not Reported	2.7
	Machine	Not Reported	Quick-0.9 Normal- 1.6 Intensive-2.0	Quick-3.35 Normal- 4.66 Intensive-7.05	Not Reported	Quick-1.6 Normal- 2.7 Intensive- 3.4
3	Manual	79	2.5	27.2	35	3.3
	Machine	15 to load/ unload. 100-150 for cycle	1-2	3.96-5.81	30	3.3-4.3
4	Manual	Not Reported	2.9	9.7	36.9	2.5
	Manual	Not Reported	0.8	11.3	23.7	3.7
	Manual	German - 0 .65 Spanish- 0.55	German- 0.013 Spanish- 0.022	German- 0.151 Spanish- 0.293	German- 0.26 Spanish- 0.41	Not Reported
	Manual	German- 0.63 Spanish- 0.45	German-0.009 Spanish-0.013	German- 0.122 Spanish- 0.179	German- 0.16 Spanish- 0.25	Not Reported
5	Manual	60	1.7	13.0	29	3.7
	Machine	152	1.3	3.49	Not Reported	4.2
	Machine Loading	9	Not Reported	Not Reported	Not Reported	Not Reported

Study 1 – A European Comparison of Cleaning Dishes by Hand

Study 2- Comparative Analysis of Global Consumer Behavior in the Context of Different Manual Dishwashing Methods

Study 3- Washing Up Behavior and Techniques in Europe

Study 4- Determination and verification of possible resource savings in manual dishwashing

Study 5- Manual Dishwashing Habits-an Empirical analysis of UK consumers

APPENDIX B.1- Green Globes Water Consumption Input

INPUT ASSUMPTIONS PAGE (Green Globes Water Consumption Calculator v. 1.3)			
Project Name/Number:		Date of analysis:	
APPLICANT/DESIGNER ENTER THE DATA IN THE FOLLOWING FIELDS (yellow cells)			
FOR A NON-RESIDENTIAL BUILDING (or portion of building)			
PROJECT COMPOSITION & OCCUPANCY			
Project (building) size		1,086,400	(gross sq.ft.)
		250	(net sq.ft./person)
Space Efficiency		0.9	(net sq.ft./gross sq.ft.)
Occupancy	Males	0.5	(fraction of total)
	Females	0.5	(fraction of total)
	Total	2200	(must equal 1)
Work days per year	Days	260	(work days per year)
Lav faucet use	Minutes	6	(minutes per each use)
Hours per week of project occupancy	Occupancy	40	(hours/week)
FREQUENCY OF USE OF FIXTURES/FITTINGS (uses per 8-hr day by each occupant/user):			
Toilets-Males		1	(uses per day per person while in the non-residential building; may be adjusted up or down if special conditions warrant such adjustment and those conditions can be documented)
Toilets-Females		3	
Urinals-Males		2	
Commercial lavatory faucet		5	
FOR A RESIDENTIAL BUILDING (or portion of building)			
		Unit Occupancy (persons/unit)	
PROJECT COMPOSITION			
Project (building) size		400,000	(gross sq.ft.)
Average size of residential units	1800	(average square feet per unit)	
Unit occupancy	2	(average no. of persons per residential unit)	
FLUSH FIXTURE USE	(flushes per day/person)		
Toilets-Males & Females	5	**NOTE:** Assumes full-time residency. Normal is 5 flushes per day. May be increased to a maximum of 7 flushes per day for occupancy by senior citizens. Conversely, may be decreased if the occupants are working outside the home and are not present.	
FLOW FITTING USE	(uses per day/person)		
Residential lavatory faucets	8	**NOTE:** May be increased to a maximum of 10 uses per day for occupancy by senior citizens, adults working at another location, or other similar circumstances.	
Residential showerheads	1		
Resid. kitchen sink faucets	4		
OTHER ASSUMPTIONS			
Shower use	6	(minutes per shower per person)	
Baseline water factor (clothes washer)	10	(gallons/cubic foot of washer drum capacity)	
Clothes washer capacity (cu.ft.)	3	(cubic feet of washer drum capacity)	
Baseline water use (dishwasher)	8	(gallons/full cycle)	
Kitchen faucet use (min)	3	(minutes per each use)	
Bathroom lav faucet use (min)	0.5	(minutes per each use)	

APPENDIX B.2- Green Globes Water Consumption Output

EPAct reqmt in GREEN	CODE requirement in BLUE

BASELINE WATER USE ANALYSIS FOR NON-RESIDENTIAL BUILDING

					TOTAL BLDG SQUARE FOOTAGE
Variables:	Net Sq Ft per person	250		Gross Square Footage	1,086,400
	Space Efficiency	0.9		Net Square Footage	977,760
	Occupancy Males	0.5	(fraction of total occupancy)	Net Square Feet/Person	250
	Females	0.5	(fraction of total occupancy)	Occupancy (persons)	3911.04
	Total	2200	(must equal 1)	Males	1955.52
	Work days per year	260		Females	1955.52
	Lav faucet use (minutes)	6			
	Lavatory faucet flow rate	0.5	gallons per minute (per code for all PUBLIC space)		

