NIST Technical Note XXX

# Measurement Challenges in Achieving Energy Monitoring Systems In Buildings

William M. Healy

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William M. Healy
*Building Environment Division*
*Building and Fire Research Laboratory*

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**Abstract**

The benefits of energy conserving approaches in buildings are often not apparent to building occupants because of the insufficient feedback provided regarding energy consumption. A review of the literature suggests that energy feedback devices can provide real energy savings by motivating building occupants to modify behavior. While the level of savings varies, typical energy reductions on the order of 10 % can be expected. Recent interest in this area has resulted in the emergence of many products that aim to provide this feedback; many of those products and their features have been identified. More sophisticated methods of providing feedback that attempt to disaggregate total energy use by end use through analysis of the main energy signal at the electric or gas meter have been developed over the last two decades. These techniques can provide a relatively accurate means to identify end uses non-intrusively, but the hardware and software have yet to reach a price point that would lead one to believe that widespread adoption is forthcoming. Despite these developments, key challenges remain to decrease the cost of these systems, to make them easier to install, and to provide a flexible platform that enables a wide range of quantities of interest to be measured and reported.

**Keywords**

Energy monitoring; building technologies; sensors

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## 1. Introduction

Many guidelines are available that provide tips for reducing energy consumption in buildings, but there is often insufficient feedback to occupants of buildings to truly give them an indication of the energy effects of those suggestions. Currently, the only feedback that is typically provided in residential buildings and many commercial buildings is a monthly electric or gas bill or a less frequent heating oil bill. This coarse information does not identify the places where energy is being consumed nor does it provide a clear causal relationship between actions and the resulting energy consumption. The end energy uses may be estimated using typical breakdowns such as those provided by the United States Department of Energy's (DOE) Buildings Energy Data Book [1], but a great deal of variation in end-use energy consumption exists in buildings. The average values given by DOE may provide a misleading accounting of energy use for a particular building. The fact that the feedback comes only once per month poses a number of problems in helping building occupants understand the effects of different energy efficiency measures. First, the long time between when an energy consuming action takes place and the accounting of that energy consumption prevents people from making the connection between an action and the energy consumption. Second, many actions are averaged over the one-month reporting period, making it extremely difficult to understand the effect of small actions that may have large consequences. Third, factors that are out of the control of the building occupants (e.g., weather) may have a significant effect on energy consumption and may be difficult to ascertain when averaged over a one month period.

More frequent and more discrete feedback on energy consumption in buildings could provide vital information that would allow consumers to better understand the effect of new equipment, maintenance, and behavior. For example, if a homeowner installs new windows, he may have a hard time noticing whether those windows lead to lower heat loss through the envelope if he only has a monthly utility bill on which to base his conclusion. While the thermal resistance of the envelope may have improved, he would not necessarily see those improvements if the weather were harsh or another use such as water heating or plug loads were extremely high during the month. This lack of feedback also prevents owners and occupants from seeing the benefits of routine maintenance such as air filter changes or refrigerator heat exchanger cleaning.

A key way in which improved feedback could decrease energy consumption in buildings is by providing occupants information on how their behavior affects energy use. The effect of occupant behavior on energy consumption has long been a topic of interest ([2], [3], [4]). Parker et al. [5] studied ten identical all-electric homes built in Homestead, Florida and found that annual energy consumption varied from approximately 8000 kWh to 22 000 kWh. A number of recent studies of buildings that were designed to approach a net-zero operational status have indicated the effect of occupant behavior on that goal. In a comparison of a zero energy manufactured home to a base home, Lubliner et al. [6] found that the inefficient behaviors of the occupants of the zero energy home led to an overall energy consumption during the summer months that was greater than that in the base house. Christian et al. [7] indicated that plug loads accounted for 60 % of the energy consumption in a Zero Energy Home built in Tennessee, and that "real-time feedback and reliable automated shutoff controls are an obvious critical technology on the path to attaining zero energy." Norton and Christensen [8] note that Miscellaneous Electrical Loads (MEL's) and appliances in typical Habitat for Humanity homes account for 28 % of energy consumption, while those end uses account for 57 % in a Zero-Energy Habitat for Humanity house. The authors point out that these loads are out of the control of the designer, and that the loads are "highly unpredictable and vary substantially from household to household." Lstiburek [9] brings up the same point, that MEL's represent a very significant proportion of energy consumption after other techniques are used to reduce the consumption in buildings. While improved design of electronics and other equipment will play a role in reducing these roles, occupant behavior can play a large part in reducing these loads.

## 2. Potential savings

Feedback can intuitively help occupants cut energy consumption in buildings, but what magnitude of savings can be expected? A significant amount of work has been published to investigate potential savings. The World Business Council for Sustainable Development reports that technical devices that provide this feedback can lead to a reduction in household energy consumption of up to 20 % [10]. In an extensive review of the literature, Darby [11] reports that savings of between 5 % and 15 % are typical for direct feedback that provides immediate information to the resident. Indirect feedback, such as that provided at the end of the month by a utility, results in savings ranging from 0 % to 10 %. Data presented by the International Energy Agency [12] summarize Darby's findings on 34 studies of feedback. Figure 1 shows the distribution of percent energy savings observed in those studies. The largest number of projects showed savings in the range of 10 to 14 %. The IEA report further examined a range of instances of feedback devices that were used in Europe and indicated similar savings throughout. Other valuable works that document that literature in this field are presented by Roth et al. [13], Stein [14], and Wiggins et al. [15].

