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LETTER

# A guide to household manual and machine dishwashing through a life cycle perspective

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## Abstract

This study evaluates and provides guidance on improving the life cycle environmental performance of dishwashing in the typical U.S. household. Typical user behaviors and recommended best practices for manual dishwashing as well as machine dishwasher use are evaluated. A sensitivity analysis shows the influence of varying grid carbon intensity, water heater type, regional water scarcity, and behaviors such as pre-rinsing and machine loading on overall results. Use-phase behaviors are observed through a small-scale laboratory study. Dishwashing following typical manual and machine practices produces 5,620 and 2,090 kg $CO_2$e life cycle greenhouse gas (GHG) emissions respectively based on washing 4 loads (8 place settings per load) a week for 10 years. Avoiding typical behaviors like pre-rinsing and selecting heated dry can decrease life cycle GHG emissions for machine dishwashing by 3% and 11%, respectively. The running tap style of manual dishwashing results in the highest life cycle GHG emissions of the alternatives in the lab study. Manual dishwashing has the potential to have the lowest GHG emmisions (1,610 kg) when recommended behaviors are followed, less than the 1,960 kg $CO_2$e for recommended machine dishwasher use. When life cycle water consumption burdens are evaluated, typical manual and machine dishwashing use 34,200 and 16,300 gallons respectively and these results are contextualized to regions with different water scarcity. A life cycle cost (LCC) analysis finds that machine dishwashing costs more than manual dishwashing over a 10-year lifetime even if best practices are followed. However, when a user's time spent washing is valued, machine dishwashers pay for themselves within a year of use.

## 1. Introduction

Machine dishwashers are unique household appliances because they can be substituted by manual dishwashing. Market penetration reports indicate that 84% of machine dishwashers shipped in 2015 achieved Energy Star standards [1]. Although 80% of households in the U.S. own a machine dishwasher, 20% use the appliance less than once a week [2]. The U.S. Department of Energy (DOE) estimates a typical household washes 215 loads annually [3]. These findings suggest that machine dishwashers are underutilized appliances with dishes often being washed manually. European studies characterized three different styles of manual dishwashing [4]. 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, initially running the tap to fill the wash tub/sink. Rinsing may occur in another tub/sink or with minimal running under the tap. Combination washers use both a water bath and a running tap for washing and/or rinsing.

Existing literature comparing manual and machine dishwashing indicates that time, energy, and water savings result from using a machine dishwasher instead of manually dishwashing [4–8]. (The testing conditions

**Table 1.** Performance standards for standard-sized residential machine dishwashers.

| Standard | Annual energy use (kWh/yr) | Water use per cycle (gal/cycle) |
|---|---|---|
| Federal[a] | 307 | 5 |
| Energy Star[b] | 270 | 3.5 |
| Stainless Steel[d] | 270 | 3.5 |
| Plastic[d] | 270 | 3.5 |
| Energy Star Most Efficient[c] | 240 | 3.2 |
| Max Tech[a] | 180 | 2.2 |

[a] Federal Energy Conservation Standards for residential dishwashers [12, 13].
[b] Energy Star Program Requirements. [14].
[c] Energy Star Most Efficient recognition in 2019 requires that machines reach a minimum Cleaning Index of 70 [15].
[d] The stainless steel and plastic machines in this study meet minimum Energy Star standards.

and results from these studies are summarized in the supporting information (SI) tables S12–14, available online at stacks.iop.org/ERC/2/021004/mmedia). However, these European studies compared typical manual dishwashing to standard testing procedures for machine dishwashers, which may not be representative of actual typical machine use behaviors such as pre-rinsing, incorrect loading patterns, and varying cycle selection. In fact, surveys indicate that 75% of machine dishwasher owners rinse their dishes prior to loading [9]. Pretreatment of dishes includes scraping, washing, or rinsing dishes before loading into a machine dishwasher. Previous studies also did not consider environmental burdens from life cycle phases beyond the use phase, so burdens from manufacturing and disposal of machines were not included.

This study provides a full life cycle assessment (LCA) of manual and machine dishwashing in the U.S. To address the variability of user behaviors and varying regional energy and water sources, sensitivity analyses were conducted to evaluate the impacts of input parameter variation. Finally, a life cycle cost (LCC) analysis was conducted to determine the financial burdens of these dishwashing methods.

## 2. Methods

### 2.1. Goal

This study utilizes LCA to consider environmental burdens in the life cycle phases from materials production, to manufacturing and assembly, through use, and end-of-life (EOL) management for different household dishwashing methods. These phases are modelled on GaBi LCA software and incorporate information from databases, literature review, and observational data. Life cycle burdens quantified include GHG emissions (kg $CO_2$e), blue water consumption (kg water), user deprivation potential ($m^3$), waste production (kg), and primary energy use (MJ). A sensitivity analysis aims to capture the possible range of life cycle burdens that result from changing behaviors, energy sources, and regional water scarcity. An LCC analysis and sensitivity analysis is used to evaluate cost of dishwashing methods.

### 2.2. Scope

This study extends to all life cycle phases of manual and machine dishwashing in the U.S. Two typical residential machine dishwashers produced by our industry collaborator are evaluated: lightweight plastic tub Whirlpool WDF354 PAH and heavier and more expensive high-end stainless steel tub Kitchen Aid KDTM354ESS (specifications in table S1 in the SI). Both are Energy Star certified [3, 10], and are traditional dishwashers (standard-sized and not smart), a category with the largest share (50%) of the products sold [11]. As mentioned, 84% of residential machines dishwashers sold are Energy Star certified and consumers purchase these appliances with the intention of minimizing their resource consumption. Table 1 summarizes current federal standards for machine dishwashers and the machine dishwasher models selected in this study are seen to be typical for their class. Figures S1 and S2 show the system boundary for machine dishwashers and manual dishwashing. Since both methods of dishwashing use a sink and water heater, manufacturing burdens for these components are excluded.

