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How Much Energy Are We Using? Potential of Residential Energy Demand Feedback Devices

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ABSTRACT

Past studies of providing instantaneous feedback on household electrical demand show promise to reduce energy consumption by 10-15%. This paper surveys past research and describes a pilot evaluation of two low cost monitoring systems in case study homes. We also develop an evaluation protocol to use such devices to determine the relative energy intensity of various energy end uses. An identified advantage of the technology is that it provides better guidance on profitable areas to reduce household electrical demand—many of which are often unexpected. Moreover, our case studies showed that use of targeted power strips and occupancy-based controls can significantly reduce electricity use associated with household entertainment centers, home office equipment and rechargeable devices.

Introduction

Homes around the world currently have no means to judge household energy use other than their monthly utility bill. Unfortunately, this does not readily provide insight as to how, or where the energy is being used. Existing studies show that providing direct instantaneous feedback on household electrical demand can reduce energy consumption by 10-15%. Recently, such feedback devices are commercially available and dropping in price. Not only are these reductions potentially large as they comprise *all* end-uses, they may provide unique opportunities to realize goals for high-efficiency buildings. Reducing and shifting electrical demand is particularly important in Zero Energy Homes (ZEH), where it would be desirable to match solar electric PV output with household loads. There are parallels with hybrid automobiles, where accumulating evidence suggests that feedback from dash-mounted displays allows drivers of Toyota's *Prius* to improve their mileage as they learn from experience.¹ As the "technical" efficiency of buildings improves, there are decreasing returns to further investment in efficiency upgrades. Behavioral changes may hold the best hope for reducing the remaining 30-40% of energy use in ZEH.

Previous Studies

Past studies show that providing household energy feedback promises to reduce consumption, although evaluations of the impact of real-time energy information are fewer and more recent (Katzev and Johnson, 1986; Farhar and Fitzpatrick, 1989). An early study in Twin

¹ "One important reason why hybrid cars result in better mileage is that drivers suddenly have an indication of how various aspects of their driving habits shape mileage. Hybrid mailing lists are filled with people talking about 'driver break-in periods' as new drivers, given immediate feedback from the car, learn how to drive in a mileage-optimal fashion. Most hybrid drivers see a steady improvement in mileage over the first year because of this." Jamais Cascio, "MPG Meter in All Cars," <http://mikecapone.blogspot.com/2005/03/mpg-meters-in-all-cars.html>

Rivers, NJ in the 1970's showed the promise of real-time energy displays to reduce energy use by 10-15% (Seligman and Darley, 1977; 1978). Other early studies showed similar savings (Palmer et al., 1977, McClelland and Cook, 1979). Potential savings also extend to non-electric fuels; Van Houwelingen and Van Raaij (1989) showed a 12% drop in natural gas consumption in Dutch homes provided with daily electric feed back. Bittle et al. (1979) showed similar beneficial results for electricity. A few studies could not reliably observe savings from energy-use feedback. For instance, in experiments in Canada and California, Hutton et al. (1986) showed uneven results with electricity savings of 5% in 92 Quebec homes compared with a control group, but minimal impact in the California sample.

There are fewer larger scale studies of the impacts of real time energy-feedback. In one conducted by *Ontario Hydro* in Canada, Dobson and Griffin (1992) found that displays in 25 Canadian homes produced overall electricity savings of 13%, which largely persisted after the devices were removed. Potentially most intriguing is a recent study of instantaneous electric demand feedback conducted in Japan. This evaluation showed 12% measured average total energy reduction from feedback in ten highly instrumented test homes (Ueno et al., 2005). The savings in electricity were even greater at 18% against those for natural gas (9%). Perhaps most compelling was that measured reductions in "other appliance" electricity use averaged 31%.

A compilation of available data on real-time feedback studies (Darby, 2000) suggests an average 10-15% reduction in overall energy. A large statistical study of 500 sites is currently under way in Canada using the *PowerCost Monitor*.