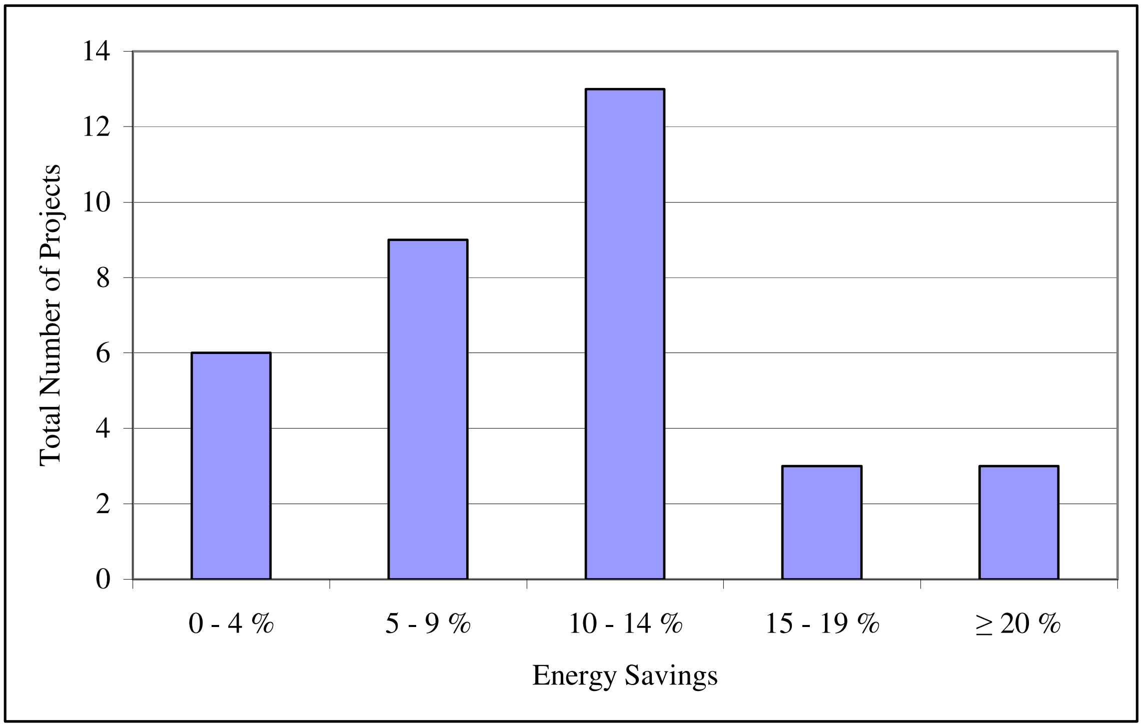


Figure 1. Distribution of energy savings from feedback devices for 34 projects analyzed by Darby [12].

In North America, a pair of studies is worth noting. Parker et al. [16] carried out a two-year case study with 22 homes in Florida. The first year served as a baseline for energy consumption in each home. During the second year, these homes were equipped with a commercially available meter that indicated instantaneous household electric power levels. The savings in energy in the second year compared to the first year were found to average 7.4 %, but there was a significant amount of variation between the homes. Energy consumption in these homes varied from an increase of 9.5 % to a decrease of 27.9 % in the second year compared to the first year (with corrections made to account for weather). A study in Ontario of over 400 homes showed an average decrease of 6.4 % in energy consumption from the previous year after the households were equipped with a device that showed instantaneous electrical power consumption [17].

## 3. Available Products

A number of products are on the market that aim to provide the necessary feedback to occupants. These devices range from meters into which one can plug any single device to systems that are attached to a circuit breaker box to monitor whole-house energy consumption. Additionally, some companies are focusing on developing the information technology tools that will present energy consumption data to building occupants in a manner that will most easily enable them to monitor and reduce their energy consumption. Tables 1-3 provide information on some of these products.[1] These

[1] Commercial equipment and software, many of which are either registered or trademarked, are identified in order to adequately specify certain products. In no case does such identification imply recommendation or endorsement by the

products are listed in alphabetical order by company, and basic information on each of the products is presented. Table 1 presents products that aim to present whole-house energy consumption information. Table 2 describes products that are designed to collect and present energy usage information. Table 3 presents products that measure energy consumption of individual end-uses.

These tables indicate that a wide variety of products are available, though the ease-of-use and accuracy of those products may not be well understood. Many of these systems provide electricity consumption data, but it does not appear that any systems provide a flexible and easy-to-implement method to incorporate sensors such as those for temperature, relative, humidity, light levels, or occupancy that might assist in evaluating environmental conditions within the building. It should also be noted that no products were found that monitored fossil fuel or water consumption and that were targeted towards the consumer. An additional point of interest is that many of the whole-building electricity monitors require the installation of current and/or voltage transducers within the circuit panel. In some jurisdictions, such an installation would legally require the services of a licensed electrician. Installation would, therefore, increase the cost of the device significantly. Finally, disaggregation of the end uses is only provided by a small number of systems. The most sophisticated approach carries the highest price tag and is meant to be purchased by utilities willing to install the power meters on many buildings. Other methods appear to disaggregate data based on average percentages for a sample of buildings.

National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Table 1. Commercially-Available Whole-House Energy Monitoring Products

| Company | Product | Features | Website |
|---|---|---|---|
| 2 Save Energy | OWL | • Sensor clips to main electric line<br>• Wireless transmitter sends data to a display unit<br>• Display unit shows instantaneous energy consumption or cost of consumption<br>• Can store data | www.theowl.com |
| Ambient Devices | EnergyJoule | • Plug-in device<br>• Changes color in response to changes in electricity price<br>• Displays weather information and energy consumption information<br>• Retrieves data wirelessly<br>• Requires special utility meter; must be ordered through utility | www.ambientdevices.com/products/energyjoule.html |
| Bell Energy | Home Energy Conservation Solutions | • Consists of a HomeBase gateway and smart controllers distributed throughout home<br>• Gateway is connected to the Internet to allow for remote access to information<br>• Communication between HomeBase and sensors and controllers is either over powerline or wireless<br>• Requires a utility to install<br>• Company is working with Ontario and Quebec power companies | bellenergy.lixarsrs.com/index.htm |
| Blue Line Innovations | Power Cost Monitor | • Electric power sensor clips on to existing rotating electric meter<br>• Indoor display unit shows instantaneous power consumption | www.bluelineinnovations.com/default.asp?mn=1.274.285.388 |