	Frequency of use per day per person	Amount per use (gallons)	ANNUAL WATER USE (GAL PER YEAR)
Flush fixtures			
Toilets-Males (flush)	1	1.6	813,496
Toilets-Females (flush)	3	1.6	2,440,489
Urinals-Males (flush)	2	1	1,016,870
Flow fittings			
Commercial lavatory faucets (flow/min)	5	3	15,253,056
SUB-TOTAL-PLUMBING (Gal/year)			19,523,912
OCCUPANCY ADJUSTMENT FACTOR			1.00
ADJUSTED SUB-TOTAL-PLUMBING			19,523,912
Other Systems			
Comfort systems (HVAC)		Gallons/yr	
Landscape irrigation		Gallons/yr	
Pools, fountains, spas		Gallons/yr	
Process equipment (food, medical, etc.)		Gallons/yr	
TOTAL WATER USE - BASELINE			19,523,912

BASELINE WATER USE ANALYSIS FOR MULTI-FAMILY RESIDENTIAL PR

			TOTAL BLDG SQUARE FOOTAGE	
			400,000	
Avg. size of residential units	1800		222	No. of units
Occupancy (persons/unit)		2	444	No. of persons/unit

	(flushes per day/person)	(gallons per flush)	WATER USE (GAL PER YEAR)
Flush fixtures			
Toilets-Males & Females	5	1.6	1,297,778
	(uses per day/person)	(gallons per use)	
Flow fittings			
Residential lavatory faucets	8	1.1	1,427,556
Residential showerheads	1	15	2,433,333
Resid kitchen sink faucets	4	6.6	4,282,667
	(U.S. EPA cycles per yr)	(gallons/yr per unit)	
Residential Appliances			
Clothes Washer	392	11760	2,613,333
Dishwasher	215	1720	382,222
SUB-TOTAL-PLUMBING & APPLIANCES		Gallons/yr	12,436,889
		Acre-feet/yr	38.16
		Acre-feet/yr/unit	0.17
Other Systems			
Comfort systems (HVAC)			
Landscape irrigation			
TOTAL WATER USE - BASELINE			12,436,889

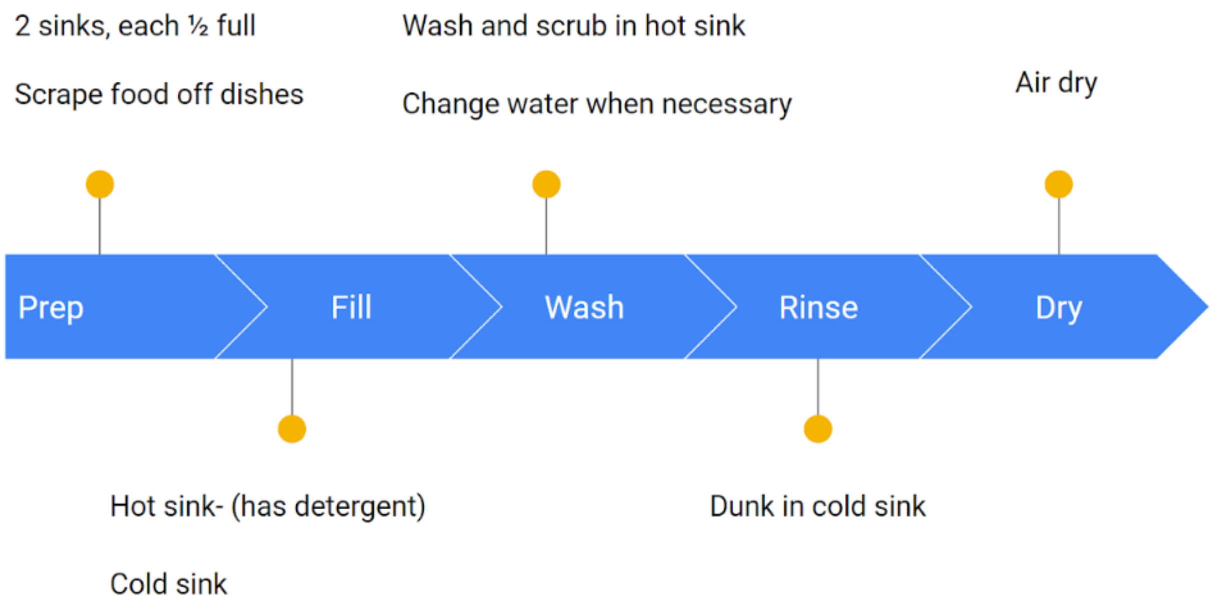
ASSUMPTIONS (from "input" tab)	
Shower use (minutes)	6
Baseline shower flow rate (gpm)	2.5
Baseline water factor (clothes washer)	10
Cubic ft (clothes washer)	3
Baseline water factor (dishwasher)	8
Kitchen faucet use (min)	3
Baseline kitchen faucet flow rate (gpm)	2.2
Baseline lav faucet flow rate (gpm)	2.2
Lavatory faucet use (min)	0.5

APPENDIX C- Machine Dishwasher Manufacturing Processes

Process	Source	Calculations and Assumptions
Metal Stamping and Bending	GaBi dataset from Fertigungsverfahren Band 5: Blechbearbeitung, 1995 reviewed by thinkstep, IBP, IABP	N/A
Injection Molding[1]	GaBi dataset from Franklin Associates	N/A
Foaming	EcoInvent dataset on SimaPro	N/A
Cold Impact Metal Extrusion	EcoInvent dataset on SimaPro	N/A
Metal Roll Forming	GaBi dataset from Metal Construction Association (MCA) reviewed by thinkstep	N/A
Coating[2]	Literature Review [60, 61]	Assumed similar to refrigerator racks
Welding and Grinding	Literature Review	
Baking of Mastic	Literature Review [62]	Assumed 30 bulbs and 1 minute of baking for steel tub machines
Painting Process	GaBi dataset from NREL USLCI	Assumed automotive painting process dataset
Pump Drain Test	On-site data	2 L/machine
Overhead Heating	Literature Review [63]	Calculated
Building Water Use	Green Globes Calculator	Appendix B

[1] Polypropylene is reused in the Findlay plant and this loop is accounted for in the model.
[2] After being formed into a basket shape, dish racks are coated. This process involves heating the metal and then passing it through a fluidized suspension of plastic powder.