Cost and Availability of Technology

Due to advances in microelectronics and computing, energy feedback devices for home use are now commercially available and low in price.² Models typically provide a small wall or desk mounted display that communicates the second-by-second electric power demand of the household. Most accumulate the data to show expected monthly utility costs or time related energy cost data. Some are now available for as little as \$140. More detailed (and expensive) systems can report on disaggregated end uses.³ However, the question remains as to whether the additional information is a benefit or liability ("valuable insight" vs. "too much information"). A more detailed assessment of the various devices is provided by Stein (2004).

Commercially available models vary in terms of capability. The most simple devices show instantaneous power use, but do not correct for power factor. Others account for power factor, but have an accuracy resolution of only 10 Watts. More sophisticated devices allow storage of obtained data or output to a host computer to produce informative plots. Some monitors now provide energy-use information in a more intuitive fashion. For instance, the new *Wattson* energy display shows both numerical data and a light that changes color and brightness

² "Cent a Meter," (*Island Power and Cenergies*), "EMS-2020," (*USCL*), "EUM-2000 (*Energy Monitoring Technologies*), "Greenwire Energy Monitor," (*Greenwire*), "PowerPal" (*Dent Instruments*), "Power Cost Display Monitor," (*Energy Control Systems*), "Energy Viewer," (*Upland Technologies*), "PowerCost Monitor" (*Blueline Innovations*), "The Energy Detective-- TED" (*Energy, Inc.*), "Wattson", www.DIYkyoto.com.

³ The *Whirlpool Corporation* has developed an advanced "Energy Monitor" system which provides information on household total electricity demand, as well as data from 14 separate circuits. The information is available on an LCD display showing current power use, demand profiles, history of past consumption and estimated energy bills. In one pilot project with monitoring, no impact was seen although the device was not fully functional. However, the project did show that over a five month period from April- August 2005, lighting and plug loads comprised 1300 kWh or 35% of total use.

to indicate relative energy usage level. An important recent innovation is systems which send the energy demand signal over household wiring, greatly simplifying installation.

Behavioral Interactions

Early research suggested that effective energy information to consumers can be a powerful means of altering behavior and consumption (e.g. Lutzenheiser, 1990). However, not only are behavioral influences of feedback largely un-researched in recent years, but information is also lacking on the impact on time-of-day demand. Also, occupant interest in energy feedback will likely be influenced by the relative price of energy (see Hayes and Cone, 1977; Battalio et al., 1979; Winett et al., 1979)—another area where available research information is dated. Little, too, is known about the degree to which feedback display design itself determines the magnitude of reduction, although the available information would suggest that bold, vivid displays are best (Winett and Kagel, 1984).

Another potentially critical topic is the potential interaction with critical utility pricing signals (Stein 2004; Mitchell-Jackson, 2005). Most studies have confined themselves to the impact of time-of-day electricity pricing, rather than the question of how such pricing might influence energy use when combined with real-time energy data (Wood et. al., 2004). Information is also lacking on behavioral persistence. Finally, the use of feedback systems as a tool for building diagnostics and occupant education, such as suggested by Harrigan and Kempton (1995), has not been effectively evaluated.

Potential Impacts in Low Energy / Zero Energy Homes

Zero Energy Home (ZEH) projects seek to dramatically lower space heating, cooling and water heating energy use. Similar reductions are also aimed at refrigeration and lighting end-uses. However, once these reductions are made, the building's remaining "other" loads became the major energy end-use loads. Beyond clothes drying, and cooking, a highly varied list of plug loads remain: home office equipment and computers, televisions, cable set top boxes and a rapidly growing level of rechargeable devices such as cell phones, MP3 players and rechargeable tools. Moreover, the energy intensity of some categories are increasing. Plasma screen and LCD televisions, PC media servers as well as digital video recorders (TiVO) can substantially elevate the energy use associated with home entertainment.

