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Recovery Act: Advanced Load Identification and Management for Buildings

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Disclaimer

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Abbreviations and Acronyms

AC	Alternative Current
ACEEE	American Council for an Energy-Efficient Economy
ALO	Always ON Load Outlet
APS	Advanced Power Strip
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BET	Breakeven Time
BMS	Building Management System
CBECS	Commercial Buildings Energy Consumption Survey
CCM	Continuous Conduction Mode
CLO	Controllable Load Outlet
CPU	Central Processing Units
CrM	Critical Conduction Mode
CTQ	Critical to Quality
DAQ	Data Acquisition
DC	Direct Current
DCM	Discontinuous Conduction Mode
DFSS	Design for Six Sigma
DOE	Department of Energy
DSP	Digital Signal Processor
ECOS	Environmental Council of the States
EEI	Energy Efficiency Index
EMI	Electromagnetic Interference
EMS	Energy Management System
ESCO	Energy Services Company
FFT	Fast Fourier Transform
GSA	General Services Admissions
GUI	Graphical User Interface
H/W	Hardware
HEM	Home Energy Management
IGCC	International Green Construction Code
ISO	Independent System Operator
JCI	Johnson Controls Institute
KSF	Key Success Factors
LEED	Leadership in Energy and Environmental Design
Load ID	Load Identification
M	Load with Complex Structure
MELs	Miscellaneous Electric Loads
MFD	Multifunctional Device
NI	National Instruments
NILM	Non-intrusive Load Monitoring
NOC	Network Operations Center
NP	Electronic Load without Power Factor Correction
NREL	National Renewable Energy Laboratory
P	Electronic Load with Power Factor Correction
PAC	Phase Angle Controller
PC	Personal Computer
PCA	Principle Component Analysis

PELs	Plug-in Loads
PFC	Power Factor Correction
PNNL	Pacific Northwest National Laboratory
PWM	Pulse Width Modulation
R	Resistive Load
R&D	Research and Development
REMS	Remote Energy Management System
RF	Radio Frequency
RMS	Root Mean Square
RSF	Research Support Facility
S/H	Software
SD Card	Secure Digital Card
SOM	Self-organizing Map
SPS	Smart Power Strip
SR	Smart Receptacle
SVM	Support Vector Machines
T	Load with Transformer-Rectifier Power Supply
U.S.	United States
USGBC	U.S. Green Building Council
UWM	University of Wisconsin Milwaukee
VoC	Voice of Customer
VoM	Voice of Market
X	Reactive Load

1.0 EXECUTIVE SUMMARY

In response to the U.S. Department of Energy (DoE)'s goal of achieving market ready, net-zero energy residential and commercial buildings by 2020 and 2025 [29], Eaton partnered with the Department of Energy's National Renewable Energy Laboratory (NREL) and Georgia Institute of Technology to develop an intelligent load identification and management technology enabled by a novel "smart power strip" to provide critical intelligence and information to improve the capability and functionality of building load analysis and building power management systems.

Buildings account for 41% of the energy consumption in the United States, significantly more than either transportation or industrial. Within the building sector, plug loads account for a significant portion of energy consumption [28]. Plug load consumes 15-20% of building energy on average [2] [28]. As building managers implement aggressive energy conservation measures, the proportion of plug load energy can increase to as much as 50% of building energy leaving plug loads as the largest remaining single source of energy consumption [2]. This project focused on addressing plug-in load control and management to further improve building energy efficiency accomplished through effective load identification.

The execution of the project falls into the following three major aspects.

1) An intelligent load modeling, identification and prediction technology was developed to automatically determine the type, energy consumption, power quality, operation status and performance status of plug-in loads, using electric waveforms at a power outlet level. This project demonstrated the effectiveness of the developed technology through a large set of plug-in loads measurements and testing.
2) A novel "Smart Power Strip (SPS) / Receptacle" prototype was developed to act as a vehicle to demonstrate the feasibility of load identification technology as a low-cost, embedded solution.
3) Market environment for plug-in load control and management solutions, in particular, advanced power strips (APSs) was studied. The project evaluated the market potential for Smart Power Strips (SPSs) with load identification and the likely impact of a load identification feature on APS adoption and effectiveness. The project also identified other success factors required for widespread APS adoption and market acceptance.

Even though the developed technology is applicable for both residential and commercial buildings, this project is focused on effective plug-in load control and management for commercial buildings, accomplished through effective load identification. The project has completed Smart Receptacle (SR) prototype development with integration of Load ID, Control/Management, WiFi communication, and Web Service. Twenty SR units were built, tested, and demonstrated in the Eaton lab; eight SR units were tested in the National Renewable Energy Lab (NREL) for one-month of field testing. Load ID algorithm testing for extended load sets was conducted within the Eaton facility and at local university campuses.

This report is to summarize the major achievements, activities, and outcomes under the execution of the project.

2.0 COMPARISON OF ACCOMPLISHMENTS TO GOALS AND OBJECTIVES

2.1 Goals and Objectives

The project is to develop advanced load identification and management technologies and solutions to reduce building energy consumption by providing fine granular visibility of energy usage information and safety protection of miscellaneous electric loads (MELs), also known as plug-in loads (PELs), in commercial and residential buildings. The project is seeking to accelerate the path toward meeting DOE's goal of achieving market ready, net-zero energy residential and commercial buildings by 2020 and 2025 [29], respectively, through cutting-edge, industry-driven R&D, and field demonstration of new technologies. More specifically, Eaton proposed to addresses Technical Subtopic 2.3 of the DE-FOA-0000115: Miscellaneous Load Prediction and Modeling.

The objectives of the project are to:

1. Develop intelligent load modeling, identification and prediction technology that will automatically determine the type, energy consumption, power quality of plug-in loads, and potentially their operation status and performance status, using electric waveforms at a power outlet level.

2. Prototype "smart power strip", an advanced power outlet / strip concept, which provides embedded load identification intelligence, low-cost off-shelf communication (e.g., WiFi), remotely-controllable relay, universal interface to building management systems, and advanced fault protection functions.

The scope of the work includes the following aspects throughout the three phases of the project:

- Develop characteristic and predictive models for typical plug-in loads in commercial and residential buildings based on outlet electrical signals. (Phase I)

- Develop automatic load identification and prediction methods for single plug-in loads and/or multiple plug-in loads connected to a same power strip, using predictive load models. (Phase II)

- Prototype smart power strip, with embedded load identification, signal sensing, remote switching, wireless communication, and advanced control and management capabilities (Phase I, II)

- Validate developed technologies and business value propositions through lab testing and field trials, including assessing energy savings, environmental, and economic impacts. (Phase I, II, III)

2.2 Accomplishments

The major accomplishments are summarized below from three aspects in comparison with the goals and objectives established at the beginning of the project.

Load Identification Technology Development (Section 3.3)

- Established a plug-in load taxonomy and a load identification technology development target that is meaningful and valuable to users;
- Built a plug-in load current/voltage waveform database;
- Developed an intelligent load modeling, identification and prediction technology that can automatically determine the type, energy consumption, power quality of plug-in loads, and their operation status using electric waveforms at a power outlet level;
- Validated the developed load identification technology through lab testing and field trials in a real building environment.

Smart Receptacle Prototype Development (Section 3.4)

- Developed a commercial-looking advanced power strip/receptacle prototype the integration of load identification, WiFi communication, remotely-controllable relay, web-service based user interface;
- Integrated the developed load identification technology into an embedded environment that enables a cost-effective plug-in load control and management solution;
- Developed and implemented a Load ID based Plug-in Load Control and Management solution that facilitates the demonstration of value proposition;
- Developed a web service, i.e., Remote Energy Management System, as a plug-in load control and management platform to demonstrate the values of the developed technologies, in particular, load identification technology, in a network and building level;
- Demonstrated all the proposed functions in a real-time embedded system;

Value Proposition Development and Validation (Section 3.2 and Section 3.5)

- Established customer/stakeholder needs for plug-in load control and management through comprehensive market research and VoC/VoM interviews;
- Identified the major barriers and gaps of existing plug-in load control and management solutions, e.g., Advanced Power Strips on the market;
- Established the Key Success Factors, as well as the values of Load Identification for an effective plug-in load control and management offering;
- Established a Value Model for plug load control and management to quantify the major value drivers;
- Validated the developed value propositions through use-case studies, lab testing and field trials, including assessing energy savings and economic impacts.

3.0 MAJOR PROJECT ACTIVITIES

This section of the report summarize project activities for the entire period of funding, including original hypotheses, approaches used, problems encountered and departure from planned methodology, and an assessment of their impact on the project results.

3.1 Original Hypotheses

Motivation and Problem Statement

Buildings account for 41% of the energy consumption in the United States, significantly more than either transportation or industry. Within the building sector, plug loads consume 15-20% of building energy on average. As building managers implement aggressive energy conservation measures, the proportion of plug load energy can increase to as much as 50% leaving plug loads as the largest remaining single source of energy consumption.

Advanced Power Strip Overview

Advanced Power Strips (APSs) are a mechanism for controlling plug loads that have been commercially available for several years. APSs are essentially surge protector power strips with outlets that can be controlled via a number of means. Power to a given outlet is shut off when the control mechanism determines that a given device is not, or should not be in use. Some APSs also measure energy consumption.

APSs can be employed in residential or commercial settings. The two uses deemed to be the most fruitful applications of APS are residential entertainment centers and office workstations (in either residential or in commercial environments).

Virtually all APS can be used as standalone devices. Some models can also have network interfaces whereby they can communicate with various energy management software packages.

Recent studies indicate that APS can reduce energy consumption an average of 12-43% for office environments [1]. Payback on APS adoption is situation dependent, but has been reported to be as high as ten years.

Advanced Power Strip Market Adoption

Penetration of APS remains very low. While there are few market forecasts available for APSs, recent studies indicate that the overall market for power strips is flat and the penetration of APSs is on the order of 2-5%. This is disappointing in light of increased awareness of building energy consumption and the advent of complementary products such as energy management software and low cost building network systems. Moreover, several sources indicate that APS use is often discontinued by end-users due to inconvenience, underperformance, or productivity losses resulting from APS operation.

Smart Power Strip Challenge and the Role of Miscellaneous Load Detection

This project was motivated by the hypotheses that the primary barriers to APS adoption are:

- Difficulty in setting up APSs

- Faulty or inappropriate control of devices by APSs (underperformance)

The ability to identify miscellaneous loads was presumed to have the following key benefits:

- Simplify, and reduce time required for APS set up
- Adapt to the ongoing user-initiated changes to devices plugged into the APS
- Provide load-specific energy consumption data to end-users and energy/building managers

This section of the report evaluates the likely impact of a load identification feature on APS adoption and effectiveness. It also identifies other success factors required for widespread APS adoption. Note that while findings regarding home use of APS are cited, the primary focus of this report is on commercial office buildings as these represent larger concentrations of building energy consumption.

This project is focused on effective plug-in load control and management for commercial buildings, accomplished through effective load identification enabled by a novel "Smart Power Strip" (SPS) to provide critical intelligence and information to improve the capability and functionality of building load analysis and building power management systems.

The envisioned SPS concept is illustrated in Figure 1, where remotely-controlled relay, off-shelf wireless communication, voltage/current sensing, signal processing functions and load identification are integrated into a single size-optimized package. We envision that the combination of the non-intrusive load identification technology and the SPS concept could lead to the next generation intelligent power outlet/strip – the very basic building block of net-zero building management systems.

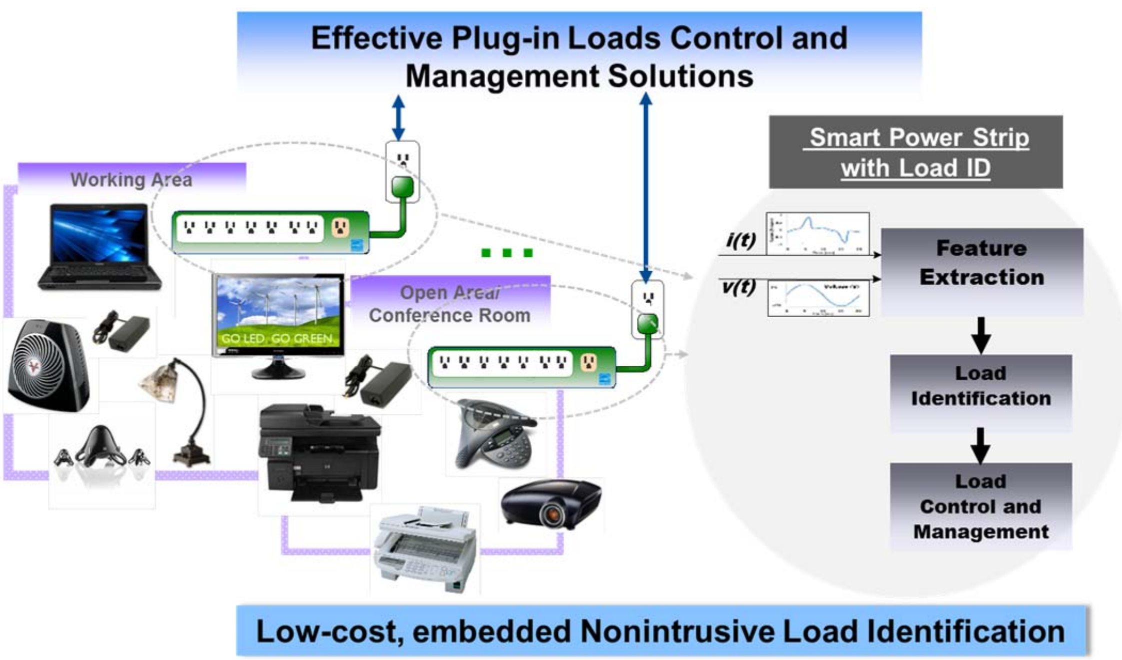


Figure 1: Envisioned Smart Power Strip Concept

The project was motivated by the hypothesis that the ability to identify plug-in loads was presumed to have the following key benefits:

- Provide load-specific energy consumption data to end-users and energy/building managers;
- Simplify and reduce time required for plug-in load control/management products, e.g., Advanced Power Strip (APS) set up. Difficulty in initial setup has been commonly experienced through the use of existing APSs on the market.
- Facilitate adapting to ongoing user-initiated changes to devices plugged into the APS, consequently reduce faulty or inappropriate control of plug-in devices that has been commonly experienced through the use of existing APS products on market.

The following steps were identified and associated tasks were executed for the technical approach, also summarized in Figure 2.

- Develop characteristic and predictive models for typical Plug-in Electric Loads (PELs) in commercial and residential buildings based on outlet electrical signals.
- Develop automatic load identification and prediction methods for single PEL and multiple PELs connected to the same power strip, using predictive load models.
- Prototype Smart Power Strip, with embedded load identification, signal sensing, remote switching, and wireless communication capabilities.
- Validate developed technologies and business value propositions through lab testing and field trials, including assessing energy savings, environmental and economic impact.

