Monitoring and Characterization of Miscellaneous Electrical Loads in a Large Retail Environment

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NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
NREL/TP-5500-60668
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Executive Summary

Background

Buildings account for 40% of primary energy consumption in the United States (residential 22%; commercial 18%). Most (70% residential and 79% commercial) is used as electricity. Thus, almost 30% of U.S. primary energy is used to provide electricity to buildings (D&R International, Ltd., October 2009).

Plug loads play an increasingly critical role in reducing energy use in new buildings (because of their increased efficiency requirements), and in existing buildings (as a significant energy savings opportunity). If all installed commercial building miscellaneous electric loads (CMELs) were replaced with energy-efficient equipment, a potential annual energy saving of 175 TWh, or 35% of the 504 TWh annual energy use devoted to MELs, could be achieved (McKenney, Guernsey, Ponoum, & Rosenfeld, 2010). This energy saving is equivalent to the annual energy production of 14 average-sized nuclear power plants (D&R International, Ltd., October 2009).

To meet DOE’s long-term goals of reducing commercial building energy use and carbon emissions, the energy efficiency community must better understand the components and drivers of CMEL energy use, and develop effective reduction strategies. These goals can be facilitated through improved data collection and monitoring methodologies, and evaluation of CMELs energy-saving techniques.

Goals

Our primary research goals were to:

1. Develop a clear, concise taxonomy for CMELs that defines the scope of the problem.
2. Develop and field test methodologies for metering, monitoring, and analyzing CMELs.
3. Use this experience to make viable and immediate energy savings recommendations, create a path to value-added initiatives that use field collection measurements, and propose research to characterize and reduce CMEL energy use.

According to the TIAX CMELs report, 75% of CMEL loads are consumed in buildings larger than 50,000 ft^2 (McKenney, Guernsey, Ponoum, & Rosenfeld, 2010). Thus, NREL focused during FY 2010 on large retail buildings, in particular on a 218,400-ft^2 big box retailer in the Denver, Colorado, area. The building represented the following categories:

- Office
- Retail (non-food sales)
- Food sales
- Food service
- Healthcare.

We tested and assessed various methodologies for each study phase, including:

- An inventory and taxonomy process
- Energy monitoring strategies

- Data acquisition
- Data analysis
- Realistic energy savings strategies.

Methodology

Our analysis consisted of several steps:

1. **We took a CMEL inventory.** NREL adapted a taxonomy, first developed at Lawrence Berkeley National Laboratory, for classifying spaces, then devised a naming convention for each CMEL and meter and defined a repeatable and consistent inventory method.
2. **In parallel, we developed a CMEL metering database to host and handle the massive quantities of CMEL data.** We also implemented CMEL analysis techniques and scripts, which included methods to check consistency and identify and remove corrupt data. We also evaluated linear and nonlinear filtering techniques for removing "data noise." We leveraged detection algorithms and developed techniques for detecting and extracting operational modes (or states) information in CMELs. This analysis informed energy savings opportunities and helped us develop CMEL modeling in building energy simulations.
3. **We identified the potential for immediate and short-term energy savings, which included standby power mode.** The lowest operating power mode of a device is usually indicative of a standby mode—a power level the device goes to when it is not in use. Figure ES–1 compares the power of the lowest CMEL operating mode to the amount of time spent in that mode. The areas of the circles are proportional to the number of CMEL types in the store.

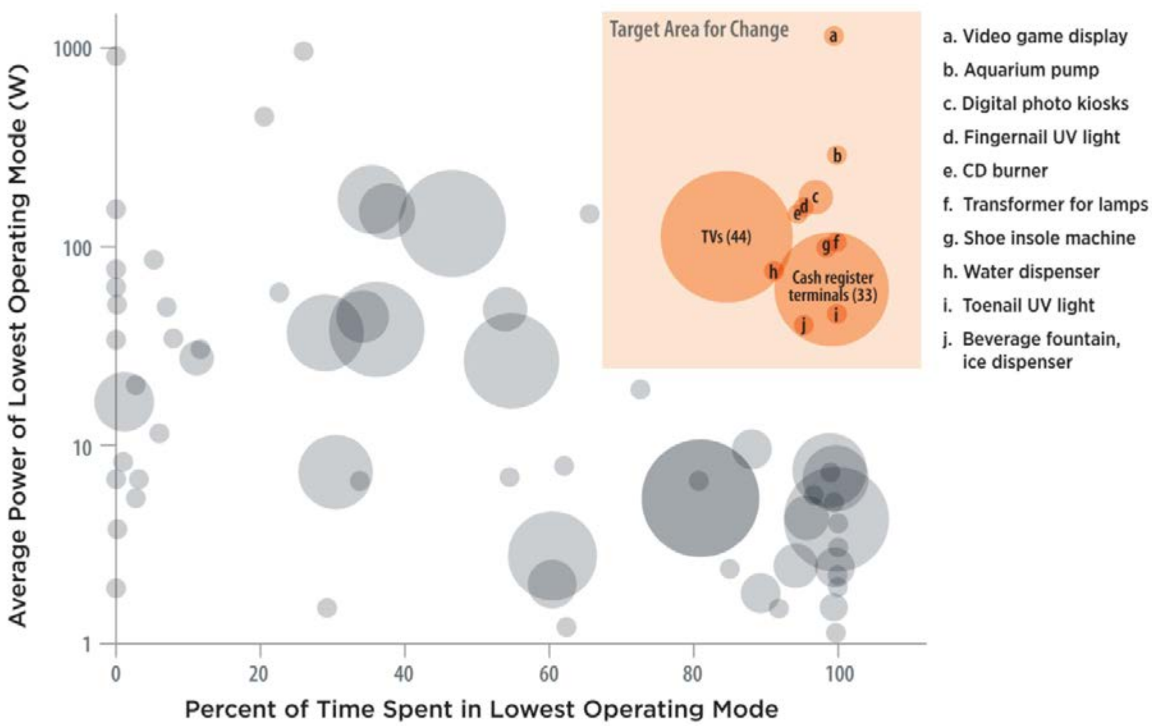

Figure ES–1 Density of CMELs lowest operating mode energy use

CMELs highlighted on the upper right corner draw at least 40 W in their lowest power mode, where they spend at least 80% of their time in that operating mode. These were identified as candidates for energy use reduction strategies.

1. **We identified the most prevalent device types, along with their combined total average daily energy use.**

   a. The most energy-intensive MEL is a video game display aisle with three game consoles, television screens, display lighting, and advertising that draw a constant 1.28 kW 24 hours/day. A simple control strategy would be to turn the display bank off between midnight and 6:00 a.m., when customers are least likely to purchase the games. Alternatively, an occupancy-based display lighting control strategy could be implemented to save 2.8 MWh/year per store.

   b. Televisions and demagnetizers are the most prevalent CMELs. Most are on a single display wall and continuously play a clip intended to demonstrate their sound fidelity, color quality, and definition. These televisions are powered on as long as the store is open, up to 24 hours/day. These can also be turned off between midnight and 6:00 a.m., when customers are least likely to purchase televisions. A manual, quick-on override would enable an employee to show televisions to customers during the off hours. A single store could thus reduce its energy use by 11 MWh/year.

   c. The large energy draw of beverage refrigerators and soda vending machines causes them (as a group) to use the most power of all devices.

   d. Cash register terminals (as a group) use considerably less power than the top three energy users; however, if all the components at a typical cash register station are considered in aggregate (cash register terminal, demagnetizer, barcode scanner/scale, handheld barcode scanner, and occasionally a conveyer belt), their total daily energy use is 109 kWh/day, which is comparable to televisions. We also learned that the cash registers can go into a "deep sleep" mode that uses 47% of their typical power (IBM, 2010). There is little or no time penalty to "wake up" such registers on demand; however, none of the seven cash registers we monitored seemed to use this feature. A simple combined control connected to the "open cash register" light switch could drive this function. If the retailer were to implement such a feature, a single store could save an average of 3.2 MWh/year on its cash register checkout lanes, and 5 MWh/year on all its cash registers (including those in the checkout lanes). A local, regional, or national chain would save more energy incrementally by using this strategy throughout its portfolio.

The most prevalent CMELs, even those with moderate individual energy use, usually have the greatest potential for energy savings and should take priority over targeting a few energy-intensive devices.

Future Work

- We will formulate recommendations for researchers and building owners who endeavor to audit CMELs devices in large commercial environments. Many general recommendations will, however, likely apply equally to a wider audience in the commercial sector, and will be of interest to members of the Commercial Building Energy Alliance.

- CMELs have traditionally been inadequately and inconsistently captured in modeling for building energy simulations. We will develop a repository of power use data for CMELs to inform whole-building energy modeling and other research areas. We could leverage the EnergyPlus platform to represent CMELs in a comprehensive building component model library. Users will be able to reference specific CMEL devices in building models to more accurately assess their effects on building energy use and analyze the impacts that different models of the same MELs have on building energy use.
- The commercially available power meters do not meet our functional, performance, and quality requirements, so we developed the requirements and specifications for suitable ones and seek to collaborate with industry partners to commercialize them for commercial and industrial applications.
- We will follow up with building managers and owners about suggested CMEL energy reduction strategies and recommendations to obtain valuable information about the accuracy of our assumptions and reveal any unknown barriers. We will attempt to use the collected data to develop other control strategies that use occupancy sensors or load sensing.

Nomenclature

CMEL	commercial miscellaneous electrical load
CSV	comma-separated value
DOE	U.S. Department of Energy
GM	general merchandise
LBNL	Lawrence Berkeley National Laboratory
MEL	miscellaneous electrical load
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
UL	Underwriters Laboratories

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1 Introduction and Motivation

Buildings account for 40% of primary U.S. energy consumption (residential 22%; commercial 18%), most of which (70% residential and 79% commercial) is used as electricity. Thus, almost 30% of U.S. primary energy is used to provide electricity to buildings (D&R International, Ltd., October 2009).

Miscellaneous electrical loads (MELs) are defined as all building non-main electrical loads, and include walk-in refrigerators, computers, cash registers, cell phone chargers, and many other devices. MELs constitute an increasingly large percentage of building energy use, partly because of the increasing number and variety of devices, and partly because of advances in the energy efficiency of main building loads (McKenney, Guernsey, Ponoum, & Rosenfeld, 2010). Overall, MELs are the largest end-use category in building electricity consumption (see Figure 1–1). MELs in residential and commercial buildings account for almost 12% of U.S. primary energy consumption.

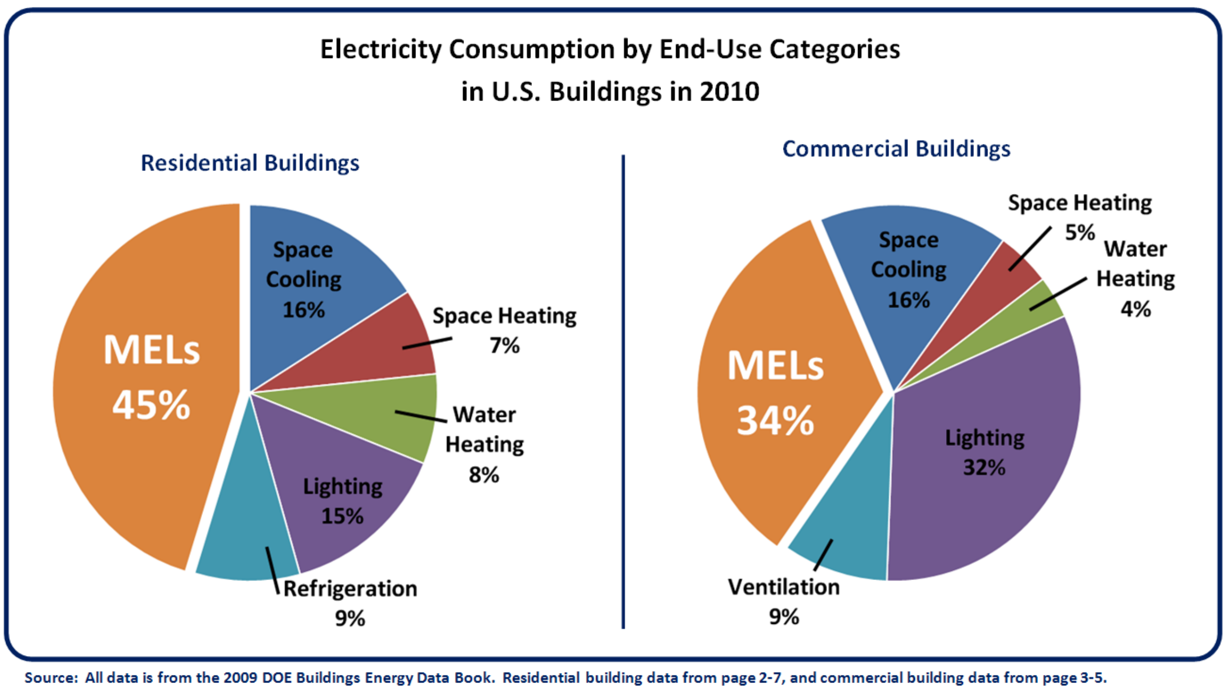

Figure 1–1 Electricity consumption by end-use categories
(Credit: Jeff Smith/NREL)

If all installed U.S. commercial building MELs (CMELs) were replaced with energy-efficient equipment, 175 TWh of energy could be saved (McKenney, Guernsey, Ponoum, & Rosenfeld, 2010). That is 35% of the 504 TWh that CMELs use annually. This energy saving is equivalent to the annual energy production of 14 average-sized nuclear power plants (D&R International, Ltd., October 2009).