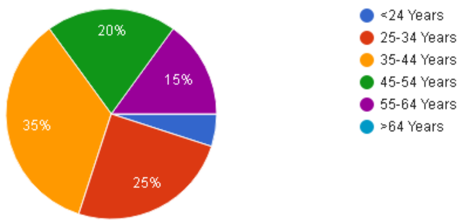
APPENDIX D- Recommended (BPT) Manual Dishwashing Behaviors Summary



APPENDIX E.1 – Survey Responses on Demographics

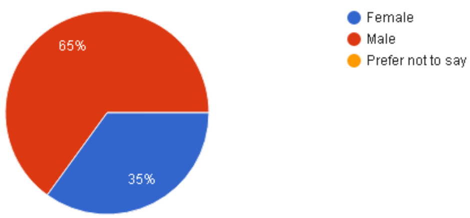
Age Group

40 responses



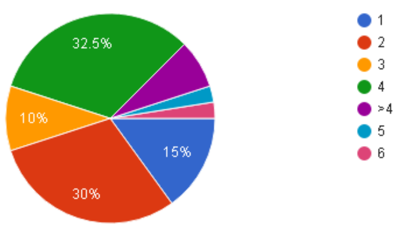
Gender

40 responses



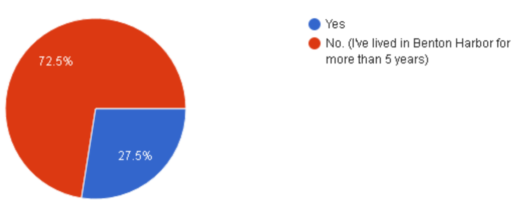
Number of people in your household

40 responses



Did you move to the Southwest Michigan area (Benton Harbor) within the past 5 years?

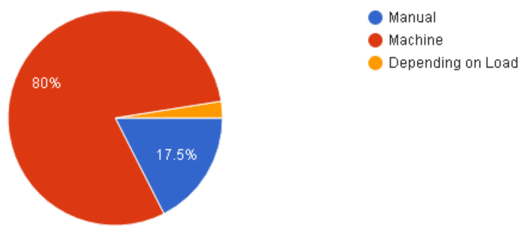
40 responses



APPENDIX E.2 – Survey Responses on Dishwashing

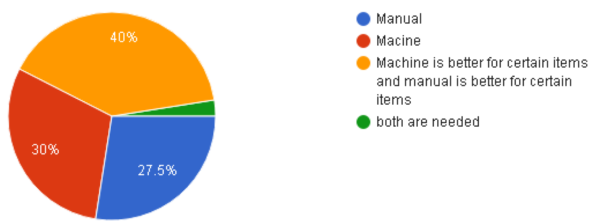
Do you think manual or machine dish washing uses less energy an resources?

40 responses



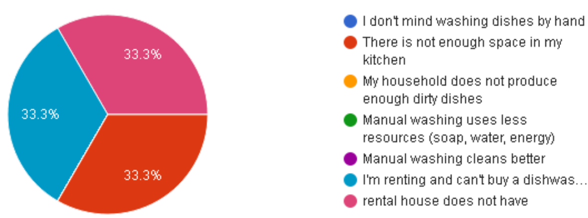
Do you think manual or machine dish washing cleans better?

40 responses



What is the main reason for not owning a dish washing machine?

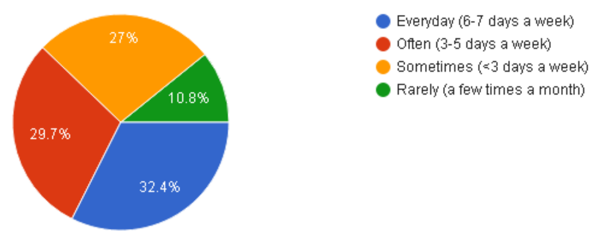
3 responses



APPENDIX E.3 – Survey Responses on Machine Dishwasher Use

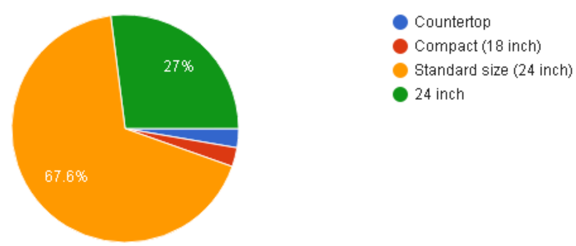
How often do you use your dishwasher?

