How Energy Efficient Are Modern Dishwashers?

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ABSTRACT

We present measurements of three recent vintage dishwashers of very different efficiencies showing that while they are substantially more efficient than older dishwashers, those tested will still use electric resistance elements for supplemental heat, even when supplied by solar water heating systems producing very hot water. We did find the DOE test results provide a reasonable guide to comparative performance, but suggest improvements that will make them more representative. We also identify a variety of influences on efficiency and performance to reduce dishwasher energy use.

Dishwasher Technology: A Short History

Dishwashers clean, rinse and dry dirty dishes–an activity previously accomplished by hand. Once loaded, a dishwasher performs an automated sequence of operations, filling with water, then providing supplemental electric heating to the desired temperature. Dishes are then sprayed with hot water and detergent, alternately draining and refilling with rinse water. After the final rinse, dishes are either passively air dried or with an electric resistance element.

Although Josephine Cochrane invented the first mechanical dishwasher in 1886, the first mass marketed electric dishwasher did not find its way into American homes until the 1950s. Since that time, the popularity of dishwashers has steadily grown. In 1980 the saturation of the appliance was 37%; in 1990 it had grown to 45% and then 52% by 2000 (RECS, 2001). The saturation of dishwashers in American homes is now approximately 60-65%. Although the dishwasher sold in 1980 had many common features with modern ones, since the 2003 energy standards, dishwasher controls have greatly changed. Moreover, the energy efficiency and reduction in water use of dishwashers has increased significantly.

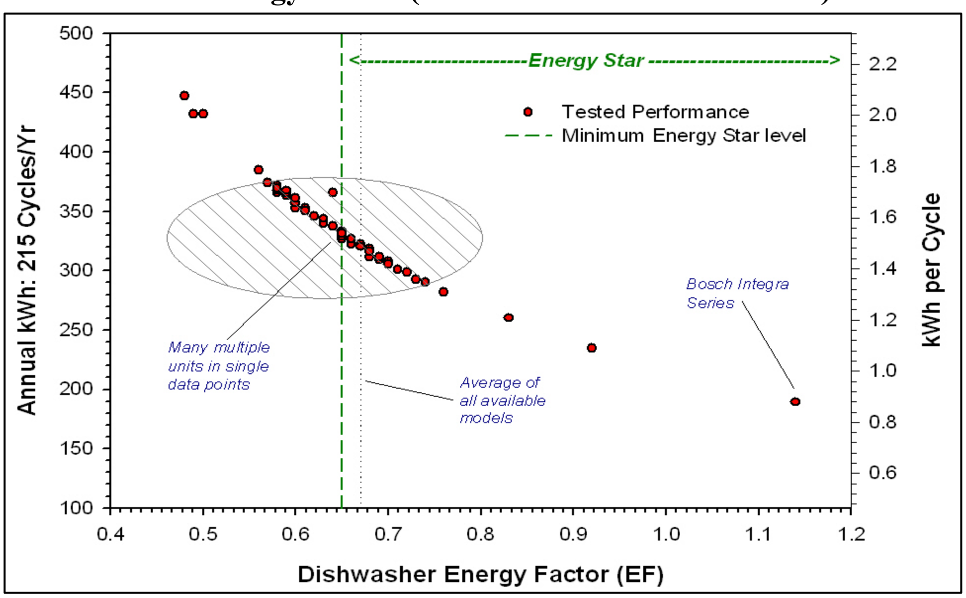
Many newer dishwashers feature computer-controlled wash cycles that adjust the wash duration for the quantity of dirty dishes or the extent to which the rinse water is soiled as determined by chemical or optical sensors. This can save water and energy if the user runs a partial or lightly soiled load. Even though energy will be saved by not pre-rinsing dishes, consumer research indicates that at least 50% of households still rinse before loading – likely due to past experiences with poorly cleaned loads (A. D. Little, 2001).

Improvements to Dishwasher Energy Efficiency

The minimum Federal energy standard for dishwashers established by the U.S. DOE 2003 rule making specifies an Energy Factor, or EF of at least 0.46 cycles/kWh for standard-size dishwashers for the “normal” cycle. Thus, a minimally compliant dishwasher would use 2.17 kWh per load of dishes. For estimating the labeled annual energy use of dishwashers, it is assumed that the typical household has 215 dishwasher loads each year so that the minimum compliant dishwasher would use 467 kWh/year, not including standby losses for control electronics which are often about 2 watts (~17 kWh/yr). However, modern dishwashers vary substantially in their energy use. *Energy Star* dishwashers have an EF of 0.65 or higher so that they would use 30% less energy than a standard model. Currently, the most efficient dishwashers of a standard size sold are *Bosch Integra* units (such as the *SHX98M09*) with an EF of 1.14 indicating they use about 0.88 kWh/cycle or 190 kWh/year.

Figure 1 shows the estimated energy use of 453 dishwashers available in 2008 and how they vary relative to the unit EF, the estimated energy use per cycle and the consumption over the year (CEC, 2008). We also plot the minimum qualifying EF for the *Energy Star* designation on the graphic against unit EF. There are several important facets of the DOE test procedure that must be understood relative to observed impacts on household energy use. First, the per cycle energy use is estimated as the machine energy use, the water heating energy use (internal and external to the machine) and one half of the dryer system energy use. The latter is important as the test procedure specifically assumes that the machine dry cycle will be used half of the time. For instance, it might be common to find a washer which used 0.4 kWh for the machine power (pumps, motors and controls) for a cycle, 0.9 kWh for internal water heating and 0.2 kWh for the drying cycle.