A small-scale laboratory study was conducted to help characterize use phase dishwashing practices and provided measurements of energy and water use for typical and recommended practices for both manual and machine dishwashing. Detailed descriptions of these practices are provided in the use phase methods section below.

There are factors beyond the scope of this analysis that can also affect sustainability performance. Plastic dishware should be loaded on the upper rack to minimize degradation of both the dish and interior of the machine. Users may wait longer before washing than the two hours specified in the American National Standards Institute/Association of American Home Appliance Manufacturers (ANSI/AHAM) tests. Users may also improperly load their machines resulting in dishes needing to be rewashed. This analysis did not evaluate how loading patterns or delays in washing effect cleaning performance outcomes. External factors such as water hardness have been investigated in other research and may reduce the service life of a machine if scaling is not removed regularly [16]. Future work should investigate how poor cleaning performance resulting from hardness influences pretreatment behaviors and detergent choice, as well as optimal replacement strategy and use of smart dishwashers [11].

#### *2.2.1. Functional unit*

Machine dishwasher manufacturers must comply with the DOE provisions for consumer products outlined in the electronic Code of Federal Regulations (eCFR) [13]. Dishwashers are 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 typical test load includes plates, cups, bowls, platters, glasses, and flatware that are soiled according to ANSI/AHAM DW-1–2010 standards. In response to user concerns about tougher soils, Whirlpool has developed more combinations of soil and dishware in addition to the standard ones. A picture and list of the normally-soiled dish load used in this study are shown in the SI figure S3 and table S2.

The service life of a machine dishwasher is approximately 10–13 years [17–19]. While Energy Guide labels assume four wash loads a week (208 annual uses), the DOE assumes 215 annual uses [3, 13]. The functional unit for this study is washing a full load of normally-soiled dishes (8 place settings) 215 times annually for 10 years. This functional unit assumes cleaning performance equivalency between machine dishwashers and manual dishwashing, an assumption validated by study results.

#### *2.2.2. Environmental impact indicators*

The five impact indicators highlighted in this study are selected since they are most often reported and are most reliable based on the quality of available data. The first indicator is life cycle GHG emissions (kg $CO_2$e), characterized using EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1), which uses 100-year global warming potential (GWP) [20]. The second indicator is life cycle blue water consumption in kilograms (kg) which is ground and surface water that leaves its watershed to be applied in a new system [21]. This metric includes upstream water use such as water needed to produce materials or electricity. The third indicator uses the Available Water Remaining (AWaRe) model to report user deprivation potential (UDP) in units of cubic meters ($m^3$) for different regions where water is used and characterizes how individual consumption affects others who use the same source of water. The fourth indicator is life cycle primary energy in megajoules (MJ) which measures the energy extracted from nature for fuels and feedstocks. Fifth, solid waste produced in (kg) is quantified.

### 2.3. Life cycle inventory

A process-level approach was used to produce the cradle-to gate inventory for the two machine dishwasher models evaluated. Whirlpool provided the Bill of Materials (BOM) for both models.

#### *2.3.1. Material production*

The BOMs provide material breakdowns for each dishwasher model, which can be found in table 2 for the stainless steel tub model and in table S2 for the plastic tub model. More than half the mass of the stainless steel dishwasher is metal, the majority being stainless steel. The next most significant material contribution is the mastic sound-dampening insulation that surrounds the tub. Plastic pieces account for 24% of the product mass. Printed circuit boards and wiring harnesses account for less than 3% of the machine dishwasher's total mass. The SI includes results for the plastic tub machine. These tables indicate that mass captured in the model is more than 95% of the total mass of both machines [22].

#### *2.3.2. Manufacturing and assembly*

Material fabrication processes such as stamping and injection molding and scrap rates were modeled based on database sources and calculations provided in table S4.

The Whirlpool manufacturing factory in Findlay, Ohio exclusively produces machine dishwashers and incorporates renewable energy into its operations by sourcing from a nearby wind farm. Approximately 22% of

**Table 2.** Material by mass for stainless steel tub machine dishwasher model.

| Material | Mass | |
|---|---|---|
| | (kg) | (%) |
| Plastic | | |
| Polypropylene (PP) | 4.34 | 9.57 |
| Low Density Polyethylene (LDPE) Film | 2.19 | 4.82 |
| Polyethylene Terephthalate (PET) | 1.02 | 2.26 |
| Nylon | 0.70 | 1.55 |
| LDPE Resin | 0.67 | 1.47 |
| Polystyrene (PS) | 0.51 | 1.13 |
| Polyoxymethylene (POM) | 0.34 | 0.75 |
| EPDM/Rubber | 0.48 | 1.06 |
| Polypropylne/Ethylene Propylene Diene Terpolmyer (PP/EPDM) | 0.22 | 0.48 |
| Poly(p-phenylene oxide)/Polystyrene (PPO/PS) | 0.18 | 0.39 |
| Polyvinyl Chloride (PVC) | 0.12 | 0.26 |
| High Density Polyethylene (HDPE) | 0.12 | 0.25 |
| Acrylonitrile butadiene styrene (ABS) | 0.05 | 0.12 |
| Thermoplastic polyurethane (TPU) | 0.04 | 0.08 |
| Polycarbonate-Acrylonitrile butadiene styrene (PC-ABS) | 0.03 | 0.07 |
| Polycarbonate (PC) | 0.01 | 0.02 |
| Vinyl | 0.001 | 0.002 |
| Total | 11.01 | 24.26 |
| Metal | | |
| Stainless Steel | 19.4 | 42.6 |
| Galvanized Steel | 4.34 | 9.57 |
| Zinc | 0.22 | 0.49 |
| Aluminum | 0.17 | 0.36 |
| Copper | 0.15 | 0.33 |
| Total | 24.3 | 53.39 |
| Other | | |
| Mastic | 6.96 | 15.3 |
| Cardboard | 1.43 | 3.14 |
| Wood | 0.86 | 1.89 |
| Wiring Harness | 0.43 | 0.94 |
| Pulp | 0.25 | 0.54 |
| Printed Circuit Board (PCB) | 0.23 | 0.51 |
| Total | 10.14 | 22.35 |
| TOTAL MODELLED MASS | 45.39 | 100.00 |
| TOTAL MACHINE MASS FROM MANUFACTURER | 47.17 | |

the annual energy requirement needed by the plant is sourced from wind turbines [23] and the remainder was modeled using the fuel mix of the Ohio electrical grid. 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 by the facility [24] (figure S4).