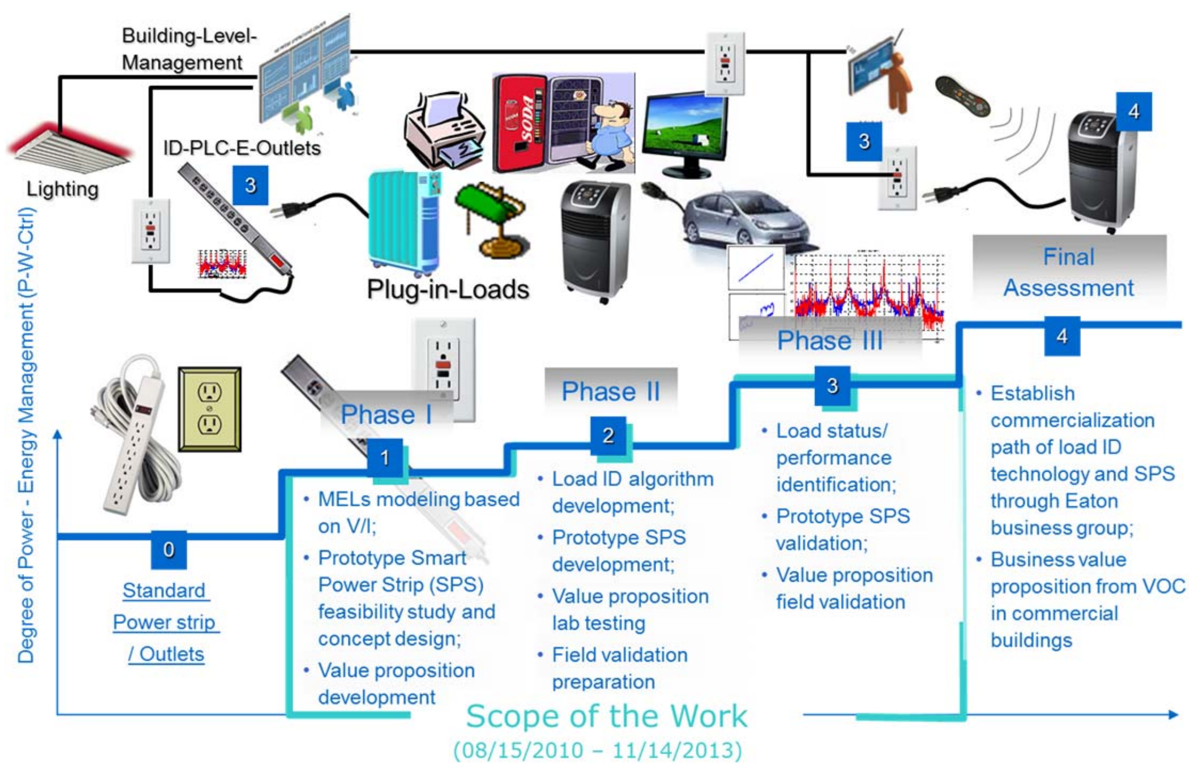


Figure 2: Project Scope

3.2 Business Value Proposition and Validation

In parallel with load identification technology development, the business value proposition has been developed and validated through collaboration within Eaton, National Renewable Energy Laboratory (NREL), and SP Insight (a strategic marketing consultant for technical innovation).

The major activities under this task include:

- Building plug-in loads energy usage baseline study;
- Literature survey on plug-in load control and management solutions;
- Market research through VoC/VoM interviews and needs analysis;
- Value Model development with use case evaluations; and
- Smart Power Strip Market forecast.

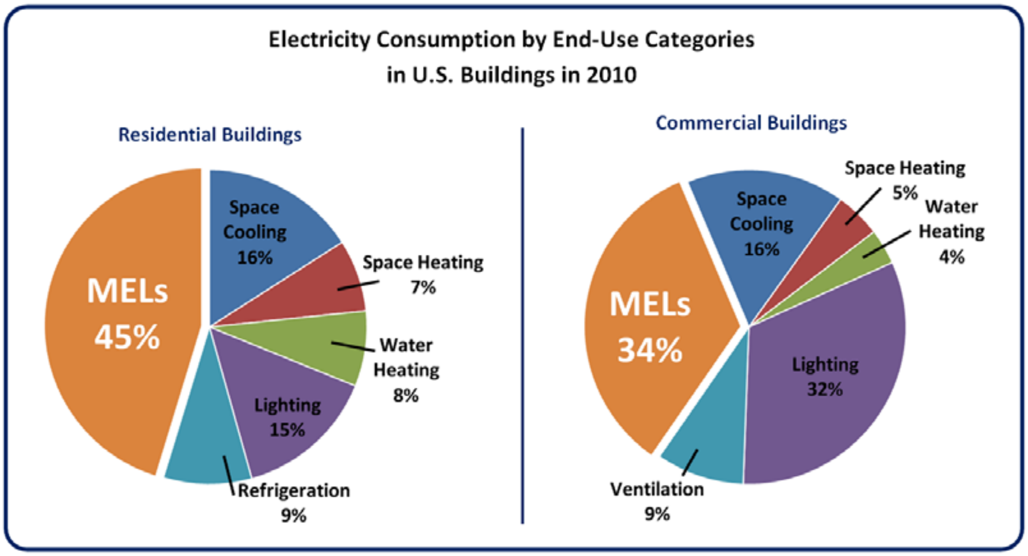
This section summarizes the market environment for plug-in load control and management solutions, in particular, advanced power strips (APSs), and evaluates the market potential for smart power strips (SPSs) with load identification and related features critical to their market acceptance.

3.2.1 Plug-in Load Overview

<u>Building Plug-in Load Definition and Usage Baseline</u>

Plug-in electric loads (PELs), or miscellaneous electric loads (MELs) in some contexts, are defined as all building non-main electrical loads, and include a variety of electrical devices from walk-in refrigerators, computers, cash registers and cell phone chargers. Buildings account for 41% of the energy consumption in the United States, significantly more than either transportation or industry [28]. Within the building sector, PELs constitute an increasingly significant percentage of building energy use, partly because of an increasing number and variety of devices, and partly because of advances in the energy efficiency of main building loads. Plug-in loads consume 15-20% of building energy on average, considered as the largest end-use category in building electricity consumption (see Figure 3) [2] [28]. Plug loads consume approximately 21% of the total electricity consumed within a standard GSA Region 3 office building [1]. PELs in residential and commercial buildings account for almost 12% of U.S. primary energy consumption. According to the IEA, proportion of plug load energy can increase to as much as 50% by 2035 leaving plug loads as the largest remaining single source of energy consumption [2].

However, a large portion of this electricity use has been wasted, and the management of this usage has often been overlooked. Many electric appliances with an external power supply, a remote control, a continuous display or a battery charger continuously draw power even when in an off or standby mode. Standby power in the U.S. accounts for over 100 billion kWh and costs over $10 billion annually. As much as 75% of this cost can be saved by proper energy management [30]. In order to achieve the Net-Zero-Energy-Building goals defined by the Department of Energy (DOE) for residential buildings by 2020, and for commercial buildings by 2025, the effective monitoring and management of PELs needs to be considered.



Source: All data is from the 2009 DOE Buildings Energy Data Book. Residential building data from page 2-7, and commercial building data from page 3-5.

Figure 3: Electricity Consumption by End-Use Categories (Credit: Jeff Smith/NREL)

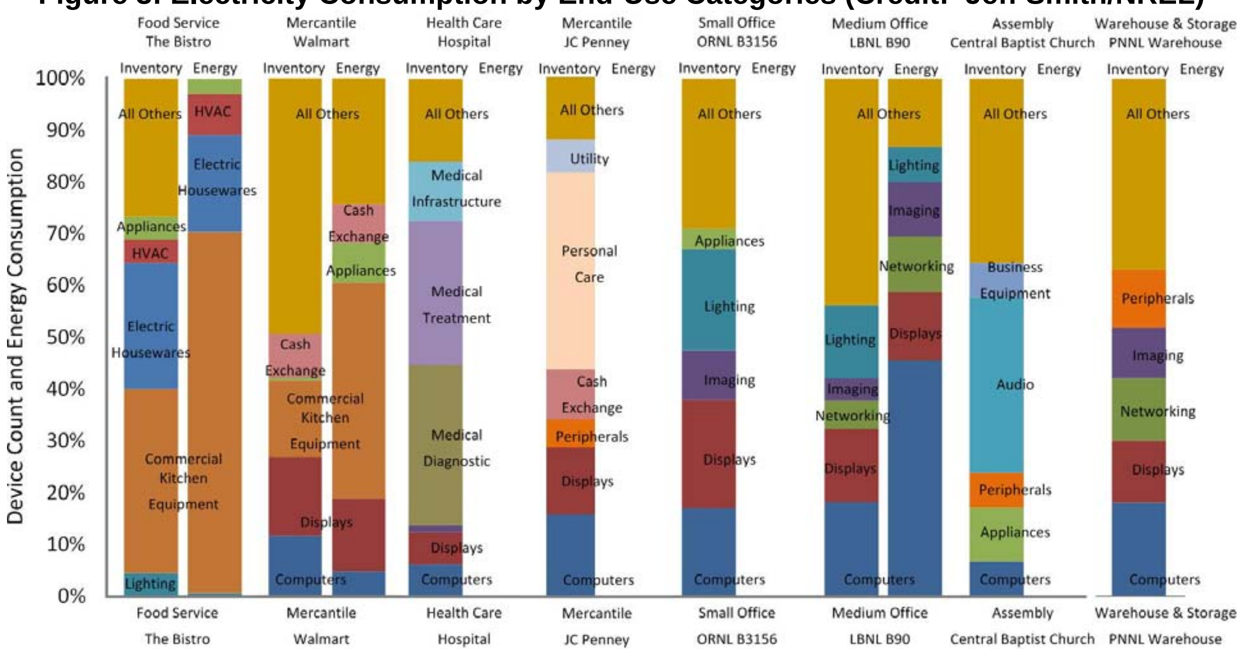


Figure 4: PELs Device and Energy Distribution by Building Types and Device Category Uses. Preliminary data is used in this chart (Credit: Luigi/NREL).

The PELs that are the most numerous or the most energy intensive vary from building type to building type. The PELs end-use is also referred to as “business process” loads, because many types of PELs equipment are used in essential business processes such as information processing, medical treatment, or food preparation. Because of this special relationship to the business function performed in a building, each type of commercial building is likely to have specific PELs that are needed to perform those functions. In the United States, commercial buildings span a wide range of types, uses, sizes, and vintages, therefore, it is critical to understand how building type and space type influence which PELs are the most important to address. Similarly, comparisons between building types are important because they show which

PEL reduction strategy may apply across building types and which are building type or space type specific. Figure 4 presents the distribution of PELs by device category and building type to provide comparisons between PELs distribution for the buildings inventoried. Each building for which data were was available is shown with the top five energy consuming PELs categories. Both the fraction of PELs energy use and the fraction of PELs devices are shown to illustrate that the PELs that consume the most energy depend on the building type.

Based on the above information, as well as the Commercial Buildings Energy Consumption Survey (CBECS) 2003 data, several commercial building types are selected and prioritized based on the PELs' energy intensity, the controllability and energy saving opportunities of PELs as the initial target study cases for future business value proposition development and validation including:

- Office buildings;
- Education (Universities and High Schools);
- Mercantile/retail stores; and
- Health care.

PELs have been classified and prioritized in terms of their total contribution to building energy consumption for different building types, as summarized in Table 1.

Table 1: Top Plug-in Load Taxonomy by Building Types

Offices	Education	Retail Stores	Health Care
Desktop	Desktop	Video game display	MRI
Laptop	Laptop	Soda vending machine	CT
Monitors	Monitors	Refrigerator in fast food area	X-Ray
Printers	Printers	Aquarium pump	Desktop
Copiers	Copiers	Freezer in fast food area	Laptop
Multifunction Devices	Multifunction Devices	Coin wrapping kiosk	Monitor
Scanners	Scanners	Digital photo center kiosk	Printers
Fax Machines	Fax Machines	Charger for floor washer	Copiers
Servers	Servers	Fingernail UV Light	Multifunction Devices
Projector, Computer	Vending Machine	Beverage foundain, ice dispenser	Scanners
Projector, overhead	Walk-in Refrigeration		Fax Machines
router	Vertical Transport		Servers
Personal space heater	Distribution Transformer		Ice Machines
Personal fan			Commercial refrigeration
Task lamp			TVs
Computer speakers			
Clock radio/small stereo			
Ethernet hub			
TV			
Broilers			
Fryers			
Griddles			
Ovens			
Ranges			
Steamers			
Microwave oven			
coffee maker			
lighting			
Cold beverage vending machines			
Large commercial coffee maker			
Water cooler			
Refrigorator, commercial			

<u>Energy Usage Baseline and Patterns for Plug Load Energy Saving Potentials</u>

In order to quantify the potential energy savings from plug-in loads usage, Eaton worked closely with NREL to understand an energy usage baseline for commercial buildings, starting with office buildings and retail stores.

Figure 5 shows the energy usage baseline study in a typical office building environment of an average building size of 14,800ft2. The PELs energy usage baseline is established based on the MEL unit intensity, their power consumption by different operating modes, as well as their usage pattern during working-hours and after-hours [31]. The study shows that office buildings are unoccupied for two-thirds of the year. A key strategy to reduce unnecessary MEL power consumption is to reduce power density during non-business hours. An initial assessment on the energy saving opportunity by turning-off the unused MELs is around 7% of total energy consumption for the case study building, as shown in Figure 5.

<u>Average Office Building (CBECS 2003)</u> (1)

- **Avg. Office Building Size:** **14,800 ft²**
- **Avg. Build Electricity Usage:** **256000 kWh/yr**
- **Number of Employees:** **~50**

After-hours + Weekends + Holidays = 6012 hours/year

	Active Mode Power (W)	Low-Mode Power (W)	Off-Mode Power (W)	on	Low	off	un-plugged	Units Intensity (/100 kft2)	Energy Savings (kWh/building)
Desktop	70	3	1.3	59%	4%	36%	1%	230	8863.6
Laptop	30	2	1.5	5%	24%	69%	2%	240	644.3
Monitor, LCT	30	1	1	20%	57%	17%	6%	144	1262.3
Printers	65	4	1.42	34%	51%	15%	0%	115	2521.7
Personal space heater	1000	3	1	5%	0%	94%	1%	7.4	338
Projector, overhead	100	2	1	10%	50%	40%	0%	15.2	156
coffee maker	332	2	2	9%	0%	90%	1%	5	158
Vending Machine	400	150	5	0%	100%	0%	0%	9	608
...									...
Total Electricity Saved (kWh/yr)				After-hours MELs Status (3)					18595.3
Total Building Electricity Consumption (kWh)									256000
Energy Saving (%)									7.30%

Figure 5: MELs Energy Usage Baseline for a typical office building (Average office building size: 14,800ft2)

3.2.2 Literature Survey

To understand the state-of-the-art, the team has reviewed available reports on the application of plug load control methodologies in various settings. These reports provided valuable information regarding features of current generation Advanced Power Strips (APSs) and complementary products; implementation challenges; impact on user experience and productivity; and resulting energy savings.

Plug-in loads control comes in two basic forms. The device is either transitioned to a low power state (a power state that is between a de-energized state and a ready-to-use state, e.g., standby, sleep modes, or parasitic mode), or it is de-energized entirely to reduce the power and energy draw. Both forms can be executed either manually or automatically. Lots of modern electronic appliances have built-in automatic low power state functionality to reduce energy consumption of idle devices. Computers, for example, can be configured in many ways after they leave the manufacturer. De-energize refers to the state when electricity is not being provided to the device. This is similar to the state when the device power cord is physically unplugged from a standard electrical outlet.

This section focuses on reviewing various control technologies and solutions applied to de-energize plugged-in loads when not in use.

Advanced Power Strips (APS) Overview

Advanced Power Strips (APS) are a straightforward mechanism for controlling plug loads that have been commercially available for several years. APS are essentially surge protector power strips with outlets that can be controlled via a number of means. Power to a given outlet is shut off when the control mechanism determines that a given device is not, or should not be, in use. Some APSs also measure energy consumption.

APSs can be employed in residential or commercial settings. Virtually all APS can be used as standalone devices. Some models can also have network interfaces to communicate with various energy management software packages. Recent studies indicate that APS can reduce energy consumption an average of 12-43% for office environments [1]. Payback on APS adoption is situation dependent, but has been reported to be as high ten years.

There are a large variety of APS products available in the market today. Despite the potential promise of APS, the general public has little knowledge of how they work, where they should be installed, and what to expect from their operation.

The sensing technologies and control strategies adopted by APSs differentiate them from traditional power strips. Table 2 summarizes the general categories of APS most commonly encountered; the technology is rapidly progressing and this is not an exhaustive list. Note that many devices fall into more than one category.

The existing APS products can be segmented via different dimensions,

- ON or OFF conditions;
- Automatic or Manual;
- Standalone or network-based;

The control strategies that are applied to APSs can be summarized from two aspects, i.e., strategies for OFF control and strategies for ON (or wake up) control. Technically, for automatic OFF control, the strategy is designed to automatically turn off the controllable outlets when the APS determines that the appliances plugged in are not actually in use, and, therefore, to reduce/cut energy consumptions during this period of time. The selection of sensing techniques as an indicator to the actual load use status is the key factor to differentiate the various types of APSs on market. The accuracy of those indicators to actual load use status is, consequently, the key to avoiding potential nuisance turn-off of controllable outlets. Controllable outlet's nuisance turn-off has been recognized as one of the issues and barriers that prevent APSs from being adopted widely.