Figure 1. Relationship of Dishwasher Energy Use per Cycle and per Year against Unit Energy Factor (EF for 466 Units Sold in 2008)

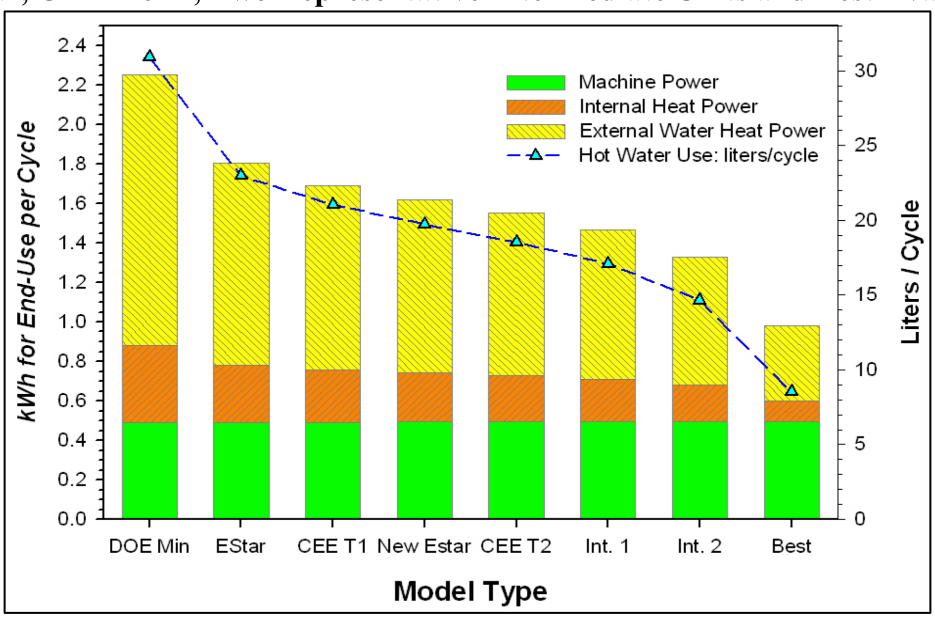


Improvements to dishwasher efficiency have advanced since the early 1990s. Not only will more efficient units use less energy, they will also generally use less water. Internal analysis by AHAM indicates that there is a general correlation between water and energy on an industry shipment-weighted basis (AHAM, 2005). For instance, in 1993, the energy per cycle for dishwashers averaged about 2.6 kWh/cycle along with a hot water use of about 10 gallons (38 liters). By 2004, with new energy standards (DOE, 2003) the numbers had fallen to about 1.8 kWh/cycle with typical water use of about 6 gallons (23 liters).

The energy use of modern dishwashers comprises several separate energy end-uses as illustrated by the engineering analysis performed by U.S. DOE for its National Impact Analysis (NIA) (Federal Register, 2007). The smallest portions are the standby losses of the control electronics–often about 2 Watts or about 17 kWh/year (Castro, 2003). The rest of the consumption is proportional to dishwasher use.

As shown in Figure 2 below (DOE Min), about 0.49 kWh/cycle per year for a minimally compliant dishwasher is used for pumps, control solenoids and machine drying. Another 0.39 kWh/cycle is used for resistance heat inside the dishwasher to boost water temperatures to the 140°F (60°C) generally desirable for cleaning operations and for machine drying. The remainder of the energy use – 1.37 kWh/cycle – is that associated with the external water heater heating the water up to 120°F (49°C) to supply to the inlet of the dishwasher. As such, although this external water heating increases the household energy use, it is not energy that is directly part of the dishwasher's energy use. It is, however, part of the DOE dishwasher rating procedure which assumes that the water is being warmed from 70°F (21°C) to 120°F (49°C). The plot below shows the energy use of the machine itself and internal and external water heating for eight generic water heater types that span the gamut of currently available efficiency units.

Figure 2. Energy End-Use of Generic Types of Standard Size Dishwashers (DOE Minimally Compliant, 2003 Energy Star, California Energy Efficiency [CEE] Tier 1, 2005 Energy Star, CEE Tier 2, Two Representative Intermediate Units and Best Available Unit



Source: U.S. DOE, NIA for dishwashers, 2007.

We note that within DOE's analysis the actual machine energy varies little from the most efficient to least efficient units. Instead, the water use and internal and external heat needed to heat the water are where the differences lie.

Electric Resistance Booster Heat

In theory, dishwasher booster heaters potentially improve household water heating energy efficiency. The booster heater consists of an internal electric resistance element (often around 900 Watts) which increases the temperature of the water entering the dishwasher to the 120-140°F (49-60°C) recommended for best cleaning with detergent enzymes or the 155°F+ (68°C+) used for dishwasher sanitize cycles. Thus, booster heaters allow the water heater thermostat temperatures to be set lower with energy savings, because every 10°F (5.6°C) below 140°F (60°C) saves about 3% of storage water heater energy use (EERE, 2007). Since, water heating energy use in U.S. households averages about 190 Therms (5,567 kWh) of natural gas or 2,550 kWh/year for electric resistance systems (RECS, 2001), this makes dishwasher booster heaters a desirable feature.[1]

Today, all modern dishwashers have booster heaters and manufacturers do not allow the feature to be disabled since the quality of the dishwashing process is compromised. The energy impact of the resistance heater in dishwashers was first seen in our study in observations in a low-energy home where the solar water heating system provided 133°F (56°C) water, the dishwasher still energized a 900 Watt heating element. This occurs because if inlet water temperatures are not greater than 140°F (60°C), the booster heating is normally activated. Thus, even with a typical 120°F (49°C) hot water supply at the tank, the dishwasher will always activate electric resistance heat. This is of concern since even with very low energy homes, solar water heating cannot avoid the resistance electricity and the solar electric system may not be able to meet the added 1 kW electric resistance load.

Tests on Three Modern Dishwashers

To learn more about efficiency issues, we instrumented three dishwashers of widely varying efficiency in detail and performed several tests. The intent of the tests was to see how the modern dishwashers would respond to high temperature water being provided to the units. The hope was that we would see power modulate with higher inlet-water temperatures to avoid booster resistance heating altogether. Each unit was standard size (12 place setting) dishwasher. The first unit was a lower efficiency unit: a *Kenmore 665-1658220* with an EF of 0.49 and a tested energy consumption of 2.03 kWh/cycle. The second was an Energy Star unit – *Kitchen Aid KUDS011 JBT1* with an EF of 0.68 and a tested energy consumption of 1.47 kWh/cycle. The third unit was the most efficient dishwasher currently manufactured, a *Bosch SHX98M09* with an Energy Factor of 1.14 and rated energy consumption of 0.88 kWh/cycle.

It should be noted that the tests were done with normal operation with no attempt to mimic the DOE test conditions. Dishes were usually lightly soiled. In most of our tests, we used the passive air dry option to reduce unit energy consumption. Thus, we expect our measured energy use to be less than that for the DOE test procedure since it includes half of the resistance drying energy.

On each of these runs we collected the inlet water temp, the inside basin dishwasher water temp, the overall dishwasher power, and the resistance element power. Data was collected with an *Onset* portable multi-channel logger with a sampling rate every two seconds. To isolate the impact of water supply temperature on the dishwasher energy use, we used a small 2.5 gallon (9.5 l) water heater located within 2 foot (0.6 m) of the dishwasher so we could be assured that line losses were not contributing to the booster heater activation.