| | | | |
|---|---|---|---|
| | | • Data transmitted wirelessly from sensor to indoor display unit | |
| Brand Electronics | Digital Power Meter | • Current transducers plus a display unit<br>• Transducers connected to display unit with a CAT5 LAN cable<br>• Displays power and integrated energy | www.brandelectronics.com/model20ctr.html |
| Brultech Research | Home Energy Monitor | • Two or more current transformers<br>• Display unit<br>• Wall transformer measures voltage<br>• Analysis software<br>• USB connection to PC<br>• Optional wireless transmitter to computer<br>• Quoted accuracy of 1 %<br>• Provides true and real power | www.brultech.com/HomeEnergy/HomeEnergy.html |
| Clipsal | Cent-a-Meter | • Clip-on current transducer at circuit panel<br>• Display unit retrieves data wirelessly<br>• "Requires licensed electrician"<br>• Also measures and displays local temperature and RH | www.centameter.com.au |
| DIY Kyoto | Wattson | • Display unit that provides instantaneous power and cost<br>• Clip-on current sensor at circuit panel<br>• Battery powered wireless transmitter from sensor to display unit<br>• Lights on display unit provide a qualitative indication of energy use (by color)<br>• Software to download and process | www.diykyoto.com/uk |

| | | | |
|---|---|---|---|
| | | data | |
| Energy Control Systems | Power Cost Display | • Transmitter installed between electric service box and power meter<br>• Data transmitted over power lines to display unit within home<br>• Displays real-time electricity usage in dollars | energycontrolsysinc.com/about.html |
| Energy Monitoring Technologies | Meter Reader | • Display monitor and two current transformer clips<br>• Voltage obtained from plug-in wall transformer<br>• Provides instantaneous power and accumulated energy<br>• Manufacturer claims 1% accuracy | www.energymonitor.com/ |
| Energy, Inc. | The Energy Detective | • Two current transducers attached to main electrical line in circuit panel<br>• Wires attached to a circuit panel to measure voltage<br>• Display unit plugged into any outlet in house<br>• Data transmitted over powerline every second<br>• Displays instantaneous power and cumulative energy consumption<br>• Optional software to display data and show how energy is being used | www.theenergydetective.com |
| Enetics | SPEED, PowerScape | • Electricity meter reports electrical loads and power factors<br>• Disaggregates end uses by non-invasive load-monitoring<br>• Requires utilities to install | www.enetics.com/prodmainSPEED.html |
| Onzo Ltd. | Onzo | • Clip-on sensor to main electrical line or individual loads<br>• Small display unit shows power | http://www.onzo.co.uk/products/ |

| | | | |
|---|---|---|---|
| | | consumption, cumulative energy consumption , and ambient temperatures<br>• Data transmitted wirelessly from sensor to display unit<br>• Projected availability in Mid 2009 | |
| Powersmiths | CyberHawk | • A range of power meters and monitoring applications that appear to be meant for small commercial applications | www.powersmiths.com |
| Tendril Networks | Tendril Residential Energy Ecosystem | • A system of products<br>• Plug-in power meters for monitoring specific loads that transmit data wirelessly<br>• Wireless smart thermostat<br>• In-home display unit that provides energy consumption data<br>• Feeds data back to utilities<br>• Web-based application can show energy information | www.tendrilinc.com |
| UpLand Technologies | Energy Viewer | • May no longer be offered | |
| USCL | EMS-2020 | • Standalone display that provides information on energy consumption<br>• Company makes smart electric meters; display unit may need to be set up with one of those meters | www.usclcorp.com/products.htm |

Table 2. Commercial products or proposed products that provide information technology basis for energy feedback.

| Company | Product | Features | Website |
|---|---|---|---|
| Agile Waves | Agile Waves Resource Monitor | • Range of products for both residential and small commercial applications<br>• Provides a web-accessible central collection point for data<br>• Designed to display data for electricity, gas, and water consumption<br>• Alerts can be sent from device to user via phone, text messaging, or email | http://www.agilewaves.com/ |
| Energy Hub | EnergyHub | • In-home display unit that receives data from a smart meter (not included)<br>• Can be configured to control energy consumption through a dashboard<br>• Wireless room temperature sensor included<br>• Optional end-use meters and power strips allow user to supplement the information from smart meter<br>• ZigBee-based<br>• Can be connected to Internet<br>• Display will contain processing capabilities and applications to view and analyze data<br>• Projected availability of Mid-2009 | http://www.energyhub.net/ |
| Google | PowerMeter | • Smart meters would report energy consumption to Google<br>• Individual user's Google Home Page would provide disaggregated data<br>• Still in development | www.google.org/powermeter/index.html |

| | | | |
|---|---|---|---|
| Greenbox | Greenbox | • Web-based method to view consumption and compare to comparable homes<br>• Offers suggestions to reduce energy consumption<br>• Still in development | getgreenbox.com |
| Lucid Design Group | Building Dashboard | • Dashboard for conveying energy consumption information<br>• Energy orb that changes color to indicate how much energy is being consumed in building<br>• Focused on commercial market but have demonstrations with residential buildings | www.luciddesigngroup.com |
| Synergy Conscious | EnergyMon | • Web-based system to monitor energy consumption<br>• Hardware that taps into circuit breaker panel<br>• Appears to be focused on commercial buildings | www.synergyconscious.com |

Table 3. Commercially available point-of-use monitoring products.