Although providing positive-off switching can be arranged with power strips or occupancy type controls, homeowners often have little information about where to best employ such devices. Providing instantaneous feedback is one of the few available means to guide reduction of miscellaneous energy use – a recurring worry in more aggressive energy reduction goals associated with ZEH projects. The potential seems particularly attractive for low energy buildings with solar photovoltaics (PV). For instance in the pioneering Livermore ZEH in California, the occupants who were previously not interested in their low energy house, found a provided energy feedback meter a powerful motivator to reduce consumption to better match the output of the solar electric system (Springer, 2005). Parallel research in Great Britain underscores the potential of feedback in grid-connected PV homes (Keirstead, 2005).

Pilot Evaluation of Real Time Feedback Devices in Two Homes

To obtain personal experience with technologies, two of the authors installed energy feedback devices in their homes. One user installed “*The Energy Viewer*.” With this device, a wall mounted display receives signals from the sending unit which is located in the household breaker box. The receiver display unit is illustrated in Figure 1.

Figure 1. Wall-mounted display of *Energy Viewer* feedback device.



Pertinent characteristics:

- With hard wiring from the sending unit to the wall-mounted display, the installation took nearly three hours. However, programming was simple, taking less than 10 minutes.
- Displays instantaneous power demand with 5 Watt resolution refreshed every second. Can display average power over last 24 hours or last 30 days. Demand can also be displayed as cost or energy as preferred.
- Measures apparent power without correction of power factor. Thus differences for loads with low power factor will be misrepresented to some degree.
- Data is stored in flash memory so that information is not lost in the event of power failure.
- Collected data can be output to a *Windows* based personal computer over an RS232 port, with minute-by-minute, hourly, daily or monthly data plotted.
- Power demand greater than 10 kW cannot be viewed. For instance, if clothes dryers and other large loads are seen simultaneously, they cannot be viewed. However, these values are logged and can be displayed if downloaded to a computer (Figure 2).

A second user installed *The Energy Detective* (TED). This is a small 3.5 x 5” display unit which plugs into the wall and receives power line carrier signals from a sending unit installed in the central breaker panel. Output is available on a digital display as shown in Figure 3.

Figure 2. Software display of collected data using the Energy Viewer.

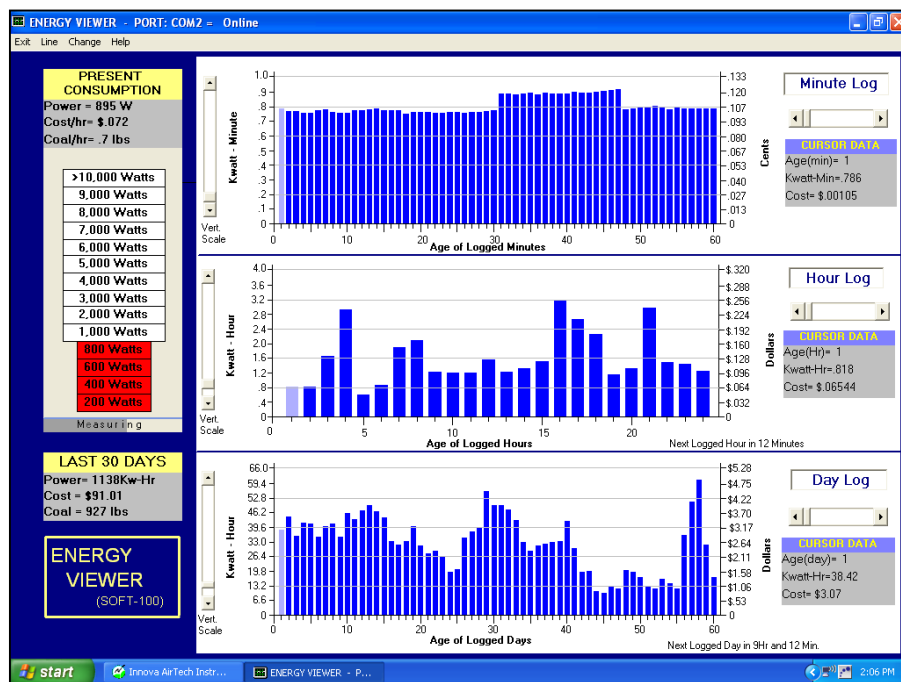


Figure 3. Free standing display of *The Energy Detective (TED)* feedback device.