Despite the clear importance of MELs vis-à-vis building energy use, current information about the consumption of specific MEL devices is not adequate to develop strategies to meet DOE's long-term goals for controlling and reducing energy use. Thus, we took the following steps:

1. Explored the most reliable methods for collecting energy use information about the CMEL devices.
2. Laid the groundwork for rigorous data collection from CMELs in a variety of commercial buildings.
3. Developed analysis techniques to transform raw CMEL data into actionable insights.

1.1 Scope of Work

The FY 2010 CMEL project was a multilaboratory effort (including the National Renewable Energy Laboratory [NREL], Lawrence Berkeley National Laboratory [LBNL], Pacific Northwest National Laboratory [PNNL], and Oak Ridge National Laboratory [ORNL]). It focused on a proof-of-concept demonstration of the methodology and technology needed to meter and monitor CMELS, and to collect and analyze data in commercial buildings. To represent the diverse CMEL data and to avoid overlap with similar occupancies and business activities, each laboratory focused on a specific subset of target building types. The nine major building categories are:

1. Office
2. Retail – Non-Food Sales
3. Food Sales
4. Food Service
5. Education
6. Warehouse
7. Healthcare
8. Public Assembly, Order, and Religion
9. Lodging

NREL focused on MELs used in building categories 1 (Office), 2 (Retail – nonfood sales), 3 (Food Sales), 4 (Food Service), and 7 (Healthcare), all in the context of a major big box retailer. According to the TIAX CMEL report, 75% of CMEL loads are consumed in buildings larger than 50,000 ft^2 (McKenney, Guernsey, Ponoum, & Rosenfeld, 2010). Our priority was to gather data from large buildings that have significant unknown or unquantified CMELs, as these have the greatest potential for addressing this type of energy use. Therefore, in FY 2010 we focused on a big box retail outlet in the Denver, Colorado, area that includes grocery sales.

2 Methodology

2.1 Inventory Process

Our first step was to inventory the plug loads. NREL adapted a taxonomy, first developed by LBNL, for classifying different spaces and devised a naming convention for each CMEL and meter, then defined a repeatable and consistent method for taking inventory. Based on the scope and time frame, we classified a subset of the CMELs as high priority for metering (see Section 2.1.3).

2.1.1 Taxonomy

The five main components of the taxonomy used for CMELs, along with typical examples, follow.

- **Space area.** A specific location in the retail store:
    - Break room
    - Cash registers/checkout
    - Customer service
    - Deli
    - Store exterior
    - General merchandise
    - Grocery sales floor
    - Hallways
    - Meat and seafood
    - Office
    - Pharmacy
    - Photo center
    - Produce
    - Rear grocery coolers and freezers
    - Front and rear restrooms
    - Receiving area
    - Stockroom.
- **Space type.** The primary purpose of a given area:
    - Active storage
    - Corridor
    - Enclosed office
    - Main entry
    - Equipment room
    - Sales area
    - Sorting area
    - Training room
    - Walkway.
- **End use.** The CMEL end use:
    - Traditional
    - Electronics
    - Miscellaneous.

- **End-use category.**
    - Audio
    - Commercial kitchen equipment
    - Networking.
- **Manufacturer.**
    - Manufacturer name
    - Model
    - Serial number.

2.1.2 Taking Inventory

We initially took inventory and then followed up to revise it. A group of researchers made a complete sweep through the store to catalog each CMEL, regardless of repeated manufacturer and model combinations. Several areas, including those containing personal, financial, or security information, were off limits. In the accessible areas, we used a digital camera and a notepad to inventory each CMEL. Three pictures were taken: one of the nameplate(s), one of the plug, and one of the entire CMEL. The information captured included:

- Manufacturer
- Model
- Production year
- Serial number
- Nominal voltage
- Rated current
- Rated power
- Electrical plug type
- Load type
- External power supply specifications (if applicable)
- ENERGY STAR® rating (if applicable).

Taking a picture of the plug was especially important to determine the type of meter that can be used. The location of each CMEL and the quantity of a given model (if applicable) were recorded on a notepad. A popular electronic spreadsheet and the CMEL taxonomy were used to transfer the information to a searchable worksheet with data validation.

Cataloging consumer electronics was difficult, because items such as televisions, radios, and notebook computers have a high turnover rate. Initially, all were inventoried. Months later, when we were ready to meter these devices, many had been replaced by new models. We determined that CMELs with high turnover rates should be inventoried just once, immediately before they are metered.

2.1.2.1 Revising the Inventory

This project was a proof-of-concept demonstration, so we avoided metering multiple instances of the same CMEL model under a similar use pattern. In a few cases, multiple instances of the same model were metered in the same area to assess meter precision and compare electrical loads to temperature and other measured variables. We wanted to be aware of these so we could determine the store's entire net CMEL power consumption.

In some cases nameplate data were unclear or missing, so we recorded the manufacturer and model information for a given CMEL in more than one way. To prevent two researchers from accidentally inventorying the same item under a different name, we implemented a consistent manufacturer naming method. We also reviewed nameplate records and remedied ambiguous model names, stripped branding information from all devices, and described only their functions.

The follow-up inventory used the initial information to count all CMELs of the same model together. This would later help us extrapolate the energy use information for the entire store. We photographed any additional unique CMELs and added them to the naming convention.

We then assigned a unique ID to each CMEL instance and followed a strict naming convention for easy identification. Because IT restrictions imposed by store management suggested that data had to be downloaded directly from meters (see Section 2.2.1.3), CMEL IDs played a vital role in tracking CMELs and meters. Also, serial numbers (and other identifying information) are not always present on CMELs, so the ID was a universal way to name all CMELs. Three pieces of information identified a CMEL:

- Location
- Device type
- Number of units.

The ID needed to be as short as possible and incorporate all three pieces of information.

The CMEL IDs used in this study had three components:

- **A five-character prefix.** The unique prefix described the location and was created by taking the first five letters from the space area name. So *break room* became *break*, and so on. If the first five letters were not unique, we used a different approach. For example, *GM – Electronics, audio* became *audio*. Each prefix was somewhat phonetic. We added zeros to the ends of prefixes with fewer than five characters (for example, *Men's* became *Mens0*).
- **A five-character suffix.** The suffix described the device type. It was made to be as simple as possible and still differentiate a like group from a similar but unlike device (for example, a beverage refrigerator is neither a soft drink refrigerator nor simply a refrigerator). We first condensed the CMEL description (for example, "Magazine Display Lighting") by removing all vowels, spaces, punctuation, and nonalphanumeric characters. Next, we made all letters lowercase (for example, *mgzndsplylghtng*) and used the first five characters (we left the vowels in if the description became unintelligible). We added zeros to suffixes with fewer than five characters.
- **Two numeric digits.** Two digits were appended to every CMEL ID to describe the number of units. The digits were 01, 02 … 99, respectively, to CMELs with identical 10-character IDs (the appended digits were 00 if the 10-character ID was unique). A barcode scanner had a prefix of *Cash0* and a suffix of *brcds*. The resulting CMEL ID was "Cash0-brcds-00." This naming convention can be readily adapted to other metering environments.

2.1.3 Metering CMELs in Order of Priority

We metered CMEL instances as high, medium, and low priorities.

- **High priority.** CMELs that are unique to retail environments:
    - Cash registers
    - Tenant equipment
    - Produce misters.
- **Medium priority.** Well-studied CMELs:
    - Refrigerators
    - Computers
    - Monitors
    - Televisions
    - Heaters, modems, etc., with semiconstant load profiles.
- **Low priority.** CMELs with:
    - Three-phase plugs, known as always-on constant loads (e.g., display lighting)
    - Unreachable plugs (ceiling fan display, ceiling mounted televisions, etc.).

(See Section 3.1.1 for a complete description of data collection barriers.)

2.2 Metering

We designed a series of experiments around each CMEL by screening plug load power meters based on metering capability, accuracy, data communication ability, data logging ability, safety, usability, and price. Then we purchased a set of meters and tested them for accuracy across a range of electrical load variables and ranges.

2.2.1 Selecting Meters

2.2.1.1 Studying Electrical Load Variables

In general, multiple electrical load variables need to be metered simultaneously to characterize CMEL behavior. If too few are metered, postprocessing analysis activities such as detecting operating modes, power transitions, and energy consumed will be more challenging and limited. If too many are metered, some meters will reach their data storage limit too quickly. We studied five essential electrical variables:

- Power (Watts)
- Voltage (Volts)
- Current (amperes)
- Energy consumption (Watt-hours)
- Power factor (unitless).

These variables enabled us to analyze real and reactive power (among other key analyses) and maintain the meters' ability to monitor for a relatively extended time.

2.2.1.2 Desired Meter Features

The CMELs were numerous and varied, so the meters had to be able to accurately meter loads of 0–1800 W. Accuracy throughout the measurable range was essential. Typically, meters can measure electrical variables accurately at the high end of the power range; however, in this environment, many CMELs have loads of up to 50 W, either in active use or in a standby mode. We define standby mode and standby power according to international standard IEC 62301 "House electrical appliances – Measurement of standby power":

- "The standby mode is the lowest power consumption mode which cannot be switched off (influenced) by the user and that may persist for an indefinite time when an appliance is connected to the main electricity supply and used in accordance with the manufacturer's instructions" (Almeida, Fonseca, Schlomann, Feilberg, & Ferreira, 2006).
- "The standby power is the average power in standby mode" (Almeida, Fonseca, Schlomann, Feilberg, & Ferreira, 2006).

The meter had to measure power, voltage, current, energy consumption, and power factor. It thus needed to have either (1) sufficient internal memory for extended data storage; or (2) a way to transmit data to a local or remote repository. A meter with internal memory only needed to be able to record the measured variables for at least 1 week at an acceptable sampling rate. Some CMELs (microwaves, conveyor belts) have transient load behaviors of interest, so a sampling rate of up to 1 second (with the ability to record for at least 1 week) was important. Unlike internal data storage, meters that can transmit data to a central repository do not run out of memory or have a limited sampling rate. Thus, we wanted meters that incorporated Ethernet, Wireless Ethernet (Wi-Fi), ZigBee, and other communication standards and an automatic time stamp on all data points.

2.2.1.3 Environment-Specific Meter Requirements

The meters had to be listed by Underwriters Laboratories (UL), as the environment presents a multitude of uncontrollable variables related to electrical safety (e.g., customer behavior, employee behavior, power outages, and environmental hazards).

Data had to be stored locally because real-time data could not be retrieved remotely. We did not have wireless Internet access. We investigated various data collection methods before deciding on a manual method (see Section 2.2.2).