| Company | Product | Features | Website |
|---|---|---|---|
| Electronic Educational Devices | WattsUp | • Plug-in device<br>• Provides instantaneous power measurement and total energy consumption of end use plugged into device<br>• Can store 2000 data points<br>• Data can be downloaded to PC via USB cable<br>• Records true power<br>• Options enable additional storage of data and ability to access data over the Internet | https://www.wattsupmeters.com/secure/index.php |
| Energate | Energate Home Energy Management Suite | • Smart thermostats that display energy consumption<br>• Enables demand response approaches | www.energateinc.com/products-sol-emp.php |
| Green Energy Options | Home Energy Hub | • A number of different models to display data<br>• Central display unit<br>• Wireless plug-in meters can be purchased as accessories<br>• Monitors overall energy consumption from meters or segregates by end-use according to individual plug-in meter | http://www.greenenergyoptions.co.uk/ |
| P3 International | Kill-a-Watt | • Plug-in device<br>• Provides current, voltage, instantaneous power measurement, and total energy consumption of end use plugged into device | www.p3international.com/products/special/P4400/P4400-CE.html |
| SeaSonic | PowerAngel | • Plug-in device<br>• Provides current, power, power | www.seasonicusa.com/power_angel.htm |

| | | | |
|---|---|---|---|
| | | factor, and total energy consumption of end use plugged into device<br>• Reported accuracy of 2 %<br>• May no longer be sold | |

## 4. Non-Intrusive Monitoring Techniques

One approach to determining the consumption of energy in buildings involves the deployment of energy monitoring sensors at each end use. While this approach is technically straightforward and promises the most reliable data, the process can be intrusive and expensive. For this reason, a number of approaches have been developed to non-intrusively monitor loads in a building. In these approaches, a single meter is typically deployed to monitor the energy flow into the building. The flow of energy, whether it is electricity or gas, is measured at the main, and software is used to analyze the flow to identify different end uses. While end-use monitoring involves significant hardware and minimal software, non-intrusive load monitoring typically involves minimal hardware investment but substantial software. A significant amount of research has been undertaken to explore different methods of non-intrusive load monitoring for electrical loads. Far less research has been undertaken to detect individual uses of fossil fuel. Some work has been undertaken to determine hot water use in residences. These techniques will be discussed in further detail.

### *Electricity*

A number of methods have been investigated for identifying specific electrical end uses in a building by their signatures in the total electrical power signal. The groundbreaking work in this area was carried out by George Hart at MIT in the 1980's and is summarized in [18]. The approach pioneered by Hart identifies changes in the electrical demand and associates those changes with specific appliances. Figure 2 shows a typical electrical demand that might be seen in a home with each increase or decrease in the

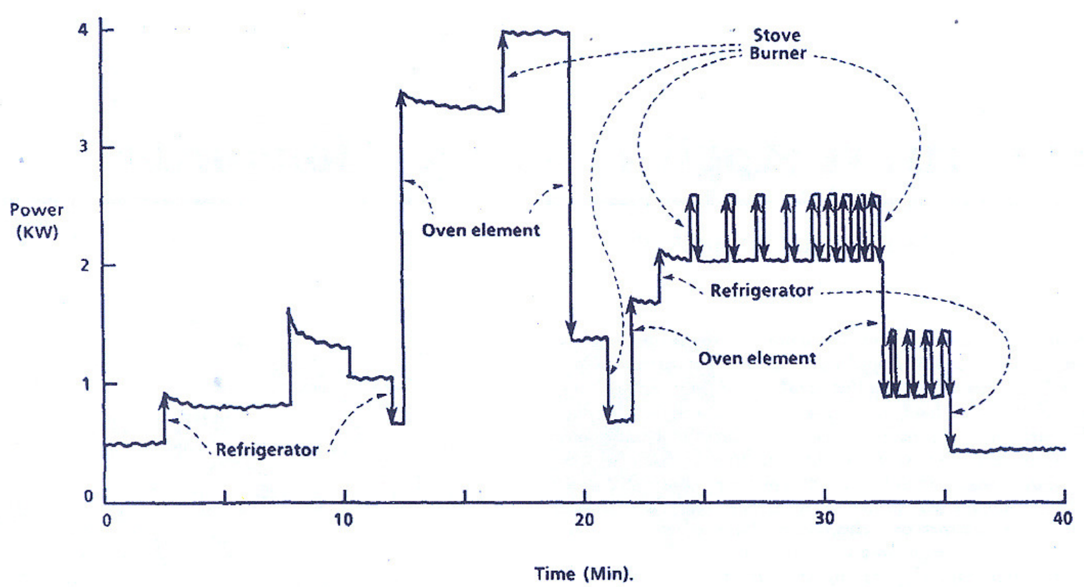


Figure 2. Example of household electricity use over time and the appliances that cause changes in the total load (from [18]).

demand being attributed to a different appliance or device. Hart found that even more information could be obtained by examining the reactive power in addition to the real power. Power is the product of the current and the voltage at a device, but the alternative current and voltage are not always in phase. Those devices with inductive or capacitive features cause the current and voltage to shift out of phase, while the current and voltage remain in phase when imposed on purely resistive loads. These characteristics are captured by expressing the power in the complex plane as:

$$P = P_{real} + j \bullet P_{reactive}$$

The real power, $P_{real}$, is expressed in W and the reactive power, $P_{reactive}$, is expressed in volt-amps reactive (VARS). Those devices with motors (e.g., refrigerators, pumps, fans) tend to have larger reactive powers than those devices that are purely resistive (e.g., electric water heaters, irons, incandescent lights). Therefore, both real and reactive powers can be used to identify end uses. Figure 3 shows a sample of the magnitudes of the power consumption of different end uses on the complex power plane.