On the other hand, the ON (wake up) control strategy is designed to either manually or automatically restore power to the controllable outlets. The key performance requirement is to determine whether the controllable outlets are needed by plugged appliances, or more precisely, by the users themselves. Because these conditions are usually driven by users' actual need, most of the existing APSs consist of a remote or local switch button to allow users to trigger the ON action. There are also automatic ON control approaches that use sensing techniques as an indicator to the need of load use.

For manual control of outlets to reduce plug level energy usage, there are various APS products on the market. Various types of network-based APS products are entering the market as a recent trend. These products often utilize the off-shelf wireless communication technologies, and consist of a user-friendly remote interface to allow users to remotely switch ON or OFF the controllable outlets. These products still require users' involvement, but try to provide a more convenient approach to promote end user green behavior.

In the load sensing based APS, each APS usually has a few controlled outlets and a few always-on outlets. When power draw on the sensor outlet drops below a manually set threshold, power is cut to the controlled outlets. Table 2 summarizes the APS products that have been evaluated by the team.

Table 2: Advanced Power Strip Categories by Sensing and Control Technologies

Control Category	Control Strategy Description		Pros & Cons
	OFF Control Conditions	**ON Control (wake up) Conditions**	
Load Sensing	Current/power draw of individual controlled outlets is less than a threshold; outlets are controlled individually	The OFF condition cannot be used to wake up the outlets, and a manual local or remote (via IR or radio signals) switch is often used.	Pros: Better potential to offer greater energy savings; Flexible and tailored to actual use pattern; Cons: Rely on the operation of the sensed appliances; require careful calibration of threshold for the transition detection
	The drop of peak power use for the all the connected devices is less than a set percentage; all the outlets are controlled together.		
	Power status of a designated "master" appliance (plugged in always-on outlet) is used to turn ON or OFF of appliances on controllable outlets, often known as "slave" appliances.		
Time Scheduling	A timer switch or a real-time clock is programmed to turn on or off the controllable outlets at a designated moment.		Pros: Ideal and reliable for use pattern with a consistent schedule; Cons: Less flexible; do not offer greatest energy savings
External sensor	The status of an external sensor, i.e., often refer to an occupancy sensor, is used as an indicator of load use status.		Pros: Directly related to the actual occupancy status with high potential for savings; Cons: Additional sensor is required for installation and maintenance; coverage issues
Remote Switches	Remote switches that use IR or radio signals to allow users to turn on/off controllable outlets remotely.		Pros: Quick and easy way to power up and down devices; Cons: Depends entirely on user behavior

In earlier years, the first generation of APSs in the market appears to be standalone devices that utilize the one or two of the above sensing techniques as indicators to determine the ON or OFF conditions of controllable outlets. With advances of wireless communication technologies and various smart devices over the past few years, the new generation of APSs on the market tends to employ network-based approaches. These network-based APSs still employ the above automatic or manual control approaches, but at the same time, also provide the potential for a more effective plug load control and management solution in a zonal or even a building level.

Appendix A provides a summary of Advanced Power Strips in the market that have been studied under this program. The research suggests that prices for APSs typically range from $20 to $100, with the majority of units around the $30~40 price mark. These types of units will have a range of four to ten outlets.

APS Adoption - Drivers and Barriers

Even though numerous efforts have been made by researchers and manufactures to provide more effective plug-in load control and management solution to the market, the authors of this report did not find any market size/forecast reports, which in itself is an indicator of the nascent nature of the market. The information that is available indicates that market penetration is extremely low. A recent report by the ACEEE concluded consumer awareness of, and interest in, APSs was "practically non-existent" [2]. Similarly, a recent report by the Northeast Energy Efficiency Partnership (NEEP) indicated that APS penetration was less than 2% [32]. Greentech Media (2011) estimates that approximately 6 million U.S. households will have some type of home energy management (HEM) device by 2015; this equals about 5% of households, and does not necessarily imply the use of APSs [3]. APSs have been demonstrated in other federal buildings but have yet to be deployed on a wide scale [1]. Little information is available on penetration into commercial workspaces, but there is no indication that the adoption rate is any higher.

From these results, we can conclude that barriers to adoption are overcoming drivers of adoption and/or that the natural diffusion of APS is in the very early stages. We will examine each of the factors discussed in this section drawing on existing literature as well as direct investigation of a combined SPI/Eaton team.

Drivers of Smart Power Strip Adoption

Potential Energy Savings: The primary motivator of APS adoption is the promise of energy savings which have been documented in several studies. In a 2011 study performed by ECOS, Portland Energy Conservation, Inc. and the New Buildings Institute [4] measured the energy savings of various plug load conservation measures at two LEED certified buildings. The study measured a 46% energy savings from installing a load sensing APS in a small office setting with computer, laser printer and computer speakers. A study performed by NREL measured average energy savings of 27% as a result of installing APSs in several GSA office buildings [1].

Standards: Standards like ASHRAE 90.1-2010 and California Title 24 and the International Green Construction Code (IGCC) call for timers and/or occupancy sensors on branch circuits serving task lighting and miscellaneous plug loads. As these codes are adopted, they will certainly raise awareness of the need to control plug loads. APSs may well serve as a more palatable way to meet the requirements of the standards as they allow more discrimination in the control of devices.

Low initial commitment: At $20-100 per unit, it is extremely inexpensive to buy one or more APSs and experiment with their use in a residential or commercial office space. This should allow potential adopters to gain confidence in the efficacy of control strategies before undertaking a larger roll-out.

Government/utility incentive programs: A number of utilities offer rebates, typically in the $10-20 range, for purchase of APSs. These programs provide a mild incentive to potential adopters who are aware of the program [5]-[8].

Executive/management focus: A key driver of energy efficiency measures in general is the increasing focus on energy conservation and sustainability by corporations. A 2012 Deloitte study indicates that 85% of businesses think that electricity costs are an important element of competitiveness. Also, new energy consumption disclosure laws in cities such as New York and

Philadelphia promise to translate energy savings into rent premiums; something sure to get the attention of commercial property owners [9].

Barriers to APS Adoption

There are several layers to the barriers impeding smart strip adoption. Some are beyond the control of APS vendors. Others can be addressed by APS design. We will address each in in turn.

Competing uses of investment dollars: Building owners are always constrained by availability of capital. Indeed, lack of funds was the number one barrier to energy efficiency cited by respondents that included mostly building owners and senior executives in the 2011 Johnson Controls Institute (JCI Energy Efficiency Index (EEI). Accordingly, potential investments are evaluated, not by whether they payback over the life of the measure, but how fast they pay back relative to other investments, including other non-energy related investments the business may be considering. Indeed the second most cited barrier to energy efficiency cited on the 2011 JCI EEI was insufficient payback/ROI. The result is that organizations establish payback hurdles for all investments, including energy efficiency investments. The 2011 JCI EEI indicates the following payback periods by organization type.

Organization Type	Mean Payback Period
Private Sector, Publicly Traded	3.08
Private Sector, Privately Held	3.79
Government Owned	4.45

A survey performed by Drexel University for the DOE Energy Efficiency in Buildings HUB indicates a slightly higher average BET hurdle of 5.26. Respondents to the Drexel survey which included building owners as well use purveyors of energy efficiency equipment and services indicated that simple breakeven time was the most important factor in weighing alternative investment decisions for building owners. The higher average BET from the Drexel survey may be the result of the fact that many respondents were sellers rather than investment decision makers [10].

Competition with other energy conservation measures: In an environment of funding limitations, organizations will prioritize energy efficient investment based on payback. The question then becomes whether plug load control with APSs pays back faster than other energy efficiency measures. While payback will depend on the particular circumstances of a building, many studies indicate that several common energy efficiency measures generate faster returns than plug load management.

The 2012 Plug-Load Control and Behavioral Change Research in a GSA Office Buildings report [1] published by NREL indicates payback on plug load control can be around one year for kitchen and print room environments but as high as four and eight years for miscellaneous loads and workstations, respectively. This makes investment in APSs for the commercial office environment marginal if the JCI EEI report is accurate.

These findings are reinforced by a Drexel university report which indicates that plug load control ranked 13 out of 25 candidate energy conservation measures. Measures receiving higher priority scores included lighting controls, efficient lighting upgrades (T5), insulation, double pane windows, efficient heating upgrades and efficient cooling upgrades.

This indicates that building owners tend to address plug loads after they have implemented more energy conservation measures with higher returns.

Lower Device energy consumption: The good news for decision makers worried about plug load energy consumption is that major plug loads are becoming more efficient, and that these efficiencies are realized relatively quickly as the stock of major energy consuming devices such as computers and monitors turns over rapidly. For example, if a three year old desktop computer that consumes 100 Watts is replaced by a laptop that consumes 20 watts, the energy savings is 80%, not including the energy management benefits of the laptop computer. Task lighting is undergoing a migration from incandescent to CFL bulbs which consume roughly one third the energy. A second migration from CFL to LED lighting which consume roughly half the energy of CFLs.

Competition from other plug load reduction measures: It has already been noted that plug load reduction initiatives face competition from alternative energy conservation measures. It must also be noted that smart power strips face competition from other plug load reduction initiatives.

The best illustration of this is this graphic taken from Plug Load Best Practices Guide, Managing Your Office Equipment Plug Load [11] published by the New Buildings Institute. Figure 6 below shows the energy savings from a small office in California. Note that energy savings resulting from APSs are a relatively small part of the overall savings. The other sources of savings are discussed below. For instance, there are many low-cost or free network-based power management software packages that allow IT managers to control the power state of devices. At $8 to $15 dollars per computer these software packages are significantly less expensive than APS and control the main power consuming devices at most commercial workstations, the computer and associated monitor. Meanwhile the Final Report Commercial Office Plug Load Field Monitoring and Assessment [4] concludes that "providing simple, easy to understand real - time feedback to users on their energy consumption can affect behavior and reduce energy consumption. Using an energy use feedback monitoring device saved around 31% or 35 kWh per year per workstation at the small office"

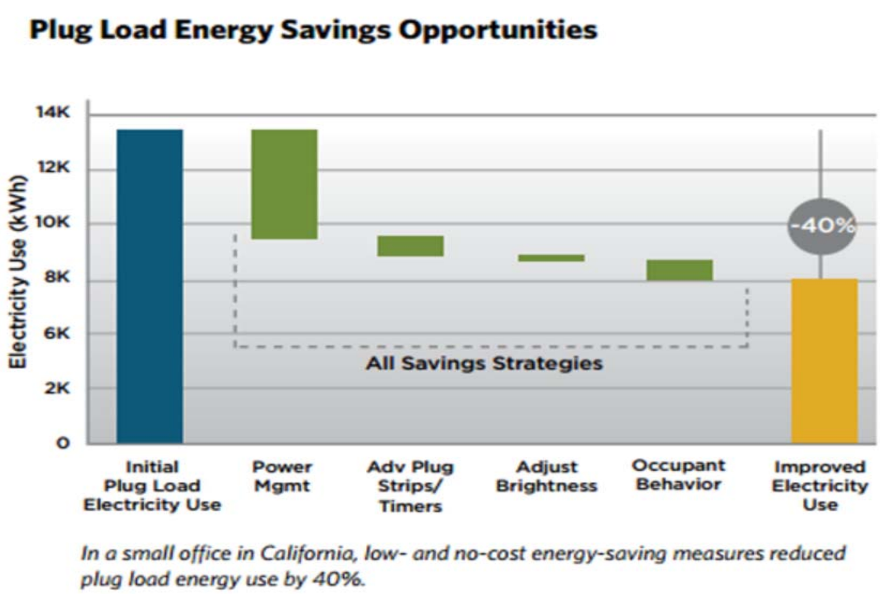


Figure 6: Plug Load Energy Savings Opportunities [sources: PlugLoadBestPracticesGuide]

Uncertain returns from plug load management: Plug load energy conservation initiatives are somewhat unique in the number and variation of devices, people and daily decisions that contribute to the aggregate outcome. Outcomes depend on complicated interaction of individual schedules, work patterns, attitudes, device control strategies, available feedback, APS features, training, communication, installation and ongoing (re) commissioning. The Plug-Load Control and Behavioral Change Research in GSA Office Buildings [1] noted that "In some instances, large variations between data sets for sites with the same control strategies were observed…. As a result, there may be significant uncertainty with average savings results". Such variation in outcomes makes plug load control a less attractive option than more predictable measures such as lighting or boiler efficiency upgrades.

Performance of current APS offerings: As noted above, plug load control involves injecting a new element into the complex interaction of devices and the workflow of people whose primary concern is not the rather modest energy consumption of miscellaneous plug loads. The available literature suggested that the design of APSs, related software and the implementation of plug load savings initiatives has not yet evolved to the point where energy savings objectives can be met without compromising the convenience and productivity of users.

From the literature reviewed we can glean several important aspects of performance including:

- Ease-of-Installation
    - Minimum need for training
    - Fast software and network installation (if applicable) by IT/facilities personnel
    - Fast/easy set-up by individual users (primarily in their workstation environment)
- Ease-of-ongoing-use
    - Workflow compatibility (Low productivity impact)
- Device compatibility
    - Synergy with built in device power management compatibility
    - Minimum damage to devices
- Visibility to actual energy being used/saved
- Resulting energy savings

Studies conducted to date indicate that the current generation of APSs, as well as complementary networks and software, fall significantly short of ideal performance. A few remarks from the research indicate some of the salient challenges.

APSs can interfere with operation of other enterprise systems

"it can be time consuming to override the advanced plug strip when maintenance was needed early in the day; conflicts with automated update schedule in middle of night for public computers and with software that manages public computer sessions" [4]

APSs can interfere with internal power management of some devices

"Interestingly, the timer plug strip reduced the electricity consumption of one workstation by 43% at the small office…., but increased the electricity use of the laser fax machine by 133% at the library. Because the laser fax power management settings were set to put the device into a low power mode after 240 minutes, the timer plug strip turned on the laser fax machine in the morning and put the device in an idle mode for 240 minutes before powering down the device to a low power mode” [4]

APS can disrupt user workflow

“Occupants experienced some issues turning devices on in the mornings or unexpected shutdowns in the evenings when working late. This typically was resolved by pressing the manual override button on the APS, which in some instances was expressed to be a nuisance. [1]

…….leading to user pushback or discontinued use

“Refined controls also resulted in increased complaints from occupants due to their computers not powering up appropriately or shutting down before they had finished their day. This control refinement proved to be unacceptable and was relaxed to the previous schedules after approximately 3 weeks” [1]

Usability is a paramount concern for consumer acceptance and persistence, and in our tests higher scores indicate fewer interactions required. If the APS demands too many changes in the habits of the users, they will be more likely to replace it with a standard surge protector. If the power strip requires too much action from the users to reduce energy consumption, then the users are less likely to go through the required motions consistently. [12]

“After the plug strips have been installed, a “second” checkup is recommended to make sure that occupants haven’t reverted back to their previous plug strips. [1]

3.2.3 VoC/VoM Interviews

During the second phase of the project, the Eaton/SPI team undertook a number of activities directed at understanding the effectiveness of current generation APSs, Key Success Factors (KSF) for widespread adoption of APS (including the role of automatic load identification), and the market potential for APSs in the event that all identified KSFs were met. The findings generated during that time were augmented with a supplemental literature review conducted during October and November of 2013 (see above).

During the course of the study, the Eaton/SPI team conducted interviews with 25 experts in various aspects of energy management. The interviewees represented the following types of organizations:

- Energy service organizations
- Energy management software vendors
- Electrical distribution equipment vendors
- Utilities and/or utility commissions
- National laboratories
- Advanced power strip vendors
- Early adopter of APSs

The results of these interviews were systematically processed to generate a number of results, including:

- Needs with regard to plug load control solutions
- Key Success Factors for APSs
- Value drivers for APSs
- Gaps in current performance

<u>Interviews</u>

Interviewees where selected to represent a range of perspectives on plug load control. Interviewees represented the following categories of stakeholders:

- Building or energy managers in end-use buildings
- Smart Power Strip Vendors
- Energy management software vendors
- Building energy service companies
- Utilities and ISOs
- Demand response NOCs

The coverage map of interviewees is shown in Figure 7.