The meters needed to be small and minimally invasive, and positioned to be hazard free. Tripping hazards were a great concern, so meters had to have minimal cables that could be routed and bundled wherever possible. Some areas had strict wire management policies that prohibited their electronics from remaining plugged in when not in use. This precluded the metering of many CMELs. From an experimental standpoint, the meters needed to be positioned to minimize risks from electric shock, and to be concealed to reduce tampering and accidental unplugging.

Certain items required special precautions. Food could spoil in refrigerators and freezers if the meters accidentally cut power. Modems and computers could be damaged, stop transferring data, or lose data if power were cut without proper shutdown procedures. Meters had to be tested to ensure they would not trip ground fault circuit interrupters or switch power off via internal relays.

The regular unplugging of CMELs posed two problems:

- How to meter devices that did not remain plugged in for the duration of the study
- How to meter devices that may be moved about and plugged in to multiple outlets.

A meter without an internal clock does not accurately reflect the data gaps in a time series. To meter mobile devices, the meter had to stay with the device and be constantly plugged in. Retail staff did not always return CMELs to the metered outlet. For perspective, a full 10% of the devices inventoried, including electric shopping carts and floor sweepers, are moved or regularly unplugged. An additional two dozen (personal fans, for example) may be moved occasionally.

2.2.1.4 Selecting a Meter

We conducted an exhaustive search of commercially available meters. We determined that for CMEL loads plug-through meters are simpler to use than clamp-on ones. We evaluated all meters to determine if they met the requirements described in Sections 2.2.1.1, 2.2.1.2, and 2.2.1.3. We evaluated five plug-through meters with the features described in Table 2–1 (brand names and models are not mentioned, and are generically identified with the letters A through E):

Table 2–1 Features of Evaluated Meters

Meter	Features
Meter-A	120,000 records, onboard display, 1 NEMA 5-15P female outlet, USB interface, accuracy of ± 1.5%, no automatic time stamp, UL listing, commercially available
Meter-B	Same as Meter-A, Ethernet with TCP/IP and http communication, power switching
Meter-C	Onboard display, 2 NEMA 5-15P female outlets, no data export, accuracy of ± 1% full scale and ± 2% in the low end of the scale, occupancy sensor connector, UL listing, commercially available
Meter-D	Onboard display, 1 NEMA 5-15P female outlet, no data export, accuracy of .2%, UL listing, commercially available
Meter-E	No onboard display, 1 NEMA 5-15P female outlet, ZigBee wireless communication, power switching, accuracy of ± 0.5% Wh over a 2000:1 current range, automatic time stamp, no UL listing, not commercially available, integrated temperature sensor

We selected Meter-A, which is designed to meter 120-Volt, 60-Hz, and 15-amp circuits. It can record the following variables:

- Instantaneous power
- Minimum power
- Maximum power
- Power factor
- Volt amp (apparent power)
- Cumulative energy
- Average monthly energy
- Elapsed time
- Duty cycle
- Frequency
- Cumulative energy cost
- Average monthly energy cost

- Instantaneous line voltage
- Minimum voltage
- Maximum voltage
- Instantaneous current
- Minimum current
- Maximum current.

Meter-A features internal data storage of up to 120,000 records, depending on its configuration. We configured it to meter power, voltage, current, energy consumption, and power factor at a 30-second sample rate, which equated to approximately 23,000 records per week. The meter is accurate to ± 1.5% of the displayed value. For loads smaller than 60 W, the current and power factor measurements are less accurate (see Section 2.2.1.4.1), but all other variables remain within the 1.5% range. The meter is listed to UL 610010-1 and CAN CAS/C22.2 61010-1.

Meter-A features a USB interface that enables us to collect data manually. It may be configured to the desired settings through the same interface while connected to a computer running the meter interface program. The sample rate may be set to record at intervals of 1 second to 24 hours. Any combination of measurable variables may be selected for metering.

Meter-A is one of the few commercially available meters that offer data storage. Others either provide only instantaneous local display or require real-time data collection via a computer. The combination of advertised low load power accuracy and sufficient data storage drove our selection. Some of its features are unique; the unit price reflects this. At the time of initial selection, Meter-A carried a market price of $195.95, which is more expensive than meters with similar capabilities (except data storage). Meter-D carried a market price of around $20.

2.2.1.4.1 Comparing Meters

We tested all five meters to assess possible accuracy-related benefits. The results are given in Table 2–2, which shows that Meter-A and Meter-B are the most accurate, an unexpected result because Meter-A was selected based on considerations other than accuracy. That said, there is an unmet market need for accurate, robust, and affordable end-use metering capability. As identified in Section 3.0, Meter-A and Meter-B are the best performers, but still fell short of the mark for this study.

Table 2–2 Accuracy of Four Power Meters

Meter Type		Meter-A and Meter-B*	Meter-E	Meter-D	Meter-C
Number of Meters Tested		38	1	1	3
< 5-W range	**Voltage**	0.03%	0.00%	–0.08%	–0.79%
	Current	–12.03%	–47.58%	–20.42%	34.58%
	Power	2.46%	–2.17%	–11.11%	–3.13%
	Power factor	20.14%	94.12%	3.92%	–2.59%
5- to 25-W range	**Voltage**	0.03%	–0.08%	0.08%	–0.85%
	Current	–18.83%	–1.73%	–18.55%	–9.53%
	Power	0.47%	–0.81%	–19.35%	–3.48%
	Power factor	3.91%	1.04%	–7.29%	1.04%
25- to 100-W range	**Voltage**	0.02%	0.08%	0.17%	–0.48%
	Current	5.48%	–0.57%	–2.99%	–0.92%
	Power	–0.51%	0.88%	–2.94%	–1.90%
	Power factor	–6.73%	1.82%	–5.56%	–2.45%
100- to 500-W range	**Voltage**	0.04%	0.09%	0.34%	–0.68%
	Current	0.40%	–0.05%	0.22%	1.50%
	Power	–0.46%	1.72%	1.56%	0.00%
	Power factor	–2.04%	0.40%	–2.04%	0.00%
> 500-W range	**Voltage**	0.38%	0.53%	2.76%	–0.30%
	Current	–1.81%	–0.39%	3.48%	–33.86%
	Power	–1.59%	0.34%	7.13%	–0.08%
	Power factor	–0.61%	0.00%	0.00%	0.00%
Maximum average error across power ranges (absolute values)	**Voltage**	0.38%	0.53%	2.76%	0.85%
	Current	18.83%	47.58%	20.42%	34.58%
	Power	2.46%	2.17%	19.35%	3.48%
	Power factor	20.14%	94.12%	7.29%	2.59%

* The percent error with respect to a highly accurate laboratory meter is averaged across these 38 meters.

2.2.1.5 Testing Meter Accuracy

We simultaneously used a meter and a highly accurate laboratory meter to take measurements from a CMEL device, then compared measurements from both to assess the calibration of each.

We chose five CMEL power ranges (< 5-W, 5- to 25-W, 25- to 100-W, 100- to 500-W, and > 500 W) to determine the meters' accuracy, because a wide variety of CMEL types were involved, and because the device had more than one power state (e.g., "standby," "off," "on").

After connecting each meter in the circuit to negate any power it drew, we connected the devices. We then simultaneously recorded measurements from both meters for voltage, current, power, and power factor. We then summarized the data to assess their overall accuracy and consistency (see Figure 2–1 and Table 2–2).

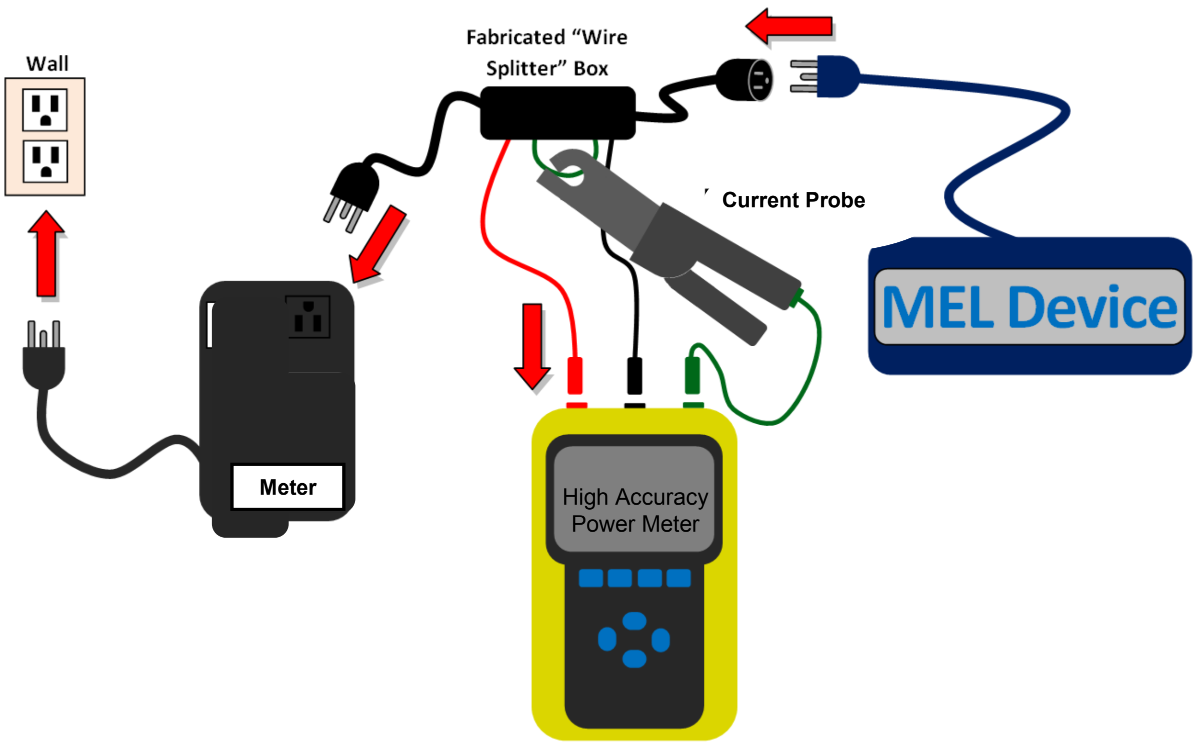

Figure 2–1 Meter accuracy experimental setup
(credit: Jeff Smith/NREL)

2.2.2 Data Collection Methods

We evaluated several data collection techniques for the inventoried CMELs to devise a robust method for monitoring (with a fine time resolution) various electrical loads at the plug level in all target areas. We targeted power, energy, current, voltage, and power factor for each CMEL. The main obstacles were meter limitations and store policies:

- We did not have access to Internet connections (wired or wireless).
- All meters and wires had to be out of sight and off the floor to prevent tripping hazards.
- All meters were required to have a UL listing.
- Certain active devices, especially computers, cash registers, modems, and refrigerators, had to be unplugged to install meters.
- We had no access to secure or sensitive areas.

We deployed 50 meters throughout the store. Each was set up to take measurements every 30 seconds and to stop recording when the internal memory was full. We plugged the CMEL in to the NEMA 5-15P female outlet on the meter. If the CMEL did not have a NEMA 5-15P male plug, we used an adapter (when possible). For example, at the checkout stands a NEMA L5-15R adapter was needed to monitor the cash registers and a NEMA L5-20R was needed to monitor the conveyor belts. We then plugged the meter in to a NEMA 5-15P wall outlet, cleared the meter's memory, recorded the start time, and left it to log data for 1 week.

To retrieve stored data, we connected a laptop to the meter with USB cables. We used the USB program to transfer data from the meter to the laptop, saved the data as a text file, then cleared the meter's internal memory data and recorded a new start time. The meter does not have an internal clock, so we had to manually enter the first time stamp with the meter's program. We repeated this process for 4 weeks for each CMEL.

