Evaluating the Electric Consumption of Residential Buildings: Current Practices and Future Prospects

Mario Bergés[1], Lucio Soibelman[1], H. Scott Matthews[1,2], Ethan Goldman[3]

[1] Department of Civil and Environmental Engineering, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, PA 15213; e-mail: {mberges, lucio, hsm}@andrew.cmu.edu

[2] Department of Engineering and Public Policy, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, PA 15213; e-mail: hsm@andrew.cmu.edu

[3] Vermont Energy Investment Corporation, 255 S. Champlain Street, Suite 7, Burlington, VT 05401; e-mail: egoldman@veic.org

Abstract
As the construction industry transitions towards green buildings, and the number of LEED certified facilities continues to increase, the question of how to evaluate as-built energy performance becomes more important. Most homeowners rely on a monthly bill to determine their electric consumption, which is not an effective way to understand the results of most energy-saving strategies. Real-time feedback and appliance-level information is necessary, but most solutions require extensive hardware sub-metering, with a high price due to the hardware and installation costs. We argue that, in order to achieve wide adoption, the solutions need to be simple, easy to install, inexpensive and be able to return the investment in a reasonable time.

In this paper we first analyze and compare the different types of technologies that are currently available for allowing homeowners to monitor their energy expenditure. Then we discuss new approaches that balance the trade-off between information and cost, and present preliminary results from a prototype Non-Intrusive Load Monitoring (NILM) system we have installed in a building.

1. Introduction

Conserving energy has become a pervasive goal across many different fields in recent years. The construction industry has been slowly embracing the concept of sustainability, partly through the application of certifications and standards for "green" buildings. It is rarely the case, however, that these sustainable buildings continue to be monitored after their construction, to assess their energy footprint. How do we know that these new facilities are in fact continuing to achieve the desired efficiency levels? How can building managers ensure this? For comparison, the

Construction Research Congress 2010

automotive industry, one whose products are hundreds of times less expensive than buildings, has been providing consumers with figures like instantaneous miles per gallon (MPG) for newer cars, helping the driver adjust their behavior accordingly.

The importance of buildings in the global energy consumption is hard to overestimate. Out of the 102 quadrillion BTU (quads) of total annual primary energy consumption in the United States, 40% is used to generate electricity. Of this number, 36% is consumed by commercial buildings and 37% by the residential sector (Energy Information Administration 2005). The remaining 27% is used, mainly, in manufacturing and transportation. Hence, reducing the consumption on any or both of these two types of facilities can have a significant effect on the total energy savings.

Facility managers (including residential homeowners), are interested in lowering their energy consumption, as it is becoming an increasingly expensive resource. But while there exist methods and tools for assessing the consumption of the various energy sources in a house, selecting the right approach in terms of costs and benefits, is not a simple task. Furthermore, most of the available solutions report static and/or aggregate information, such as monthly consumption, making it difficult to base energy-efficiency decisions on that type of data.

1.1 Motivation

As researchers in the intersecting field of information and building/construction technology, we believe it is our responsibility to shed some light on the different aspects of the problem of continuously evaluating the electric consumption of residential buildings. Specifically, we would like with this paper to (a) provide a brief summary of the different considerations that need to be taken when designing a measurement system for monitoring electricity consumption in residential buildings; (b) provide some insights into the type of data that homeowners may need in order to effectively reduce their electric consumption, based largely on literature findings; (c) survey some of the currently available solutions that exist in the market and analyze their similarities and differences; and (d) describe what some of the future technologies, currently being researched, could bring about.

A key motivation in the building industry is the Leadership in Energy and Environmental Design (LEED) family of certified facilities by the US Green Building Council. The LEED criteria have spawned a generation of high-performance buildings, yet they were devised for the design and construction of facilities. The bronze/silver/gold level achievements are awarded soon after buildings are occupied. In the future we expect that amendments to such standards will require life cycle monitoring of the facilities and/or require continuous energy improvements to maintain the ratings. To continuously improve energy use, significant improvements will need to be made in either user behavior and/or energy efficient technologies.

The behavioral impacts of providing users with real-time energy use feedback, even at the aggregate level (e.g., overall consumption of the building) can produce savings of up to 10-15% according to some studies (Fischer 2008; Parker et al. 2006). Larger savings are potentially achievable if more detailed data were available to the user, to automated building control systems or to electricity suppliers (allowing them to reward peak-shifting loads or subsidize equipment upgrades). We believe that if decision makers had real-time access to the operational schedule and energy consumption of all the appliances in the building, better decisions could be made towards managing the building's electrical consumption. Furthermore, access to such fine-grained data would also benefit the building industry in many ways: informing designers about the effect of their choices on the energy consumption, supporting electricity audits and building commissioning processes, etc.