Given annual machine dishwasher production for the plant, the process-level (bottom-up) base case results were checked against annual facility-level (top-down) data that summarized volumetric inputs and outputs for the facility as a whole as described in the SI.

### 2.4. Use

A small-scale observational laboratory study and a survey were completed to gather data for the use-phase model. Manual and machine dishwashing were each evaluated following recommended and typical behaviors. For each scenario, water consumption, water temperature, soap consumed, and time were recorded. Cleaning performance was assessed by dishwashing team graders and related calculations are described in the SI.

#### *2.4.1. Recommended machine dishwasher use*

Testing of machine dishwashers has a standardized procedure known as the DOE Uniform Testing Procedures found in the eCFR [13]. Best recommended practices (for optimal performance) for machine dishwasher use are sourced from manufacturer's instructions in owner's manuals and Energy Star recommendations [9]. The manual includes a diagram that demonstrates optimal loading of the machine as well as recommends 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 the default setting on machines modelled. The Energy Star website and owner's manuals advise to avoid pre-rinsing [25]. The stainless steel and plastic tub machines were each tested on the normal and heavy cycles three times following the Uniform Testing Procedures.

#### *2.4.2. Recommended manual dishwashing*

Best recommended practices for manual dishwashing are sourced from literature and describe a two-basin dishwashing method where dishes are soaked and scrubbed in hot water, rinsed in cold water, and are air dried [7]. These steps are summarized in figure S5. Participants were trained on best practices and then asked to manually wash a load of normally soiled dishes.

#### *2.4.3. Typical machine dishwasher use*

Typical behaviors for machine dishwasher use may include sub-optimal loading patterns and pretreatment. The only pretreatment recommended in the owner's manual is scraping food off dishes without pre-rinsing [26]. Participants were asked to load a machine dishwasher as they typically would at home.

#### *2.4.4. Typical manual dishwashing*

Typical behaviors for manual dishwashing are categorized into one of the three different styles from literature (running tap, water bath, combination) [4]. Participants were asked to manually wash the test load and were categorized by observers.

#### *2.4.5. Observational study details*

Forty-three participants were invited from within the Benton Harbor Whirlpool campus. Demographics for this group are summarized in figure S16. Forty participants were asked to first load a machine dishwasher as they typically would at home, then to manually wash as they typically would at home, and finally to answer survey questions related to their dishwashing behaviors. Three other participants were asked to manually wash following best practices. The sample size of selected employees is small (SI) but use-phase results are corroborated by previous studies (tables S12–S14). The testing room was intended to replicate a common kitchen sink area in the average household (figure S6), and contains a two-basin sink with a single-handle tap. Hot and cold water temperature and volume supplying the sink were metered. Before beginning the tasks, participants were asked to set up the test station to resemble their kitchen sink at home using an assortment of tools provided. All four scenarios were tested using the test load described in the functional unit.

Using the recorded metrics, energy requirements were calculated as explained in the SI. Energy for manual dishwashing includes only energy to heat water while energy for machine dishwashers includes energy for running the machine during use, heating water, the heated dry cycle, and standing-by when not in use. Inputs such as water, energy, rinse aid, soap, and cleaning tabs are included in the model (figures S7 and S8). Calculations for additional inputs like sponges, and towels are described in the SI.

### 2.5. End-of-Life

Unlike in other countries, there is no federal legislation in the U.S. that mandates recycling of appliances. There is also no U.S. federal mandate for Extended Producer Responsibility (EPR) that requires Original Equipment Manufacturers (OEMs) to establish 'take-back' schemes or similar programs for recovery of appliances. White goods (like machine dishwashers) can be recycled by commercial facilities and other programs, and it was found that 62 percent of major appliances were recycled in the U.S. in 2015 [27]. White goods can also end up in a landfill in states that have not banned this action [27].

The end-of-life for a machine dishwasher depends on regional access to recycling facilities. When recycled, machine dishwashers are shredded and then ferrous metals are separated magnetically [28, 29]. Recycling centers prefer receiving steel tub rather than plastic tub dishwashing machines since they contain more metal that can be sold to material processors. Plastic, nonferrous metals, and other separated materials are sent to landfill. The SI discusses the calculations for modelling recycling and landfilling of machine dishwashers.

### 2.6. Life cycle cost (LCC) analysis

An analysis of a washing machine found that the use phase contributes the most to the total cost of ownership (TCO) [30]. The scope of the LCC analysis for this study includes purchase price, maintenance and replacement part costs, annual cost of consumables, and annual cost of utilities. The LCC uses the same base case scenario as the LCA and initially assumes typical household dishwashing behaviors. (These are explained in the results section). Inflating annual utility rates for water, sewage, electricity, and natural gas are shown in table S6. Inflating costs for dishwasher detergent, rinse aid, and manual dishwashing liquid soap are shown in tables S7 and S11 based on a −0.478% inflation rate, derived from an average of the previous ten years for household cleaning products [31]. The discount rate for a machine dishwasher is assumed as 4.5% and yearly discount factors are shown in table S5 [32]. The fixed initial cost for the machines is based on the Manufacturers Suggested Retail Price (MSRP), which is includes the cost of installation; MSRP is typically higher than actual retail prices with installation included. Costs for replacement parts and pre-rinsing are summarized in tables S9 and S10. Corresponding equations, tables, rates, and calculations for the LCC are explained in the SI.

The LCC will present results for the base case following typical behaviors as well as a sensitivity analysis if best practices were followed, if households already own the machine, and if time saved by loading a machine instead of manual dishwashing is valued.