Some characteristics of *TED*:

- Computes true power every second (kW) with a resolution 10 Watts. Voltage is sampled on one side of the breaker panel. Energy use of the system itself was measured at 0.8 Watts. Installed in 30 minutes with little difficulty. Programmed the receiver unit in 10 minutes.
- Sends signals on instantaneous electric power over house wiring by power line carrier so that the display device can be installed in any room and simply plugged into the wall. This confers a substantial time savings in installation and set-up.
- Shows both instantaneous and cumulative electric power for the month. Also records daily and monthly peak electrical demand. Can also be configured to show cumulative \$/hr.
- The unit maintains its programming and cumulative data in non-volatile memory. Thus, no problems are encountered with power interruption.

Relative Accuracy of the Energy Feedback Monitors

To assess the accuracy of the feedback monitors, we compared derived loads for individual devices to those measured using a very accurate power analyzer. To measure derived loads, we found the difference between whole-house power draw, both before and after turning off a given device. For the direct measurements, we used a calibrated *Valhalla 2100* power analyzer. As this reference instrument can only record plug-in loads we were only able to evaluate 120 Volt devices. However, even given the limitations of both devices, they seem accurate enough to guide consumer decisions for all but the smallest household loads.

Even though the *Energy Viewer* does not correct for power factor, we found the estimates made by using the device to be acceptable, if not research quality. In 19 comparative measurements on loads ranging from 2 Watts to 1,910 Watts, the average error in the *Energy Viewer* estimate was -2.6 Watts. The average relative error of the full scale reading was 7.9% with the larger errors coming from smaller loads, particularly from inductive loads or those with low power factor. The largest relative error for commonly used devices was in the energy use of home office equipment where the *Energy Viewer* estimated 205 Watts while the reference device measured 270 watts. For an inductive refrigerator compressor motor, the *Energy Viewer* estimated 245 Watts against the 200 W measured. As expected, measurements for resistance loads were quite accurate. Given the 5 Watt resolution of the device, loads smaller than about 3 Watts did not show up on the meter when turned on and off. The accuracy of the device could be substantially improved by sampling voltage and correcting for power factor.

The *Energy Detective* device does correct for power factor, but has a resolution of only 10 Watts. In 26 comparative measurements ranging from 3.6 to 1440 Watts, the average error of *TED* was -3.6 Watts. The average relative error of the full scale reading was 3.7%. As expected, the largest relative errors were for small loads where the 10 Watt resolution became an issue. As with *Energy Viewer*, *TED* did well with resistive load accuracy. However, with power factor compensation, *TED* also performed well with inductive and low power factor loads. In measurement of home office equipment, *TED* measured 120 Watts against 117 measured. For a refrigerator compressor, use of the differencing method with *TED* predicted a load of 200 Watts against 192 Watts measured. However, *TED* was unable to discern small loads such as a 4.4 Watt garage door opener or a cordless phone using 3.6 Watts. The measurement resolution could be favorably improved if the user could change the display resolution to 5 Watts.

Surprising Findings through Use of the Feedback Devices

Both users quickly found that the energy use of individual appliances could be readily approximated by looking at differences in demand from turning on and off individual appliances.

Homeowner Using *Energy Viewer*:

- Baseload without major appliances on was very large—up to 350 watts. The house is a “Smart Home” with a dozen *X-10* (home automation system) devices. The *X-10* switches were found to use about 5 W each.
- Was able to quickly recognize the large nature of the load associated with swimming pool pump operation (1,410 Watts operating four hours per day).
- The household did develop increased awareness of the energy use associated with clothes drying – 5.8 kW when operating.

- Demand of the electric heat pump showed use of resistance electricity on start-up in winter morning hours after setback.
- Home entertainment center is a major energy user with 220 Watts (5.2 kWh/day) of constant energy use even with the television and sound system off. TiVO digital recorder uses 28 Watts continuously. A media PC server used 144 W constantly.
- Home office and computer system draws 25 W continuously even when not operating.