In principle, one way to obtain detailed appliance usage information would be through extensive hardware sub-metering. However, such an approach would have a high price due to the hardware and installation costs, as will be seen in later sections of this paper. Utilities provide their customers with monthly reports of their consumption, but automated meter reading (AMR) systems are starting to provide more frequent updates. Additionally, there are a growing number of commercially available power meters that can provide traditional power metrics in real-time at varying degrees of detail: the building's main electrical feed, circuit panels, individual circuits or individual outlets. These latter solutions range from hundreds to tens of thousands of dollars, their cost increasing with the level of detail obtained. The challenge, then, is to find a technology that balances this tradeoff.

In light of this, when discussing future technologies, we are going to give special attention to a technique called Non-Intrusive Load Monitoring (NILM), which attempts to deduce the energy consumption of each individual appliance in a building by matching their "*fingerprints*" on the overall voltage and current coming into the facility as measured by a single measurement system installed at the main electrical feed of the building.

1.2 Paper Organization

We will start by giving a brief overview of the different hardware and software considerations that we believe are important for effectively designing a system to continuously measure electricity consumption in buildings. These recommendations are based, primarily, on our past experience installing commercially available systems in different buildings around the city of Pittsburgh, PA. As an example, we have installed circuit-level power meters in two separate buildings in Carnegie Mellon University's (CMU) campus; collected data from 7 other previously installed panel-level meters; designed and built 3 custom panel-level systems for residential buildings; and evaluated a number of other commercial meters in our laboratory.

We then provide a brief survey of the currently available technologies, putting special attention to the average costs of installation and the information that can obtained from each of them. Following this, sections 4 and 5 are devoted to what we believe are possible future technologies. Section 5, in particular, focuses on NILM, and provides early results from a prototype system installed in a residential building in Pittsburgh. Finally, we present our conclusions and discuss possible future work.

2. Measuring Electricity Consumption in Buildings

To understand what, where and how we need to measure electricity consumption in residential buildings, it is important to first understand some basic principles of power systems. Energy, the physical quantity we are interested in, is computed by integrating power over time. Electric power, in turn, is a function of voltage and current. Hence, by measuring these last two phenomena we can then use some basic mathematics to obtain energy measurements. The question then is: where should the voltage and current be measured? The electric distribution system in each housing unit can be thought of as having a tree-like structure where the leaves would be the individual loads (i.e. appliances), and the trunk would be the main feed coming from the utility. In between these two extremes, there are electrical circuits branching out of distribution panels. Thus, measuring energy at different points in this distribution system yields different levels of aggregation.

2.1 Hardware Considerations

As discussed earlier, there exist a wide variety of commercially available tools for measuring the electricity consumption of buildings. They can be differentiated, primarily, in two dimensions: (1) their time resolution (i.e., how frequently they sample the waveforms and compute measurements); and (2) what we will call their space resolution or, in other words, which points in the power distribution system they are measuring. Therefore, to properly select the appropriate hardware for the task, one needs to match these resolutions to the requirements of the application.

2.1.1 Time Resolution

The speed at which the voltage and current signals are sampled generally depends on the type of information that needs to be extracted from them, as well as the accuracy that is sought for the measurements. If the meters are designed for power quality analysis/control purposes, then higher sampling rates (in the kHz order) are necessary. This rate does not correspond to the rate at which the power-metrics are reported to the user.

2.1.2 Space Resolution

Meters are typically designed for measuring specific points in the distribution system: the main feed, the distribution/circuit panels, the individual circuits in those panels, in between the outlets and the appliances, etc. The choice of any of these depends mainly on the information that is being sought. If the user is simply interested in the overall energy consumption, then measuring the main feed would suffice.

As installing meters in the panel must be done by certified electricians, the cost for their installation scales with the number of circuits measured. The total installed cost, then, can be more than twice the price of the hardware. Such was the case for one of our installations in a 100-year old building at CMU.

3. Current Practices

Now that we have described some of the main considerations, we turn our attention to the different commercially available solutions. Table 1 shows the different devices that we considered in our analysis. Far from being a complete list of commercial products, this sample was obtained by making use of an on-line store specialized in power meters (www.powermeterstore.com), as well as a traditional web search engine (www.google.com). A more thorough review can be found in (EPRI 2009).