The meter's internal memory limited the time a CMEL could be monitored without the stored data being retrieved. It also limited the sampling rate and the number of electrical load variables. We thus researched the following alternative methods:

- **Connect multiple meters to a laptop via a USB cable, bypass the meter's internal memory, and store the metered data directly on the laptop.** Having the storage capacity of an entire laptop alleviates memory limitations, but a laptop is unreliable because cables may come unplugged or power outages may occur. All studied CMELs had to be within a USB cable length of a laptop. This option was infeasible.
- **Connect multiple meters to a laptop via a wireless USB adapter.** The benefit of (nearly) endless memory does not outweigh the drawbacks of this method. The wireless USBs have a range of approximately 10 feet and the CMEL density in many parts of the store is not high. Possible power outages and laptop operating system failures were also concerns.
- **Store data through a Web server.** A type of the meter can transmit data to the manufacturer's website, which expands the meter's memory. The Internet-capable meter, however, occasionally tripped ground fault circuit interrupters, which would be unacceptable in a retail environment. Ultimately, our lack of Internet access deterred us from this option.

Limited memory was deemed to be a less severe issue than meter reliability, so we chose the manual method.

2.3 Database Design

To leverage previous work, knowledge, and procedures, we adapted a database to store CMEL data. To achieve the greatest flexibility in data processing, presentation, and interoperation, we stored the data in a raw comma-separated value (CSV) data format. We stored CMEL identification information (manufacturer, model, end-use category, etc.) as well as raw metered data in a central database.

2.3.1 Goals

The database enabled us to organize, store, and share CMEL data. The following major goals support this:

- Store CMEL identification data in a central location.
- Store CMEL metered data in a central location.
- Visualize standardized metered data from a Web application.
- Download raw data to develop new analyses and visualizations.

2.3.2 Software Used

The CMEL data were stored in a MySQL database. The Web application was implemented in Ruby on Rails. Both are open-source and well-supported.

2.3.3 Structure and Functionality

2.3.3.1 Structure

Several types of CMEL-related information are stored in the database. Project-level data such as company name, location, climate zone, building type, and subtype were stored first, then general information about each CMEL was stored (see Section 2.1.2).

Measurement data—the names and descriptions of all measurements recorded for each CMEL—were stored in the database next. Measurement types included Volts, amps, Watts, power factor, and Watt-hours. The raw data were recorded by a meter, then stored in multiple text files, which were then converted to CSV format. Once information about the data files—such as file name, file type, and number of header lines—was recorded, the raw data contained in the data files could be uploaded to the database.

We built a mechanism for correcting erroneous or missing data into the application. It did not overwrite the original data values; we wanted to retain the raw values for historical reasons, so we corrected the data in a separate table and annotated them with an identifier representing the user who made the change.

2.3.3.2 Functionality

The Web application enables users to enter new and updated CMEL identification information into the database. Methods for batch upload of information via CSV files are also available.

CMEL time series data can be aggregated and displayed. The raw data resolution stored in the database is one sample per 30 seconds; these data can be aggregated to hour and day resolution and graphed as an annotated timeline. Multiple measurements can be plotted on the same graph or on separated graphs. Zooming enables users to view data windows ranging from 1 day to 1 year.

Figure 2–2 illustrates an annotated timeline generated for the Wattage measurement of two CMELs and displayed on the Web application.

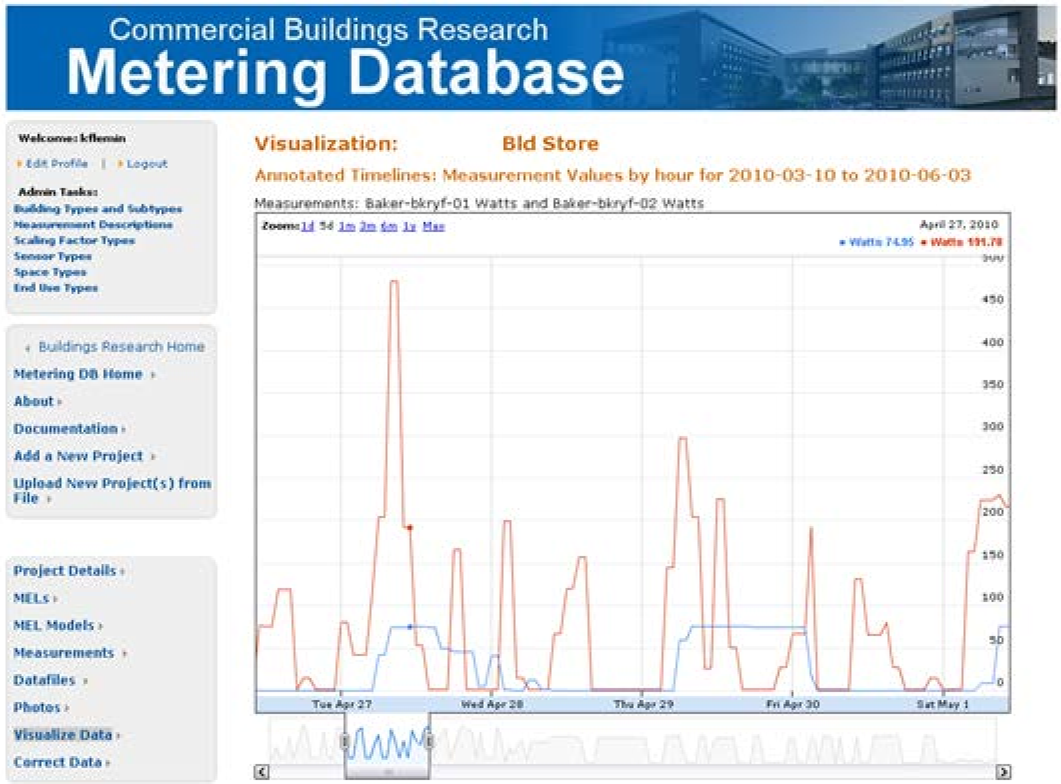

Figure 2–2 CMEL data visualization

2.3.4 Challenges

Storing massive quantities of data was challenging. The database had to be properly indexed and queries optimized so the Web application could remain responsive and the user could visualize data usefully and quickly.

Allowing so many data to be downloaded so new analysis methods could be developed was also a challenge. Although data can now be downloaded for each CMEL separately, the time this process takes is not practical for more than a few data. This problem eased when researchers were given access to a local data repository where the analysis software could retrieve the data programmatically.

Other challenges included maintaining consistent CMEL information and propagating changes across the database. Changes to unique identifiers cannot be automated, because this process relies on the unique identifiers to find the appropriate entries. Minimizing the need to make changes to the database and defining a robust set of procedures for populating and updating the database were essential.

2.4 Data Analysis

The CMEL Combined Action Plan identified analysis and characterization of CMELs as key project outcomes. We implemented this analysis as a collection of scripts written in R, a language and computational environment for statistical analysis and data visualization (R Development Core Team, 2010). Consistent with the objectives identified in this plan, these scripts automatically compute key statistics for metered CMELs and produce high-quality plots for effective visualization of CMEL behavior.

2.4.1 Goals

Our overarching purposes in collecting CMEL data were to characterize typical CMEL use under real conditions, improve the detail and accuracy of building performance evaluation, and identify energy savings opportunities in a retail environment. The following analysis goals support these purposes:

- Summarize key statistics for CMEL electrical data, including total energy consumption, average power, and duty cycle.
- Identify and quantify device operating modes, including "off," "standby," and "active" states.
- Compute and plot typical device load profiles at least hourly.
- Aggregate and compare power data among various devices.
- Provide effective plotting and visualization for the previous goals.
- Identify specific energy savings opportunities based on analysis results.

2.4.2 Software Used

To achieve our goals, we identified six key abilities for the analysis software package:

- Compute and report energy statistics.
- Report and plot time series load profiles.
- Extract device operational modes.
- Have high-quality plotting.
- Be robust.
- Be extensible and flexible.

We evaluated a number of commercial and free software packages for statistical analysis of CMEL data:

- Dedicated software specific to the analysis of electrical power systems
    - Useload (The SINTEF Group, 2010)
    - Google Power Meter (Google, 2010)
- Various bundled software packages
    - Included with Tendril Networks' products (Tendril, 2010)
    - General use computational software that is applicable to a wide variety of analysis needs (Microsoft Office and OpenOffice.org productivity suites, MATLAB, GNU Octave, and R). Of these, OpenOffice.org, GNU Octave, and R are free and open-source.

Software that is dedicated to analysis of electrical power data has advantages in usability and polish; however, we determined that it is generally inadequate for advanced statistical analysis of CMEL data. It also must be paired with specific hardware devices, which greatly limits its flexibility. Several (notably, the spreadsheet components of the major office productivity suites) are also ill-suited to complex statistical analysis.

MATLAB, GNU Octave, and R can all perform highly complex analysis tasks and are extensible via scripting. From these and other options, we selected R, which is “a language and environment for statistical computing and graphics” (R Development Core Team, 2010) based on the S language. R is designed specifically for statistical analysis and visualization, two key requirements for the CMEL software package. It is well developed, well supported, and widely used in academic research. R is also free, open-source, and cross-platform. Although R lacks tools specifically designed for electrical power systems analysis, it is readily extensible via scripting and packaging and supports interactive bindings to other code languages, notably C++. Thus, our strategy has been to develop CMEL-specific scripts within R that perform all required functions.

2.4.3 Information Flow

CMEL data and information flowed in the following order:

1. We collected data manually from meters installed at the retail store.
2. We time corrected and stored data on a central network drive, recorded information about the individual data files in a working spreadsheet, which we uploaded to a centralized database.
3. Automated scripts compiled the individual data files into unified time series and uploaded these to a centralized database. The time series were also available for processing in R.
4. We used R to import and analyze CMELs data. Analysis outcomes could be exported as CSV files or plotted directly, at the researcher’s discretion.

2.4.4 Analyses Performed

We used the R statistical computing and graphing language to develop analysis scripts and functions and provide the key capabilities required by the analysis software package. We are also exploring the option to organize and publicly distribute these scripts as an R package.[1] The software had to be robust and easy to use, and be able to:

- Perform statistical analyses and computations.
- Reliably identify and flag missing or corrupt data.
- Identify CMEL operating state transitions.
- Perform CMEL operating mode analyses.
- Possess flexible plotting capabilities.

2.4.4.1 Identifying Missing or Corrupt Data

The R language includes robust features for dealing with missing values. We incorporated these into the CMEL analysis scripts so missing data could be automatically identified and skipped without compromising the results.

Corrupt data are more difficult to automatically detect, isolate, and reject, because multiple data collection failure paths result in multiple types of data corruption (see Section 2.4.5). We implemented a method for manually flagging and removing corrupt data as well as an internal consistency check that can determine whether voltage, current, power, and power factor are

[1] R packages are collections of scripts that have been tested and bundled to be readily installed as add-ons to R. Hundreds of packages are publicly available as extensions to R.

consistent in relation to each other. We also evaluated (with some success) various linear and nonlinear filtering techniques for noise attenuation (for these data, noise is fluctuations in the collected data samples that can be attributed to the compounded effect of metering device random errors and internal fluctuations in the load around its nominal values for the current operational state). As additional types of data corruption are identified, we will modify the scripts accordingly to check for them.

Figure 2–3 shows an example technique that we used to identify corrupt or invalid datasets.