Interviewees

Organization	Position	ESCO/NOC	BAS Vendor	BEMS Vendor	APS Vendor	Eaton Internal	Building Design	Govt Agency	Key Influencer	Utility	Academic User	Govt User	Commercial User	Energy Manager	Facility Manager	IT	End User
Property Management Firm	Global Energy Manager												■		■		
	General Manager of Facilities at Adobe												■		■		
State Technical University	Manager of Energy Services										■			■			*
	Manager, FP&M Information Systems										■					■	*
Private University	Building Services										■			■			
State University	Office of Sustainability										■			■			
Private University	Assistant Professor of Eelectrical Engineering			■							■						
Private University	Director, Sustainable IT										■			■		■	
	Office of Sustainability, Bldg Level Sust. Program										■			■			*
State Plug Load Research Center	Technology Manager								■		■			■			
National Laboratory	Sr. Engineer											■					
	IT											■				■	
	Building Area Engineer											■			■		
Energy Services Firm	CEO		■														
IT Equipment and Services Firm	Industrial Lead, Global Technology Development			■	■												
Building Energy Managemnt System Provider	SVP International			■													
Energy Management and APS Vendor	COO			■	■												
Energy Efficiency Engineering Company	Principal						■										
Demand Response Management NOC	CTO	■															
Demand Response Management NOC	Director of Energy Services	■															
State Public Utility Commission	Regulatory Analyst, Commercial New Construction							■									
Green Building NGO	Vice President, LEED Technical Development								■								
APS Vendor	CEO				■												
Electric Utility	Manager, Demand Response Program Policy									■							
Regional ISO	Principal Analyst - Demand Resources Department									■							

Figure 7: Coverage Map of Interviewees

The interviews where exploratory in nature. Interviewees where asked relatively broad questions about several aspects of plug load energy management including:

- Current building and energy management systems configuration
- Previous energy savings initiatives
- Plans for new energy savings initiatives, including plug load management
- Drivers of, and barriers to, effective plug load management
- Experience with plug load management initiatives

Interviewee responses were recorded verbatim and each discrete interviewee statement was placed in a database. Interviewee statements where then translated into "Need statements" or "observations" regarding plug load energy management. The team consciously avoided screening responses to ensure that all interviewee considerations were addressed in the analysis process. Finally, all of the needs statements were grouped into similar themes and the relationship between major themes was noted.

Plug Load Management Context

In office buildings plug load management is pursued in the context of broader business, energy efficiency and environmental goals. As noted in the literature review, plug load control is one of many potential energy savings measures. Among the few entities that had implemented plug load control programs, several phases of a comprehensive energy conservation plan, including implementation of other energy conservation measures, were already underway. These early adopters had demonstrated a commitment to energy conservation and were willing to experiment with measures that advanced aggressive energy savings goals. The behavior of these early adopters indicates that comprehensive plug load management programs are likely to be built on existing energy management systems/measures and phased in over time.

Major players supplying office building products and systems are advancing different modes of plug load energy savings. Suppliers of IT devices and other miscellaneous loads like task lighting are offering devices with progressively greater efficiency. Building management system vendors are offering device interfaces that can be extended to progressively more granular load control. New energy management software offerings specifically directed at plug load control are offered in conjunction with advanced power strips. Software is widely available for comprehensive network-based energy management of IT devices. All of the foregoing trends combine to create a dynamic environment where there are many approaches to plug load energy management that can be either competitors to, or complements of, advanced power strips. Figure 8 summarizes the stakeholders and influencers in plug load control and management solutions.

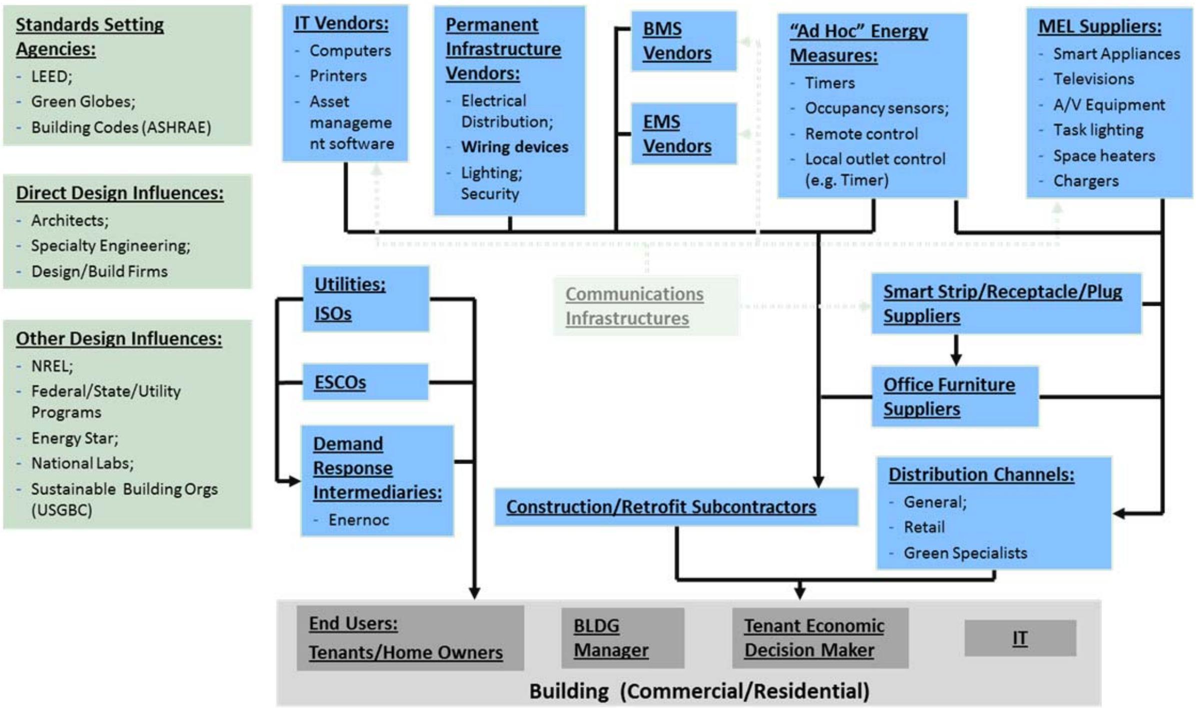


Figure 8: Representation of stakeholders and influencers in plug load control and management solutions

Needs Analysis

The needs analysis methodology involved taking the entire set of need statements derived from the interviews and combining them into groups of similar statements that comprise "intermediate needs". Groups of intermediate need statements are in turn clustered to form a manageable set of "high level needs". Figure 9 is a summary representation of the interview needs analysis. The high level needs are discussed below.

Attractive Financial Return: An attractive financial return is the most central need from the perspective of building owners and managers. Even for organizations with aggressive energy and greenhouse reduction goals, managers must select initiatives with attractive financial outcomes. This is consistent with the results of previous studies. The simplest expression of financial attractiveness is payback. A key element of achieving an attractive return is the persistence of the savings over time. If savings deteriorate rapidly then financial objectives will be in jeopardy. Sometimes managers look for value streams beyond simple savings in order to justify energy conservation objectives. In the case of plug load management, potential value streams could include control of plug loads for demand response (though the team did not encounter any cases of this being implemented).

Provides Means of Reducing PEL Energy / Power Demand: The central element of this high level need is reduction of plug load energy consumption. This can be achieved through direct control of existing plug loads. It can also be achieved indirectly by identifying inefficient loads for upgrade or removal. The information provided by plug load monitoring can inform the planning and execution of demand response. Of course, plug load control must be achieved without offsetting harm to devices that are sensitive to power cycling.

Flexible/Scalable: Plug load solutions must be flexible in order to address different building configurations, device populations, and user work patterns. Flexibility is also critical to the persistence of savings as changes are made following the implementation of a plug load management solution. Scalability is important as plug load management solutions lend themselves to a progressive roll-out among the building user population.

Promotes/Enables Desired Behavior: As noted above, any effort to control plug load energy consumption will be highly interdependent with the behavior of building occupants. Many plug load management schemes assume that users will respond constructively to feedback from the plug load management system. Since users can easily manipulate the system in a fashion that reduces its effectiveness (for example by replacing plug strips and/or plugging devices into uncontrolled outlets), the system must induce or enforce user compliance.

Easy to Design and Implement within Existing Systems: Before the advent of standards such as ASHRAE 90.1 2010 and aspects of California Title 24, plug loads and their control have typically been an afterthought in building design. There is increasing use of tools to design for efficiency with regard to HVAC, lighting, etc. Similar tools are required to bring plug loads into the design process. These tools should characterize existing plug load populations and their use, then use this information to design optimal plug load control strategies.

As mentioned earlier, plug load control initiatives are built upon existing initiatives which often entail use of existing building management systems. The ability to seamlessly integrate with these systems is seen as important for successful integration of plug load management into a progressive energy management program roll out. Ease of installation is important to keeping the initial cost of the solution low, thereby contributing to fast payback.

Easy operation by building management is also important for keeping costs low and effectiveness high. More importantly, ease of use by occupants is critical as the ongoing cooperation of occupants is necessary to achieve large and consistent savings. Building managers among the interviewees indicated that occupant compliance with the use of APSs was a significant issue. This lack of compliance leads to the need for periodic audits and re-commissioning of the advanced power strips. This problem indicates a difficult trade-off between achieving aggressive energy savings and inconveniencing occupants with the use of current generation APSs.

Enables Energy Savings Measures by Building Manager: Building managers typically have limited visibility into building electrical loads. Plug loads are particularly challenging because they are so diffuse, heterogeneous, and changeable. Building managers require the ability to interpret and act on PEL inventory and usage information.

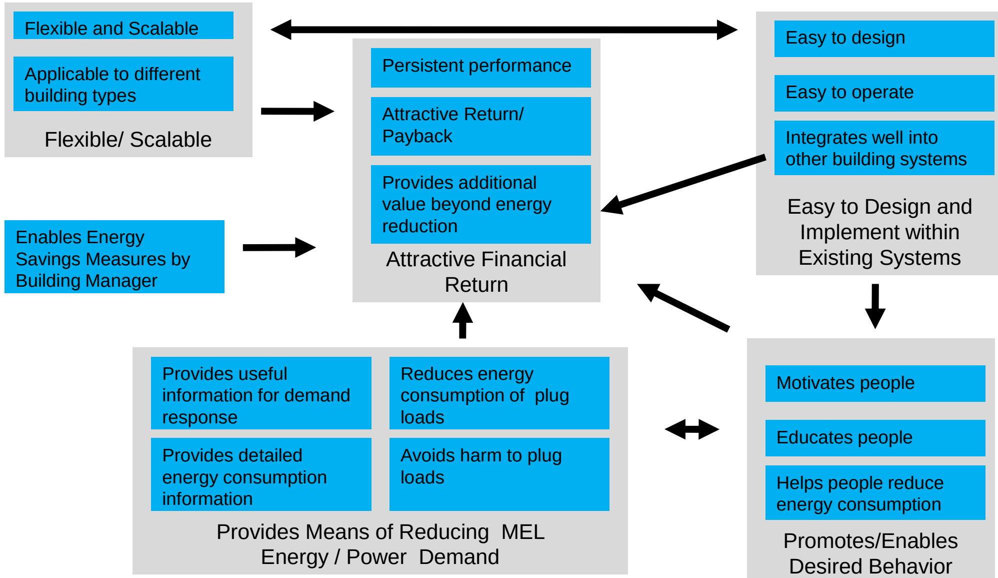


Figure 9: High level representation of stakeholder needs from stakeholder interviews

The needs were ranked based on team judgment resulting from dialog with the interview participants. Needs were then characterized by how well they were addressed by the current generation of APSs. Some of the needs identified in the interview process are both important and insufficiently addressed by current solutions. These represent the most salient gaps to be addressed by next generation APSs. Table 3 and

Table 4 below summarize the identified gaps for plug-in load control and management. Note that most of these gaps can be addressed, at least in part, by automatic Load ID.

Table 3: Gap Analysis for Plug-in Loads Control and Management

Specific Need	Corresponding Intermediate Need (where applicable)	Corresponding High Level Need	Nature of Gap
The solution is easy to use	Easy to Operate	Easy to Design and Implement within Existing Systems	Current generation of APSs are conceptually simple but cause productivity loss due to inappropriate control
The solution is easy to install	Integrates well into other building systems	Easy to Design and Implement within Existing Systems	Set up of current SPS is time consuming, especially version that provide energy consumption information over a network
The solution determines if a plug load device is sensitive to power cycling	Avoid harm to plug loads	Provides Means of Reducing PEL Energy / Power Demand	Without the ability to discriminate between device types, current generation APSs can damage certain devices by suddenly depriving them of power
The solution automatically adapts to changes in building configuration		Flexible/Scalable	Current APSs and related software cannot adopt to changing plug load mix/distribution without user intervention to characterize the new configuration
The solution identifies inefficient plug		Enables Energy Savings Measures by Building	Some APS can meter energy consumption, but recognition of an inefficient device require knowledge of the

loads		Manager	device type and energy consumption norms
The solution determines optimal plug load control algorithms			APS frequently apply inappropriate control strategies resulting from the wrong assumptions about the type of device it is controlling

Key Value Drivers

In addition to gathering needs and related performance gaps, value drivers were derived from interviewee expressions of needs and/or reports of user frustrations. This is the first step in developing and quantifying the value of employing APSs.

Energy Savings: Energy savings is the obvious value obtained from controlling plug loads. In addition to savings resulting directly from controlling power to plug loads, information generated from APSs can be used to motivate user behavior and/or guide subsequent energy reduction measures/algorithms employed by building/energy managers. Additional potential savings measures based on availability of real-time plug load use information include participation in demand response programs, internal demand management programs to avoid peak period charges from utilities, and prohibition of inefficient or undesirable loads.

Offsetting costs: Costs directly associated with plug control are those related to the cost of acquiring, installing, operating, maintaining, and re-commissioning APSs as well as any associated software or network infrastructure. The primary indirect cost is the lost productivity resulting from inappropriate control algorithms and hard-to-use devices/software. End user productivity loss is typically caused by:

- Untimely denial of power to devices when they are working
- Unavailability of devices when they start, or return to, work
- Inability to remotely access devices during off hours

Building and IT management productivity loss is typically caused by:

- Interference with scheduled software upgrades and system maintenance
- Time spent dealing with end-user complaints
- Ongoing efforts to enforce compliance in the face of user resistance
    - APS use audits
    - Re-commissioning of APSs

3.2.4 Value Modeling with Use Cases Evaluation

The team attempted to quantify the major value drivers in “value model”. Acquisition costs are the expenditures related to purchasing and installing APSs and any complementary software and network infrastructure. The model calculates energy savings, operating costs and productivity loss resulting from use of APSs. Net savings are energy saving less operating cost and user productivity loss. The payback period is the acquisition costs divided by net savings. The basic structure of the model is illustrated in Figure 10.

Acquisition Costs: Acquisition costs are comprised of the purchase and installation of APS and complementary products. Installation cost is the time to perform installation multiplied by the compensation rate of associated employees.

Energy Savings: Energy consumption is a function of the device population mix, the power consumption of each device in its various power modes (e.g. Active, Idle, Sleep, Off), the user population and behavior (i.e. user schedule and compliance with regard to energy conservation), and the device control strategy (i.e. physical control of device power states). Energy savings are the difference between the energy consumption before and after the implementation of a new combination of APS, complementary products and related implementation policies.

Operating Costs: Operating costs are a function of the time spent by employees maintaining and re-commissioning APSs and complementary products. Re-commissioning entails checking the status of plug strips and attached device, then restoring them to a configuration that conforms to the intended control strategy. The time spent on these tasks is multiplied by the compensation rates of associated employees to yield the operating cost.

User Productivity Loss: User productivity loss is the estimated productive work time users lose as a result of inappropriate APS control algorithms multiplied by their compensation rate.