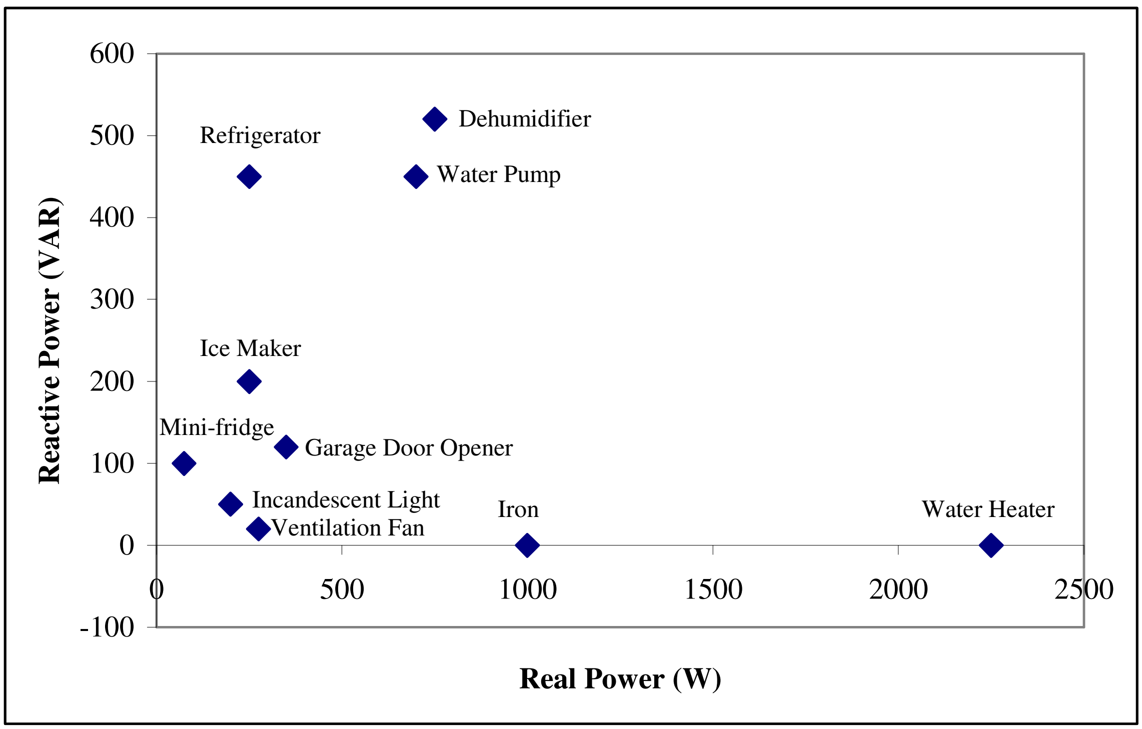


Figure 3. Sample real and reactive powers for a variety of equipment.

By sampling the instantaneous voltage and current through a main circuit, algorithms can identify changes in the power. Hart normalized the power to 120 V to avoid problems with voltage variations over the line and then detected edges where the power changed. The additional real power and reactive power introduced by a device that turns on is plotted on the complex power plane, and it was found that these power levels were sufficiently repeatable so that points cluster together. When the devices turn off, there is a corresponding point in the complex power plane that is the negative of the value of power for turning on. These corresponding points are coupled and their time stamps are used to identify the run time for the device. To identify the specific end use for a particular pair of edges, a library of common devices was built, and the points are matched to that library to allocate energy consumption to a certain piece of equipment. Drenker and Kader [19] discuss a commercial implementation of this algorithm.

Extensions to the procedure first described by Hart and slightly different approaches have been investigated in ensuing years. Sultanem [20] presented similar findings to those reported by Hart, namely that appliances could be identified by the changes that they bring about in the total real and reactive powers measured at the main electric meter. Marceau and Zmeureanu [21] use a series of filters on the real power signal to identify major end uses such as water heaters, refrigerators, and baseboard heaters. Further work has taken place to try to automatically identify new appliances. Prudenzi [22] used artificial neural networks to identify major loads at a relatively coarse data acquisition rate of 15 minutes. Baranski and Voss [23] recognize that the equipment needed for event detection using the methods discussed is rather complex. To overcome this challenge, they promote a method that utilizes real power measurements from an electric meter taken at one second intervals along with a genetic algorithm to discern events. Shenavar and Farjah [24] described in detail a hardware and software implementation of a system that would yield the desired data.

The approach just described is considered a steady-state approach in that appliance usage is identified via changes in the steady power consumption. Laughman et al. [25] discuss some of the limitations of this approach. First, a steady-state approach relies on the fact that different appliances and equipment possess different signatures in the complex power space. This assumption may be true in residential applications where relatively few loads exist, but it runs into difficulty in larger buildings where there are many loads, many of which may appear similar. Additionally, equipment designed for commercial buildings is often designed to minimize reactive loads, thereby eliminating one of the parameters that can be used to distinguish end uses. A second limitation is that there are many loads that do not show a simple on-off behavior. Some devices have more than two finite states (e.g., refrigerators with defrost cycles as well as normal refrigeration) while others may have a continuously variable level of power consumption (e.g., variable speed drives). A related issue is that some devices, especially in large commercial systems, often take from 30 seconds to several minutes to reach a steady state value. Detecting the edge for these devices is difficult. These major challenges have driven work to detect end uses in other ways. Two methods that have gained attention are the investigation of transient signatures and of higher harmonics in the electrical signal caused by end uses.