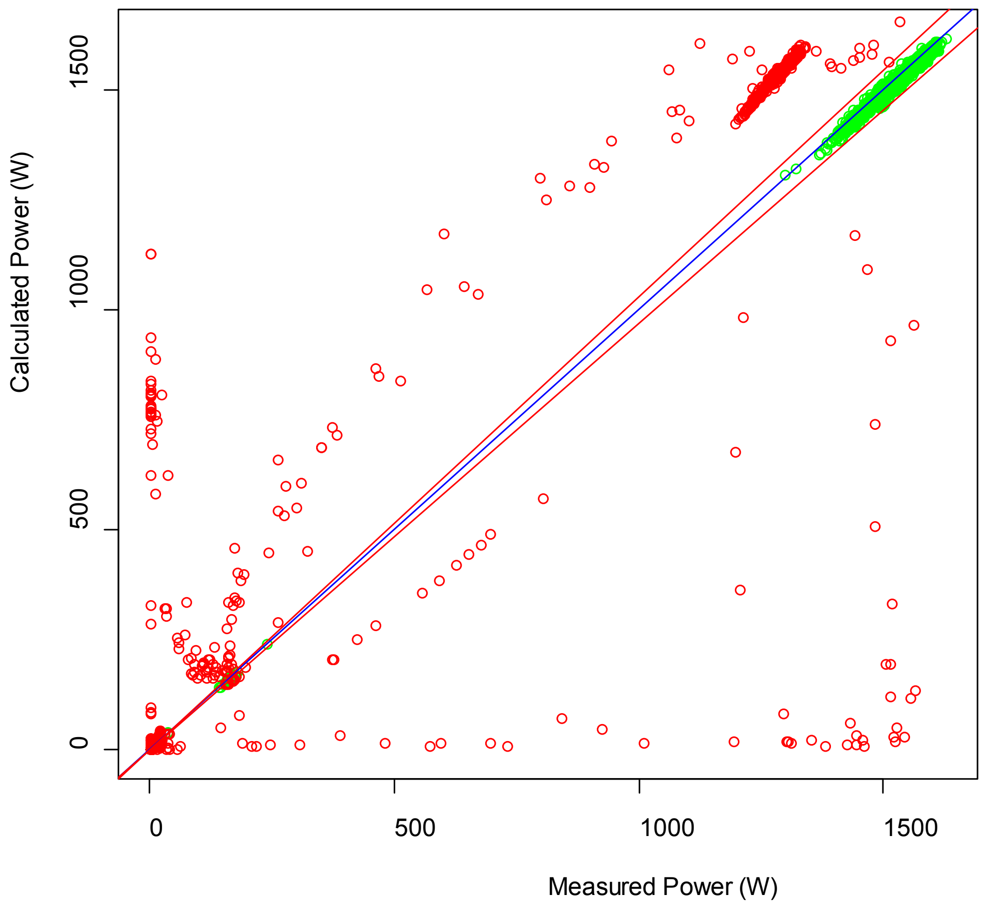

Figure 2–3 Data quality check using measured power versus calculated power

The plot shows data points collected every 30 seconds over a 4-week period for a microwave oven in the break room. To identify corrupt data, the power [W] calculated from the measured voltage, current, and power factor data (V [Volts] * I [Amps] * PF [Power Factor]) is plotted against the measured power data [W]. Ideally, if the measured data were consistent within predefined error tolerances (3% in this example, represented by the region between the two red lines), there should be a nearly 1:1 ratio between the measured power and the calculated power; the blue line bisecting the x-y plane shows this. The green circles show the data passing the consistency check. Given a tolerance range matching the published metering device's nominal tolerance, this should be the expectation for most data points. We learned, however, that this was not always the case: for the microwave oven, 71.8% of the collected data points (red circles in the plot) fell outside the expected tolerance region. The technique enabled us to easily identify consistent datasets for all metered CMELs and eliminate the faulty data from further analyses. Such simple techniques also enabled us to verify that the meters were not defective or miscalibrated. A few needed minor factory calibrations, but all those employed in the study produced qualitatively comparable data, leading us to conclude that the data inconsistency was likely attributable to a general hardware design issue rather than to specific defects.

2.4.4.2 Basic Statistics

We developed R analysis scripts to compute basic statistical quantities for any CMEL under analysis, including average power, total energy used, extrema in the data, and measures of variance. The data used with the analysis scripts were preprocessed for quality and screened using the technique illustrated in Section 2.4.4.1, so the analysis scripts worked on reliable data. We also implemented R scripts to compute quantities of particular interest in the analysis of electrical loads given the set of measured quantities, such as device reactive and apparent power. These provide valuable information for advanced multidimensional analysis; for example, for modes and state transition identification and modeling.

2.4.4.3 Transitions in Operating State

To identify use patterns and device duty cycles, it is advantageous to determine when transitions occur between operational modes. The most basic is an on/off change, but transitions between other modes (e.g., standby to active) are also interesting. We are investigating digital signal processing techniques and modified image sharpening algorithms to detect edges (transitions) in preconditioned time series data. Preliminary testing shows promising results (see Figure 2–4). The plot shows the power consumption change for a fan in the bakery area over a one-month period. The vertical red lines represent the identified magnitudes of the transition between two power states. We used this and other types of analysis to identify power states and operational modes for various CMELs.

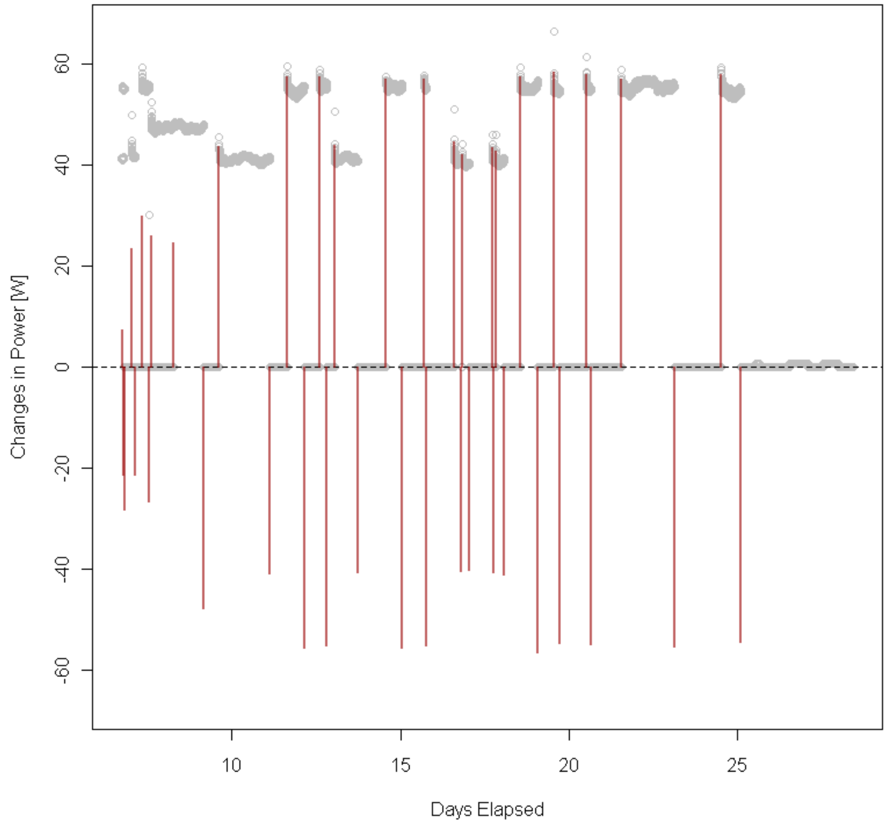

Figure 2–4 Plot of edge/transition detection for a fan in the bakery

2.4.4.4 Mode Analysis

Several transition analysis and clustering techniques described in the literature are applicable to CMEL mode detection. Laughman et al. defined a process for load disaggregation that can be applied to mode identification (C. Laughman, 2003). It includes edge detection and a cluster analysis algorithm. Image sharpening techniques, such as those found in (Tabbone, 1998) provide the means for edge detection.

Clustering data into logical subsets forms the backbone of mode identification, because power modes are clusters. Some researchers have applied cluster techniques to preprocess residential MELs into on/off, constant, and continuously variable categories for nonintrusive load monitoring (Hart, 1992) and (Roth, 2010). A summary of most available clustering techniques can be found in (Wunsch, 2009) and (P. Tan, 2005). The application of these techniques to the datasets is documented in (S. Frank, 2011).

We leveraged the experimental transition detection algorithms described in Section 2.4.4.3 and developed techniques for detecting and extracting operational mode information in CMELs. A goal of mode analysis is to classify device behavior into operational modes, or states, with distinct characteristics. This analysis is critical for computing such metrics as duty cycle and standby time, and for informing energy savings opportunities and developing adequate modeling of CMELs in building energy simulations.

Mode extraction for electrical loads may be viewed as a clustering problem: each CMEL power mode represents a distinct cluster within the load data that must be identified and extracted. Cluster analysis returns modes as groupings, or clusters, of data points, which may then be further analyzed to determine duty cycle, average power in each mode, expected mode transitions, etc. For example, the vending machine power data displayed in Figure 2–5 suggest a dominant state near 600 W and two distinct but closely spaced states at 150–230 W.

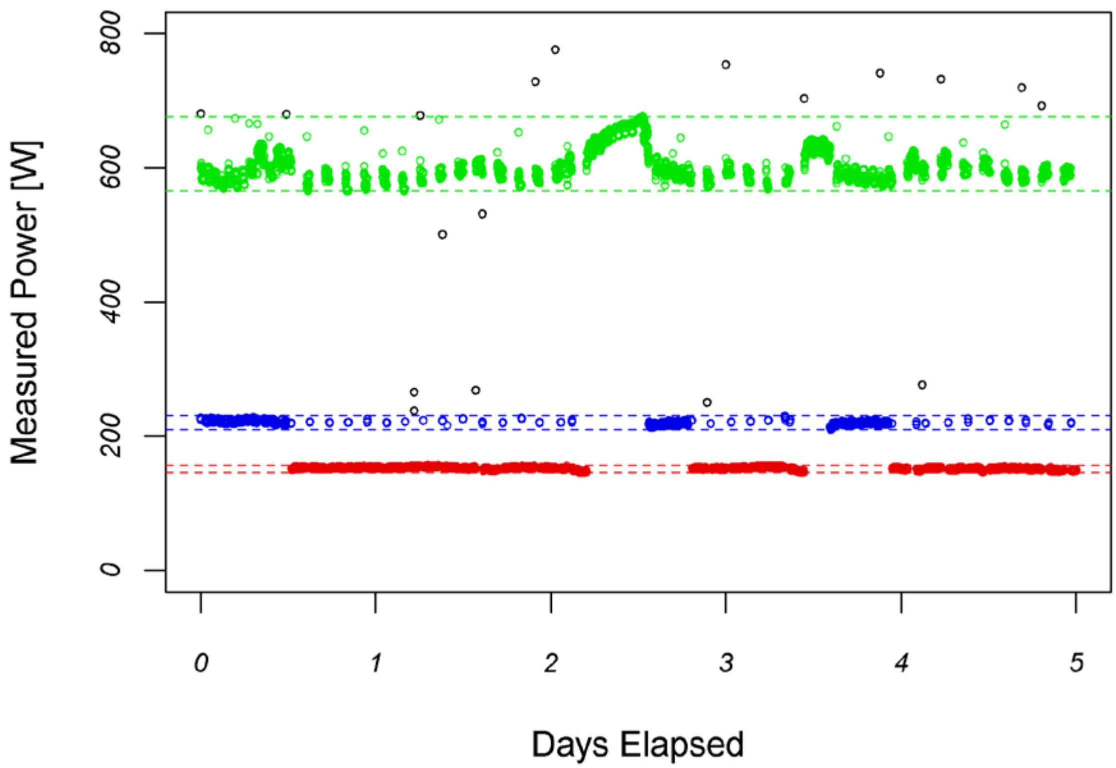

Figure 2–5 Data classification: operating modes of a cold drink vending machine

Clustering the data should extract each state as a power mode. We pursued centroid-based techniques, expectation-maximization algorithms, and density estimation partitioning techniques for mode analysis. Density estimation is a promising technique for CMEL mode extraction because it requires minimal initialization and has potential for automation; however, density-based approaches are computationally intensive. We are exploring less computationally intensive and less tedious variations that use a histogram to estimate data density. One of these variations is based on the concept of visual classification of electrical load data and then automating an otherwise tedious manual process. It is fast, linearly scalable, and yields robust results across a diverse range of CMEL power profiles (S. Frank, 2011), but is strictly heuristic. Preliminary tests show that our technique can in many cases isolate operating modes with a high degree of accuracy (see Figure 2-5). We tested it with 163 CMEL datasets. The mode identification script identified 100% of the single-mode devices. In 75% of the multimodal cases, the returned clusters agreed with manually identified clusters. The remaining 25% were misidentified, mostly because the algorithms could not identify loads with spiking power use (for example, microwave ovens), for which an increased time resolution in the datasets would be needed.