37 responses



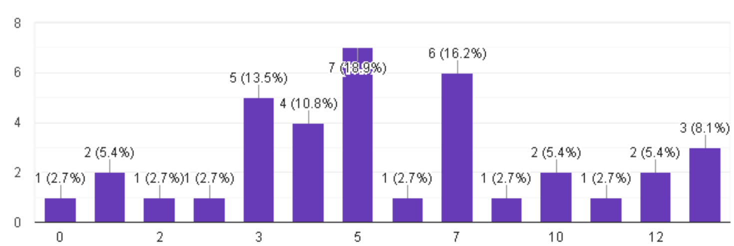
What size machine?

37 responses



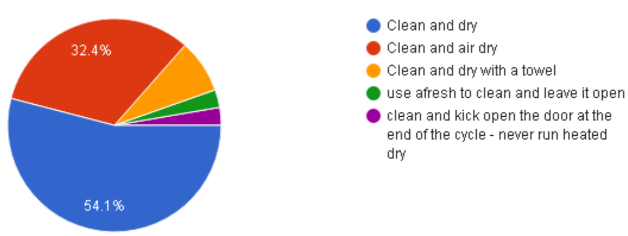
How old is your machine? (years)

37 responses



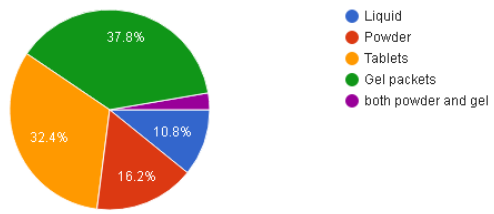
Do you clean and dry your dishes in your dishwasher?

37 responses



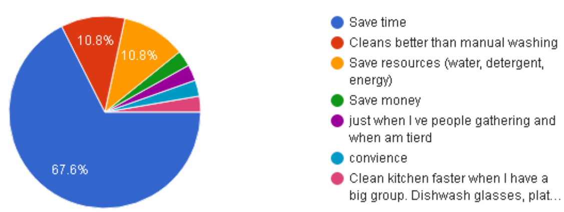
What kind of detergent do you use?

37 responses



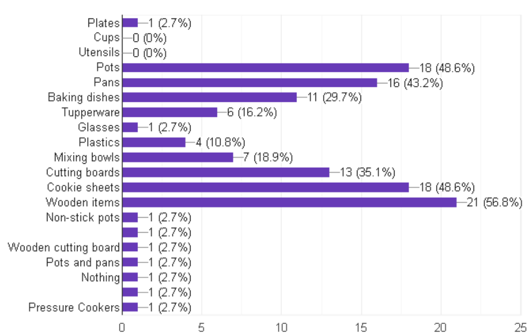
What is your main reason for using a dishwasher?

37 responses



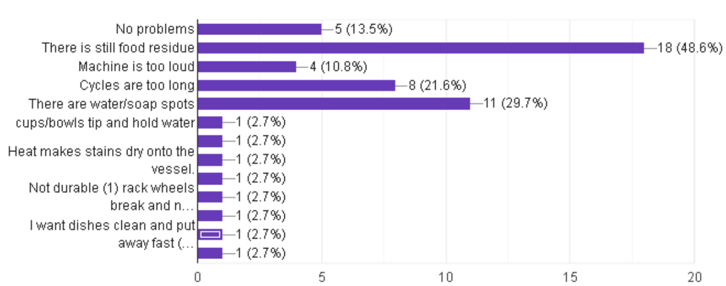
Select Items that you DO NOT put in the dishwasher and that you wash manually.

37 responses



What problems do you experience with machine dish washing?

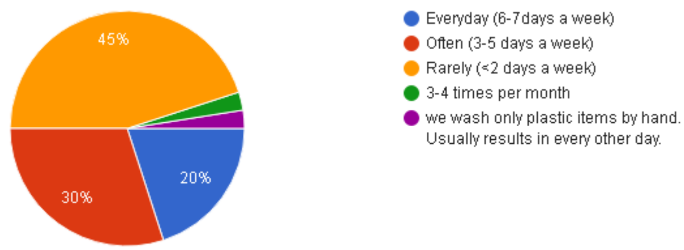
37 responses



APPENDIX E.4 – Survey Responses on Manual Dishwashing

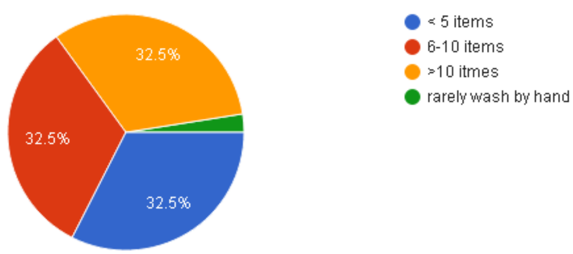
How many times do you manually wash dishes per week?

40 responses



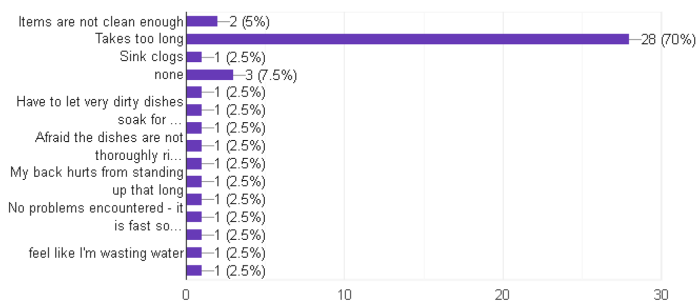
How many items do you wash each time?