In a series of papers [26-27], researchers from MIT demonstrated that different pieces of equipment have transient signatures that could be used to identify their operation. This approach is particularly attractive for commercial buildings because the overlap in steady state operation by the significant number of energy consuming devices is difficult to differentiate. Start-up periods vary, so algorithms must be able to handle the different lengths of transients. For example, banks of fluorescent lights may have a start-up period of about 0.1 second while variable-speed motor drives may have start-up transients lasting for several minutes. These varying lengths necessitate significant hardware capabilities to monitor the data at a high frequency over a long period of time. Data management becomes an issue when such volumes of data are required. In their work, the researchers suggest that real power is sufficient to identify loads in commercial buildings via transients as opposed to the methods proposed for residential buildings. The reasons for this fact is likely twofold. First, as previously mentioned, equipment for commercial buildings is often designed to minimize the reactive component of loads, so the real component of power is dominant in most equipment. Second, the finer temporal resolution and the longer period over which an identification can take place better enables the differentiation of various loads. Norford and Leeb also report that the investigation of transients in commercial HVAC systems can be used to enable detection of faults in equipment, using improper controller gains and improper switching logic as examples of faults that can be detected using the electrical signature at the main.

A third approach, which is sometimes combined with the transient approach, involves the analysis of higher level harmonics in the electrical signal that are created by different loads. Sultanem [20] was one of the first to combine steady state and transient analyses with an in-depth evaluation of the frequency components of an electrical signal powering a device. It should be noted that Sultanem also discusses the possibility of using time of day to help identify end uses. Laughman et al. [25] describe a load monitor that samples at 8000 Hz to compute spectral characteristics of the electric power signal. They note that certain loads such as an incandescent light bulb and a computer are indistinguishable in the complex power space, but the computer creates a component in the third harmonic signal that is negligible for the energized light bulb. This feature can be used to further differentiate loads from a signal. Nakano et al. [28] provide an in-depth evaluation of a non-intrusive scheme based on harmonic pattern recognition. After a training phase that associated harmonic signatures with different appliances, the scheme was tested in four households in Japan. The authors report that the system allocated the loads to the correct end use so that the consumption of each end use was within 20 % of the actual consumption. The system generally overpredicted the energy consumption of a device, meaning that the harmonic detection algorithm picked up a number of false positives. In a study initially aimed at detecting activity in homes to monitor the well-being of people, Patel et al. [29] used a simple meter that plugged into a wall outlet to monitor noise on the power line. Their approach relied “on the fact that abruptly switched (mechanical or solid-state) electrical loads produce broadband electrical noise either in the form of a transient or continuous noise.” After filtering out the 60 Hz component of the electrical signal, they examined both the frequency components of that noise and the amplitude of those frequencies to detect different equipment in a home. The authors note that the transmission line has a significant effect on the results, so the method may need to be well-tuned to a particular application. Nevertheless, the technique involves a relatively simple instrument that can be plugged into any outlet in a home.

### *Gas*

One study was uncovered that attempted to disaggregate end uses of gas appliances through a single measurement of the gas consumption going into the home. Yamagami et al. [30] used a pulse-type gas flow meter along with heuristics to identify an end use. The heuristics are based on the gas flow rate and the duration of the flow. The three key end uses were water heaters, space heating equipment, and cooking appliances. Water heaters tend to draw a large flow rate of natural gas at short intervals, whereas space heating equipment tends to use a large flow rate at relatively long intervals and in periodic fashion. Cooking appliances tend to use low flow rates for short periods of time. These rules were then used to identify end uses by the single reading at a gas flow meter. Their approach was applied to 600 homes in Tokyo, Japan, and the authors report that the technique allocated the consumption to the proper end use 95 % of the time. Of interest, the authors note that the technique would not be as successful in the United States because of the use of pilot lights, the presence of variable-rate gas appliances, and the larger number of gas appliances in U.S. homes.

### *Water*

While not specifically an energy use, it is valuable to discuss methods to non-intrusively monitor water consumption. Lowenstein and Hiller [31] first proposed a method to disaggregate end uses of hot water in a home with 15 second readings of a meter by focusing on the flow rate and the total draw of water. While the results were excellent, overlapping draws caused problems. The authors followed up with a second study [32] that showed how the use of strategically placed temperature sensors on pipes or time-of-day information could greatly improve the prediction of the hot water end uses. DeOreo et al. [33] used trace analysis on a home's water meter to disaggregate all water uses in a home. The procedure involved the initial identification of patterns by a user that a computer program then used to match subsequent draw patterns to end uses. The technique was put to use in a number of field studies [34]. Henze et al. [35] further extended the flow trace signature approach by augmenting the data with measured temperature data. As can be seen, research has zeroed in on a hybrid approach of intrusive and non-intrusive monitoring to disaggregate end uses of water in residences.

## 5. Emerging Sensor Technology

To enable energy monitoring in buildings, emerging sensor technology will play a key role in making the systems more feasible, more accurate, and more affordable. The current state of sensing in buildings varies widely. In single family residential buildings, typical sensors are often limited to safety-related sensors (e.g., smoke, fire, carbon monoxide), a temperature sensor that is part of the thermostat, and whole-house electricity, gas, and water meters installed by the utilities. Some equipment, such as a heat pump, is starting to include sensors that can help in diagnosing problems with that equipment. Multi-family buildings with central heating and cooling may submeter each unit to determine thermal energy consumption and electrical consumption in that unit.

Depending upon the sophistication, commercial buildings likely have more sensors as part of a building automation system. Sensors may be installed to measure temperature, relative humidity, carbon dioxide, occupancy, lighting levels, and energy consumption of individual pieces of equipment.

When considering the types of sensors required for a complete energy monitoring system, one could likely develop a large number of candidates. Table 4 lists a collection of sensors that would be needed to make up a monitoring system in a building. These sensors range from those commonly available (e.g., temperature sensors) to those that will require development work (e.g., indoor air quality sensors). While the initial focus of an energy monitoring system is simply to show the current and recent status of a building, these systems should be capable of providing information that can be used to provide a baseline for energy consumption (e.g., outdoor weather conditions), could help identify faults in building operations, and could eventually be used to control equipment in buildings. A key component of an energy monitoring system is also a means to monitor the environmental quality inside the building. Such sensors would monitor comfort quantities such as temperature, relative humidity, radiant temperature, and air flow as well as the broader category of indoor air quality. The list provided in Table 4 also includes sensors for safety and security, as it is conceivable that a sensor network to monitor energy and comfort-related issues would be integrated with sensors for safety.