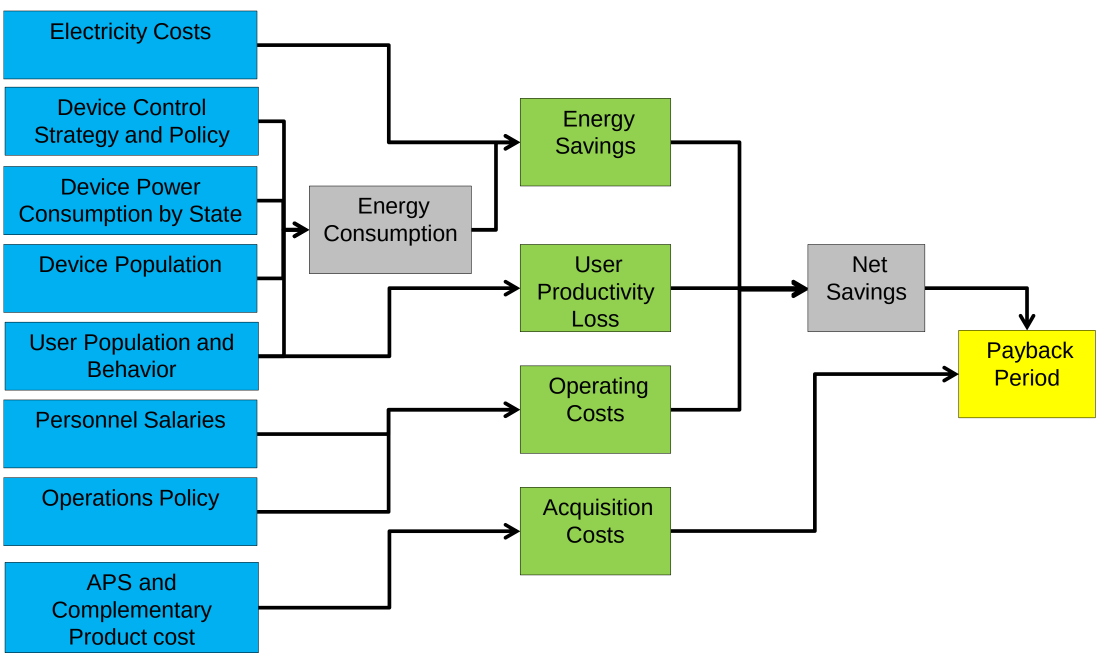


Figure 10: Value Model Structure

Use Cases

As mentioned above, two of our interviewees were kind enough to support an initial attempt by the Eaton/SPI team to quantify some of the key drivers in their specific situation. As a first set, the Eaton/SPI team built the value model described above. The team then populated the model with their best estimate of key parameters by reviewing statements made during the interview process. The team then reviewed the model results with the two interviewees and asked them to confirm or amend the initial estimates. Note that no direct measurements of energy consumption were made either before or after installation of APSs were recorded.

Major Private University

Overview: This University has forty thousand workstations spread over the many buildings that comprise its campus. The majority of the electricity consumed is produced on campus at a cost of 10.45 cents/kWh. While there is no utility demand response program, the university sees a long term capital avoidance benefit by limiting peak electricity use growth. The University is committed to reducing energy consumption and contributes up to five years projected energy savings toward energy conservation initiatives. The choice of initiatives is up to the individual departments. Two hundred employees were selected to participate in the application of APS in their workspace.

The average distribution of plug categories among occupants, as well as the power consumption of each category, is indicated in

Table 4. Occupants were estimated to be 25% compliant with regard to turning off devices on their own prior to the installation of APSs.

Table 4: Average plug load distribution and power consumption for Private University

Device Categories	Average Number of Devices per APS	Power Consumption			
		Active (W)	Idle (W)	Sleep (W)	Standby (Vampire) (W)
Desk top	0.50	118.97	59.75	2.38	0.80
Laptop	0.50	40.86	25.41	1.09	0.65
Personal Inkjet Printer	0.05	31.60	3.56	3.56	0.00
Personal Laser Printer	0.25	54.00	9.82	9.82	0.27
Personal Inkjet MFD	0.01	42.18	8.62	8.62	0.30
Personal Laser MFD	0.01	72.60	14.60	14.60	0.00
Primary LCD Display	0.50	40.47	40.47		0.98
Primary CRT Display	0.00	70.60	70.60		2.60
Second LCD Display	0.20	40.47	40.47		0.98
Second CRT Display	0.00	70.60	70.60		2.60
Computer Speakers	0.10	6.00	2.43		1.66
Table Lamp	0.20	41.70			0.00
Task Light	0.20	35.40			0.00
Space Heater	0.05	938.00			0.00
Coffee Maker	0.00	464.00			0.00

Simplified estimates regarding typical employee schedules are summarized in

Table 5. There are 251 business days per year for the premises, of which employees come to the office for 223 days. Normal business hours for the premises are presumed to span a continuous twelve hour time frame. Each employee is assumed to be on the premises for ten hours per day. Each employee is assumed to leave their workstation for one hour twice a day for lunch and/or meetings. All other departures from the workstation are presumed to be of short duration as to be immaterial for the analysis.

Table 5: Estimated Employee Work Patterns

Annual Office Hours	
Weekend Days	104
Holidays	10
Business Days	251
Average business hours/day	12
Business hours	3012
Non-business hours	5748
Annual Private Office/Work Station Hours	
Vacation days	15
Sick/personal leave days	8
Business travel/work at home days	5
In-office days	**223**
Average hours in office per day	10
Lunch/break hours/day	1
Away-from-desk meeting hours/day	1
Annual away-from-desk hours during office hours	892
Annual at desk hours during office hours	1784
Annual hours away from office during office hours	336

Plug-Load Control Measures: Two measures were employed to reduce plug load consumption. The first measure was use of power management software ($7.20 per seat) that enforces energy conservation settings on desktop/laptop computers. Monitors were turned off after ten minutes and the computer was put in sleep mode after thirty minutes. This software was used in conjunction with an APS ($25/unit, installation time of ten minutes ($4.17 at $25/hour)) which sensed when the computers were in a low power state and shut off power to the remaining devices connected to the strip.

While no direct end-user feedback was available, the program evidently met with significant resistance. Quarterly audits of occupants found that usage levels of advanced power strips had dropped to 40% of originally installed units. Quarterly re-commissioning (two minutes per employee ($1.67 at $25/hour) was required to restore compliance to 90%. One of the reasons for non-compliance cited by management was that the current threshold on the smart strips would drift occasionally and need to be reset. This led to untimely denial of power to desktop plug loads.

Impact of plug load control: The combined use of the power management software and smart power was estimated to reduce average energy consumptions per workstation from 1134 kWh/year to 403 kWh/year (a 64% reduction), a savings of $49.68. Interestingly the combined energy savings exceeded the sum of the savings from the individual measures, indicating strong synergies between the approaches. By itself, the power management solution resulted in workstation consumption of 712 kWh/year while the advanced power strip by itself yielded 1130 kWh/year. The miniscule savings resulting from using the power strip by itself is explained by the fact that, in the absence of the power management software, 75% of computers never go into sleep mode during either non-business hours or away from office hours, thereby failing to turn off controlled outlets.

Just taking initial costs, energy savings and periodic re-commissioning into account the payback on this investment is a very attractive 0.76 years. The team did not directly measure the productivity lost to the inconvenience caused by the solution, but we can surmised that it is nontrivial given the drop-off in smart strip usage. Assuming a productivity loss of just three minutes per month (36 minutes per year ($39 at $65/hour)), the breakeven time increases to 4.03 years. This result is illustrated in Figure 11 below where productivity losses substantially offset energy savings in each year.

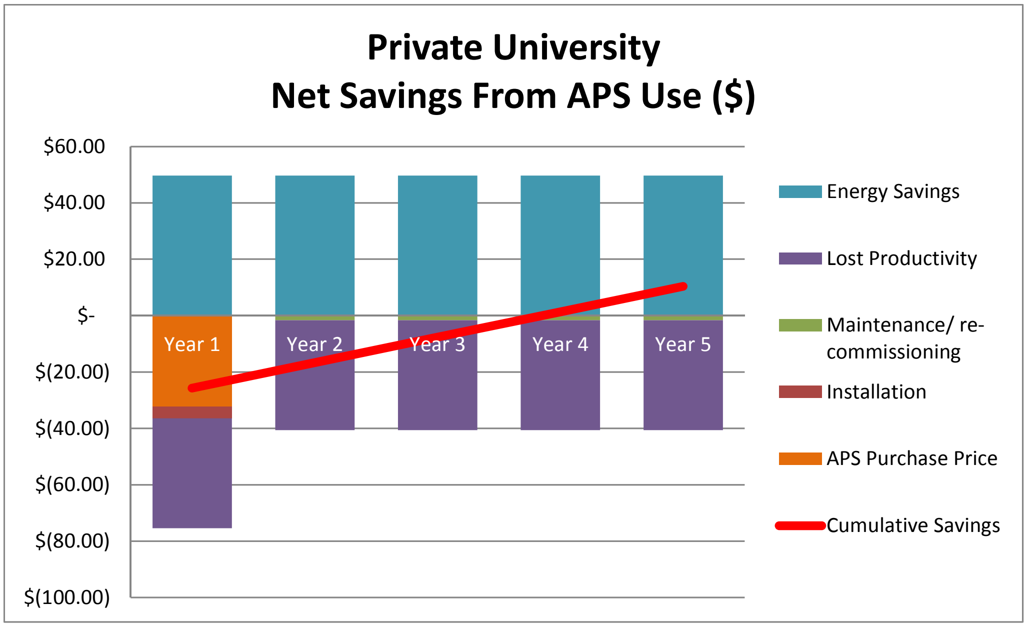


Figure 11: Estimated payback of use of power management software and load sensing power strip at a private university

Major Software Vendor

Overview: This major software company occupies a one million square foot triple office tower housing 3,000 employees. Building operations are subcontracted to a major property management firm. Average electricity rates are 13.80 cents/kWh. Both the tenant and property management firm are committed to energy conservation and have been early adopters of other energy conservation technology.

The energy management company has licensed energy management software from another major software company. This software provides a view of energy consumption throughout the facilities. At the time of the interview, demand was broken down to the level of major energy-related subsystems such as air handling unit, chiller plant, kitchen, etc. "Other" loads, which include miscellaneous plug loads, were reported as a single value.

The average distribution of plug loads per workstations is indicated in the table below, as is the preferred device policy. Occupants were estimated to be 50% compliant with regard to turning off devices on their own prior to the installation of APSs.

The average distribution of plug categories among occupants, as well as the power consumption of each category, is indicated in

Table 8. Occupants were estimated to be 50% compliant with regard to turning off devices on their own prior to the installation of APSs. Note that while the distribution of devices for this case is different than for the private university case, the estimated power consumption for each class of device is the same. The typical employee schedule is assumed to be the same as in the private university case.

Table 6: Average plug load distribution and power consumption for Software Company

Device Categories	Average Number of Devices per APS	Power Consumption			
		Active (W)	Idle (W)	Sleep (W)	Standby (Vampire) (W)
Desk top	0.20	118.97	59.75	2.38	0.80
Laptop	0.80	40.86	25.41	1.09	0.65
Personal Inkjet Printe	0.03	31.60	3.56	3.56	0.00
Personal Laser Printe	0.03	54.00	9.82	9.82	0.27
Personal Inkjet MFD	0.01	42.18	8.62	8.62	0.30
Personal Laser MFD	0.01	72.60	14.60	14.60	0.00
Primary LCD Display	0.50	40.47	40.47		0.98
Primary CRT Display	0.05	70.60	70.60		2.60
Second LCD Display	0.45	40.47	40.47		0.98
Second CRT Display	0.00	70.60	70.60		2.60
Computer Speakers	0.50	6.00	2.43		1.66
Table Lamp	0.02	41.70			0.00
Task Light	0.75	35.40			0.00
Space Heater	0.01	938.00			0.00
Coffee Maker	0.01	464.00			0.00

Plug Load Control Measures: The property management firm, in cooperation with the software company, already implemented a lighting replacement program that reduced electricity consumption by 10%. As a first phase of a plug load control program, the property management firm installed APS with occupancy sensors ($65/unit, installation time twelve minutes ($9 at $45/hour) in every workstation. The APSs were set to turn off controlled outlets ten minutes after a user left their workstation. In addition, a plug load policy was published which prescribed power management settings for personal computers (monitors off after ten minutes, computer put in sleep mode after thirty minutes) and prohibited the use of certain plug loads such as incandescent table lamps, space heaters and coffee makers.

Conformance with these measures was good, but not uniform. During the interviews it was noted that noncomplying (i.e. banned) devices could still be seen in the facility and that users confessed to violating the power management settings policy for the sake of convenience and productivity. A quarterly audit and re-commissioning sweep of every workstation (ten minutes ($7.50 at $45/hour) was considered necessary to maintain compliance levels at 95%.

Impact of plug load control: The combined use of power management settings and an APS with occupancy sensor was estimated to reduce average energy consumptions per workstation from 721 kWh/year to 308 kWh/year (a 57% reduction and $23.49 annual saving). By itself the power management settings resulted in workstation consumption of 455 kWh/year while the advanced power strip by itself yielded 323 kWh/year, both significant relative savings. Note that, with an occupancy based control, the APS is not reliant on complementary power management software to achieve a reduction of plug load energy consumption during non-business hours and out of office hours.

Just taking initial costs, re-commissioning and energy savings into account the payback on this investment is a relatively attractive 2.96 years. The team did not measure the productivity lost to the inconvenience caused by the solution, but we can again surmise that it was significantly lower than the private university case as compliance rates were much higher. If we assume a productivity loss of one minute per month (twelve minutes per year, ($28, at $140/hour) plus re-commissioning costs exceed energy savings and the smart strip investment does not pay back. This is illustrated in Figure 12 below, which shows that annual savings are more than offset by re-commissioning costs and productivity losses.

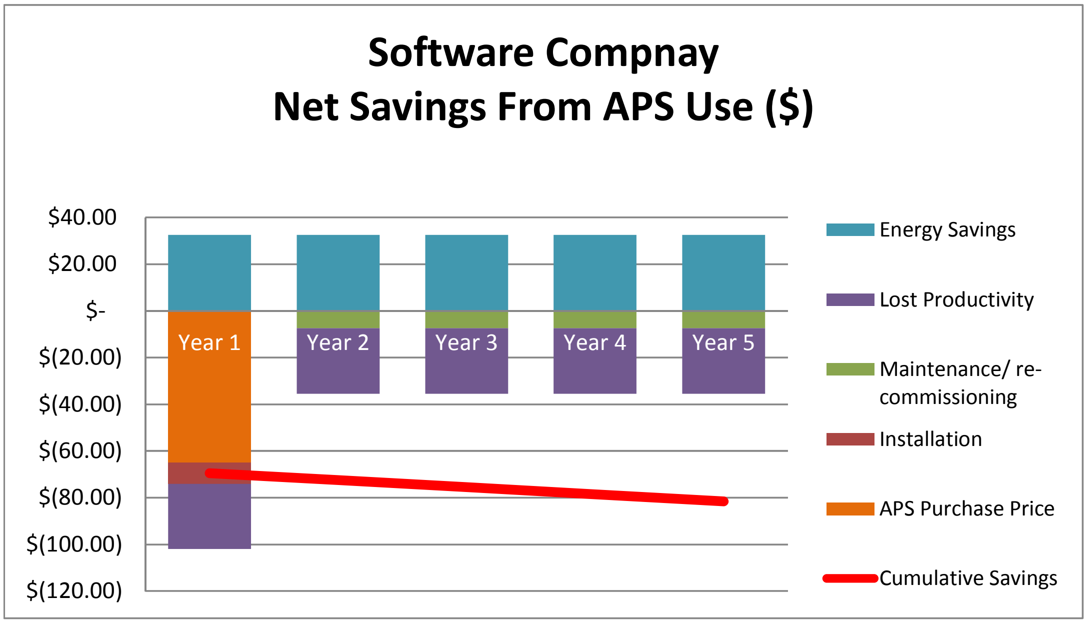


Figure 12: Estimated payback of use of prescribed computer power setting and occupancy sensing power strip at a software company

Case Study Implications

Because the team did not take direct energy measurements directly observing the APS users, the assumptions used in the foregoing analysis were, of necessity, rough approximations using the best judgment of the team and our interviewees. We can, however, draw a few conclusions from the analysis.

Energy savings from the use of plug strips is the results from the interaction of user schedule, the initial plug load population, APS control mode and associated settings, use of complementary power management measures, as well as user compliance. The energy savings per workstation at the software company (413 kWh/year) was significantly lower than those for the private university (731 kWh/year) in large part because population of plug load devices at the university consumed significantly more energy before the APSs were employed, and the user population was more diligent regarding turning off unused plug loads prior to implementation of APSs.

A comparison of the cases also indicates that the cost of productivity loss can be a large component of the economics of APS use. Moreover, productivity loss as a proportion of energy savings is a large determinant of payback time. In the software company case, the inclusion of productivity loss in the analysis resulted in negative net savings.