## 3. Results

### 3.1. Cradle-to-gate comparison of machine models

The cradle-to-gate burdens as GHG (kg $CO_2$e), primary energy, blue water consumption, and waste production for producing machine dishwashers are mainly due to material production (figures S9–S12). The stainless steel machine weighs more and has 53% higher overall cradle-to-gate GHG emissions than the plastic machine. On the other hand, the injection molded plastic tub machine has higher manufacturing burdens than the stainless steel tub machine.

### 3.2. Observational laboratory study outcomes

Resource consumption and cleaning scores from dishwashing behaviors are summarized in table 3. Observation of typical manual dishwashing behaviors indicated that of the 37-person study group, 43% of participants use the combination, 41% run the tap, and 16% practice the water bath style. The majority (80%) of participants air dried their dishes. The three participants who manually washed following best practices were asked whether or not they would be willing to adopt these behaviors. Two participants responded that they had already established their own habits and stated that they did not like rinsing dishes with cold water. Of the 38 participants who loaded a dishwasher as they typically would in their household, approximately 74% pretreated their dishes with water (pre-rinsed), approximately 24% did no pretreatment, and approximately 3% pretreated dishes by scraping food off. Loading of the machine varies from the manufacturer's recommended arrangement (figure S14). When asked what cycle they typically run on their machine dishwashers, participants responded that they mostly select the normal cycle (figure S14). Fifty-four percent of participants stated that they wash and dry dishes when using their machines. Only 16% of respondents stated they have machines older than 10 years.

Figure S15 in the SI shows the distribution of energy needed by machine dishwashers to wash one normally-soiled test load and indicates that the majority of energy involved with machine dishwashing is associated with the energy required to heat water.

Table 3 indicates that both the machine dishwashers and almost all of the manual dishwashing participants scored above the DOE acceptable standard of 70 AHAM Cleaning Index and can be assumed to be functionally equivalent. However, the cleaning scores illustrated here demonstrate manual dishwashing has much more variability in the range of scores received while machines had less variability. Running tap washers used more energy and more water than any other method of dishwashing.

### 3.3. End-of-life models

For the stainless steel and plastic dishwashers, landfilling results in GHG emissions of 2.7 and 2.8 kg $CO_2$e, respectively. Recycling results in 1.9 and 2.2 kg $CO_2$e, respectively. figure S17 in the SI shows the main drivers of recycling burdens are mainly recycling processes including shredding and sorting. Since recycling machine dishwashers recovers ferrous metal pieces, there are still plastic and other materials going to the landfill. The stainless steel machine dishwasher has a significant portion of non-plastic wastes (such as dampening mastic) that contribute to landfill emissions.

**Table 3.** Average observed resource use and cleaning scores for cleaning a normally-soiled (8 place setting) test load, with confidence intervals[i].

| Method of Washing | | | Sample Size | Time[h] (min) | Water (gal) | Energy[a] (kWh) | Soap (g) | Clean Score[b] |
|---|---|---|---|---|---|---|---|---|
| Manual[c,d] | | Combination | 15 | 33.2 ± 3.6 | 12.8 ± 2.8 | 2.46 ± 0.6 | 26.8 ± 11.1 | 88 ± 3.1 |
| | | Running Tap | 16 | 44.7 ± 7.8 | 22.8 ± 5.5 | 3.02 ± 0.9 | 20.9 ± 6.6 | 87 ± 4.7 |
| | | Water Bath | 6 | 38.7 ± 8.3 | 6.9 ± 1.5 | 1.22 ± 0.4 | 13.0 ± 6.3 | 94 ± 3.7 |
| | | Best Practices[e] | 3 | 44.3 ± 8.6 | 9.5 ± 3.6 | 0.68 ± 0.5 | — | 95 ± 2.5 |
| Machine[f] | Operation | Stainless Steel Normal | 3 | 118.0 ± 0.0 | 3.5 ± 0.0 | 1.56 ± 0.0 | 15.4 ± 0.0 | 88 ± 1.2 |
| | | Stainless Steel Tough | 3 | 148.0 ± 1.3 | 5.5 ± 0.0 | 2.26 ± 0.0 | 15.4 ± 0.0 | 90 ± 0.2 |
| | | Plastic Normal | 3 | 134.0 ± 0.7 | 3.0 ± 0.3 | 1.44 ± 0.1 | 15.4 ± 0.0 | 83 ± 4.0 |
| | | Plastic Heavy | 3 | 155.0 ± 0.7 | 7.5 ± 0.0 | 2.46 ± 0.0 | 15.4 ± 0.0 | 87 ± 0.7 |
| | Loading[g] | Pre-rinsing and soaking | 28 | 13.8 ± 2.4 | 3.5 ± 1.0 | 0.53 ± 0.2 | 5.3 ± 3.0 | — |
| | | No Pretreatment | 9 | 8.8 ± 2.3 | — | — | — | — |
| | | Pretreatment by scraping | 1 | 6.0 ± 0.0 | — | — | — | — |

[a] Energy for machines includes energy to run, dry, standby, and heat water (using natural gas).
[b] Cleaning scores calculated from ANSI/AHAM DW-1-2010.
[c] Thirty-seven participants were categorized into three manual dishwashing styles and loaded a machine dishwasher.
[d] Three outliers for typical manual dishwashing of forty participants were not included in the results.
[e] Three other participants manually washed following best practices (water bath with cold water rinse).
[f] Each machine cycle test was replicated three times.
[g] Thirty-eight participants were categorized by loading behavior, two outliers for the loading behaviors were not included in the results.
[h] Time includes user's time for manual washing and machine loading behaviors, and cycle time for machines. User's time used in life cycle cost calculations.
[i] The confidence intervals assume a normally distributed sample with alpha equal to 0.05.