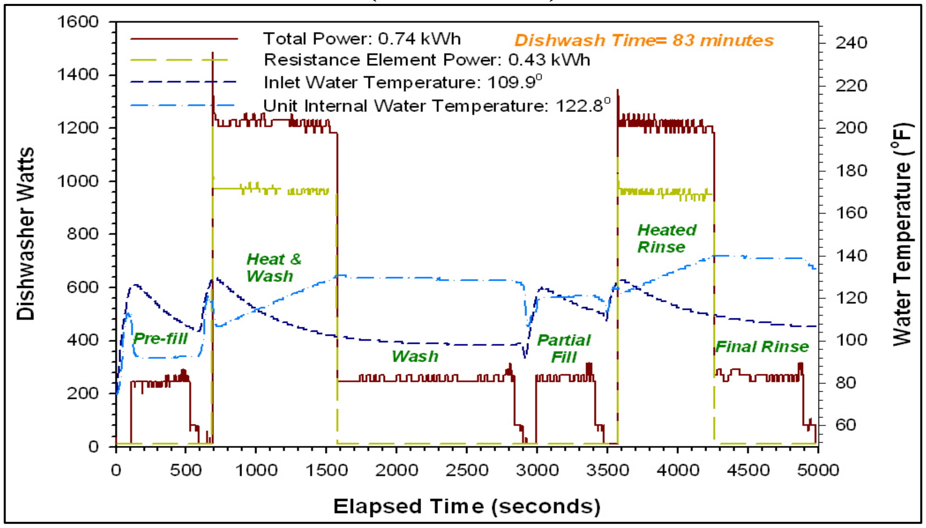
Standard Efficiency Kenmore Dishwasher

A series of tests were performed on a standard efficiency *Kenmore* dishwasher. This dishwasher is served by a solar water heater which feeds through an instantaneous gas water heater set to 125°F (52°C). On the day of the first test on 12 December 2007, conditions were

[1] This may not be true from a greenhouse gas perspective, however. For instance a standard gas storage water heater with an EF of 0.59 will produce half as much CO_2 for 1 kWh of equivalent heat than will the electric element in a dishwasher booster heater when primary energy consumption is considered.

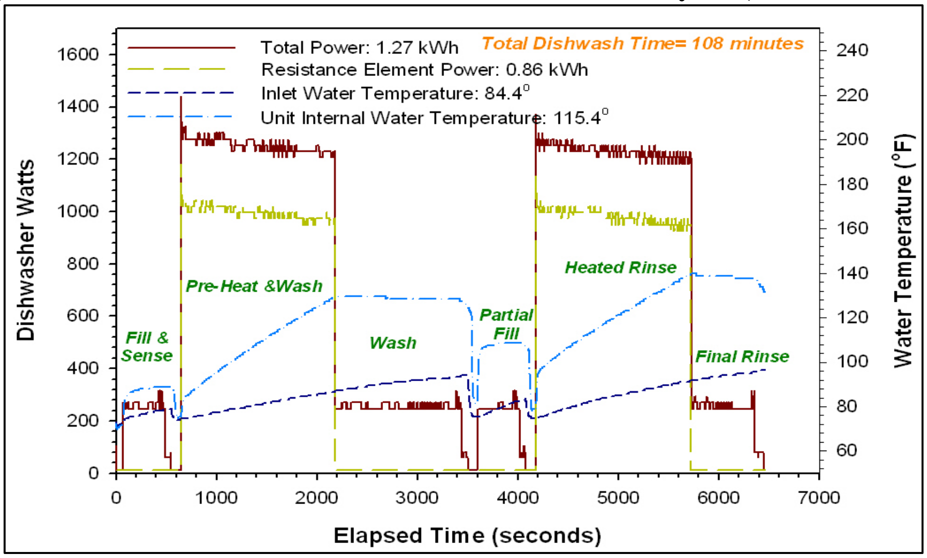
sunny and by afternoon when the test began, the water heater was producing 133–135°F 56–57°C water. Figure 3 shows the test data for this unit operating with the Normal cycle. This dishwasher uses 6.7 gallons (25.4 liters) in this configuration with three fills and a partial fill as seen in the plot. Regardless of the draws with water entering at nearly 130°F (54°C), the resistance elements inside the dishwasher are still powered twice, both for the wash and heat rinse cycles. Total cycle energy is 0.74 kWh with 0.43 kWh (58%) used for internal resistance heating. Another test, not shown here, included the machine drying cycle which increased energy use to 0.94 kWh/cycle. This indicates that avoiding the machine drying cycle will save about 0.2 kWh/cycle.

Figure 3. Kenmore Dishwasher Test Data, Normal Cycle: Solar Water Heating (inlet = 130°F)



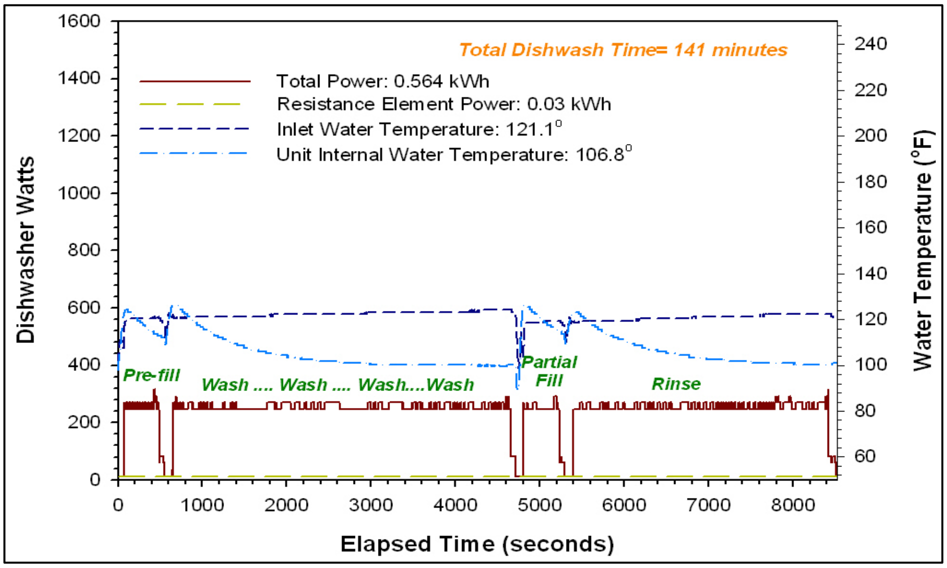
A second test of the *Kenmore* dishwasher (Figure 4) examined its performance when cold water was supplied to the unit. The inlet water temperature was about 80°F (27°C).