With outcomes sensitive to initial conditions and impact on users, the ability to pilot APS use and generalize the results to a larger user population will be critical to determining whether a large scale roll-out of APS is economically advisable.

Finally, it should be noted that the managers interviewed in these case studies did not volunteer that productivity loss was a factor in their own analysis of APS use economics. Rather, the concept of productivity loss was a concept introduced by the Eaton/SPI team in order to quantify the adverse effects of APS use that emerged in the literature and our interviews. We do, however, believe that lost productivity (or some other measure of user inconvenience), along with uncertainty with regard to actual energy savings, goes a long way toward explaining the low adoption of the current generation of APSs.

3.2.5 Key Success Factors for Advanced Power Strips

Given the sensitivity of plug load control economics to offsetting cost resulting from difficulties installing, commissioning (and re-commissioning) and ongoing use of smart power strips, widespread adoption of smart plug strips (and complementary products) hinges upon significant improvements in control effectiveness as well as ease of use, installation and re-commissioning. These improvements could be enhanced four interrelated features summarized in Table 7.

Automated Load Identification (ID): Automated Load Identification would have a number of direct and indirect benefits. By automatically identifying attached devices plugged into each outlet, installation and commissioning costs would be lower if companion energy management software was used to automatically determine proper configuration of the device. It would also be an enabler for self-configuration (SC) where installation and commissioning would be fully automated.

Automated Load identification would also support analysis and building/energy managers by identifying loads that are candidates for replacement or outright prohibition.

Finally Automated Load Identification would support application of appropriate control algorithms to minimize damage to devices and/or loss of end-user productivity.

Outlet Level Monitoring (MON): Outlet Level Monitoring is a prerequisite for Automated Load Identification. Outlet Level Monitoring also supports Adaptive Control (see below) by accumulating detailed usage pattern information on each device. Outlet Level Monitoring also has intrinsic value including the ability to monitor devices individually or by class in order to inform energy management usage. Finally Outlet Level Monitoring (combined with ID) supports awareness of devices suitable for demand response.

Adaptive Control (AC): Adaptive Control is the concept of striking the best balance of user convenience and energy savings by monitoring and responding to patterns in user behavior. For example, if the user has a pattern of leaving their desk for frequent short breaks during the day, an adaptive control algorithm would avoid shutting down peripherals after a short period of time so as to have all devices available when the user returns to their desk. Adaptive control could also employ location services in smart phone to ensure that equipment is ready to run when a user is near their workstation. Load Identification and Outlet Level Monitoring are prerequisites for Adaptive Control. The ability to accumulate time series of energy consumption associated with specific device types and correlate this information with indicators of user behavior and the energy consumption of related devices would provide the raw data necessary development of Adaptive Control algorithms that are customized to the current behavior of each user. Note that the derivation of Adaptive Control is beyond the scope of this report.

Self-Configuration (SC): Self Configuration describes the concept that devices plugged into smart strips could automatically announce their identity (type) and location to a monitoring network and complementary energy management software. This would significantly lower installation costs and inadvertent inconvenience to users based on out-of-date information regarding device types and locations on the network. Note that Automatic Load Identification is a prerequisite for Self Configuration.

Table 7: Key features that increase value and/or decrease offsetting cost in plug load management solution

Prospective Feature	Benefit	Value
Automated load Identification (ID)	- Remotely determine types of devices attached to power strip, outlet	- Save money/time on commissioning and re-commissioning of devices (i.e map load identity to outlet) (assumes integration with a control system)
	- Identify loads sensitive to power cycling	- Avoid damage to MEL devices
	- Identify prohibited loads	- Eliminate power consumption from prohibited loads
	- Match of loads to appropriate control algorithms	-Additional energy savings from appropriate control strategy - Increased user participation due to appropriateness of control algorithm
Outlet (i.e. device) Level Monitoring (MON)	- Understand consumption of individual devices	- Identify high consuming devices for energy reduction
	- Understand real-time status of device population (i.e. power state of each device)	- Real-time identification of devices suitable for demand response events
	- Track usage and energy consumption of devices over time	- Identify device level usage pattern to inform appropriate control algorithm (see AC)
Adaptive Control (AC)	- Derives control algorithms/mechanism that minimizes user inconvenience and productivity loss without user intervention	-Continued use/participation by end users - Minimizes loss of user productivity
	- Derives control algorithm/mechanism that minimizes unnecessary energy consumption without user intervention	- Reduce MEL energy consumption
Self Configuration (SC)	- System can be configured (and reconfigured) without excessive labor by building/IT management and/or end users	- Lowers installation costs and ongoing commissioning (and re-commissioning) costs

Impact of Key Success Factors on Payback: We can get some sense of the impact of these Success Factors if we look at their potential impact on the case of the software company above. If these factors combined to lower maintenance cost and productivity loss by half through greater ease of use, and the cost of auditing and re-commissioning by 80% through automation, payback at the software company would be an attractive 4.21 years as shown in Figure 13

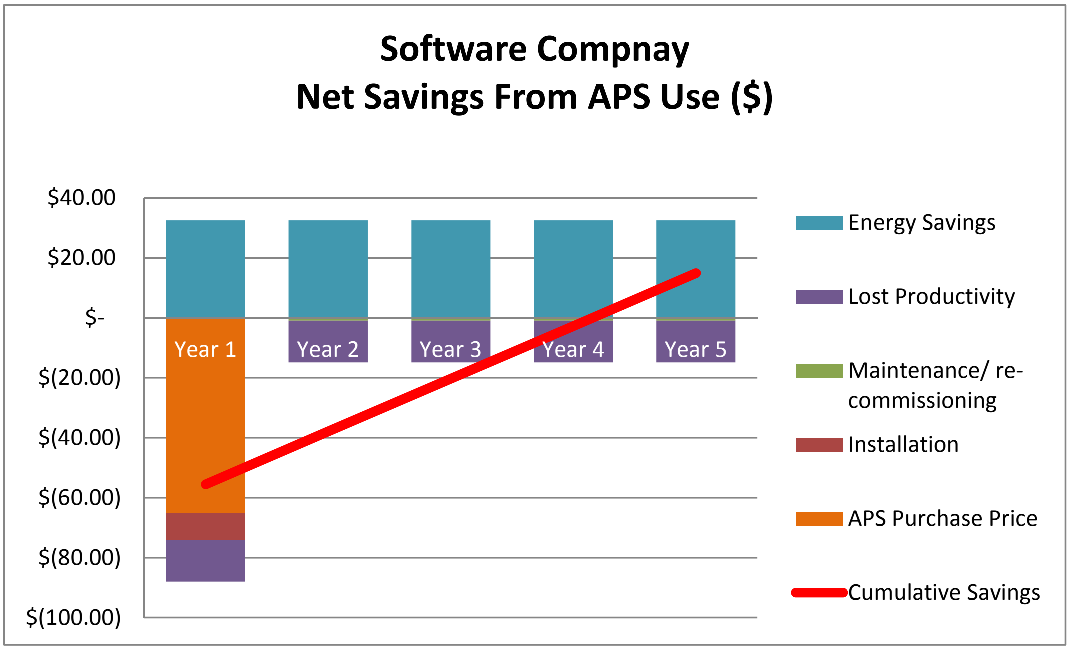


Figure 13: Estimated payback of use of prescribed computer power setting and occupancy sensing power strip at a software company with improvements in productivity losses, installation time and re-commissioning time.

Price: Since the energy savings potential of plug load control will decrease along with the energy consumption of increasingly efficient devices, the price of smart power strips will also need to decline in order to provide attractive payback.

<u>Values of Load Identification on Plug Load Control and Management</u>

The ability to automatically identify loads promises to overcome some of the barriers to advanced power strip adoption.

Avoid disruption/frustration: In standalone use of APSs, miscellaneous load identification ensures that the appropriate control strategy is applied to each device plugged into the power strip. This avoids inappropriate denial of power to devices which could lead to user inconvenience and/or device damage.

Simplify set-up/commissioning: In networked applications load identification serves to reduce user frustration associated with set-up as there is no need to manually map loads to outlets for the purpose of interfacing with energy monitoring software.

Simplify plug load characterization and monitoring: Time series (Aggregate) information regarding energy consumption by device type could be used to inform awareness programs and possible investments in permanent plug load management hardware. This information can also be used to adaptively modify algorithms to maximize energy savings while conforming to occupant usage patterns. APSs with load identification could also be temporarily installed in a workplace to characterize the install of plug loads and monitor their energy consumption.

Other key success factors

Load identification can help overcome barriers to smart strip adoption, however, the following additional conditions for success need to be considered.

Price: In order to achieve prevailing hurdles applied by building decision makers, the price of smart power strips must be low enough to result in significantly faster payback times than is typically achieved today. Prices must continue to decline as the efficiency of plug load devices is steadily increasing, and the savings from control is declining.

Ease/simplicity of use: While load identification should help to simplify set-up and apply appropriate control strategies, it is not clear that this would reduce enough lost time to make smart power strips an attractive investment. Prescriptions for achieving sufficient ease-of-use are beyond the scope of this study. Suffice it to say that future APSs with broad appeal will likely reflect the insights gained from a thorough usability analysis.

3.2.6 Market Forecast

The foregoing analysis indicates that advanced power strips must satisfy several Key Success Factors before they will gain significant market penetration. The question then becomes, what would be the market potential of smart power strips if the Key Success Factors were met?

This question presents a challenge as:

- The advanced power strip market is in its infancy
- There is no available data on current markets size aside from the impressions of industry participants
- There are no third party market forecasts for smart power strips known to the team

In circumstances similar to this, diffusion modeling is frequently employed to project products sales of emerging products. Diffusion modeling is based on the observation that new products frequently follow a classic S-Curve trajectory in the market. The shape of the S-curve is dictated by the total market potential and the diffusion coefficients which indicate the rate at which the technology is adopted.

Advanced Power Strip (APS) Diffusion Modeling Approach

The modeling approach assumes that Key Success Factors will be met in next generation APSs and that focus on reducing plug load energy consumption will increase once more attractive energy conservation measures have been implemented. Since it has been established that plug load control initiatives are likely to be pursued by committed parties who have already invested in more attractive energy conservation measures, LEED certification is an observable indicator of buildings that meet this criteria.

LEED certifications are projected using a Bass diffusion model with coefficients (p=.001, q=.35) selected to match historical data published by the US Green Building Council and the UC Berkeley School of Business. (PNNL-14231,US-GREEN BUILDING COUNCIL). The model assumes that all office buildings are ultimate candidates for LEED certification. The 2011 penetration for the LEED certification for office buildings was 11% (KMQ_AER_2011).

Advanced power strip penetration is also projected using a Bass diffusion model using coefficients (p=.03, q=.38) that represent an average across many new product introductions [13]. The model projects adoption among office building occupants. This occupant population is derived from the CBECs database. The model assumes that all buildings retrofitted for LEED certification are candidates for APS adoption. In the case of new buildings, 50% potential adoption is assumed as these buildings will have other plug load control mechanisms , such as branch circuit control, available to (or required of) them. The 2011 penetration of APS in LEED certified buildings is estimated at 3% as this is consistent with the limited information available in the literature and yields annual sales volume estimates consistent with estimates given by interviewees.

Forecast Outcomes

The base case model results are shown in Figure 14 below. The model indicates that, based on a continuation of current trends, 82% of office building space will be conforming to green building standards (LEED as proxy) by 2021 and advanced power strips will be used by 48% of the green building population and 38% of the total building population by 2021.

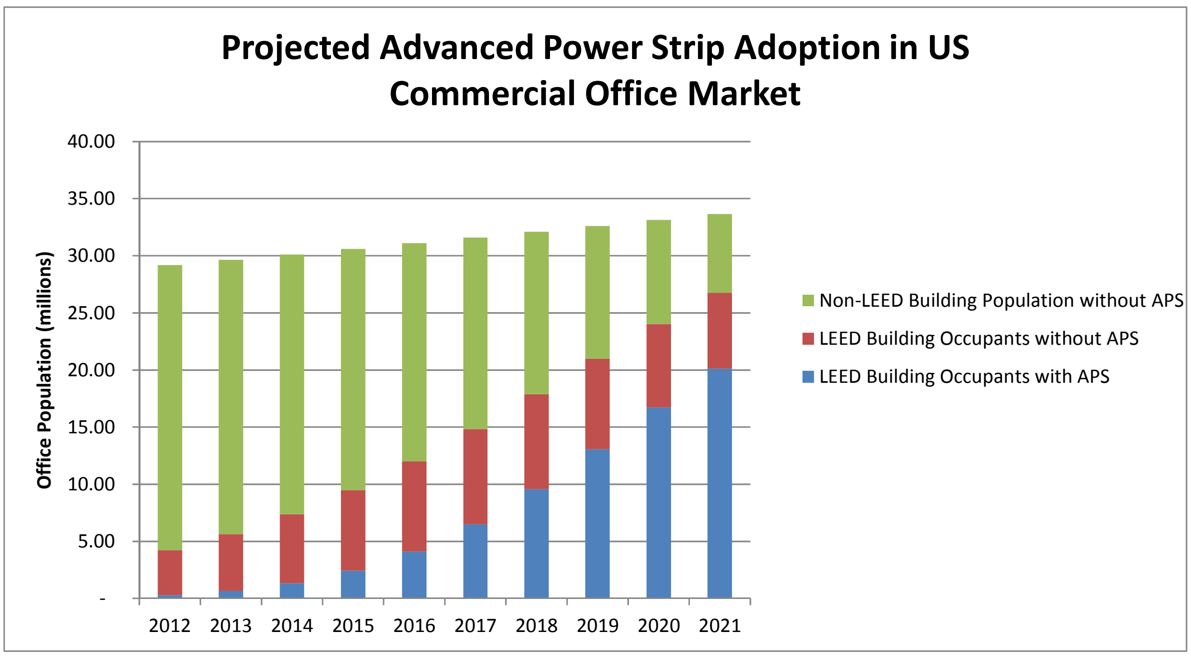


Figure 14: Penetration of Advanced Power Strips among end-users on US commercial office buildings

This projected penetration results in annual initial sales for smart power strips as indicated in Figure 15. Note that replacement sales are even more difficult to predict as embedded power management and wireless network capabilities of plug load devices could be significantly advanced in a decade, obviating the need for advanced power strips. The decline in sales at the end of the forecast period reflects a projected 78% penetration of the available market.

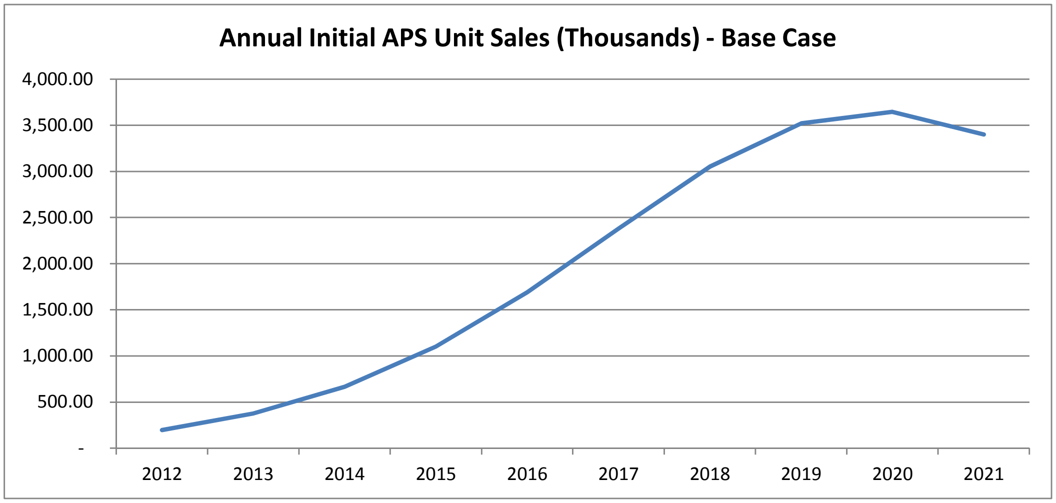


Figure 15: Base case estimate of initial sales of smart power strips into US commercial office buildings

Recognizing the inherent uncertainty in this combination of assumptions, a range of potential outcomes is presented on Figure 16. The base case remains the same as discussed above. The low case is derived by dividing the diffusion coefficients in half (p=.015, q = .19), the high case is derived by multiplying the diffusion coefficients by two (p=.06, q=.76). Note that in any case there appears to be an upper bound on sales of about 3.6 million units before the market begins to saturate and initial annual sales start to decline. As mentioned before, this model does not account for replacement sales.