### 3.4. Base case scenario

A base case scenario is created to evaluate environmental performance of dishwashing in a typical household in the U.S. Natural gas water heating (51% of households) [33] and the U.S. national average electrical grid carbon intensity from eGRID are assumed for use-phase modelling [34]. Typical behaviors are modelled based on observations in the laboratory study and responses from the survey-average observed values for each style are used in calculations. Dishes washed manually are assumed to air-dry. Typical users of machine dishwashers are assumed to pre-rinse dishes and select heated dry, as observed in the laboratory study and survey responses. Machines are assumed torun at 100% capacity although observation indicates only 93% of participants were able to fully load the machine. Monthly cleaning tablets and yearly vinegar cleaning cycles are also included. Replacement parts including rack adjusters, spray arm hubs, and inlet vales are assumed to be replaced once during the machine dishwasher's service life of 10 years. Machines are assumed to be recycled. Life cycle environmental burdens are calculated using the system boundaries discussed in the methods section. Results for life cycle burdens as GHG (kg $CO_2$e) are shown in figure 1 for 2150 life cycle loads following typical behaviors. The use phase drives emissions across the entire life cycle for both manual and machine dishwashing. Even when typical behaviors such as pre-rinsing are followed, manual dishwashing still results in higher life cycle emissions. Express cycles produce more emissions than tough cycles.

#### *3.4.1. Simplified base case scenario*

For the simplified base case, the stainless steel model is used to represent machine dishwashers where selected cycles for machines are weighted proportionally to survey responses (figure S15). Similarly, a weighted average from the three manual dishwashing styles represent typical behaviors. For the simplified base case scenario, typical machine dishwasher use and manual dishwashing produce 2,090 and 5,620 $CO_2$e respectively (figure S18). The sensitivity analysis that follows will be based from these two values. Figures S19–S21 show the simplified base case results using other environmental metrics.

### 3.5. Sensitivity analysis for LCA

A sensitivity analysis was conducted on the simplified base case scenario to explore how life cycle emissions are affected by changing energy sources and typical behaviors. Recommended best practices were also investigated to illustrate how ideal dishwashing impacts life cycle performance. Finally, a sensitivity analysis regarding water stressed regions was done.

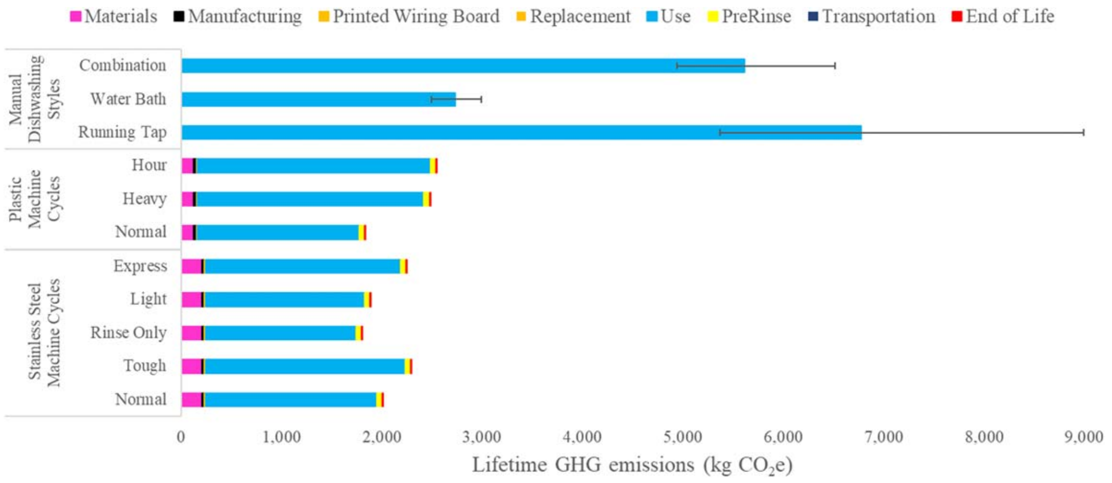


**Figure 1.** Life cycle GHG emissions for typical household dishwashing. Natural gas water heating and U.S. average electrical grid is assumed for 2150 life cycle loads. Typical behaviors for machines include pre-rinsing. Typical behaviors for manual dishwashing include air drying. Error bars shown for manual dishwashing styles indicate the range (maximum and minimum) of life cycle emissions. Tested machine cycles show minimal variation in water and energy consumption.

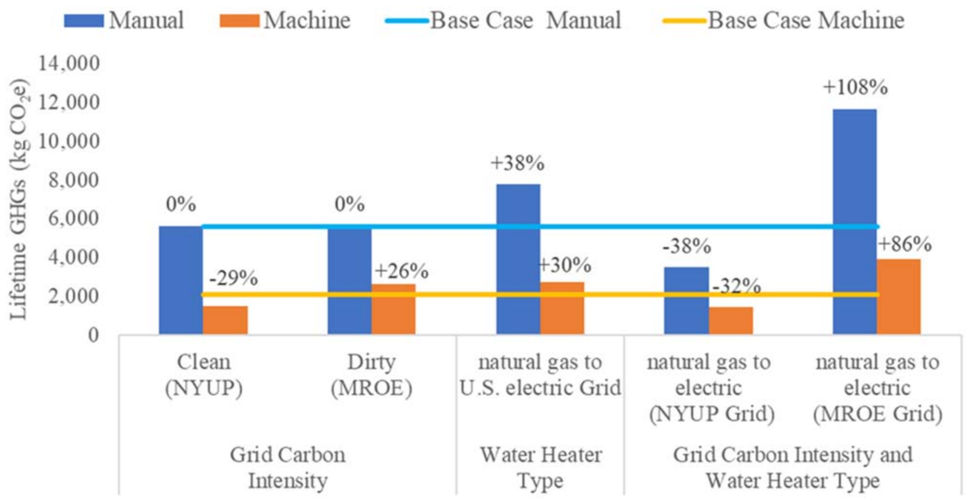


**Figure 2.** Varying eGRID subregion carbon intensity and water heater type. (Manual dishwashing is not affected by the grid carbon intensity since the base case assumes natural gas water heating). Base case emissions for manual and machine dishwashing are 5,620 and 2,090 kg $CO_2$e, respectively. The base case assumes natural gas water heating and average U.S. grid carbon intensity.