Homeowner Using *TED*:

- Learned that baseload electricity use was over 160 Watts with all major appliances off.
- From an initial examination, it was found that a potter's wheel had been left on in the porch (for months) drawing 20 Watts. The heating and cooling system transformer used 10 Watts even when not on and the household entertainment center drew 20 Watts when off. Also the home office system (computer, monitor, printer, DSL cable box) drew 25 Watts when off. A powered sub-woofer consumed 10 W even when unused.
- User dropped over one kWh a day from his household loads with little effort other than locating standby loads and providing a means to deactivate them:
 - Entertainment center and sub-woofer when not in use (power strip)
 - Computer and peripherals when not in use (occupancy-activated power strip)
 - Rechargeable tools in garage (power strip)
 - Standby power dropped from 160 W to 70 W
- Learned that even with very hot supply water from the solar water heater (135°F) a new *Energy Star* dishwasher activates a one kW element during its use in both the *Normal* and *'Smart'* cycles.⁴ Moreover, in contrast to older dishwashers, the new generation machine had no way to disable the supplemental resistance booster heater.
- Watering the lawn within 10 feet of the outdoor condenser unit during the heat of the afternoon dropped air conditioning power by 80 - 140 Watts without direct spray on the unit.
- Observed unexpected electrical loads during the operation of gas appliances. This revealed that the gas dryer uses 700 Watts of electricity when drying clothes. Similarly the gas range uses 400 Watts of electric power when the oven is on, but none with stove-top burners.⁵

Protocol to Evaluate End-Uses and Locate Energy Waste

One objective of our exploratory investigation was to develop a protocol and educational element to help homeowners or auditors for Zero Energy homes use the feedback information effectively (Harrigan and Kempton, 1995). Based on our experience, we found such a protocol could potentially be a powerful means to reduce household energy use. The simplified protocol:

1. Install energy feedback meter and verify function.
2. Team of two; one records data from feedback meter, and the other turns off appliances and controls breakers. Communicate actions; data is entered into spreadsheet on laptop.

⁴ The DOE test standard for dishwashers reveals that resistance heating boosts water temperatures to 140°F if unit inlet water temperatures are below this level.

⁵ Both the dryer and oven have 400 W "hot surface" electric resistance igniters which are on anytime the gas is flowing. Further inquiry revealed that virtually all new ovens and dryers use such resistance ignition devices in contrast to the electric ignition devices previously utilized. The reasoning is that such ignition devices are more reliable (and thus safer) than solid state ignition systems.

3. Locate breaker box and record major rooms and loads controlled by each breaker. Note results on spreadsheet.
4. Read data on feedback meter (pre) and then turn off all breakers except the one powering the device (record data in off position). Turn each breaker back on and record again (on).
5. Repeat for each breaker, recording loads on each.
6. Determine breakdown for “as found energy use” by breaker and loads.
7. Go to area controlled by first breaker. Turn off (or unplug) each appliance and load as possible within that zone, recording data with “off” and data in “on” position. Note room of load for each appliance as possible. Where control is not possible with hard-wired appliances (e.g., doorbells, garage door openers, security systems), note power use with all controllable devices turned off.
8. Repeat for each breaker until entire home has been covered
9. Repeat measurements for locations where there are questions about individual measurements or the total power for particular breakers differs significantly from the sum of individual measurements for each appliance.
10. Prepare evaluation based on results, ranking electrical demand by appliance and breaker.

Based on results, the homeowners or auditors can prepare a plan to eliminate loads that can be avoided without loss of amenity to the homeowner. Such information can guide retrofits such as positive power off switches for entertainment systems, home office equipment or other such reductions to miscellaneous electric loads.⁶ Figure 4 shows how standby loads were reduced in the household using *TED* using the protocol. Power strips were used to reduce standby loads in office #1, garage rechargeable tools and the home entertainment center.