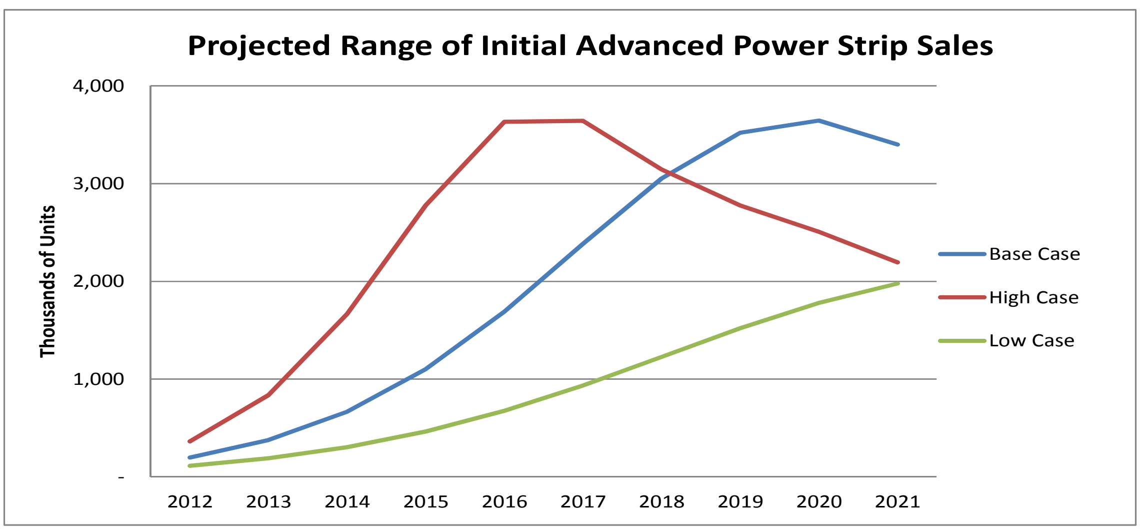


Figure 16: Projected Range of Initial Advanced Power Strip Sales into US commercial office buildings

3.2.7 Summary

As observed, plug loads are likely to become the largest component of energy consumption in commercial buildings. Advanced Power Strips are one among several measures that can be employed to reduce plug load energy consumption. The current generation of Advanced Power Strips however have performance gaps that offset the energy savings that result from their use. This study has made a first pass at quantifying the costs that result from these performance gaps and has identified Key Success Factors that would make the use of Advanced Power Strips economically viable. Automatic load identification would enable most of these success factors. The study went on to make a first pass estimate of the market potential for Advanced Power Strips if the identified success criteria were met.

The economic analysis and market projections in this report involve approximations that could be improved on by gathering more empirical data. There is scope for further studies that combine value modeling with actual measurement of plug load energy consumption, user behavior and offsetting costs using the principles of value modeling applied in this report. Empirical data on Advanced Power Strip sales would also be a welcome addition in understanding this market. The development of adaptive plug load control algorithms appears to be a rich topic for further research.

3.3 Non-intrusive Load Modeling and Identification Development

Non-intrusive load modeling and identification development is the major task under this program. Eaton has been collaborating with Georgia Institute of Technology to develop an automatic, intelligent load modeling and identification technology to automatically determine the type, energy consumption, power quality, operation status and performance status of plug-in loads, using electric waveforms at a power outlet level.

The major activities under this task include:

- Literature survey on Load characterization and identification;
- Plug-in Appliances Circuit topologies a research and modeling;
- Plug-in Loads Voltage/Current signals data collection and Database Construction;
- Nonintrusive load Identification algorithm development;
- Laboratory PC-based load ID demonstration platform development; and
- Load Wellness diagnostic and Detection development.

3.3.1 State-of-art in Load Identification and Challenge Discussion

The electrical loads often present unique characteristics in the electric signals (i.e., voltage, current, and power). Such load characteristics provide a viable means to identify the type of a load (e.g., PC, heater, lamp, etc.) and its operational status (e.g., active, ready, standby, etc.) by analyzing the electric signals. Since the introduction of non-intrusive load monitoring (NILM) in the 1980s, numerous prior proposals have sought to develop various NILM solutions. A literature survey has been conducted to understand the methods already published on load identification and classification. A wide-range of known solutions is disclosed by Yi Du et al., “A review of identification and monitoring methods for electric loads in commercial and residential buildings,” [14]. The existing literatures teach us that a load identification system typically consists of several modules including data acquisition, data processing, event detection, feature extraction, and load classification/identification. Among the needed modules, most of the research efforts have been focused on feature extraction and load classification/identification, as the core in the field of NILM.

Even though numerous methods for single-phase and outlet-connected electrical loads identification through voltage, current and/or power measurements have been proposed by various researchers, there are still quite a few open issues that are yet to be diligently addressed and still remain unsolved. This is also part of the reason why there is no commercially available product that can offer a load identification solution with satisfactory performance.

Feature Extraction

The selection and extraction of features that are unique for a particular load is the foundation to enable an effective and reliable load identification solution.

With reference to their electrical characteristic, building plug-in appliances can be classified into linear loads and non-linear loads, as summarized in

Table 8. Linear loads are loads with constant internal resistance, capacitance or inductance, such as heaters. Nonlinear loads are divided into direct AC connection loads or loads with electronic converters. Direct AC connection loads are connected directly to the outlet, with variable internal impedance, such as fluorescent light, whose impedance changes with time. Loads with electronic converters are very common in the buildings. Many appliances have an AC to DC converter inside, such as computers. Other converter-connected loads in the buildings are typically motors with drive.

Numerous researches have been conducted to select and extract useful features for various building loads to drive an effective NILM solution. The most commonly investigated features can be categorized into 1) steady-state features; 2) transient-state features; and 3) operating pattern features.

For steady state feature exploration, real and reactive power is utilized to identify load types [15]. Also, peak current, average current and RMS current values can be used for load identification [16] [17]. Current harmonics are applied as the core features for identification to mainly address those loads with a nonlinear DC power supply [15], [18]-[20]. Further, a voltage-current (V-I) trajectory modeling method for load identification uses purely graphical shape features of the V-I trajectory of each load [21]. For transient state features, such as instantaneous admittance curves and transient power curves, can be employed [22].

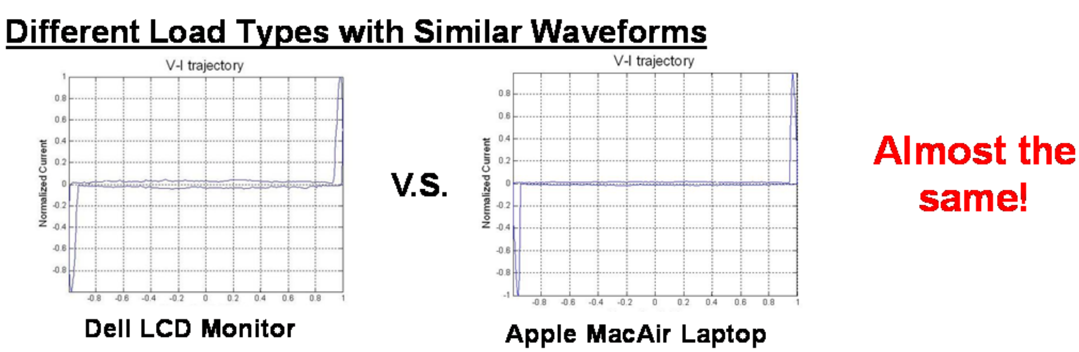
Table 8 also summarizes and comprises the features' effectiveness to identify different types of building plug-in loads.

Table 8: Comparison of Features Effectiveness for Different Plug-in Loads in Buildings

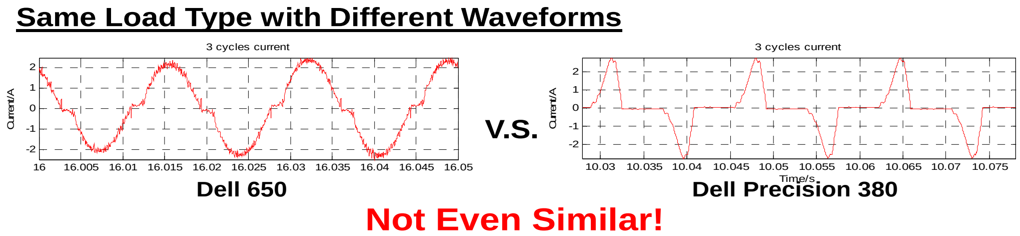
Methods	Loads in Buildings				
	Linear	Nonlinear Property			
		Electronic Converter	Machine Saturation	Appliance Dependent	Process Dependent
Real and Reactive Power	✓	✓			
Current Characteristic	✓	✓			
Current Harmonics		✓			
Current Wavelet Transform		✓			
Instantaneous Admittance		✓			
Instantaneous Power		✓			
Current Eigenvalues			✓	✓	✓
Transient Power			✓	✓	✓
V-I Trajectory	✓	✓			

One of the biggest issues that is not yet addressed by most researchers is there is not a guideline available to drive an optimized feature selection for load identification. Almost all of the approaches disclosed in literature are based on a data-driven approach, where the load distinction has only been addressed via a statistical analysis of the available dataset. The connections between the utilized features and the load's physical circuit topology have never been explicitly addressed and analyzed.

This particularly presents challenges to ensure a reliable identification performance and effectiveness for loads with similar electronic front-ends, e.g., various office electronic equipment, and/or audio/video equipment, etc. For instance, Figure 17 provides two examples to elaborate the above point. Figure 17 (a) shows the V-I (voltage and current) trajectories for a Dell LCD monitor and an Apple MacAir laptop. The two loads of two different load types share almost the same electric waveforms in steady state. On the other hand, Figure 17 (b) shows the V-I trajectory waveforms of Personal Computers but for two different models (Note that, same brand, i.e. Dell). The steady state waveforms of the two loads present entirely different signatures, even though they belong to the same load type.



(a)



(b)

Figure 17: Steady State Current and Voltage Waveforms of Typical Electronic Loads

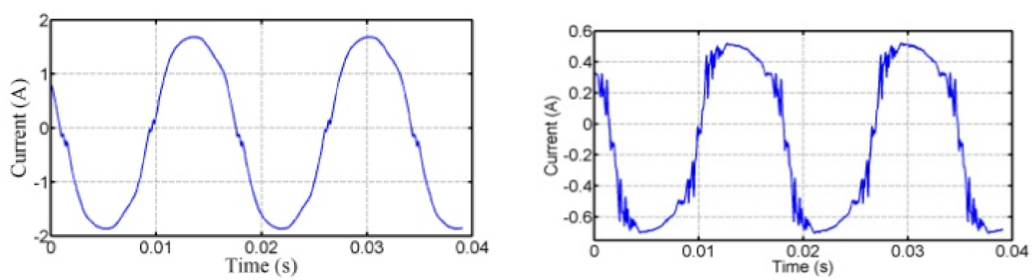
The above example also suggests that a data-driven approach cannot drive a meaningful load identification solution in the office electronic loads category no matter how sophisticated the algorithms are. This fact has been well understood through the front-end circuit topology analysis presented in the next section.

The survey results show that it is almost impossible to identify all types of the loads using a single method. Therefore, high-dimensional load features/signatures with multiple, hierarchical identification structure methods are proposed and developed in this project to classify/identify PELs, especially those with a similar electronic front-end.

<u>Operating Mode Detection</u>

Very few investigators have considered identifying the operating status or modes (i.e., standby, active, or sleep) of loads in real-time; ignoring such information may lead to incorrect load identification.

Existing load identification methods may assign an incorrect identity to an electric load that exhibits different current waveforms (and thus different characteristics) under different operating modes. Furthermore, the rapidly changing designs of front-end power supply units and worldwide implementation of regulations on energy efficiency further complicate the load identification. Many electronic appliances are currently equipped with power factor correction (PFC) units which may be turned on or off automatically while in different operating modes. For example, the current waveforms of a LED TV in active mode (PFC on) and in energy saving mode (PFC off) are shown in Figure 18.



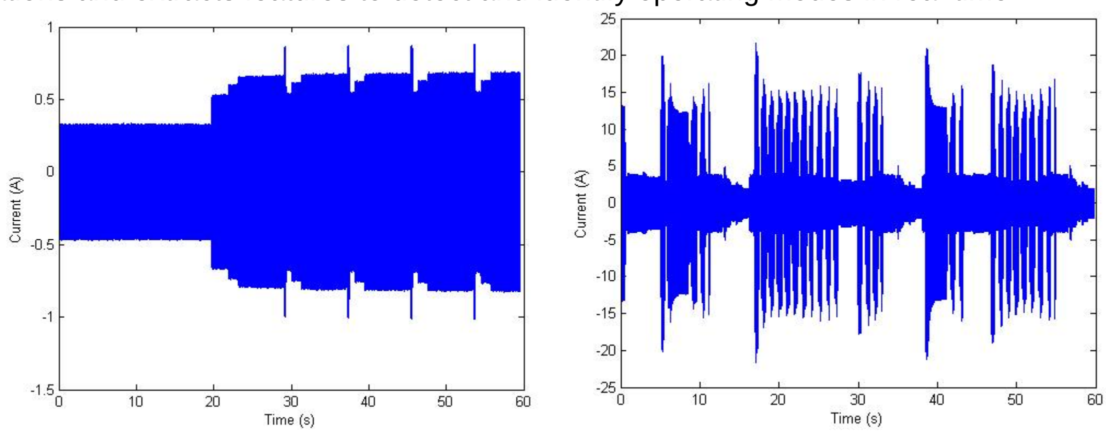
(a) (b)

Figure 18: An LED TV in (a) active mode and in (b) energy saving mode

Moreover, instead of identifying loads based on features extracted from several cycles of waveforms, recent work has started to identify operating modes from long-term (hours or days) waveforms. A recent report by the German Federal Ministry [23] analyzed four operating modes of communication devices: normal, standby, off-mode, and off. In the U.S., a study by the Lawrence Berkeley National Laboratory [24] employs a non-intrusive inventory-based method to study the power status of office appliances during night-time. It only considers snapshots at single points in time and thus does provide the time spent in each power status. The National Renewable Energy Laboratory presented a histogram heuristic clustering technique to divide a data set of electric load operation for several days into clusters based on similarity criteria and extracted operating modes [25].

Figure 19 shows the current waveform (of 60 seconds) of office appliances. Figure 19 (a) shows the transition from standby mode to faxing (active) mode, and Figure 19 (b) represents a multi-functional device (MFD) in double sided photocopying mode.

The detection of transition from standby to active mode in Figure 19 (a) is a crucial step for energy management, which should not only rely on detecting the change in power. Also, in Figure 17 (b) the instantaneous peak current is time-varying and typical identifying features in the literature vary from cycle to cycle. Thus, existing methods may fail to correctly identify this MFD. Therefore, a method is needed which can extract features from long-term and time-varying operations. This paper proposes a simple but yet efficient representation of long-term operations and extracts features to detect and identify operating modes in real-time.



(a) (b)

Figure 19: Current waveforms of office appliances in different operating modes

Load Disaggregation

In buildings, electric power can be supplied to a PEL directly through a wall outlet, or through a power strip that is plugged into a wall outlet in order to distribute power to multiple outlets of the power strip. The latter scenario is more commonly adopted by users to enable the wall outlet to simultaneously supply power to more than a couple of PELs.

A technology that is capable of decomposing/decoupling power consumption of PELs by only measuring the aggregated electric signals at the wall outlet level is often desired as a cost-effective, nonintrusive load monitoring and identification (NILM) solution. An early example NILM apparatus and method is disclosed by U.S. Patent No. 4,858,141.

Many researchers worldwide have been working toward a new generation of electricity measurement systems that are capable of providing disaggregated data about consumption at the individual appliance or device level. In general, the features and the disaggregation approaches that are used to monitor down to the appliance-level or the device-level can be categorized into three groups: (1) detecting the sharp changes in both the aggregate real and reactive power consumption; (2) current consumption and startup characteristics; and (3) voltage signatures.