Table 4. Sensor needs in buildings

| **Measured Quantity** | **Purpose** |
|---|---|
| *Energy Measurements* | |
| Electrical Energy | Whole-building or end-use energy consumption<br>On-site energy production<br>Fault detection |
| Gas Flow Rate | Whole-building or end-use energy consumption<br>Fault detection |
| Oil Flow Rate | Whole-building or end-use energy consumption<br>Fault detection |
| Water Flow Rate | Hot Water Consumption<br>Water Consumption<br>Solar Water Heating Production |
| Water Temperature | Hot Water Energy Consumption<br>Solar Water Heating Energy Production |
| | |
| *Indoor Measurements* | |
| Temperature | Heating and Cooling Control<br>Comfort |
| Relative Humidity | Dehumidification/Humidification Control<br>Comfort |
| Carbon Dioxide | Ventilation Control |
| Light Intensity | Lighting Control |
| Light Color | Lighting Control |
| Occupancy | Equipment Control |
| Radiant Temperature | Comfort |
| Air Flow | Comfort<br>Equipment Performance |
| Air Quality | Comfort |
| Moisture Content | Comfort<br>Durability |
| | |
| *Outdoor Measurements* | |
| Temperature | Control<br>Baseline |
| Relative Humidity | Control<br>Baseline |
| Solar Insolation | Baseline |
| Wind Speed, Direction | Baseline |
| Rainfall, Snowfall | Baseline |
| | |
| *Safety Measurements* | |
| Smoke, Fire | Fire Safety |
| Carbon Monoxide | Combustion Equipment Safety |
| Explosive Gas | Combustion Equipment Safety |
| Intrusion | Criminal Safety |

As mentioned, many of these sensors exist, but the fact remains that energy monitoring systems have yet to achieve widespread use. A number of promising sensor technologies, however, could help make these systems more prevalent.

### *Wireless Communications*

One of the key enabling technologies for energy monitoring systems is the use of wireless communications between the sensors and data collection points. Wireless communications eases the installation of sensors in a building by avoiding the intrusiveness of wired connections and allowing the installation of sensors in places that may be difficult to reach if they were tethered to wires. This ease of installation also reduces the labor cost of sensor installation, though those cost savings are partially offset by increases in the equipment cost.

Wireless technologies for sensors have advanced significantly in the last decade. One of the key design considerations for these systems compared to wireless internet or cellular telephones is the need to operate on low power since the devices will be expected to last a long time on battery power. Data rates will typically be very small, aiding the requirement to conserve energy. To help address these needs, IEEE 802.15.4 [36] has standardized the physical aspects for a low data rate wireless network. The ZigBee Alliance has adopted this standard and developed other routing protocols in an effort to standardize wireless sensing just as the WiFi Alliance standardized wireless Internet. It should be noted, however, that other technologies may prove to be viable contributors to wireless sensor networks, including Ultra-Wideband Communications (as standardized by IEEE 802.15.4a) and technologies supported by the enOcean Alliance (http://www.enocean-alliance.org/en/). Many other potential wireless technologies could find a foothold in the energy monitoring realm for buildings.

A key feature that helps make wireless practical today is the development of self-forming, ad-hoc mesh networks that are capable of sending messages through different sensors to the eventual destination of the data. These sophisticated networks have created higher reliability by allowing for a self-healing network. While the mesh networks are not necessary in every application, they provide for a means of achieving wireless communications in challenging buildings, such as those with significant amounts of metal walls.

### *Advanced Sensor Technology*

Advances in microelectronics promise cheaper and smaller sensors for a wide range of constituents. Micro ElectroMechanical Systems (MEMS) continue to offer alternative sensing methods, relying on the ability to manufacture small machines at the microscale. Advances in nanotechnology promise to create materials that are particularly sensitive to quantities of interest. It is anticipated that these key technologies will lead to better sensors at a lower cost than those that exist today.

### *Smart Grid*

Recent interest in the so-called Smart Grid will enhance the chances of energy monitoring systems making their way into buildings. A key aspect of the Smart Grid is the provision of Smart Meters at all buildings. These meters will be able to feed data to and from the utilities, but they may also provide a means for providing data to occupants of the building. The push of this technology will open up opportunities for industrious uses of the data that can be acquired through such metering. There is also a desire to connect equipment inside buildings to those meters to enable demand reduction. The presence of automation on this equipment should provide more data available for energy monitoring in buildings. Recently, several appliance manufacturers have shown interest in so-called smart appliances that would report energy usage and would work with Smart Grid applications. Once again, Smart Grid is changing the way that homeowners and other building occupants think about energy consumption in their homes and workplaces, and acceptance of energy monitoring systems is likely to grow as products become more prevalent.

## 6. Measurement Science Challenges

Energy monitoring systems are receiving significant attention, but challenges still remain in making these systems most effective. The measurement science required to achieve these systems can be described as follows.

### *Cost*

An overriding theme is the need to decrease the cost of the systems. Estimated energy savings achieved through the behavioral modifications arising from feedback systems have been reported to range between 5 % and 20 %. As an example of the financial impact of savings, consider the potential savings in a typical residence. From the United States Department of Energy's Buildings Energy Data Book [1], the residential building sector in the United States is projected to spend a total of $154.7 billion in 2009. The estimated number of households is 115 million, resulting in an average annual energy bill of $1956 per household. If an energy monitoring system results in 5 % savings, the household would expect to save $98 over one year. If the savings are at the higher level of 20 %, the household would save $391. It is unclear what type of payback would be expected of an energy monitoring system, but these numbers suggest that an energy monitoring system that cost on the order of $100 would provide a fast payback. Considering the large uncertainty in potential savings, however, one would expect that the first cost of the system should not rise to the point where a multiyear payback is needed to justify the cost of the system. Decreasing the initial equipment cost and installation cost will be a challenge.