Figure 4. Kenmore Dishwasher Test Data, Normal Cycle (inlet = ~ 80°F (~ 27°C))



With cooler supply water, the dish wash time was increased by 25 minutes from 83 to 108 minutes with total energy increasing from 0.74 kWh (0.43 kWh for resistance heat) to 1.27 kWh (0.86 kWh for heat). For a third evaluation (Figure 5), we again tested the Kenmore dishwasher with solar hot water being available in mid afternoon in excess of 125°F (52°C). However, for this test using the *Normal* dishwash cycle, we added a contact relay so that the electric resistance heater for the dishwasher could be disabled.

Figure 5. Kenmore Dishwasher Test: Normal Cycle (No Resistance Element; Solar Hot Water at 125°F (52°C))



As seen in the plot, the total dish wash time was then very long at 141 minutes (versus 83 minutes with the resistance element). The four dishwasher fills are again seen, with inlet temperatures of about 122°F (50°C). Even so, the control microprocessor was unable to reach the desired washing temperature (140°F; 60°C) and thus, increased the cycle times attempting to compensate for the lower temperature. Total load electric power was reduced at 0.57 kWh vs. 0.74 for the same cycle with the element – a 23% reduction in energy. However, in using this cycle repeatedly for several dish washing loads, we observed that the cleaning was not acceptable. Residual films were sometimes left on the dishes–indicative of the problems well known to the dishwasher design industry of the need to provide water at 120-140°F (49-60°C) to break up surface residue from oils and fats. We concluded that although disabling the element can save a modicum of energy, it is not satisfactory with current generation dishwashers even when solar water heaters are providing 125°F (52°C) water. Moreover, for the "sanitize" wash cycle to provide dish and kitchenware sanitization in accordance with established standards water temperatures must exceed 156°F (69°C) (NSF, 2003). Thus, without solar hot water temperatures greater than 160°F (71°C) – clearly impossible due to scald danger – internal dishwasher supplemental heat will always be needed.

A final shown test was performed for the same unit with the *SmartWash* cycle chosen with the same 125°F (52°C) water supplied. Moreover, based on recommendations made for the 2003 energy standards, modern units are tested for dish soiling conditions (TIAX, 2002). Here the soil sensing system is used to alter the cycle length and water heating. A full dish wash load was used (as for all the other tests) with the dishes moderately soiled from a spaghetti dinner.

Even with the same temperature of supply water and a similar dish load we found the total dish wash cycle length was reduced from 83 to 65 minutes with also a savings in energy which dropped from 0.76 kWh to 0.64 kWh. This shows that often with lightly soiled dish loads that choice of the soil sensing cycle can reduce dishwasher energy use. Two additional tests with this cycle, while showing variation, also indicated savings over the normal cycle. We believe this is due to the fact that the standard DOE test procedure assumes dishes that are more soiled than a typical household will pose to the dishwasher. Table 1 below summarizes the results:

Table 1. Kenmore Dishwasher Test Data Summary

Cycle	Inlet Water °F	Total kWh	Resistance Element kWh	Minutes
Normal, Solar	130	0.74	0.43	83
Normal	120	0.76	0.45	90
Normal	80	1.27	0.86	108
Normal/Machine Dry	120	0.94	0.63	14
Normal	140	0.38	0.14	43
Element Disabled, Solar	130	0.57	0.03	141
Sanitize	120	1.58	1.09	108
Gentle Cycle	120	0.42	0.26	48
SmartWash	120	0.64	0.43	65
Pots & Pans	140	1.21	0.80	112

Energy Star Kitchen-Aide Dishwasher

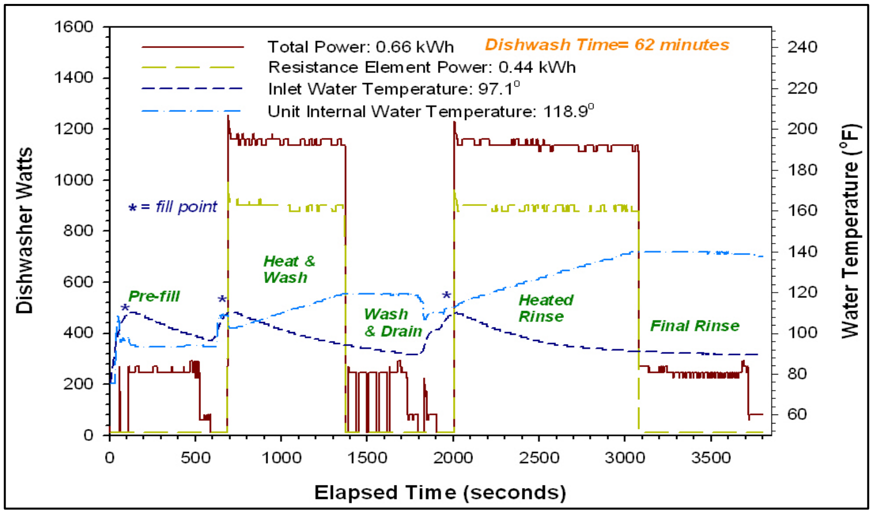
A second series of tests were performed on the *Energy Star* compliant *Kitchen-Aide* unit, all using the normal wash cycle:

- A normal run: uses the regular hot water line from electric WH tank with 120°F (49°C) water (same as the DOE test procedure). Distance from tank to dishwasher: 15 ft (4.6 m).
- A run with 140°F (60°C) pre-heated water supplied directly to the dishwasher.
- A cold run (approximately 78°F (25.6°C)) inlet water from the kitchen mains.

All loads were with soiled dishes, and using the normal cycle. As the intent of the tests was to find the most efficient cycles, all had air dry enabled. The recorded time for each test run is from the cycle start until the final cycle ends and the dishwasher drain pump turned off. The time does not include any resistance drying as was not activated in most of our tests.