We needed to make some assumptions in order to perform an equitable comparison between devices of different types. To start, we did not consider those meters which did not have a data link for communicating with a computer and uploading the measurements. An asterisk is used in Table 1 to indicate such cases. Secondly, for circuit- and plug-level devices, we needed to assume the number of measurement points that would be required in order to provide an estimate of the whole-building consumption. For circuit-level meters the number we used was 18, which corresponded to the number of circuits of the device with the least number of inputs from our list. Similarly for plug-level devices, we chose 20 as the number of required measurement points since according to (Energy Information Administration 2005), that number of appliances accounts for approximately 85% of the electricity consumption of residential buildings in the U.S..

Table 1: List of commercially available residential power meters considered for this paper. An asterisk (*) is used to indicate that the meter does not provide a computer data port.

Type	Name	Model	Manufacturer
Whole-house	e2		Efergy
	Wattson	01	DIY KYOTO
	The Energy Detective	5000	Energy, Inc.
	Shark	100S	Electro-Industries/Gaugetech
	SIMEAS	P50	Siemens
	ELITEpro	DT EPB-VAL	DENT Instruments
	PowerScout	DT PS18-D	DENT Instruments
	Nexus	1250	Electro-Industries/Gaugetech
	OWL Wireless Elec. Monitor*	CM119	2 Save Energy Ltd
	Power Monitor*		Black & Decker
	PowerCost Monitor*	28000	Blueline Innovations
	Cent-a-meter*	ER CAM	Eco-Response
	EM*	2500	Energy Monitoring Tech.
	RFXMeter*		Cheapertronics
Circuit-level	PowerScout	DT PS18-D	DENT Instruments
	EnerSure		TrendPoint Systems LLC
	Smart	20	Elec. Educational Devices
Plug-level	Smart-Watt	SW25015	Smart Works, Inc.
	WattsUp?	PRO	Elec. Educational Devices
	Brand Meter	20-1850/CI	Brand Electronics
	Kill-A-Watt*	P4460 EZ	P3 International

As shown in Figure 1, the least expensive solutions we found for continuous monitoring of the overall consumption of a residential building were in the \$50-150 (US Dollars) range without considering the installation costs. For more detailed data as can be obtained by measuring each individual circuit, the least expensive solutions were in the ten to twenty times more expensive. The price increases even more when considering the plug-level meters, which have a minimum cost of approximately

$3,000, without considering the networking costs and assuming that only 20 different loads in the house will be monitored.