2.4.4.5 Seasonal Analysis

The CMEL Combined Action Plan identified seasonal, weekly, and daily load variations as key parameters in CMEL analysis. We still have a few meters in place to monitor CMELs (highly temperature- or occupancy-dependent devices), which will likely experience seasonal changes. Additional techniques worthy of exploration include statistical autocorrelation and frequency domain analysis, such as via the Fast Fourier Transform and discrete wavelet transformations.

2.4.4.6 Correlation With Additional Parameters

CMEL power use depends on line voltage, ambient temperature, occupancy, and other factors. Temperature sensors were installed along with plug load meters on CMELs that had the potential for temperature correlations. The refrigerators and soda vending machines depend on zone temperature, which can be used to predict or model their behavior. Occupancy sensing would provide further information for correlating our energy data.

2.4.4.7 Plotting and Visualization

We focused on flexible and effective visualization and plotting techniques for measured and computed CMEL data. The R software provides powerful and flexible tools for producing static plots. In addition to the interactive data visualization implemented in NREL's CMEL Metering Database (see Section 2.3.3), we wrote customizable plotting routines for CMEL data that enable us to perform rapid visual inspections of many CMEL datasets. This has enabled NREL researchers to make key observations about CMEL use in a retail environment (see Sections 3.3 and 3.4).

2.4.5 Challenges

We encountered significant challenges as we implemented analysis techniques. These fell into two primary categories:

- **Quantities unavailable for analysis.** The meters measure only electrical quantities. We did not have access via the installed meter base to environmental information such as occupancy level or device use level. Therefore, we could not correlate CMEL behavior with these conditions without installing additional sensors and extending the project.
- **Quality issues with metered data.** The meters exhibited failure modes, including applying incorrect calibration constants, recording constant power when power was not constant, and recording noisy time series (see Section 3.1.2). The data collection process was also subject to human error, especially because incorrect time stamps were assigned to the data files, resulting in overlapping or shifted data points in the time series.

Taken together, these failure modes made automated detection and removal of corrupt data difficult, as many failure modes had to be checked. Sometimes data corruption could be detected only subjectively. We thus visually inspected CMEL data to determine corruption. A user would flag certain portions of the data as corrupt. The script would then remove these from future analyses. In the future, failure modes first detected by visual inspection may be incorporated into the scripts' data verification routines to automate detection and removal of corrupt data.

3 Results

3.1 Evaluating the Methodology

We identified several key challenges in three broad categories that inhibited effective and accurate data collection: data collection, accuracy, and scalability. Overall, however, our methodology is suitable for small-scale metering but is not readily scalable without significant modification.

3.1.1 Data Collection Barriers

We encountered several barriers that prevented us from metering certain CMELs. Most commonly, some plugs were physically inaccessible: behind immovable objects (such as beverage vending machines), inside locked cabinets (such as self-checkout stands), or at heights reachable only with a ladder. Other plugs were accessible but did not conform to the typical 120-V standard NEMA 5-15P plug. Some devices (e.g., cash registers) used twist lock plugs, requiring a NEMA L5-15R adapter meter. Others operated at 240 V or 480 V; these could not be metered because of meter limitations.

A few devices were accessible but could not be metered because of security or privacy considerations. For instance, the local bank branch did not allow us to inventory or meter ATMs and other banking equipment. We also could not access many healthcare-related devices because the Health Insurance Portability and Accountability Act Privacy Rule "provides federal protections for personal health information held by covered entities and gives patients an array of rights with respect to that information" (U.S. Department of Health and Human Services, 2010).

We often encountered difficulties in discerning which accessible devices were being metered. Some were combined in a single plug and we could not isolate individual loads. Multiple interconnected devices were sometimes plugged in separately, but because of the cord routing we had to make educated guesses about which cord corresponded to which device. The metering process also presented challenges. One was that the meters had no internal real-time clocks. Metered data thus had to be manually tagged with a time stamp during the data download process, which introduced errors. We later observed that some time stamps were offset in increments ranging from a few minutes (because the clock being consulted was inaccurate) to more than a week (because an incorrect start date was entered). Some meters exhibited inconsistent internal timers such that the reported total length of collected data did not match the actual run time of the meter. In a few cases, a single 7-day period of metered data yielded a range of time stamps spanning as many as 9 days or as few as 4. The shorter ranges may correspond to weeks in which the meter was unplugged for an indeterminate period. Unfortunately, without an internal clock, it is impossible to determine when the meter was unplugged. These errors caused 20% of the data to have questionable time series.

3.1.2 Meter Accuracy

We selected the most appropriate, commercially available meter and performed in-house testing to address accuracy concerns.

3.1.2.1 Observations From Collected Metering Data

Thirty-one percent of the CMELs metered had some significant inaccurate data series, caused by 21 meters (41% of those used). This suggests a problem with the model rather than with individual meters. We tried to remeter each device that had corrupt data with a different meter to obtain a complete 4-week dataset. The television bank posed a special problem, because of a sudden, apparently independent jump in line frequency.

According to the Meter-A user's manual:

> For loads less than 60 watts, the current and power factor displays will have lower accuracy. However, the wattage and other displays will still be within 1.5%. So for instance, the meter should display 1.0 +/- 0.3 watts (1.5% = 0.0 watts, plus 3 counts = 0.3 watts, for a total of 0.3 watts), or between 0.7 - 1.3 for a 1 watt load. However, the meter will likely display 0.010 amps, which would be off considerably if the actual load had a low power factor and the actual current was 0.040 amps.

Meter testing verified that the electrical current readings are highly inaccurate at power levels lower than 60 W (see Section 3.1.2.2). We concluded that the current and power factor data in this range are of little value and should be omitted from any analysis that requires measurable accuracy. The unreliability poses a significant problem because 61% of the CMELs studied have at least one operating mode below 60 W, and 40% operate entirely below 60 W. Therefore, any analysis technique requiring current or power factor data cannot be used for any of these devices.

3.1.2.2 Results of Benchtop Meter Testing

Forty-eight meters were tested against a baseline from an accurate laboratory meter; more than 20% had significant measurement problems and were returned to the manufacturer for recalibration. The most common error was that a meter would read 0.00A when connected to a < 25-W MEL device.

The following results were measured only from correctly functioning meters. Meter testing revealed several strengths and weaknesses in measurement capability. Measurements taken from MELs at different power ranges showed different degrees of accuracy, as expected. Most noticeably the meters measured power in all five power ranges quite precisely, but current and power factor were much less accurate, especially in the lowest two power ranges.

Overall results are summarized in Table 3–1. Graphical representations of the findings are included in Figure 3–1 and Figure 3–2 (note the vertical scales on the power and current accuracy plots).

Table 3–1 Summary of Meter Accuracy for the Selected Meter Model

	< 5-W Range	5- to 25-W Range	25- to 100-W Range	100- to 500-W Range	> 500-W Range	Overall
Voltage measurement average % error	0.03%	0.03%	0.02%	0.04%	0.38%	0.10%
Current measurement average % error	–12.03%	–18.83%	5.48%	0.40%	–1.81%	–5.36%
Power measurement average % error	2.46%	0.47%	–0.51%	–0.46%	–1.59%	0.07%
Power factor measurement average % error	20.14%	3.91%	–6.73%	–2.04%	–0.61%	2.94%

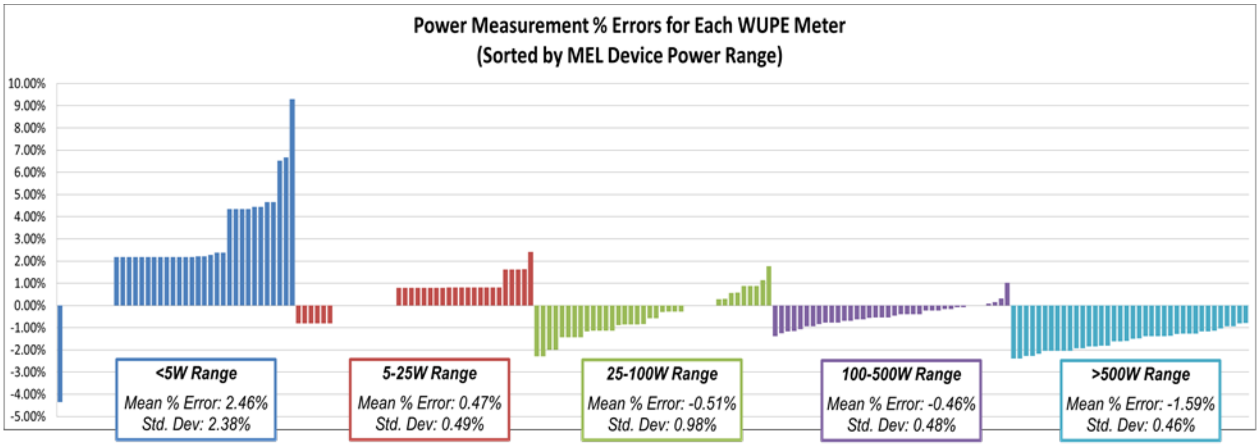

Figure 3–1 Power measurement accuracy of the individual meters employed for the study

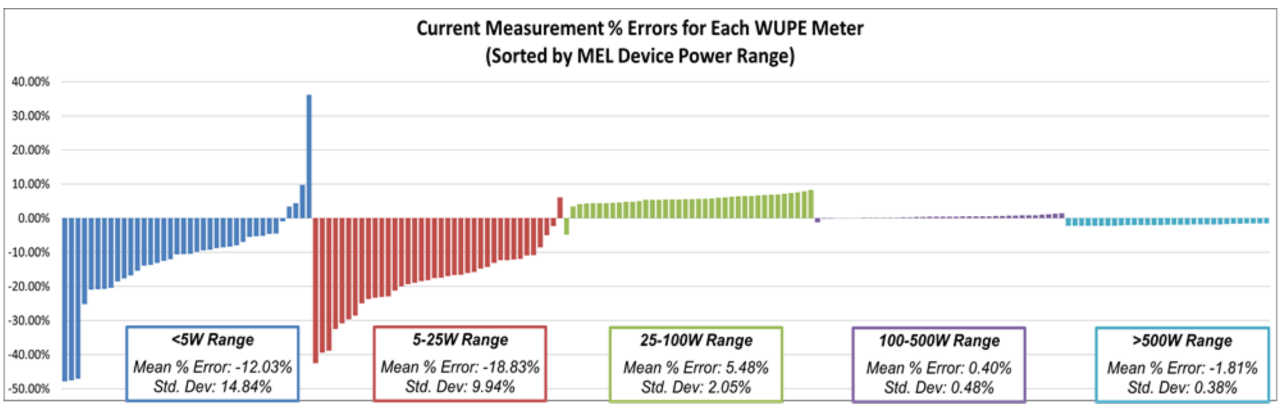

Figure 3–2 Graphical representation of 50 meters: current measurement accuracy

3.1.2.2.1 Limitations in Benchtop Meter Testing

The laboratory meter displays fewer significant digits in its power measurements than does Meter-A in the top three power ranges. In the 25- to 100-W and 100- to 500-W ranges it reads only to the nearest Watt, and in the > 500-W range reads only to the nearest 10 W. This lack of displayed precision affects the comparison for power readings in those ranges.

The laboratory meter current probe had to be rezeroed every time a new MEL was connected, and could only be consistently zeroed to within 8.0 mA. This has some impact on the errors between the selected meter and laboratory meter measured currents, especially in lower power ranges. NREL's Metrology Department verified that the laboratory meter and probe performed within factory specifications.

3.1.3 Scalability

The manual data collection process is well suited to small-scale data collection (fewer than 10 meters deployed); however, at the intermediate scale (50 meters deployed), several factors combine to increase the time burden and limit the effectiveness of data collection. With stand-alone meters at large scales (100 or more meters deployed), the methodology we used would likely be infeasible without significant modification because the time investment would be too great.

Connecting to a meter and downloading a full dataset takes at least 4 minutes; however, each metered device takes 6–8 minutes per week to access and reset because the meter must be accessed for cable connection, its settings checked, and its memory reset. At 50 deployed meters, this represents 5–7 person-hours of labor for data collection (excluding travel time to and within the site, time spent in meter deployment or removal, and other tasks such as inventory). We typically sent four researchers for a half day each week to collect data.