40 responses



What problems do you generally encounter when manually washing dishes?

40 responses



APPENDIX F- Resources of Interest at Findlay Factory

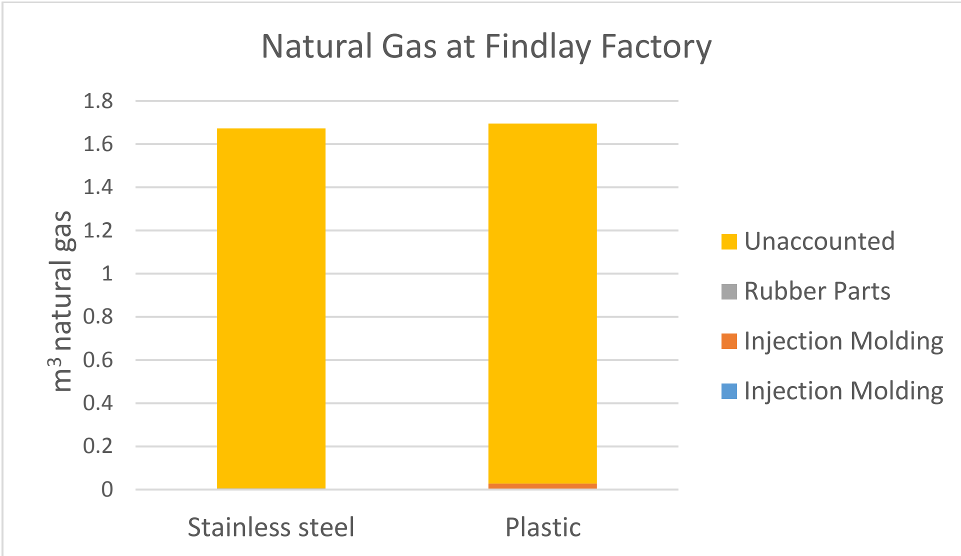


Figure 26-*Natural Gas Use at Findlay factory to produce one machine dishwasher following the process-level approach where unaccounted water is the difference between the facility-level and process-level approach total*

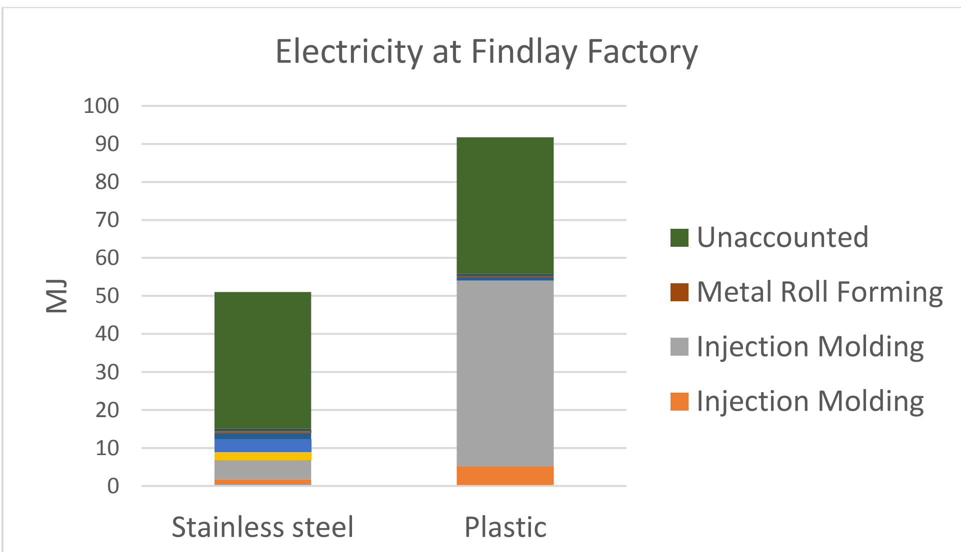


Figure 27-*Electricity Use at Findlay factory to produce one machine dishwasher following the process-level approach where unaccounted water is the difference between the facility-level and process-level approach total*