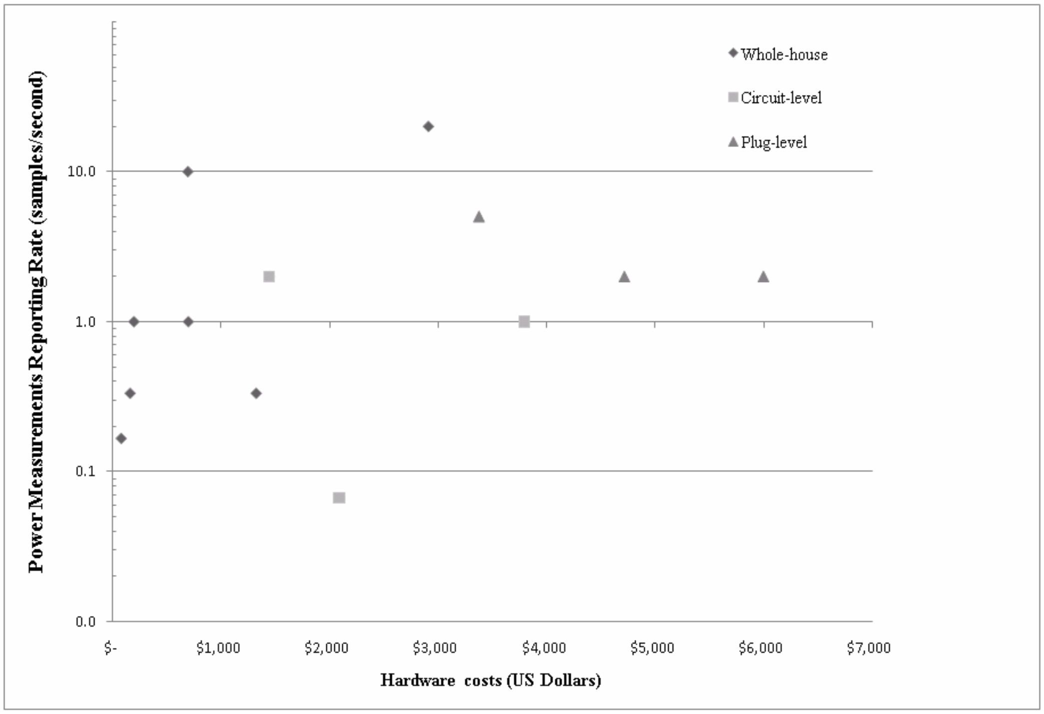

Figure 1: Cost of hardware versus update rate (logarithmic scale) for different types of power meters, all of which have a data port for uploading the measurements to a computer.

This last consideration is based on the idea that it is possible to limit the number of loads being continuously monitored in a house and still obtain valuable feedback that can guarantee savings. According to the Residential Energy Consumption Survey, just 5 end-uses account for roughly 50% of U.S. household electric consumption: refrigeration, air conditioning, space heating, water heating, and lighting (Energy Information Administration 2005). However, even if we know which appliances are responsible for the greatest portion of the energy consumption, many of these loads may offer very little room for modification. For example, besides changing the thermostat configuration in an old and inefficient refrigerator, the only other options left to reduce its consumption would be to repair it or replace it. This alternative may not be cost-efficient when compared to the energy savings it would bring about, even if it would greatly reduce the total consumption of the building.

Clearly, information has its price in this context. The more details homeowners want to know about their energy consumption, the more they would have to pay to obtain them. The real challenge, however, is that potential savings based on these different feedback mechanisms extend the payback period of these investments to unacceptable figures: decades in some cases.

3.1 Measuring green buildings

In the case of verifying the as-built energy performance of a residential building, the energy consumption of air conditioning, space heating, water heating, and lighting are of particular interest. Since appliance choice and usage can be responsible for a great deal of variation in a home's total energy use, it is informative to separate these loads from the total consumption reflected by utility bills. Of course, not every home has all-electric space heating, cooling, and water heating, but according to the 2001 US census, approximately 40% of the space and water heaters in residential buildings are fueled by electricity (Energy Information Administration 2005). Table 2 notes some of the pros and cons of using different metering techniques to measure each type of load, with color shades indicating the difficulty, darker meaning more challenging. This analysis might suggest that a hybrid approach is best for achieving accurate measurements for each category.

4. Future Prospects

In recent years, there has been an increase in the number of product offerings that are targeting the residential and/or commercial building energy monitoring sectors. Many companies are focusing on creating better interfaces, specifically designed to appeal to the homeowner. Big names in the information technology industry, such as Google (Google) and Microsoft (Microsoft), have recently revealed their free products that make use of the energy-related data that is currently available, to manage and efficiently display electricity consumption information for building managers or owners. These products are implicitly assuming that more data will become available.

Table 2: Comparison of metering solutions for four major load-types. Shading indicates level of difficulty, with darker shades being more difficult.

	air conditioning	**space heating**	**water heating**	**lighting**
Whole-house	Measure spring/fall baseline and correlate cooling degree days (CDD) with elec. consumption.	Measure spring/fall baseline and correlate cooling degree days (CDD) with elec. consumption.	Measure watts of single off-on change and multiply by typical duty cycle.	Observe change in power when switching each light on or off.
Circuit-level	Central air conditioning can be easily measured; window units may share circuits with other plug loads.	Most likely isolated on one or more dedicated circuits.	Most likely isolated on a dedicated circuit.	Loads spread across many circuits; often on shared circuits and can even change circuits.
Plug-level	Central air inaccessible (hard-wired); window units usually require specialized outlets.	Central or baseboard is hard-wired (no plug). Portable space heaters overload some plug-load meters.	Hard-wired; impossible to metter.	Plug-in fixtures are easily measured. Hard-wired fixtures cannot be measured.
NILM	Easily recognized, but power varies during cycle, complicating energy calculation.	Easily recognized; if heat pump, power varies during cycle, complicating energy calculation.	Easily recognized, but hard to train on sample transitions without user controls.	Lights are often confused with other lights. Category-level recognition may help.

However, even though hardware costs may decrease with time due to technological improvements and economies of scale, labor costs for installing these solutions in

Construction Research Congress 2010

homes will likely not, thus maintaining the total price for intensive sub-metering solutions at a high level. It follows, then, that many of the near future prospects for residential energy monitoring will likely be utilizing easy-to-obtain aggregate consumption data. The advent of the so-called "Smart Meters" (meters that establish a two-way communication with the utility company) could also support this vision by providing energy readings that are closer to real-time.