To aid understanding, a document can be prepared showing the rank order of the electrical demand of each major and minor appliance as evaluated in the home. Although such a guide would not show the frequency of use, it would indicate those appliances which are most important to control. Figure 5 shows an example in graphical format of the same household for the 19 appliances with greatest electrical demand.

Based on experience in several homes, we find that the protocol takes 2-4 hours to complete. While this may seem a large effort, it should be kept in mind that the procedure is intended to aid motivated consumers that want to shed loads and/or for Zero Energy Homes (ZEH) where reducing household power levels by 50-100 Watts with a three hour effort can be quite cost effective.⁷ Although separate power meters could be used to conduct such an audit, the advantage here is simplicity and cost-- no separate meter is required except for very small loads. Also, although low cost handheld meters can be effectively used for 120 Volt plugged loads, they cannot evaluate the many hard-wired loads in the home -- a unique advantage of the feedback meter approach. Finally, to maintain savings persistence, we suggest that consumers evaluate new appliances and devices as they are purchased and installed so that better products

⁶ One minor issue with the procedure is that the power state may change for low-wattage devices when the breaker is turned back on after being off. For instance, battery chargers may come back on at a higher power level than they will reach after having time to stabilize. Also, due to the low resolution of the feedback monitors, it may be useful to use a hand-held meter such as "Kill-A-Watt" for small, but collectively important loads such as cordless phones and other devices powered by DC-output wall transformers.

⁷ For example, if the protocol can reduce loads in a ZEH by 50 Watts on average, this represents a daily electrical reduction of 1.2 kWh. Using photovoltaic (PV) electric power in a grid-tied system in a location with five equivalent full sun hours would require approximately 300 Watts of PV modules to supply that amount of daily electricity. At current module prices, this would represent a minimum investment of \$1500.

and appropriate control strategies can be implemented. If installed by the builder in a ZEH, with the protocol documented in a homeowners guide and the new homeowner trained in the use of the feedback device as part of the homeowner orientation, it is possible this could be a powerful tool for long term electric savings.

Figure 4. Evaluation of standby electric power in home using *TED* feedback device with described protocol, pre and post intervention with 90 Watt reduction.