APPENDIX G- Observed Loading Behaviors

Manufacturer's Directions

Participant

APPENDIX H.1- Lifetime burdens under Base Case following different metrics

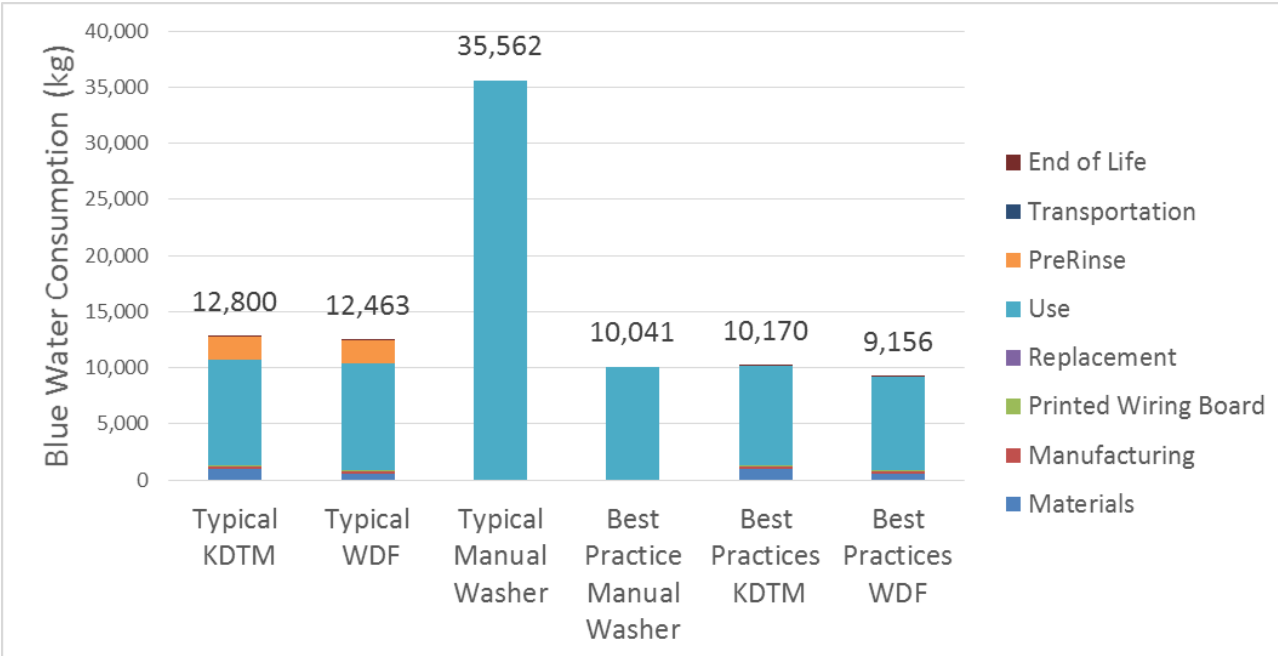


Figure 28-*Blue Water Consumption under Base Case*

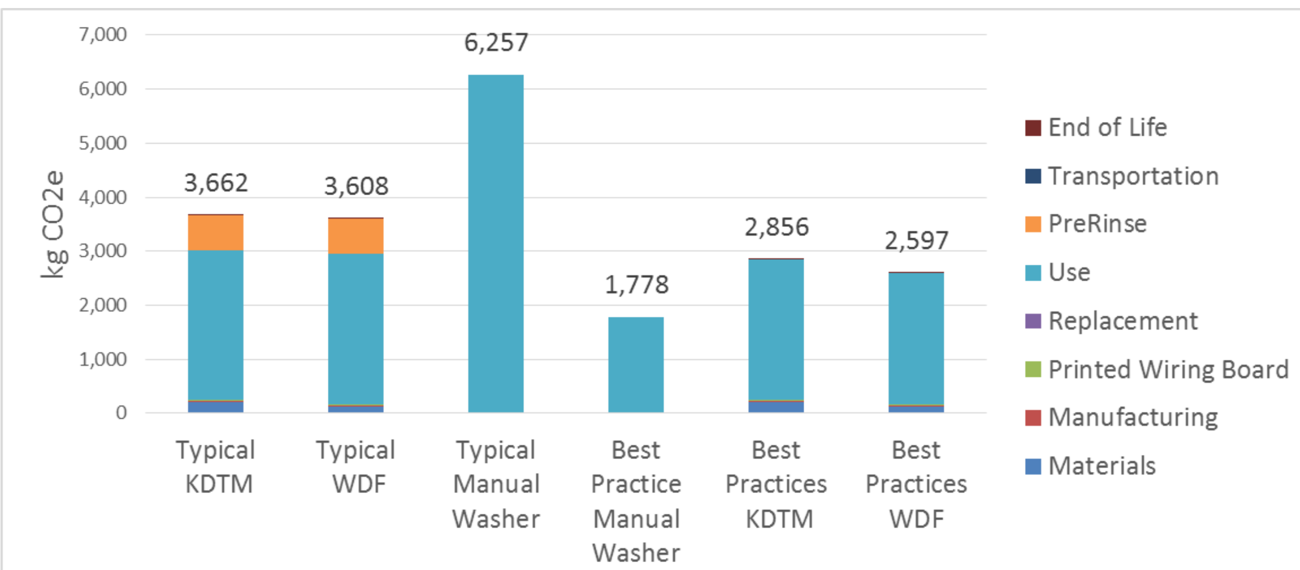


Figure 29-*kg CO2e under Base Case*