#### *3.5.1. Energy source*

The energy for machine dishwasher use and manual dishwashing depends on type of water heater used and electricity impacts change with grid carbon intensity. Figure 2 shows how these changes impact life cycle GHG emissions (the base case is represented by the lines). Changing the grid carbon intensity can reduce emissions from machines by 29% (NYUP grid) or increase them by 26% (MROE grid). If the base case water heater assumption is changed from natural gas to electric, life cycle emissions increase by 38% and 30% for manual and machine dishwashing, respectively. An electric water heater powered by the most carbon intense grid increases life cycle emissions by 108% and 86% for manual and machine dishwashing respectively. When considering emissions from water heater options, using an electric water heater rather than using natural gas results in lower GHG emissions in only four of 26 eGRID subregions (table S15).

#### *3.5.2. Typical behavior changes*

There is a very small increase in life cycle emissions if manual dishwashers opt to towel-dry instead of air-dry dishes (0.07%). Cotton towels are assumed to be machine washed and machine dried on a weekly basis (as described in the SI). Material burdens for manufacturing are included.

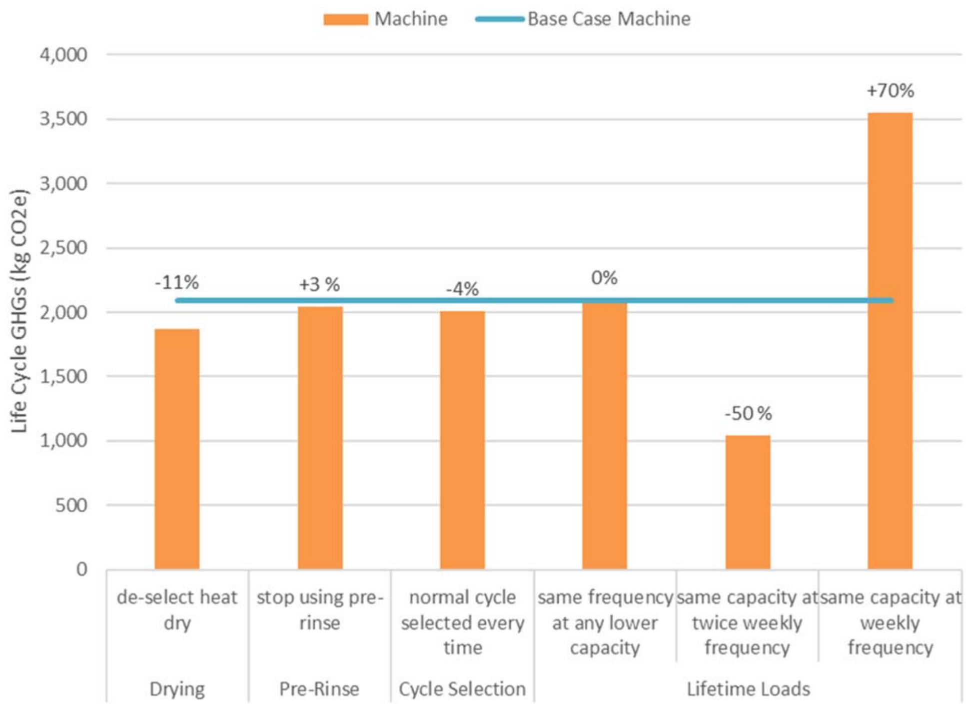


**Figure 3.** Varying parameters for machine dishwashing. The base case is 2,090 kg $CO_2e$ life cycle GHG emissions assuming the U.S. electrical grid and natural gas water heating. Pre-rinsing, heat dry and normal cycle selection is assumed in the base case.

Figure 3 shows machine dishwasher parameter changes and their impact on life cycle emissions. If the dry cycle is de-selected for every run of a machine dishwasher, between 399 and 495 kWh of energy can be saved over its life time (figure S14). Using the average U.S. grid, this can result in life cycle emissions reduction of 11%. Pre-rinsing is not recommended and as seen from the cleaning results, is not necessary for machine dishwashers to achieve acceptable cleaning scores. Avoiding pre-rinsing reduces life cycle emissions by 3%. Survey respondents stated that they do not always select a normal cycle as was modelled in the base case. If the normal cycle was selected for every load during the life cycle, emissions can be reduced only 4%.

*3.5.3. Load size and frequency*

Previous studies found that people believe that a smaller household size does not justify using a machine [4]. Surveys indicate that the average U.S. household is only 2.54 people [9]. This household may choose to either wash dishes in their machine at the same frequency but at a lower capacity or wash less frequently at full capacity. If they choose to wash at the same frequency, then the results will be the same as in the base case since results have been normalized per load (figure 3). However, if this household chooses to wash only when the machine is full, then they will wash one fully loaded dishwasher (8 place settings) less frequently. The impacts of these two alternatives are shown in figure 3 and table 4.

Life cycle emissions are based on the recommended and conservative assumption of a 10-year lifetime. However, if consumers keep their machines longer, they can further reduce their emissions per place setting.

*3.5.4. Recommended best practices*

This study aims to create a robust evaluation of household dishwashing by comparing recommended best practices to typically observed behaviors. Figure 4 demonstrates under typical behaviors in a small-scale lab study, machine dishwashers produce 63% less GHG emissions over their life cycle than manual dishwashing. Pre-rinsing accounts for only 3% of life time burdens, while the use phase (including pre-rinsing) accounts for 88%, and cradle-to-gate burdens account for 12%. Under recommended best practices, manual dishwashing produces less (18%) life cycle GHG emissions than machine dishwashing. If manual dishwashers switched from typical to recommended practices, they could reduce emissions by 249%. However, two of the three participants who manually washed dishes following recommended behaviors stated that they would not adopt this technique. Typical machine dishwasher users can reduce emissions by 11% by switching to best practices.