Figure 6 below shows the energy use of the *Kitchen Aide* dishwasher with Normal Cycle selected and 120°F inlet water provided to the dishwasher. This condition most closely mirrors the DOE test procedure where 120°F (49°C) water is provided. The lines show the total dishwasher power and resistance element power in Watts on the left axis and the dishwasher inlet and internal water temperatures on the right axis. Note how the inlet water temperatures can be seen at the three observed fill points (*) marked by an asterisk. Even though the water heater tank temperature is set to 120°F (49°C), the inlet temperature seen 15 meters from the tank at the dishwasher is no more than 110°F (43°C). Also as the hot water comes in for the first fill, it is rapidly cooled by the dishes and dishwasher interior to a still lower temperature. Here, booster heater resistance heat must be used anyway because the inlet water temperature is not sufficient for the dishwasher operations which prefer about 120-140^{o}F (49-60°C). Thus, even with a typical 120^{o}F (49°C) hot water supply at the tank, the dishwasher will activate electric resistance heat.

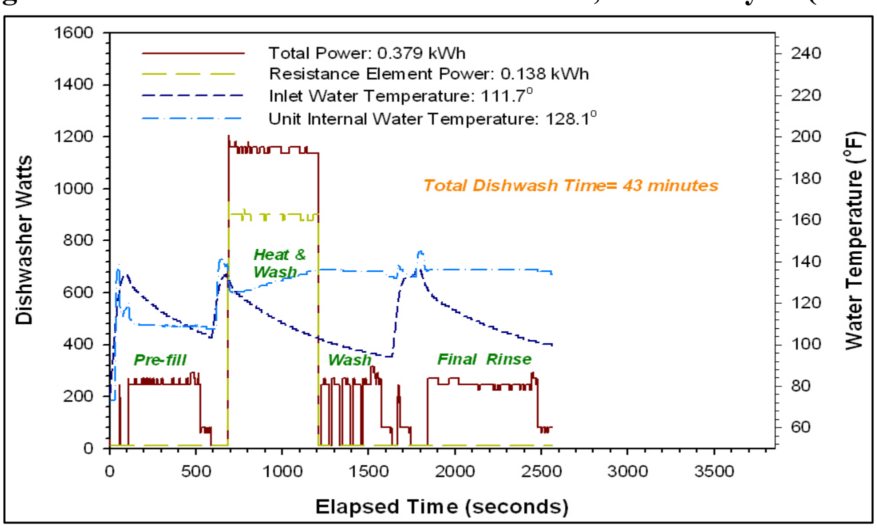
Figure 6. Kitchen Aide Dishwasher Test Data, Normal Cycle (inlet = 120^{o}F (49°C))



Note that the machine power is 0.66 kWh over the course of the 62 minute cycle with the measured power of the resistance element booster heater making up the lion's share (0.44 kWh or 67%) of the total. We do see that energy use is lower than for the standard dishwasher. A second test of the same unit shown in Figure 7 varies only the inlet water temperature. Would providing 140^{o}F (60°C) water directly to the dishwasher eliminate its resistance heat? We accomplished this using an instantaneous water heater just before the dishwasher inlet.

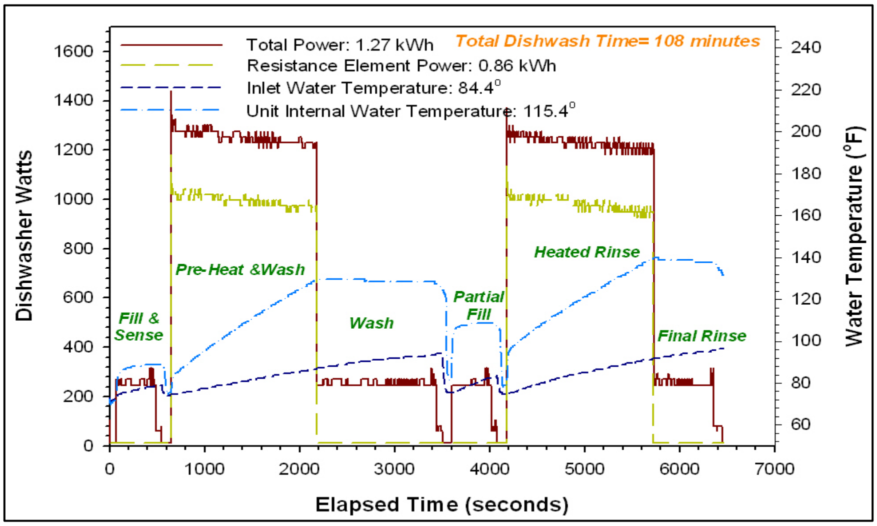
We note from the graph that even with very hot inlet water, resistance heat is still activated. However, the total dish wash time is shorter at 43 minutes with the much higher temperature seen at the three fill points. Observe also, that although the water enters at the proper temperature required for cleaning, the thermal capacity of the dishes and internal surfaces cools it so additional heating is still needed. Although internal heating is still used for the wash cycle, no heating is needed for the final rinse which is normally heated. The total dishwasher power for the cycle is 0.38 kWh of which resistance electricity is only 0.14 kWh or 37%.

Figure 7. Kitchen Aide Dishwasher Test Data, Normal Cycle (inlet = 140^{o}F)



Within the tests we noted heat was lost in lines reaching the dishwasher such that a water heater commonly set to 120°F (49°C) will only be providing 110°F (43°C) water at the dishwasher inlet. Accordingly, we wondered if it would not be reasonable with electric resistance storage water heaters to simply plumb cold water to the dishwasher. This was done for the same dishwasher using the same cycle with results shown in Figure 8.

Figure 8. Kitchen Aide Dishwasher Test Data, Normal Cycle (inlet = ~78°F)



With cold water supplied to the unit, the time to complete the load is nearly doubled (62 minutes vs. 112 minutes) with dishwasher unit energy use increased from 0.66 kWh to 1.24 kWh. Since the dishwasher uses 5.0 gallons of water for its measured load, the increased consumption is greater than the theoretical increase due to heat required to raise the temperature of the water during the 27 and 25 minute heating phases for the wash and rinse cycles, respectively. This means that the thermal insulation of the dishwasher basin and interior casework and the ambient temperature around it will impact the degree to which supplemental heat is needed to reach the target cleaning temperatures.

Table 2. Energy Star Dishwasher Test Summary

Cycle	Inlet Water °F	Total kWh	Resistance Element kWh	Minutes
Normal	120	0.66	0.44	62
Normal	80	1.27	0.86	108
Normal	140	0.38	0.14	43

Thus, using cold inlet water roughly doubled the dishwasher energy use while supplying 140ºF water (as could be accomplished with a solar water heater at mid day) was able to reduce energy use by about 40%.