The meter's storage limitations further increased the time commitment. Each meter was limited to 23,000 data records (see Section 2.2.1). This limited us to a minimum recording interval of 30 seconds with a collection period of 1 week. We would have preferred to record at a higher time resolution for some devices, but the time investment involved in collecting data more than once per week would have been prohibitive. Sub 30-second data are critical for devices such as conveyor belts that may not operate for a full 30 seconds. Entire instances of use may be lost between the metered points.

The lack of automation in the collection process is a second key scalability barrier. The time stamping process is prone to human error, which may be introduced when collected data are assigned to the correct CMEL. Despite carefully crafted internal processes, we could not completely eliminate errors. Initially, we did not find it difficult to manually correct these types of errors; however, as the project scale increased, confusion also increased, for two reasons.

- The number of devices to sort through became too large to manage effectively without automation.
- The number of people managing the data increased proportionally to the labor requirements, necessitating much more communication between researchers to fix errors. Where originally one person could find and correct problems in a few datasets, five people ultimately had to coordinate error correction for hundreds of datasets. Without automation, 50 meters is the approximate limit for effective data collection.

3.2 Collected Data

We collected 637, 1-week datasets from 185 CMELs, representing approximately 165 unique CMEL device models. Thus, we have representative data for almost half the unique CMEL device models inventoried. We also collected 40, 1-week temperature files.

As discussed in Section 2.2.2, we typically metered each selected CMEL for 4 weeks before moving the meter to a new location. Most have 4 consecutive weeks of associated data; however, complications during metering caused some CMELs to have discontinuous data or fewer than 4 weeks of total data. We also identified some data as erroneous, because of meter calibration errors, time stamp errors, or other factors. These data were flagged and retained in the database. Nevertheless, 590, 1-week files of useful data remain.

The inventory revealed that only one device of a certain model was in the store for 80% of the inventoried models. These singular devices made up 44% of the total CMEL stock. This shows that energy reduction strategies should typically focus on CMEL-dense areas to minimize the energy of this wide variety of devices.

3.3 Categorizing CMELS

The CMEL Combined Action Plan gave high priority to categorizing CMELs into a common set of modes. The mode analysis performed through our analysis scripts identified one to five operational modes per CMEL. Common patterns of mode transitions were observed among the 185 devices analyzed; these CMELs were grouped into six families based on their load profiles:

- **Single-mode.** This was identified as being always on, without significant fluctuations in power use. Twenty-six percent of the CMELs studied were single-mode devices. Examples include demagnetizers (a component of a cash register setup) and televisions running 24 hours/day.
- **On/off.** Many CMELs clearly exhibited only one non-zero mode but also spent a considerable amount of time drawing zero power. These were categorized as on/off, as they consistently transitioned between on and off states. On/off CMELs can be subcategorized into those with a regular, cyclic switching pattern and those with a pseudorandom pattern dictated by occupant behavior. Twelve percent of the CMELs studied were on/off devices (those turned off when the area was closed to the public, for example).
- **On/standby.** The second state (on/standby) is a non-zero low-power mode. Thirteen percent of the CMELs studied were on/standby devices. A self-checkout stand is an on/standby device.
- **Standby with spiking.** These devices are usually in a low- or zero-power mode, but infrequently and irregularly jump to a higher state that is not a second mode. Twenty-five percent of the CMELs studied were low mode with spiking devices. Examples are all components of a cash register terminal (except the demagnetizer), microwaves, hair dryers, and paper shredders.
- **Decaying.** Refrigerators and battery charging devices exhibited a multimode pattern with a characteristic "decaying" transition back to a lower state. Although the number of modes used is an important characteristic of a CMEL, the pattern of transitioning between modes is distinct. Eight percent of the CMELs studied were decaying devices.
- **Multimode.** When we found more than two distinct modes, the CMEL was labeled as a multimode device. The more modes that were exhibited, the more possibilities arose for transition patterns. The exact pattern of the load profile becomes more unusual with more modes. No more than five non-zero operational modes were identified in any device we studied. Eleven percent of the CMELs are multimode devices. Coffee makers and vending machines are examples.

Five percent of the CMELs studied did not fall into any of these families, instead exhibiting no distinct mode(s) (see Figure 3–3 for a distribution breakdown; see Section 2.2.1.2 for definitions of standby mode and power).

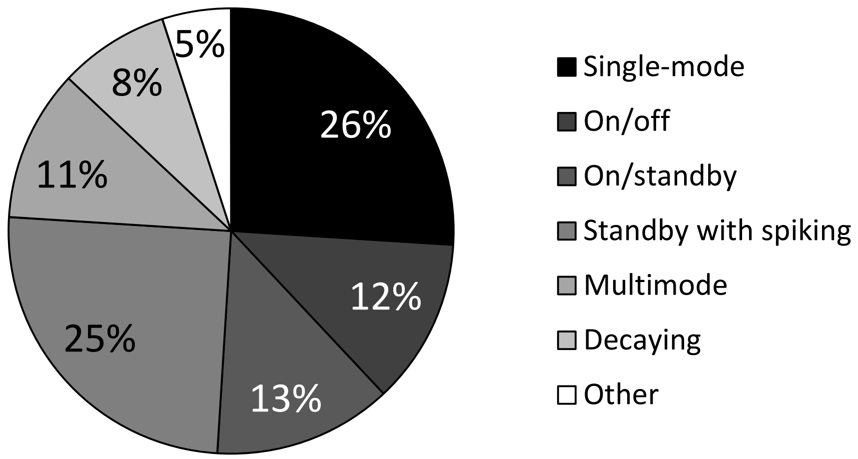

Figure 3–3 Distribution of CMELs studied into their respective families

3.4 Energy Efficiency Opportunities

The retail store contains a grocery, but more than 99% of CMELs were not grocery related. Thus, the energy reduction potential for CMELs is equally applicable to other big box stores, with or without groceries.

The lowest power mode usually indicates a standby mode—a default power level when the device is not actively used. Figure 3–4 compares the power of the lowest operating mode to the amount of time spent in that mode. Devices on the right are in their lowest power mode for a long period. The highlighted devices draw more than 40 W in their lowest power mode and spend at least 80% of their time in that mode. These CMELs should be the starting point for strategies aimed at reducing CMEL energy use.

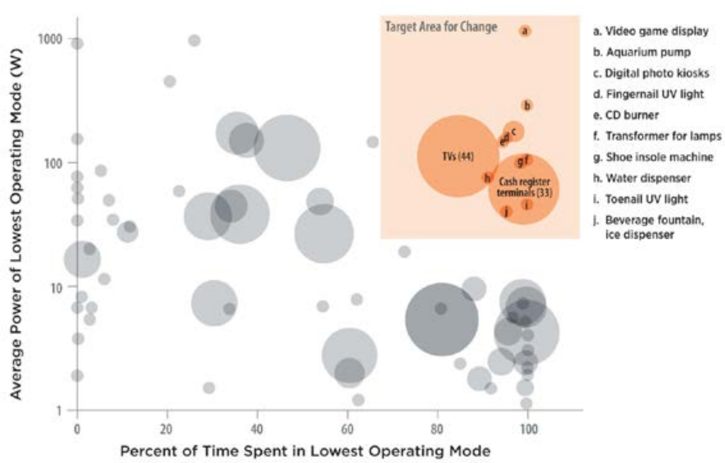

Figure 3–4 Density of CMEL lowest operating mode energy uses
(CMELs with large lowest operating modes that spend a large percentage of time in that mode can be identified as areas of potential energy savings. Bubble size indicates the number of that device type found in the large retail building.)

Three distinct approaches can be used to save CMEL energy:

- **Reduce the power of the lowest operating mode as much as possible.** Unfortunately, building owners and operators have no control over this measure. CMEL manufacturers must have an incentive to research and develop devices with the lowest possible power draw, particularly for standby modes.
- **Reduce the amount of time a device spends in the lowest power mode.** Turning off a CMEL when it is not being used can save energy. For example, the televisions in this study exhibited only one non-zero power mode. The more frequently these televisions are switched off or put into standby, the less time they will spend in their lowest power mode (112 W on average).
- **Limit the number of devices from the highlighted area.** Knowing that these devices draw considerable power, even when they are not being used, can help building owners and operators decide which (and how many) devices they will allow in a space.

Figure 3–5 shows the most prevalent device types and their combined total average daily energy use. Televisions and demagnetizers are the most prevalent CMELs, but the large energy draw of beverage refrigerators and soda vending machines cause them to use (as a group)the most power amongst all devices. Cash register terminals (as a group) use considerably less power than the top three energy users; however, if all the components at a typical cash register station are considered in aggregate (cash register terminal, demagnetizer, barcode scanner/scale, handheld barcode scanner, and occasionally a conveyer belt), the total daily energy use is 109 kWh/day, which is comparable to televisions. They are thus good candidates for energy reduction strategies.

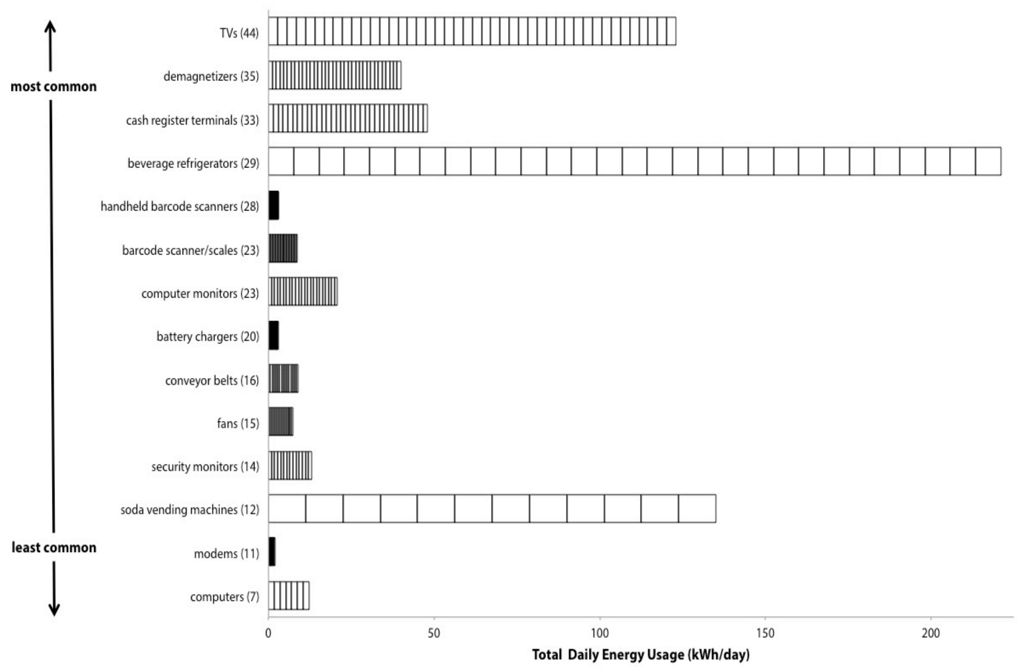

Figure 3–5 The most prevalent devices in the store (quantity is in parentheses)
(The bar represents an extrapolation of the total energy used by devices of that type.)

The cash register model used at this store can go into a “deep sleep” mode that uses 47% of their typical power (IBM, 2010); however, none of the seven cash registers we monitored seemed to use this feature—they operated at a constant load of 55 W on average, 24 hours/day. The peripherals (all of which can be safely powered off by a smart strip) add another 20 W of vampire load at full cash register lanes.

A control that links the light switch indicating lane closure to the cash register terminal “deep sleep” mode, coupled with a smart strip for the peripheral loads operating off the same signal, could save significant energy. Employees run a particular lane throughout their shifts; therefore, cash register lanes are not frequently switched on or off (such a control strategy would be a burden in this case). Our data suggest that the average cash register lane is closed for 17 hours/day. Were this implemented, a single store could save an average of 3.2 MWh/year on its typical cash register checkout lanes, and 5 MWh/year on all cash registers.