An important case to consider is the 80% of U.S. households that already own a machine dishwasher but opt to manually wash [2]. If these households switched from typical manual to recommended machine dishwashing behaviors, they could reduce their life cycle emissions by 65% and use-phase emissions by 70% when machine

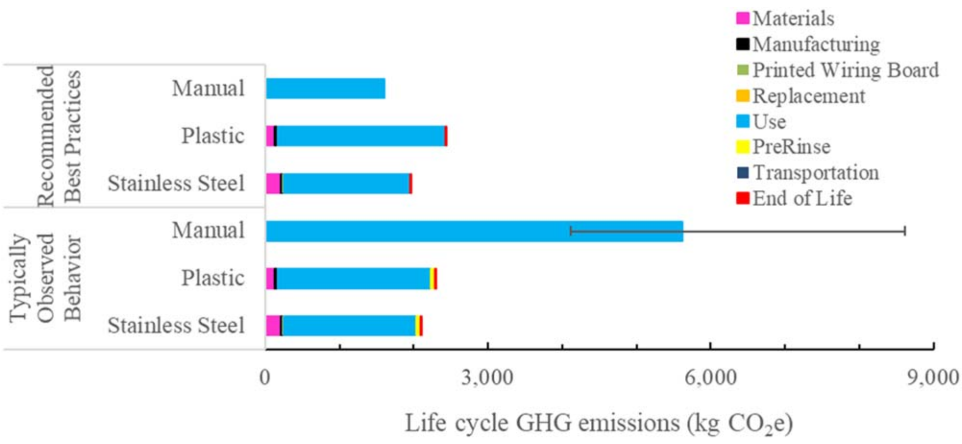


**Figure 4.** Typical and recommended behaviors for manual and machine dishwashing. Life cycle GHG emissions depicted. Natural gas water heating and U.S. average electrical grid is assumed for 2150 life cycle loads. Typical behaviors are weighted averages of observed typical behaviors and survey responses. Typical behaviors for machines include pre-rinsing while recommended behaviors exclude it.. Tested machine cycles have minimal variation. Participants who manually washed following recommended behaviors showed minimal variation (not shown).

**Table 4.** Dishwashing burdens normalized per place setting.

| | | Capacity | | Frequency | |
|---|---|---|---|---|---|
| | Base Case[a] | ½ | ¼ | Daily | ½ |
| Capacity (place settings per load) | 8 | 4 | 2 | 8 | 8 |
| Frequency (loads/week) | 4.13 | 4.13 | 4.13 | 7 | 2.07 |
| LC Loads | 2,150 | 2,150 | 2,150 | 3,640 | 1,075 |
| LC place settings (ps) | 17,200 | 8,600 | 4,300 | 29,120 | 8,600 |
| LC GHG per ps (kg $CO_2$e/ps) | 0.12 | 0.24 | 0.49 | 0.12 | 0.12 |
| LC GHG[b] (kg $CO_2$e) | 2,090 | 2,090 | 2,090 | 3,550 | 1,050 |

[a] Base case is 8 normally soiled place settings and frequency of 215 annual loads (4.13 weekly loads) for 10 years.

[b] Life cycle emissions include cradle-to-grave burdens.

dishwasher production burdens are excluded. Behavioral barriers will be hardest to overcome because people believe that manual dishwashing is better in terms of resource consumption and cleaning performance. Studies showed that 45% of people do not own a machine because it is too expensive and 24% believe it is more resource efficient [4]. In the survey from this study, 28% of respondents believe manual dishwashing has superior cleaning performance.

*3.5.5. Water used throughout value chain*

A life cycle inventory (LCI) of water needed for typical machine dishwasher use under the base case scenario indicates 16,300 gallons of water use where 0.8% is used for manufacturing, and 99.8% in the use phase. Typical manual dishwashing under the base case scenario results in 34,200 gallons of water use, all during the use phase.

Under the base case life cycle, typical manual dishwashing consumes 1,320 kg (347 gal) of blue water while typical machine dishwashers use 10,600 kg (2,790 gal). For machine dishwashers, material production requires 10%, manufacturing requires 2%, electricity needed in the use phase requires 74%, pre-rinsing requires 2%, and the remainder of the use phase requires 11%. For manual dishwashing, 100% of the blue water is consumed during the use phase.

*3.5.6. Geographic sensitivity to water use*

Although the metrics just described indicate how water is used within the system boundaries, the impacts have not been contextualized to where this water is being used. Regional impacts for water use can be assessed by using characterization factors from the Available Water Remaining (AWaRe) model (details in the SI). Characterization factors measure water use relative to water scarcity in a region. A high characterization factor indicates a water-stressed region while a low characterization factor indicates a less water-stressed region. In table 5, the high characterization factor is from the southwest U.S., the low characterization factor is from the

**Table 5.** AWaRe outcomes (as UDP) for use phase water consumption of one household for 2150 lifecycle uses.

| | | | Characterization Factor ($m^3/m^3$) | | |
|---|---|---|---|---|---|
| | | | High 100 | Average 33.1 | Low 0.14 |
| User Deprivation Potential ($m^3$) | Base Case | Manual | 12,900 | 4,290 | 18 |
| | | Machine | 6,180 | 2,050 | 9 |
| | Best Practices | Manual | 1,980 | 657 | 3 |
| | | Machine | 739 | 245 | 1 |

**Table 6.** Best-and worst-in-class for Energy Star certified standard-sized residential machine dishwashers.

| | Best-in-class | Stainless Steel[b] | Plastic[b] | Worst-in-class |
|---|---|---|---|---|
| Annual Energy Use[a] (kWh) | 199 | 270 | 270 | 307 |
| Annual Energy Cost ($) | 12.0 | 32.0 | 32.0 | 41.0 |
| Annual Emissions (kg $CO_2$e) | 373 | 505 | 505 | 575 |
| Water use per cycle (gal) | 1.95 | 3.50 | 3.50 | 5.00 |

[a] Annual Energy Use and Annual Energy Cost are based on electric water heating.
[b] The stainless steel (KDTM354ESS) and plastic (WDF330PAH) are the models selected in this study.

lower Mississippi, and the average is the average U.S. value. Multiplying the characterization factor by the volume of water used results in the User Deprivation Potential (UDP), with lower values indicating less water stress (i.e., more water available for other uses after washing dishes). The base case water consumption used here is the water consumed during the use phase under typical behaviors.