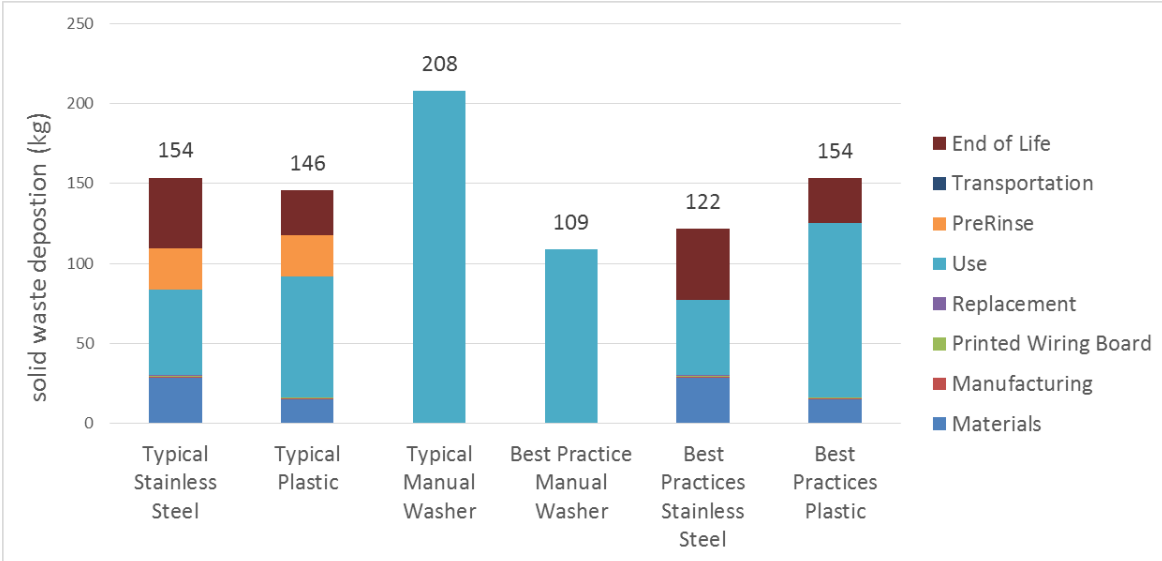


Figure 30-*Waste Deposition through Life Cycle following Base Case*

APPENDIX I.1- Base Case GHG emissions with varying regional electrical grid

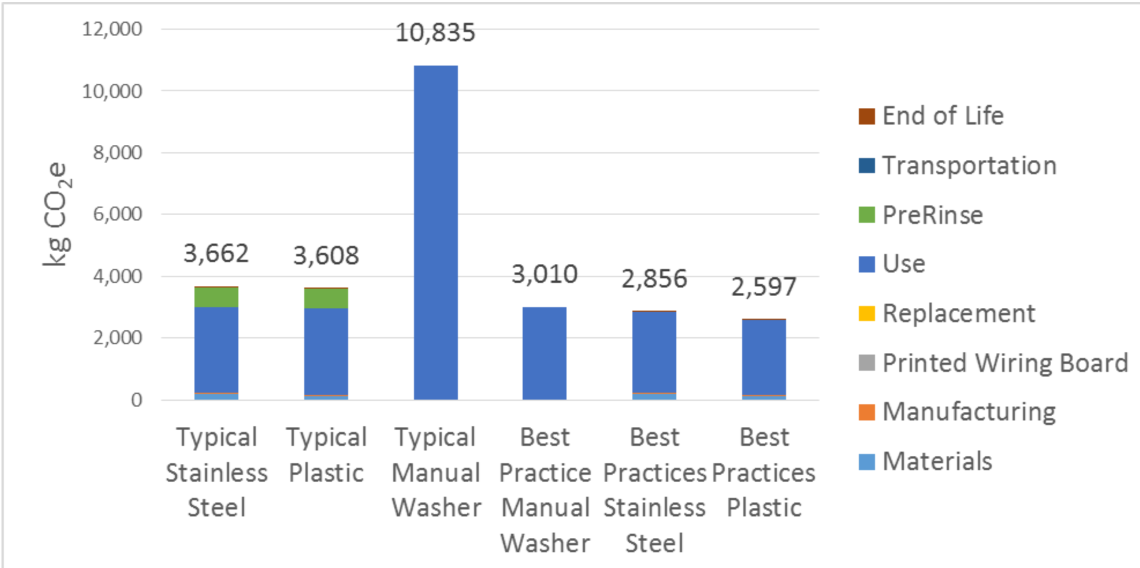


Figure 31-*Base Case (Michigan electricity grid)*