Figure 3–5 shows that the three highest energy-using devices (due to a combination of their prevalence and power consumption) are televisions, beverage refrigerators, and soda vending machines. Little can be done to reduce the energy use of beverage refrigerators beyond reducing their numbers. This begs the question: Could the number of beverage refrigerators be reduced to one for every two checkout lanes (rather than one every lane) without reducing beverage sales?

Deru et al. found that combining a load manager with delamping could reduce energy consumption in vending machines by 55% (M. Deru, 2003). If the low end of energy savings potential by the load manager is assumed in a more highly occupied retail environment, the energy reduction may only be 46%. Applied to the vending machines in this store, this strategy could save 22 MWh/year. Delamping may not be totally feasible in a retail environment, in which case the savings would be reduced to an estimated 11.8 MWh/year per store.

The most prevalent consumer electronics devices are televisions. Most televisions in this store (and in many other stores with large electronics sections) are in a sizable array and play a clip intended to demonstrate their sound fidelity, color quality, and definition. Typically, these are powered on 24 hours/day. A simple control strategy would be to turn off this bank between midnight and 6:00 a.m., when customers are least likely to purchase televisions. A manual override would allow an employee to show televisions to an interested customer. A single store could reduce its energy use by 11 MWh/year with this strategy. With the increasing prevalence of ENERGY STAR and EPEAT, lower power drawing CMELs will continue to reduce the overall energy load on this space, as long as the number of televisions being displayed does not increase.

The combined power use of the larger CMEL types brings to light important information about plug load energy profiles, and the list of the most energy-intensive items holds valuable information (see Table 3–2).

The single most energy-intensive plug is a video game display case with three game consoles, televisions, task lighting, and advertising. This aisle-long case draws a constant 1.28 kW, 24 hours/day. The task lighting is not technically a CMEL, but it is wired in with other CMEL devices and is not part of the store’s lighting control system. A similar control strategy to the one suggested for televisions could be implemented for this display to save 2.8 MWh.

Table 3–2 Top 10 Most Energy-Intensive CMELs

CMEL	Energy Use
1. Video game display (includes 3 game consoles, 3 TV screens, and display case lights and ad lighting)	29.7 kWh/day
2. Soda vending machine #1	14.2 kWh/day
3. Refrigerator in fast food area	11.8 kWh/day
4. Soda vending machine #2	10.8 kWh/day
5. Soda vending machine #3	8.84 kWh/day
6. Aquarium pump	6.95 kWh/day
7. Freezer in fast food area	6.78 kWh/day
8. Coin wrapping kiosk	6.55 kWh/day
9. Digital photo center kiosk	6.35 kWh/day
10. Charger for floor washer	6.03 kWh/day

The energy use of some other CMELs is unexpectedly high. A typical coin wrapping kiosk uses 6.55 kWh/day; a photo printing kiosk uses 6.35 kWh/day. Presumably no one powers off these devices, even in stores that do not operate 24 hours/day. Switching these off for 6 hours/day could save a typical store 2.2 MWh/year. If that is not feasible, the vendors could be encouraged to create kiosks with standby settings, as most daily energy use occurs while the kiosk is not being used.

This study confirms that the most prevalent CMELs usually have the most potential for energy savings, and should take priority over targeting a few energy-intensive devices. CMEL-dense spaces (such as the electronics area) where the same control strategy can be applied to a large number of CMEL devices can be targeted for energy reduction across a number of device types.

4 Conclusion

We developed and tested a methodology for metering CMELs on a building-wide scale and gathered information that can help big box retailers reduce plug load energy use.

4.1 Metering Recommendations

We recommend the following steps for researchers and building owners to audit CMEL devices.

1. Develop and maintain an accurate inventory.
   a. Collect all available nameplate data.
   b. Record quantities of each model to enable calculations of whole-building CMEL energy use.
   c. Check changes in the building inventory periodically. Consumer electronics such as televisions, radios, and notebook computers have a high turnover rate, so you should inventory these items only once, immediately before they are metered.
2. Once all CMELs are inventoried, enact a prioritization system.
   a. Highlight CMELs that are unique to a metering environment.
   b. Have an order firmly in place to ensure CMELs are metered effectively.
   c. Determine which spaces will be off limits.
3. Obtain occupancy information.
   a. Consider occupancy sensors.
   b. Assign each CMEL a unique phonetic ID to help collect data, navigate the retail environment, and sort and analyze data.
4. If possible, fully automate the data collection, error checking, and data uploading tasks to save time and minimize human error.

We developed strategies for working more effectively with available meters:

- Do not rely on current or power factor measurements below 60 W. These data are questionable in this power range.
- Increase the metering period or resolution by omitting these variables on low power devices.
- Because there is no internal clock, develop a procedure for automating time stamping to avoid errors.

Ideally, a meter would:

- Meter loads of 0–1800 W.
- Accurately measure power, voltage, current, energy consumption, and power factor.
- Provide more than 1 week of data storage capability at a higher sampling resolution.
- Be UL listed and ruggedly constructed.
- Meter mobile loads by remaining connected with either the CMEL or with the outlet.
- Have a low profile, low parasitic load, and internal clock.

4.2 Results of CMEL Energy Analyses

CMELs in a large retail environment are diverse, so efforts to reduce energy use should concentrate on devices that are the most energy intensive, those with high, rarely active standby loads, and those that are the most prevalent. Items that are grouped closely and that could be tied to the same control system should be considered high priority.

Cash registers (and their peripherals) draw a significant standby load, and sleep modes are not always used. User interface kiosks should have a sleep mode to prevent large power draws while not in use. In a 24-hour environment, aisle display and task lighting may run continuously, which may do little or nothing to increase sales between midnight and 6:00 a.m.

The store could use simple scheduling and load management strategies for a few types of CMELs (cash registers, televisions, soda vending machines, an electronics display aisle, and some user interface kiosks) to save a combined 43 MWh/year.

The data files from 185 CMELs showed that operating mode identification for large numbers of collected CMELs data is feasible and can fit comfortably into a researcher's workflow.

4.3 Future Work

A repository of power use data for a largely unstudied field such as CMELs provides a good opportunity to inform other areas. Building energy modeling, for example, has significant impact potential, as CMELs have traditionally been inadequately and inconsistently captured in simulations. We can leverage DOE's EnergyPlus building simulation software platform to use the processed data to represent CMELs in a building model component library. Users will be able to reference specific CMEL devices to more accurately assess their effects on building energy use.

All the national laboratories involved in this study found the commercially available CMEL meters wanting. A meter with a real-time network synchronized internal clock and better data storage capacity must be developed that can accurately measure current and power factor at low power ranges. The meter should retain its calibration settings and be attachable or securable to CMELs that are routinely unplugged to eliminate lost data. An internal battery backup would enable the meter to retain its clock settings and the stored data while unplugged.

A follow-up on the implementation of CMEL energy reduction strategies would provide valuable information about the accuracy of our assumptions and any unknown implementation barriers. Other control strategies using occupancy sensors or load sensing could be developed with the data collected through this study. Finally, remetering activities would inform us about the long-term progress of our work.

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Appendix A CMELs Metered

Description	Average Power (Watts)
Air compressor	0.0126
Air compressor, cake decorations	0.1393
Alarm clock	2.2102
Barcode scanner and scale	16.9713
Barcode scanner and scale	14.6968
Battery charging station, 2-Way radio	8.9242
Battery charging station, portable printer	6.8144
Battery charging station, single battery	0.5716
Battery charging station, wireless scanning tool	8.0391
Battery charging station, wireless scanning tool	7.6165
Beverage fountain, ice dispenser	44.2221
Beverage refrigerator	241.6060
Beverage refrigerator	240.6648
Beverage refrigerator	222.9174
Beverage refrigerator	207.6569
Beverage refrigerator	198.2374
Beverage refrigerator	129.9108
Beverage refrigerator	114.8940
Beverage refrigerator	114.6299
Beverage refrigerator	108.9515
Beverage refrigerator	76.8295
Beverage refrigerator	51.8711
Blood pressure monitor	8.6188
Bug lamp	76.8206
Bug lamp	76.0723
Bug lamp	30.9228
Carbonator pump	11.5121
Cash register terminal	61.2365
Cash register terminal	60.1121
CD burner	158.1260
Charger for floor washer	251.1661
Circular fan	32.2089
Coffee grinder station	25.4244
Coffee maker	170.7290
Coffee maker	49.5241
Coin-Wrapping station	273.1020
Computer monitor	52.2815
Computer monitor	37.7847

Description	Average Power (Watts)
Conveyor belt	46.4656
Conveyor belt	0.6200
Cream refrigerator	336.5340
Credit card scanner	7.5064
CRT TV	71.9039
Customer convenience barcode scanner	29.5613
Customer convenience barcode scanner	16.3121
Customer convenience barcode scanner	9.3720
Demagnetizer	89.9231
Demagnetizer	5.2929
Demagnetizer	5.2104
Densitometer	1.9277
Desktop computer	72.7048
Digital photo center	264.6659
Digital photo center	188.3268
Digital photo center	89.8668
Display lighting, coffee grinder station	32.3441
Double door refrigerator	60.0254
Electric wheelchair/cart	4.8084
Electric wheelchair/cart	3.9233
Employee badge swiper	6.5905
Fingernail grinder	74.9953
Fingernail UV light	158.7435
Floor cleaner	93.3888
Form printer network connection	4.7249
Form printer network connection	4.0347
Frame tracer	10.2276
Frame warmer	1.4478
Freezer	282.3316
Hair dryer	4.1798
Hair dryer	1.7497
Hair dryer	0.4105
Handheld barcode scanner	4.4550
Handheld barcode scanner	4.0498
Handheld barcode scanner	4.0081
HD component video-audio distribution amplifier	6.9700
Key cutter	5.3934
Label writer	1.5293
Large format plotter	6.9229
LCD TV	200.4697

Description	Average Power (Watts)
LCD TV	107.3671
LCD TV 52"	222.2890
LED HD TV	83.1695
LED HGTV	173.9711
LED HGTV	156.7549
LED HGTV	140.9478
LED HGTV	104.6375
LED HGTV	94.5009
LED HGTV	84.0588
LED HGTV	83.0761
Lens analyzer (Humphrey)	3.9525
Lens grinder	0.0253
Lensmeter	0.3144
Massage chair	5.0310
Microwave oven	74.8924
Microwave oven	2.7791
Microwave oven , commercial	47.1185
Mini fingernail UV light	115.2361
Modem	6.8182
Negative viewer	0.0000
Netgear switch	7.2870
Optical scope	3.4963
Optical test instrument (Humphrey/WelchAllyn)	0.0000
Outdoor lighting display	3.0537
Paint color scanner	0.5103
Paint mixing station	1.7018
Paint shaker	6.7865
Paint shaker	1.5025
Paper shredder	200.4976
Paper shredder	4.0964
Point-of-sale terminal	7.8610
Printer	5.5166
Radio CD player	1.6619
Rectangular fan	9.3149
DVD Rental Kiosk	111.1160
Refractor (Acuitus)	2.7741
Refrigerator	491.5029
Reverse osmosis systems store water use meter	13.8616
Reverse osmosis systems water system	67.1523
Scale	19.1656

Description	Average Power (Watts)
Security alarm and camera charger	8.4002
Security alarm and camera charger	7.3545
Security monitor	38.6064
Self checkout point-of-sale terminal	204.8739
Self checkout point-of-sale terminal	162.9019
Shoe insole machine	98.9537
Slicer	285.5158
Soda machine pump	3.1322
Soda vending machine	449.0608
Soda vending machine	368.3402
Solenoid for produce sprinkler system	120.9978
Solenoid for produce sprinkler system	0.1793
Standard household refrigerator	60.1495
Task light	5.9178
Transformer for lamps	105.3603
Triple door refrigerator	85.5915
Ultrasonic Cleaner	0.0000
UV sterilizer	1.2700
UV sterilizer light	14.9794
Video game consoles, lights 4' T8	1236.7036
Wall mounted insect zapper	83.6813
Waste filter for photographic chemicals	7.0309
Water dispenser	69.9073
Water purifier/dispenser	105.2964
Water resistivity meter	1.2249