High Efficiency Bosch Dishwasher

The third tested dishwasher was a *Bosch SHX98MO9* model which is currently listed as the most efficient standard sized unit on the market. It has an Energy Factor of 1.14 suggesting

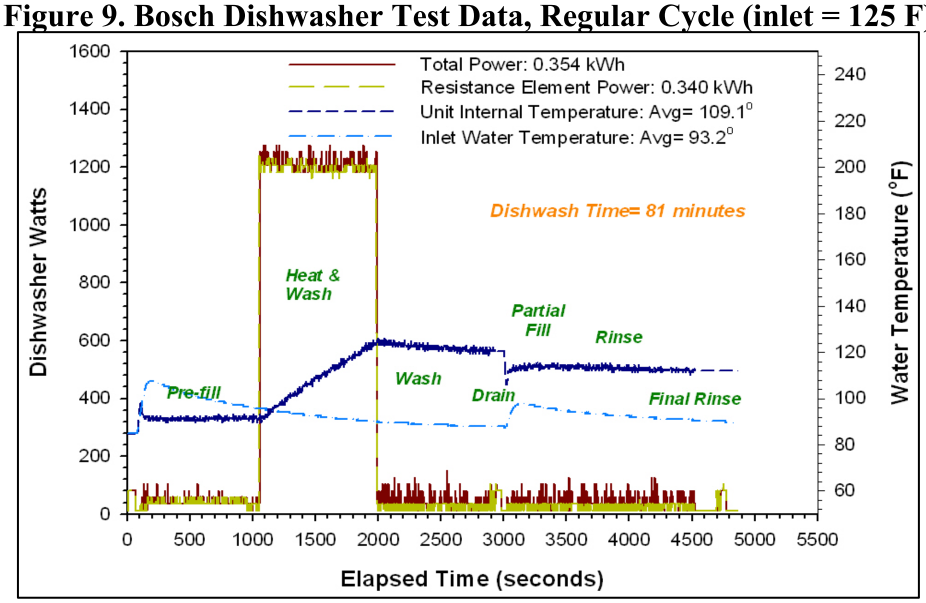
0.88 kWh used for each cycle and an annual estimated energy use of 190 kWh. It features low-energy pumps and motors, a very high level of cabinet insulation and sophisticated computerized control. A key aspect of its performance is its very low use of hot water for operation and the absence of any electrical drying.

As with the other units a portion of the 0.88 kWh is due to the water heat necessary to external heat up its wash water. For the standard regular wash cycle this was verified with lightly soiled dishes to be about 2.3 gallons (8.7l). This would mean that 0.28 kWh of the total 0.88 kWh/cycle is due to external water heating – implying about 0.60 kWh consumption for the dishwasher itself.

The dishwasher was substituted for the original *Kenmore* standard efficiency model for comparative testing in the same household. Within the evaluation, we found the dishwasher was exceedingly quiet in operation and, on a subjective basis, provided superior dishwash quality. A series of tests were performed similar to those done with the two previous units, but with additional emphasis to evaluate how dish soiling level would influence results, having been alerted by engineers on energy performance implications.

Figure 9 below shows the performance under standard conditions that prevail in the household – a full load of lightly soiled dishes with 120°F hot water being supplied to the dishwasher. We observed only a single period of resistance element heating of the water. Energy use was very low, however, at only 0.35 kWh – 54% lower than the previous dishwasher in its normal cycle.

Figure 9. Bosch Dishwasher Test Data, Regular Cycle (inlet = 125 F)



Several other tests were performed as summarized in Table 3 where results can be compared to those in Table 1 for the previous unit. Energy consumption was 0.27 kWh when fed 140°F hot water from a household's solar water heater – 63% lower than the consumption of the preceding dishwasher in the same test condition (Figure 12).

We also tested the new dishwasher with unheated water; energy use was 0.45 kWh (65% lower than the previous unit). The sanitize cycle used 49% less energy than before (Figure 10). Table 3 summarizes the results.

Figure 10: Bosch Dishwasher Test Data, Regular Cycle with Sanitize (inlet = 125°F)

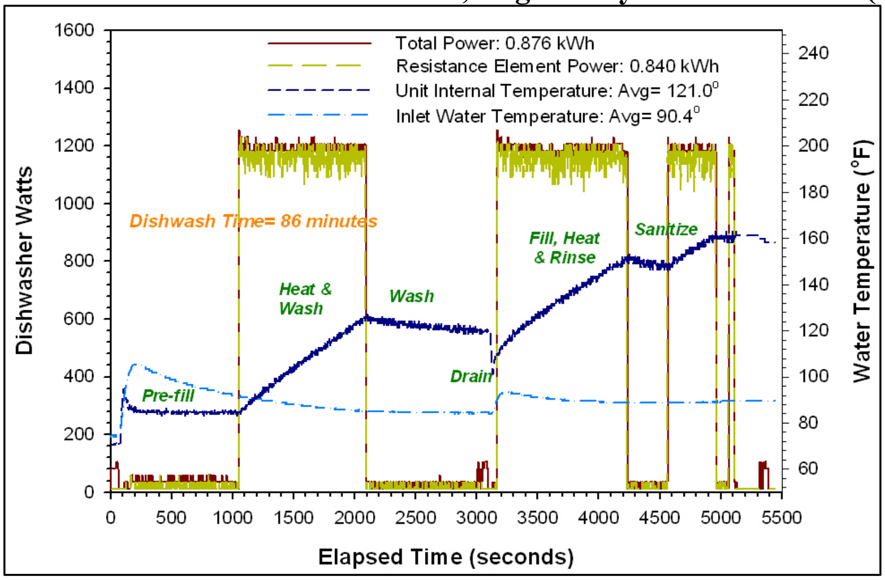
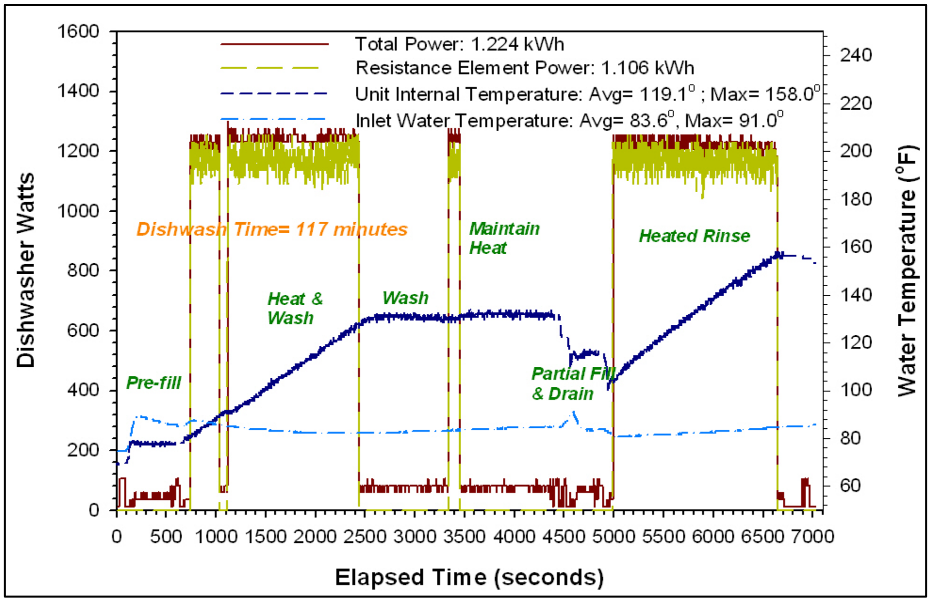