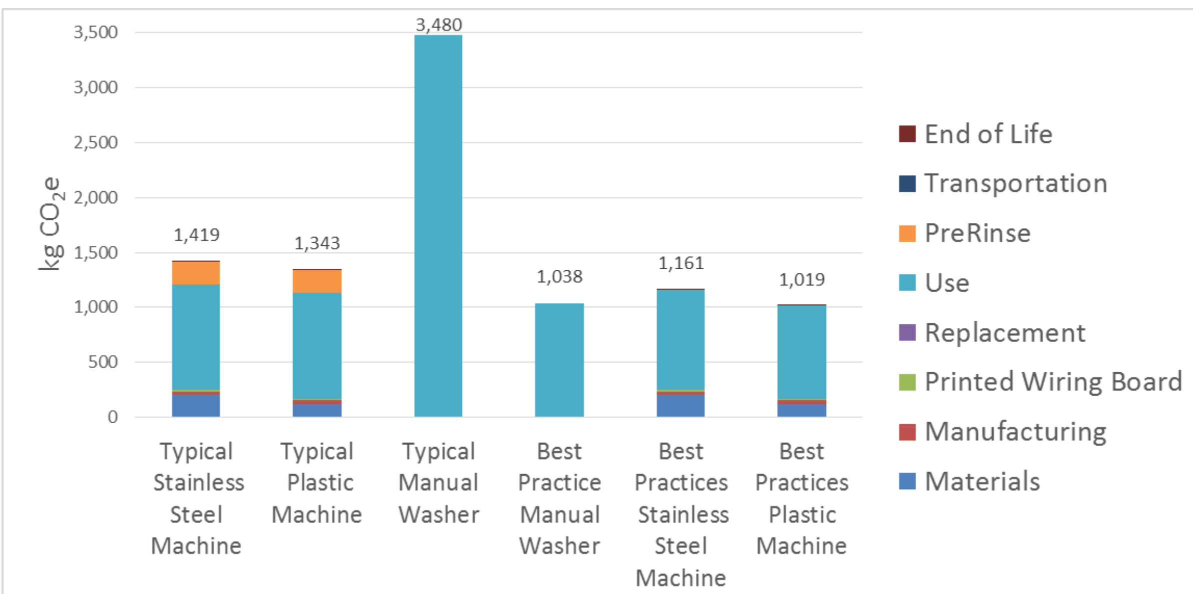


Figure 32-*Base Case but with NYUP Electrical Grid*

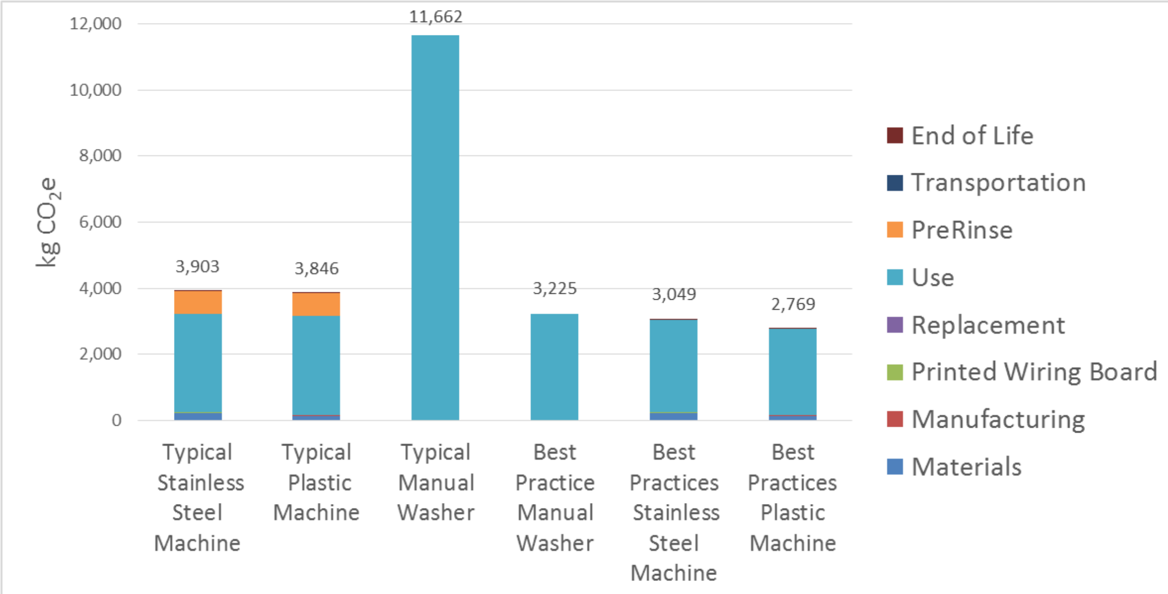


Figure 33-*Base Case but with MROE Grid*

APPENDIX J- Base Case with Natural Gas Water Heater

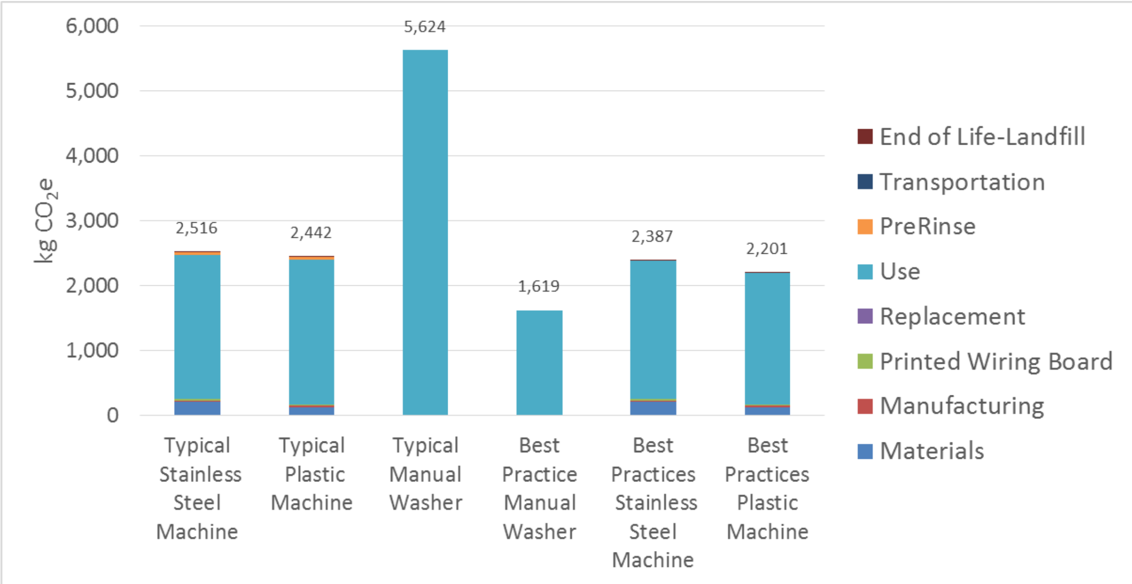


Figure 34-*Base Case but with natural gas water heater*