Of particular importance is one technology that tries to extract as much valuable information as possible from these aggregate data streams: Non-Intrusive Load Monitoring. First investigated more than twenty years ago (Hart 1992), this approach aims at identifying patterns in the total voltage and current signals which it can relate to the operation of individual appliances in the building. The technology has yet to reach the consumer market, probably due to hardware costs and the challenges posed by having to train the system (Smith, Leslie Norford, and Steven Leeb 2003). We believe that technological improvements in recent years have decreased the costs of hardware enough to overcome the first barrier, and ongoing research is now tackling the human-computer interaction problems posed by training.

Given the promising outcomes that NILM could provide, we devote the following section of this paper to share our experience implementing a simple prototype system based largely on the techniques described in the literature.

5. The Case for Non-Intrusive Load Monitoring

To test the effectiveness and analyze the potential of NILM, we developed a prototype system and installed it in an apartment unit. The system measured voltage and current on the two voltage sources (phases) coming into the apartment from the utility's transformer. A computer with a data acquisition card sampled these signals at a rate of 10kHz, and computed estimates of the spectral envelope as described in (S.R. Shaw et al. 2008). Using an event detection algorithm inspired by (Luo et al. 2002), the system could identify the precise moments when an appliance in the house had changed its state. Following this, we applied kernel regression on a fixed window of samples of the power signals around the event, and used the coefficients of this regression as a "signature" for the given state-transition. These signatures were stored during the training phase, and used during regular operation to compare new, unknown state-transitions against them and provide proper labels. More details on the system can be found in (Berges et al. 2009).

Our tests in the laboratory, before deploying the system in the apartment unit, showed that after events were detected, it was capable of assigning the correct label, out of 34 possible ones (e.g. toaster turning on, fan going from low to high, etc.) with an average 10-fold cross validation accuracy of approximately 80%. Additionally the detector gave very few false positives in our lab tests, and virtually no false negatives.

The situation proved to be different in the apartment unit. Because we did not implement the multi-resolution techniques for the event detector described in (Luo et al. 2002), some slow start-up transients triggered many false positive predictions. The electric heating system of the building especially contributed to this type of error. Nonetheless, these start-up transients did not occur very frequently, and we were able to reduce the number of false positives by fine-tuning the parameters of the detector.

Validating the NILM system requires hardware sub-metering (either plug-level or circuit-level if on a dedicated circuit). To test the accuracy of the energy estimates, we installed a plug-through power meter in the top-consuming appliance: the refrigerator. Using these isolated measurements we could compare the estimates of the NILM system and evaluate the performance. Figure 2 shows the result of this experiment. The difference between the energy usage as computed by NILM and the plug-meter was less than 0.5 kW-h (15%) for a 1 day period partly shown in Figure 2.