Table 3: High Efficiency Bosch Dishwasher Test Summary

Cycle	Inlet Water °F	Total kWh	Resistance Element kWh	Minutes
Regular, Solar	140	0.27	0.25	91
Regular	125	0.35	0.34	81
Regular, Sanitize	125	0.88	0.84	86
Regular, Unheated	80	0.45	0.42	86
Regular, Sanitize Solar	140	0.81	0.76	87
Regular, Heavily Soiled	125	1.22	1.11	117
Super Wash	125	1.11	1.02	96

We noted the energy use of the *Bosch* dishwasher with its regular cycle was lower than predicted by the rating, likely due to the level of soiling assumed in the three-soil-level DOE test procedure. Although no attempt was made to duplicate the ANSI/AHAM DW-1 calibrated dirty dishes, we did load the dishwasher with an embarrassingly soiled load (replete with un-scraped food). As shown in Figure 11, we did see increased water (3 gallons or 11 l) and energy use (1.22 kWh). Although such a test is given weight in the DOE test procedure, we felt this unlikely to reflect typical conditions (or would even be tolerated) in the kitchens of any of the three authors.

Figure 11. Bosch Dishwasher Test Data, Regular Cycle with Heavily Soiled Dishes (inlet = 125°F)



Summary of Comparative Performance

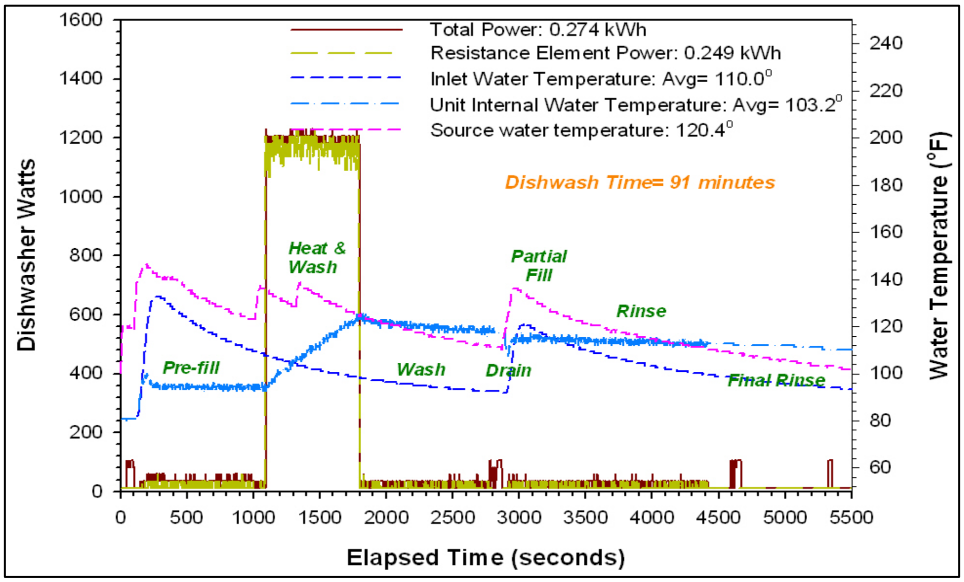
Generally, we found dishwasher energy consumption to follow the DOE ratings. The standard efficiency EF 0.49 dishwasher used about 0.76 kWh for a typical dishwash cycle in our tests, the EF=0.68 *Energy Star* dishwasher used about 0.66 kWh for the same job (13% lower) and the 1.14 EF *Bosch* unit used 0.35 kWh (54% lower). Each dishwasher used less than suggested by the DOE test procedure, even after accounting for external water heating. Partly, this is due to the fact that no resistance drying was used in our tests. However, it also seems influenced by the exaggerated soiling levels used in the DOE test procedures.

How Much Dishwasher Water Is Actually Heated by the Water Heater?

In our tests of three dishwashers with short 15-20 ft. (4.6-6.1 m) runs to the water heater, we still saw temperature drops of 5-15°F (3-8°C) from the water heater to the dishwasher inlet. We also found typical draws are only about 1.65 gallons (6.25 l) for each fill (3 to 4 fill process depending on chosen wash cycle). This is similar to other test data showing cycle consumption from 1.3 to 1.5 gallons (4.9 to 5.7 l) for other typical units (Castro, 2003). Given the small volume of the fills for the various draws and the length of the time between them leads to the question of how much of the heat in the water heated by the remote hot water tank actually reaches the dishwasher? This is a function of draw amount, length of plumbing to dishwasher, pipe insulation, temperature differences and time between dishwasher fills within a cycle. Many households where the water heater is plumbed closest to the bathrooms have 30 ft (9 m) or longer hot water runs from storage to the dishwasher.