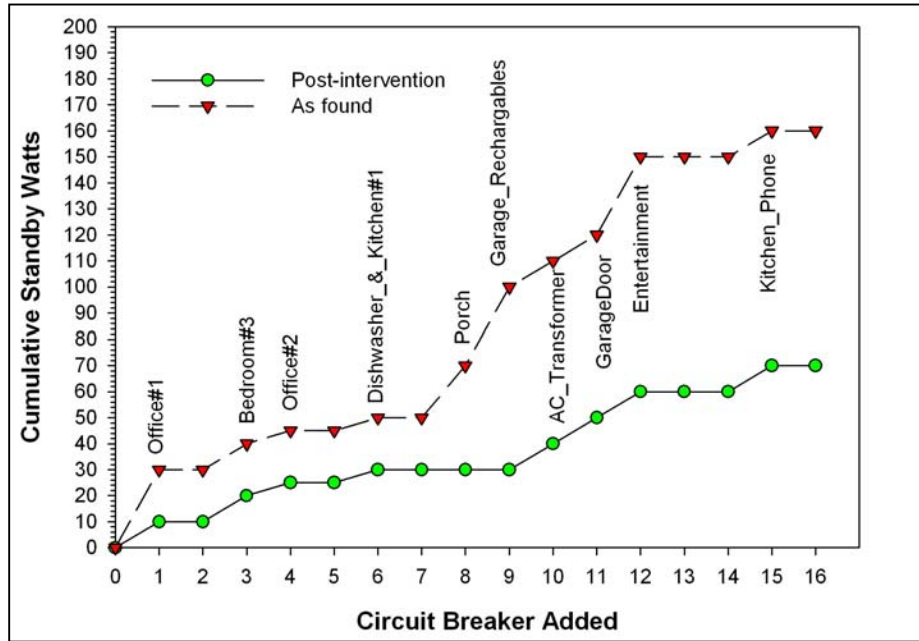
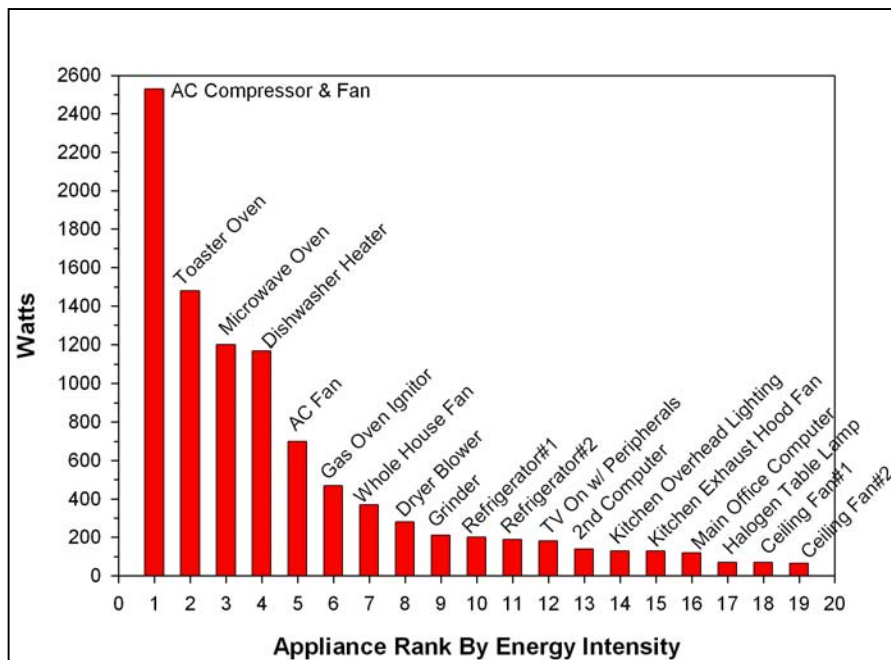


Figure 5. Energy intensity histogram for top 19 appliances in study household.



Future Research

Energy feedback device technology and our understanding of its impact on energy use is evolving with experience and display technology. Within future research, we hope to expand the pilot feedback projects both in standard as well as low energy buildings. The overall user-interface design for feedback displays is another area to be further refined.

Similarly beneficial research in homes could investigate the effectiveness of feedback when combined with new energy control systems. For instance a dedicated wall-circuit in each room could be centrally controlled via structured wiring based on house occupancy by tying the into a home security system. New types of controls should also be developed, such as occupancy sensors that signal electronic equipment to go into low-power mode (rather than completely shutting off power). Similarly, occupancy-based control in a dedicated wall plug could be provided in spaces designed for home entertainment centers and home offices. Central solar-powered DC charging stations might be provided in the office and garage to obviate the rapidly increasing need for wall-mounted transformers.

Conclusions

Earlier research dating from the 1970s have shown that providing effective feedback from appliance use decisions can be a powerful means to impact energy use. Until recently, however, few methods have existed for households to gauge influences on household electricity use. Fortunately, a series of low cost energy monitors are now becoming available which allow consumers to obtain such information. Recent evaluations in Canada and Japan suggest a typical range of energy savings from providing feedback of 10-15%. Moreover, feedback has potential to reduce miscellaneous energy use which is otherwise difficult to accomplish.

Within the paper, we performed a pilot evaluation of two low cost monitoring systems in case study homes. We also developed an evaluation protocol to use such devices to determine the relative energy intensity of various energy end uses. We found that loads larger than 10 Watts are generally accurately measured by the meters. However, very small loads or those with low power factor may not be reliably represented.

An important advantage of the technology is that it provides good guidance on profitable areas to reduce household electrical demand. Moreover, our case studies showed that targeted use of targeted power strips and occupancy-based controls can significantly reduce electricity use associated with household entertainment centers, home office equipment and rechargeable devices – areas in modern homes where energy use intensity is growing rapidly.

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