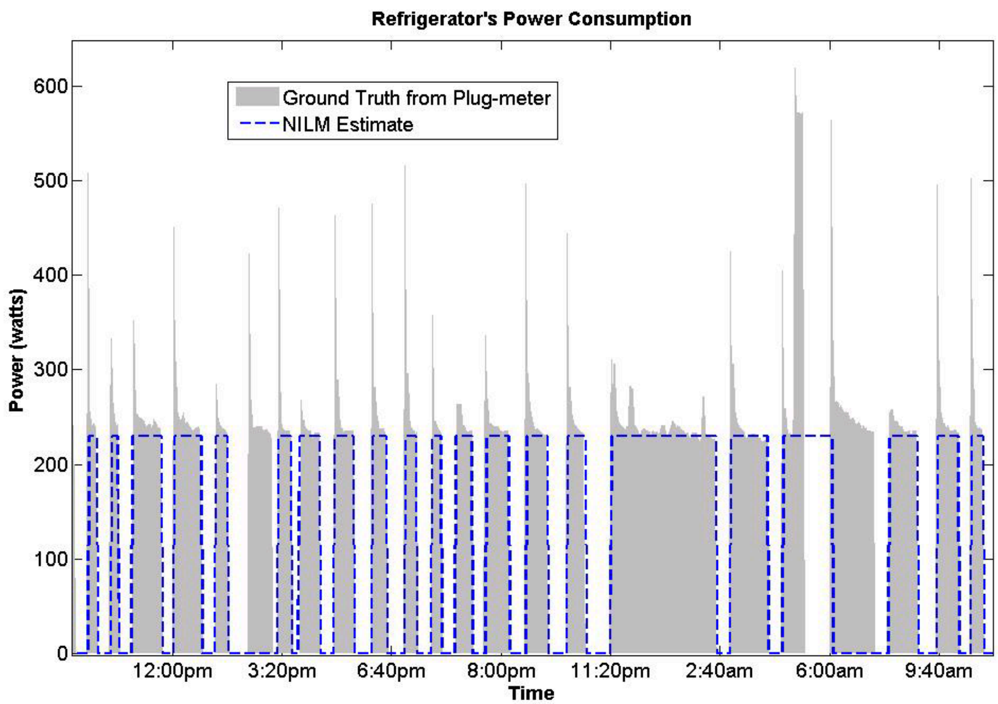

Figure 2: Power consumption of the refrigerator during a 12 hour period as estimated by NILM (dashed line) and the plug-meter attached to the appliance (solid line).

6. Conclusions and Discussion

Future technologies for continuous, detailed measurement of the electricity consumption of buildings will likely rely on a hybrid approach combining advanced techniques for extracting useful information out of low-cost data sources present in buildings, as well as direct measurements of the consumption of individual appliances. We have shown some examples of currently available technologies and provided a brief comparison which indicated that the level of information provided by them is proportional to their cost.

Detailed feedback on electricity consumption can benefit many facets of the building industry. It may facilitate the implementation of LEED standards that go beyond the design and construction of facilities, inform building designers on how buildings really operate, and provide support for building commissioning and energy audits.

NILM techniques show promising results to provide detailed information at a low cost. However, more research is needed to bring this technology to market. We believe that ways of achieving this include a combination of better training processes and interfaces, more generalized appliance signatures that can be shared across buildings, and the integration of other sources of information (e.g., motion sensors, temperature sensors, etc.) into the framework. As lower-cost sources of detailed consumption data become available, we anticipate the growth of more sophisticated software for analyzing those data, as well as more reliance on such analysis for investment planning and verification.

7. Acknowledgements

The authors would like to gratefully acknowledge the support of the Robert Bosch LLC Research and Technology Center in Pittsburgh, PA and the U.S. National Science Foundation (NSF) under grant #09-3086. The opinions expressed herein are those of the authors and do not necessarily reflect the views of the NSF.

8. References

Berges, Mario, Ethan Goldman, H. Scott Matthews, and Lucio Soibelman. 2009. Learning Systems for Electric Consumption of Buildings. In *2009 ASCE International Workshop on Computing in Civil Engineering*. Austin, TX.

Energy Information Administration. 2001. Residential Energy Consumption Survey (Viewed 05-03-2009). http://www.eia.doe.gov/emeu/recs/.

EPRI. 2009. *Residential Electricity Use Feedback: A Research Synthesis and Economic Framework*. Palo Alto, CA: Electric Power Research Institute.

Fischer, Corinna. 2008. Feedback on household electricity consumption: a tool for saving energy? *Energy Efficiency* 1, no. 1 (February 3): 79-104.

Google. Google PowerMeter. http://www.google.org/powermeter/.

Hart, G.W. 1992. Nonintrusive appliance load monitoring. *Proceedings of the IEEE* 80, no. 12: 1870-1891.

Luo, Dong, Leslie Norford, Steven Shaw, and Steven Leeb. 2002. Monitoring HVAC Equipment Electrical Loads from a Centralized Location - Methods and Field Test Results. *ASHRAE Transactions* 108, no. 1: 841-857.

Microsoft. Microsoft Hohm. http://www.microsoft-hohm.com/.

Parker, Danny, David Hoak, Alan Meier, and Richard Brown. 2006. How Much Energy Are We Using? Potential of Residential Energy Demand Feedback Devices. In *Proceedings of the 2006 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficiency Economy*. Asilomar, CA, August.

Shaw, S.R., S.B. Leeb, L.K. Norford, and R.W. Cox. 2008. Nonintrusive Load Monitoring and Diagnostics in Power Systems. *Instrumentation and Measurement, IEEE Transactions on* 57, no. 7: 1445-1454.

Smith, Vernon A., Leslie Norford, and Steven Leeb. 2003. *Final Report Compilation for Equipment Scheduling and Cycling*. Technical Report. California Energy Comission, October. http://bit.ly/8pPCzW.

Construction Research Congress 2010