### *Installation Complexity*

Related to the issue of cost is that of installation complexity. A system that requires the services of a licensed electrician, plumber, or HVAC technician will be significantly more expensive than one that can be installed by a homeowner. Jurisdictions typically require any modifications to the circuit breaker panel to be performed by a registered electrician, so systems that require such an installation may result in a high cost. Likewise, many modifications to plumbing fixtures and heating and cooling systems require a similar level of professional involvement. While systems that require such professional installation are not automatically out of the running for success, systems that are available to consumers at retail outlets that can be easily and safely installed may find a significant market. Installation not only includes the physical installation of sensors, but also the set up of any software required to operate the system.

***Improved Sensors and Measurement Methods***

As mentioned in the previous sections, a wide range of sensors are needed for a complete monitoring system, yet the cost of those sensors must be low. Those two issues call out the need for continued advances in sensor technology for conditions within buildings. Even those sensors that already exist could afford improvement to bring costs down and make them easier to install. As part of this process, consideration must be given to alternative ways to measure quantities of interest. For example, one could measure water consumption by installing a flow meter in line, but perhaps there is a way to use a temperature sensor at the pipe outlet to make the measurement. In many cases, the accuracy of the sensors does not necessarily need to be that which would be expected of laboratory grade sensors, so consideration must be given to techniques that give sufficient accuracy at a lower cost and installation complexity.

***New Sensors***

While the previous item refers to improvements in existing sensors, numerous quantities of interest currently have no feasible way to be measured. Among these items are effective measures of indoor air quality, ventilation rates, air flows, radiant temperatures, and mold. Such sensors could greatly help in ensuring that indoor environmental quality is maintained or improved while reducing energy consumption.

***Optimization of Systems***

Two key approaches can be implemented in energy monitoring systems, the so-called non-intrusive load monitoring systems that rely on sophisticated hardware and software at one point in a building and distributed systems that use many less-sophisticated sensors at the key end uses in a structure. Methods need to be developed to find the optimal use of these systems, keeping in mind that the best solution may involve a hybrid approach utilizing both techniques to some degree. The total cost should be minimized while providing the necessary amount of information to influence behavior.

***Power for Wireless Sensors***

It was pointed out that a key enabling technology to the success of energy monitoring systems is the use of wireless communication systems for sensors. One of the key challenges will be providing power for sensors so that the systems continue to work for an extended period of time. Designs of radios and protocols aim to minimize energy consumption, but batteries will run out at some time. Where line power is not available, energy scavenging techniques may enable long-term operation of the sensors without the need for battery replacement. Research has been undertaken to find ways to scavenge vibrational, thermal, and optical energy. Some products are already available, most notably light switches that are powered by the user pressing the button. These and other techniques will greatly help in maintaining the systems in an operational state for an extended period of time.

### *Presentation of Information*

Acquiring the data on conditions within the building is only the first step in an effective energy monitoring system. Another key aspect involves the presentation of data to the user. Significant work has been undertaken to best convey energy consumption information to users in a manner that will not overwhelm them, will encourage them to make behavioral modifications, and will clearly show where energy is being used in a building (e.g., Roth and Brodrick [13] , Darby [11], IEA [12], Wood and Newborough [37]). Displays can range from those that provide detailed breakdowns of the energy consumed at different end uses in a building to those that simply change color to indicate high overall consumption. Darby concludes that “monitors would be most useful if they showed instantaneous usage, expenditure, and historic feedback as a minimum.” The information can be presented via stand-alone displays, websites, television, or computer. Consideration must be given to a minimization of energy consumption of the display device and the convenience with which building occupants can use the data. The International Energy Agency concluded that the effectiveness of feedback and display devices is not yet known, stating that “studies should be carried out to quantify the specific value of the different feedback methods.”

### *Validation of data*

A challenge in distributed sensor networks such as those proposed for energy monitoring is validation of the data coming from those sensors. If a use of the sensors is to find faults that may be occurring in buildings, one must be sure that the sensors themselves are providing accurate data. Doing so in the field can be challenging, so methods should be developed to verify that the data are valuable. Methods to do so could include redundant sensors and modeling to determine if a sensor’s readings are inconsistent with other measurements being taken in the building. Self-calibrating and self-healing sensors would help make a system more robust by automatically detecting a problem and correcting it.

## 7. Conclusion

Energy monitoring systems can provide feedback to occupants that will result in energy use reductions through behavior modification. A wide range of potential savings have been observed from the use of these devices, with maximum savings approaching 20 %. Many commercial products are emerging, with some providing an indication of whole house energy consumption while others provide more detailed information on energy consumption at different points of use. To make these systems more effective and less costly, research has been carried out over the last 20 years in an effort to disaggregate end uses of energy through analysis of the main electric or gas signal. These sophisticated algorithms appear to perform well in residential applications, but the plethora of devices in commercial buildings make their application more of a challenge. Additionally, the high cost of the hardware and software needed for these devices makes their widespread adoption problematic. Efforts are still needed to bring costs of energy monitoring systems down and to make the installation of the products simpler. Emerging sensing technology can help make these goals achievable. In particular, wireless technology should make the systems easier to install. Nevertheless, challenges still remain. Improved sensors are needed to provide a complete picture of the status of a building. Costs of the hardware must continue to decrease. Installation methods, both on the hardware side and the software side, must make it simple for untrained homeowners and building professionals to set up the systems. And, finally, presentation of the data must be carefully thought out so that the information results in the behavioral changes that are desired. Considering several findings that indicate that achievement of low energy operation of buildings is highly dependent upon occupant behavior and unique situations in a building, the development of energy monitoring systems can contribute significantly towards achieving the goal of net zero energy buildings.

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