For instance, with a 30 foot (~ 9 m) plumbing run, it can be shown that only a portion of tank-heated water actually reaches the dishwasher. Some of the water drawn per cycle has been heated by the water heater, only to cool in piping, and then to be reheated by the dishwasher – inherently inefficient. For instance, there is 2.29 (8.69 l) gallons of water in each 100 foot (9 m) run of 3/4-inch (1.9 cm) pipe. Thus, in a 30 foot run (~ 9 m), the first 0.7 gallons (2.6 l) of water each cycle is residual water in the line that has cooled down. This means the mix temperature will never reach the 140°F (60°C) needed for dishwashing. In large houses where 70 feet (~ 21 m) runs are possible, none of the hot water in each cycle would be directly heated. Also, in cooling dominated climates, much of the residual heat in the pipes is lost to the interior, becoming internal gains that must be removed by the cooling system. Figure 12 illustrates these problems. Here, we show the *Bosch* dishwasher with solar hot water temperatures plotted immediately after the water heater and at the inlet to the dishwasher. Note that inlet water temperatures 15 ft (4.6 m) away are about 15°F (8°C) lower than supply water temperatures immediately after storage

Figure 12: Bosch Dishwasher Test Data, Regular Cycle (inlet = 140°F from solar water heating)



One recommendation might be to plumb cold water to the dishwasher if the water heater is a resistance electric type and users are willing to tolerate the 20-30 minutes longer dishwasher cycle times. Cold water connection may use the least combined water heater and dishwasher energy since the dishwasher heats its own water only for the parts of the cycle where hot water is needed, but the energy (in the form of electricity) generally costs more. However, if one has a gas or solar hot water system, connecting them to hot will save carbon dioxide emissions and operating costs, particularly if plumbing runs are short.

Recommendations for the DOE Test Procedure

The DOE test procedure require three separate tests with a full 8 place setting where varying amounts of the dishes are heavily soiled in a very deliberate fashion according the ANSI/AHAM standard DW-1 (ANSI, 2005). This varies from 1 to 4 place settings soiled with differing weights attached to each run. However, based on survey data analyzed by A.D. Little (2001) for development of the test procedure 70% of consumers pre-treat dishes with water before loading the dishes into the dishwasher such that these will have very light soiling. A further 20% scrape food off plates before loading. This would indicate that 90% of the dish wash loads are light whereas the actual DOE procedure gives the light soiling load only a weight of 62%, perhaps because the industry is trying to discourage the pre-rinsing with water which dominates consumer behavior. In any case, the DOE predicted energy consumption for dishwashers is likely often overstated with the soil-sensing models that now dominate the market. This has implications for the predicted energy use of dishwashers.

Moreover, in its research, *Consumer Reports* uses a different soiling method than that used by DOE where all 10 settings are soiled, two with baked-on food as would befit a "worst case" scenario. Thus, in its recent testing of 47 dishwashers, it found energy use in dishwashers not to conform to the same ranking as would be obtained from DOE's procedure (Consumer Reports, 2008). Not only would our research suggest that careful scrapping of food prior to loading a dishwasher will save energy, but also that the predicted relative ranking of the energy use of dishwashers will be influenced by the soil loading prescribed for the tests. While the *Consumer Reports* methodology may well evaluate dishwasher cleaning performance under difficult challenges, we believe the DOE procedure is more representative of likely energy performance in most households. Further, although our research was a series of case studies, we identified potential improvements to the accuracy of the DOE test procedure:

- Soiling weights: Based on the data developed in support of the test procedure (A.D. Little, 2001), the typical soiling of loaded dishes is lighter than that used in the procedure. This is important since the energy use of dishwashers in response to light loads is more representative of realistic performance. A simple way to accomplish this: alter the soiling weights from the three tests to 80% light, 15% medium and 5% heavy.

- Hot Water temperatures: The 120°F (49°C) hot water temperature provided to the dishwasher in the DOE test is not realistic relative to the way water is delivered from storage water heaters. Typically the plumbing run is about 15-30 ft (4.6-9.0 m) of uninsulated 3/4" (1.9 cm) pipe. Since many dishwashers only draw 1-3 gallons (4-11 l) for each fill cycle, much of the water in the line has cooled close to room temperature. The DOE procedure, on the other hand, supplies 120°F (49°C) water directly to the dishwasher. Although the energy needed to raise the water from 70°F (21°C) to 120°F (49°C) is added to calculated dishwasher energy use, the actual situation is worse, since the water heater must heat this water, but the slug of water between the water heater and dishwasher loses heat from the piping and then must be partially re-heated by the dishwasher internally. For better accuracy, it is suggested that a 20 foot (6 m) length of uninsulated 3/4" (1.9 cm) copper pipe in a 70°F (21°C) ambient environment separate the dishwasher from the hot water supply source at 120°F (49°C) in the DOE procedure.

Recommended Practices to Reduce Energy Use

Since the COP of solar and heat pump water heaters is much greater than that of the resistance booster heater element in dishwashers, methods should be employed to reduce the frequency and duration with which the dishwasher booster heater is activated. The same is true of gas water heaters which are considerably more efficient relative to cost and greenhouse gas emissions than the resistance heating element. We offer these suggestions:

- Set external water heater to the minimum acceptable hot water temperature (120^{o}F, 49^{o}C)
- Minimize length of plumbing runs from the water heater to the dishwasher and insulate them.

Will washing by hand use more energy than using the dishwasher? Modern dishwashers use about 3.5-8 gallons (~ 14-30 l) per load. According to AHAM, washing by hand uses approximately twice as much hot water. Other research indicated 37% less water use in a dishwasher. One careful study with comparative measurements in Europe concluded that dishwashers, when fully loaded, use less electricity, water and detergent than even the most efficient hand-washers (Stamminger, 2003). For very low energy homes with solar water heating the time length of the resistance heating cycle will be influenced by the hot water feed temperature such that dishwashers will use least energy if run when stored water is hottest– around 2-3 PM when storage has reached a high temperature and collectors can easily replace the water used by the dishwasher.

- Avoid pre-rinse. Unnecessary rinsing can waste 10 (38 liters) gallons of water per dishwasher load. Instead of pre-rinsing, scrape off the excess food well using a rubber spatula or similar implement, load everything into your dishwasher, and let the machine do the rest. However, if this habit cannot be broken, select the soil sensing mode to reduce the length of cleaning cycles or choose the light wash or gentle cycle.
- Avoid Electric Resistance Drying Cycle. Selecting the non-resistance heated air drying option is a big energy saver and with our test units could often eliminate 0.2 kWh/cycle.
- Load efficiently and choose best cycles. Wash only full loads following manufacturer's directions. Also, when possible avoid sanitized or enhanced wash cycles (e.g., "super wash", "pots and pans", etc.) that will increase water and energy use.

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