Table 5 contains the UDP values for using a stainless steel machine dishwasher in regions of the U.S. with different water scarcity characterizations. By switching from typical practices to recommended behaviors, manual and machine dishwashing UDP can be reduced by 85% and 88% respectively. If a household changes from base case typical manual dishwashing to recommended machine dishwashing, UDP can be reduced by 94%.

#### *3.5.7. Machine dishwasher market*

Table 6 compares the dishwashers observed in this study against the best and worst in class for similar machines. The best in class machine can reduce annual use-phase emissions by 26% and water use by 44% when compared to the machines in this study, which furthers the advantage of the machine dishwasher over manual dishwashing. The worst in class machine increases annual use-phase emissions by 14% and annual water use by 43%.

### 3.6. Life cycle cost analysis

When following base case typical behaviors, the cumulative cost of the stainless steel machine, plastic machine, and manual dishwashing at the end of the 10-year lifetime are $2,600, $1,770, $1,560 respectively. Costs for the machines include purchase, maintenance, consumables, and replacement parts in addition to pre-rinsing which costs approximately $30 annually. At 13 years, the cumulative cost of a plastic machine breaks even with manual dishwashing. Notably, the annual costs for utilities and consumables for the machines are less than manual dishwashing. However, the high initial cost of the machines outweighs these savings.

#### *3.6.1. LCC sensitivity*

If best practices are assumed, the cumulative costs of the stainless steel machine, plastic machine, and manual dishwashing at the end of the 10-year lifetime are $2,240, $1,660, $1,180 respectively. The biggest savings are possible by adopting recommended best practices for manual dishwashing.

The cost of labor is an important criterion because the majority of participants in this study (67%) responded that their main reason for owning a dishwasher is because it saves time. If time spent doing physical work for dishwashing is valued at the average hourly income in the U.S. ($23.4/hr), annual operating costs can be reduced by up to $2,590 if users switch from typical manual dishwashing behaviors to best practices for loading a machine dishwasher [35]. (The time considered for machine dishwashing is time spent loading without pre-rinsing and for manual dishwashing this includes washing and time spent towel drying. Cycle run-time, air drying, and putting away dishes are not included.) If these valued time savings are included in the LCC, then under the base case typical behaviors, the stainless steel and plastic machines would breakeven with manual dishwashing within a year of use. The SI discusses tradeoffs with time used for dishwashing.

Literature review indicates that 80% of households in the U.S. already own a machine dishwasher [2]. If initial purchase of the machine is excluded, at the service life of 10 years, the cumulative cost of the stainless steel, plastic, and manual dishwashing following typical behaviors are $1,450, $1,190, and $1,560 respectively. Then, plastic and stainless steel machine dishwasher models break even with manual dishwashing at around 7.5 and 4 years respectively.

## 4. Discussion

This study seeks to improve environmental performance of typical household dishwashing. Seven key insights can be drawn from the results of this study.

First, laboratory results indicate that both manual and machine dishwashing achieve acceptable cleaning performance, with machines exhibiting much less variability in cleaning scores, energy use, and water consumption than manual dishwashing. In most cases, machine dishwashers use less water, energy, soap, and require less time doing physical work than manual dishwashing. Although the sample size is small, these use-phase results are in agreement with previous studies.

Second, observational laboratory testing and the survey demonstrated recommended practices for machine dishwasher use are not always performed, with the majority (67%) of participants typically pre-rinsing dishes before loading and only 59% typically choosing the normal cycle. When manually washing, 84% of participants typically use the running tap and combination style.

Third, the use phase is the most important life cycle phase for machine dishwashers, accounting for as much as 88% of life cycle GHG emissions and almost all the water consumption under the base case. A majority of products sold by OEMs achieve Energy Star criteria for energy and water consumption. Behavioral barriers may be the biggest obstacle for reducing environmental burdens associated with dishwashing in the average household, as most likely already own an Energy Star certified machine. Of standard household appliances, machine dishwashers only use 9.5% of the total energy and account for only 2% of residential water use [36]. Although machine dishwashers have a marginal impact on household energy and water use, their greatest benefit is demonstrated when they displace typical manual dishwashing behaviors, which can use several times more energy and water. Selected dishwashers in this study represent machines that reach minimum Energy Star criteria. Therefore, buying best in class dishwashers will further optimize energy and water consumption results.

Fourth, when evaluating life cycle GHG emissions as described in the base case scenario, typical machine dishwasher emissions can be reduced 6% and typical manual dishwashing emissions can be reduced by 71%.

Fifth, selected machine dishwashers rely on external water heaters that consume the majority of use-phase energy associated with running a machine. A sensitivity analysis on energy sources indicates natural gas water heating is preferable to electric water heating in most areas of the U.S., except where the emission intensity of the grid is less than 0.077 kg $CO_2$e/MJ (e.g., New York, Alaska, California).

Sixth, the LCC demonstrates that the initial cost of machine dishwashers is the biggest life cycle financial burden and causes them to be cumulatively more expensive than manual dishwashing even though machines have lower annual utility and consumable costs. When the time spent washing and loading is monetized, the machine dishwasher has the lowest life cycle cost.

Seventh, sensitivity analysis indicates that life cycle GHG emissions for machine dishwasher use can be reduced the most by de-selecting heated dry. The next best strategy is to select normal instead of more intense cycles. Finally, avoiding pre-rinsing also reduces emissions. Life cycle GHG emissions are minimized by only running the machine when it is at full capacity. When following typical manual dishwashing behaviors, the water bath method produces the least life cycle GHG emissions.

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