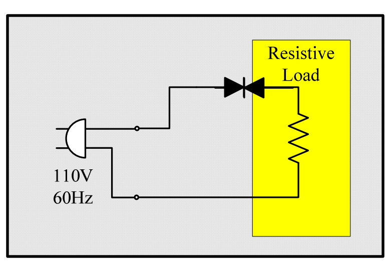
Even though NILM technologies have been developed since the 1980s, no known commercially available disaggregation method is believed to be easily deployable, highly accurate, and cost effective. Most of the known methods require either an observation of hours or longer, and some other methods require central processing units (CPUs) and operating systems to run artificial intelligence algorithms, which usually need an expensive platform to support the implementation. There is room for improvement in methods of estimating power consumption of a plurality of electric loads.

3.3.2 Plug-in Appliance Topologies Research and Modeling

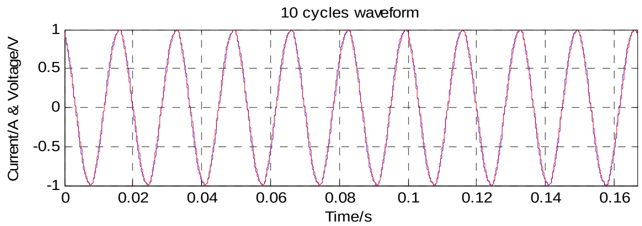
Research for the plug-in load appliances has been conducted in order to capture a complete feature space of each load type. The work has been conducted by four areas, including 1) the front-end circuit topology of the load, 2) the electrical operating principles, 3) the functional nature of the load, and 4) user behavior. This research forms the foundation for a model-driven load identification. The terminal voltage and current characteristics can be defined in a much more technical manner than through mere data mining. The interface circuit topology mainly affects the steady-state signature. The operating principle, on the other hand, helps to shape the load profile during start-up, or when operating in a particular functional state. Lastly, the user behavior drives the load's energy usage profile/pattern over long periods, e.g., on an hourly or daily basis.

Plug-in Appliances Topology Analysis
The front-end electronic circuit of an appliance is composed of one or several of the following modules, including a front-end filter, a rectifier, a transformer, an isolated dc-dc converter, a phase angle controller (PAC), a current\voltage regulator, and/or a power factor correction module.

Resistive Load Category (Category R)
A resistive load, as the name suggests, contains a resistance directly connected to the terminals. Therefore, there is no phase angle displacement between current and voltage waveform, and the power factor is close to unity. Figure 20 (a) shows a typical circuit of a heater. The normalized current and voltage waveforms of a heater are shown in Figure 20 (b)



(a)

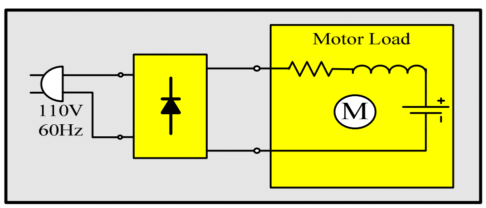


(b)

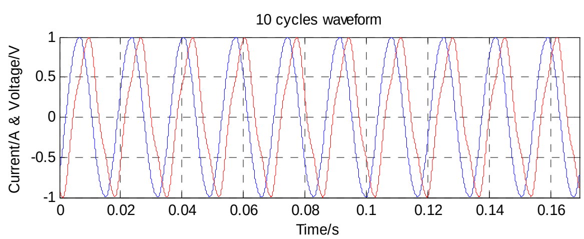
Figure 20: (a) The conceptual front-end circuit of pure resistive loads; (b) Normalized steady state voltage and current waveform of pure resistive loads.

Reactive Load Category (Category X)

In this category, an inductance is connected to supply through a rectifier. Figure 21 (a) shows the electronic circuit for a fan driven by a DC motor. A large phase angle displacement between supply current and voltage is one of the dominant characteristics of this type of loads as shown in Figure 21 (b).



(a)



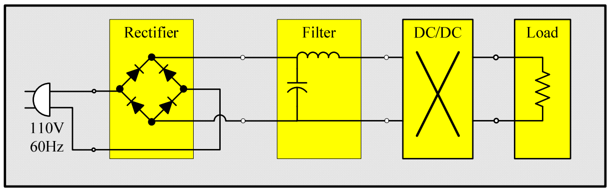
(b)

Figure 21: (a) The conceptual front-end circuit of inductive loads; (b) Normalized steady state voltage and current waveform of inductive loads.

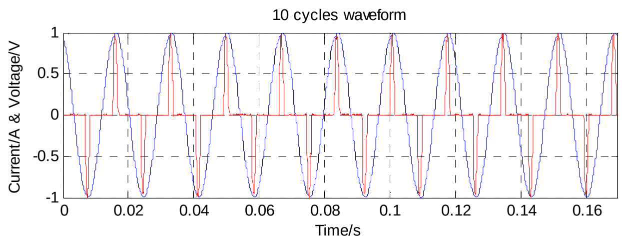
Electronic Load without Power Factor Correction Category (Category NP)

An appliance in this NP-category often needs a DC power supply to power the downstream electronics. The front-end power electronic circuit typically consists of a front-end electromagnetic interference (EMI) filter, a rectifier, a voltage or current filter and a DC-DC converter, shown in Figure 22 (a).

As shown in Figure 22 (a), a filter capacitor is utilized to supply constant DC voltage to the DC/DC converter. Because of this capacitor, the rectifier bridge conducts only when the magnitude of input voltage is greater than the magnitude of the voltage across the capacitor. Consequently, the typical utility supply current waveform to this load type appears as a periodic pulse waveform at the power frequency (i.e., 60 Hz in U.S.), as shown in Figure 22 (b).



(a)



(b)

Figure 22: (a) The conceptual front-end circuit of NP; (b) Normalized steady state voltage and current waveform of NP.

The width of each pulse is affected by the capacitor voltage as well as the load power. The charging duration varies directly with the load power. Furthermore, the front-end EMI filter also affects the shape of the pulse. It is important to note that, the load input current (i.e., the current measured at the point of the front-end plug) is not related to the DC/DC converter, mainly because of the signal isolation caused by the capacitor filter. When a DC power supply is designed for an appliance with the power level below 75 Watts, the manufacturers often choose a topology among three types of filter configurations and four types of DC-DC converters, as summarized in Figure 23.

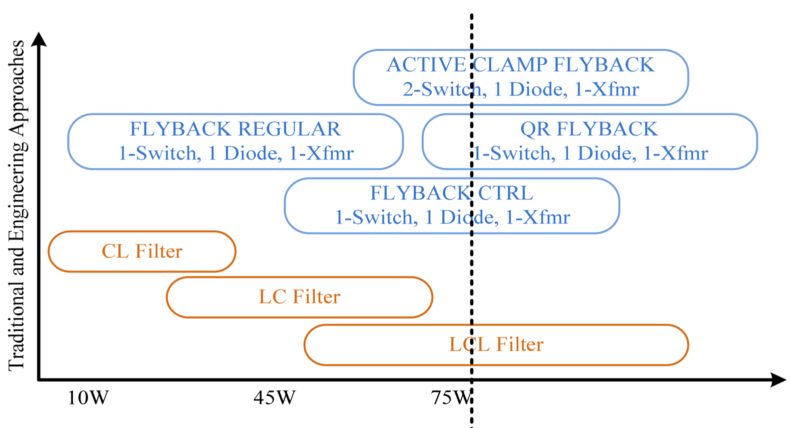


Figure 23: Industrial selections of switch power supply and V/I filters.

With reference to Figure 23, a C-L filter is usually used for portable loads such as cellphone chargers. An L-C filter is commonly selected for loads with power below about 45 W, and an L-C-L filter is used in loads with power over 45 W with a wider pulse. The representative load types that use the three types of filters are illustrated in Figure 24. In fact, these three types of loads have most of their characteristics in common and they have therefore been roughly recognized as one kind of load in most of the previous publications.

For loads in Category NP, there is no phase angle displacement between the power supply current and voltage waveforms; however, the current waveform contains abundant harmonics.

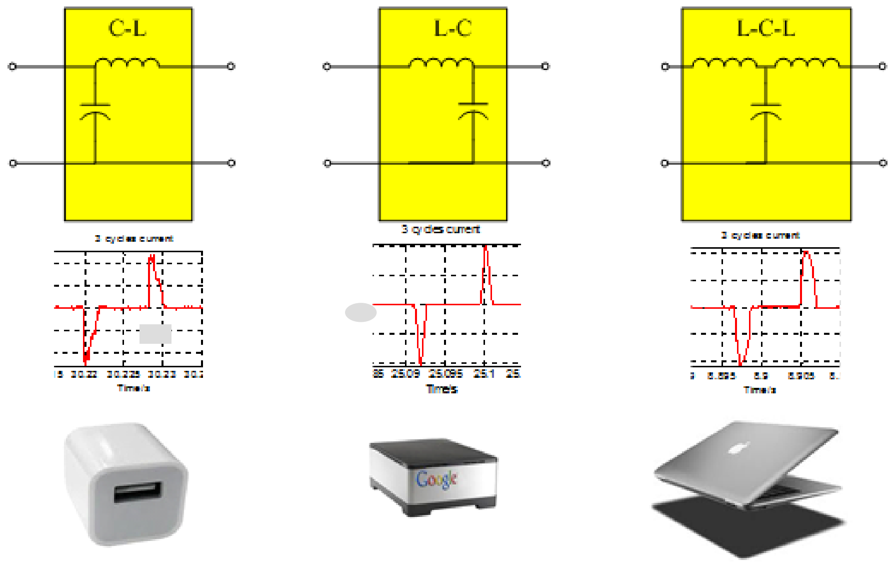
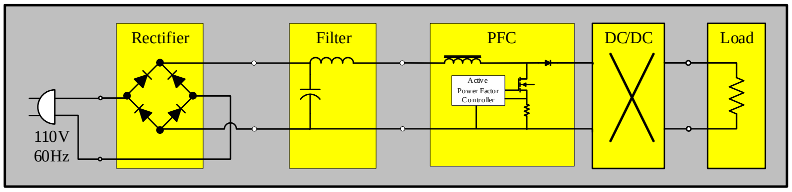


Figure 24: Three kinds of filters in power supply and their representative load types e.g. a cellphone charger, a set top box, and a laptop.

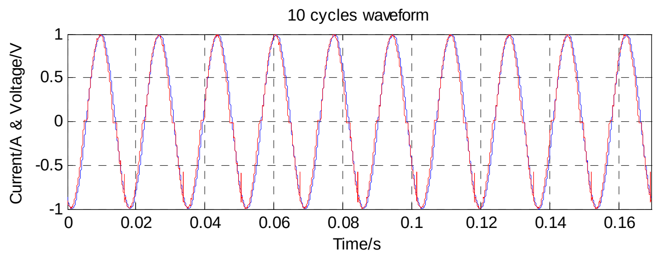
Electronics Load with Power Factor Correction Category (Category P)
A DC power supply is also used in the appliances in Category P. In these cases a typical front-end electronic circuit consists of a front-end EMI filter, a rectifier, a voltage regulator, a power factor correction circuit and a DC-DC converter, shown in Figure 25 (a).

In this category, an L-C-L filter is typically used. As required by the IEC 61000-3-2, a front-end EMI module is always adopted, since loads that fall into this category consume more than 75 W. Unlike loads in Category NP, the input current in Category P loads appears to be sinusoidal, similar to resistive loads. The PFC causes the rectifier to conduct for a complete cycle as shown in Figure 25 (b). These PFCs can further be categorized into active PFCs and passive PFCs as shown in Figure 26. Active PFC modules can be further classified into three structures, i.e. boost converter structures, full bridge structures and interleaved structures. For the boost type, there are three distinct control strategies which affect the signature. These are continuous conduction mode (CCM), discontinuous conduction mode (DCM), and critical conduction mode (CrM).

It is important to note that, for loads in Category P, there is always a short time period of discontinuous current when the voltage crosses zero. This current characteristic forms a typical feature for the P loads, and is useful to distinguish them from a purely resistive load. For interleaved PFC structures, the PFC driver needs to verify the voltage polarity and the dead-zone at the voltage zero-cross point results in the current discontinuity. For the critical conduction mode or the discontinuous conduction mode PFC, the switching frequency is very low when current is close to zero, which causes the discontinuity.



(a)



(b)

Figure 25: (a) The conceptual front-end circuit of P-Category; (b) Normalized steady state voltage and current waveform of P.

Figure 26: A classification of PFCs with different structures and different control strategies

The detailed principles of PFC converters can be found in [13]. Figure 27 summarizes the waveforms for different PFC topologies. Continuous Current Mode control is a current tracking strategy, thus the current waveform follows a sinusoidal reference as shown in Figure 27 (a). DCM is a pulse width modulation (PWM) control strategy, thus a front-end high frequency filter is obligatory. The waveform after the filter is smooth as shown in Figure 27 (b). Passive PFCs are simply an inductor which can only increase the conduction period shown in Figure 27 (c). An interleaved PFC is a full bridge structure with two boost converters. Its control strategy is like the CCM control strategy, but uses a combination of two DCM PWM controls. All the information above is useful to identify those loads with the most similarity.

Appliances in Category P often appear to be very similar to resistive loads in terms of their current waveforms. However, the existence of the current discontinuity and higher order current switching noise are the recognizable signatures for loads of this type.

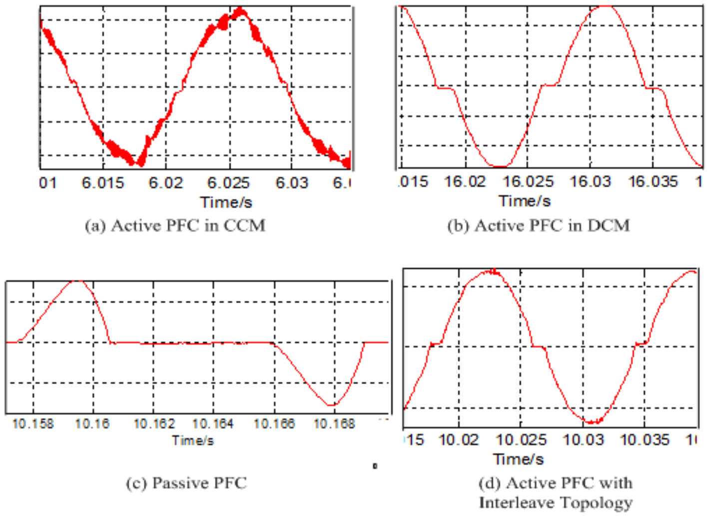
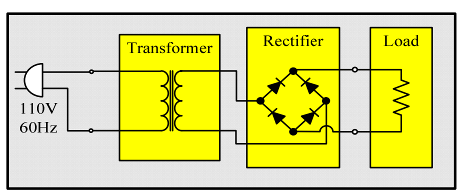


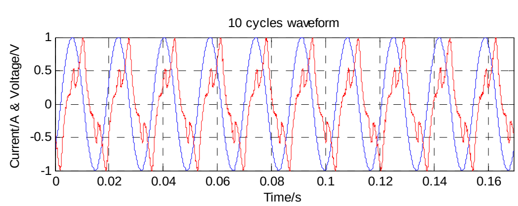
Figure 27: Different waveforms in terms of different PFC modules.

<u>Transformer-Rectifier Power Supply Category (Category T)</u>

The transformer-rectifier DC power supply is the most traditional power supply, which is still commonly used in low power devices. Figure 28 (a) presents a typical circuit of a transformer-rectifier DC power supply. It consists of a transformer, a rectifier, and a linear regulator. The current of this load type is highly distorted because of the transformer saturation. Figure 28 (b) shows a typical current waveform of a transformer-rectifier power supply. The current pulses observed at peak voltage are caused by the downstream bridge rectifier, which is similar to the electronic loads without PFC connected to the rectifier (similar to the analysis for loads of Category NP). To summarize, a large phase angle displacement exists in this category and so do the high order current harmonics.



(a)

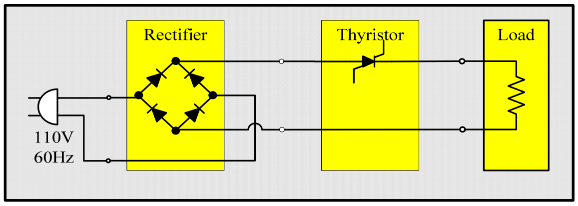


(b)

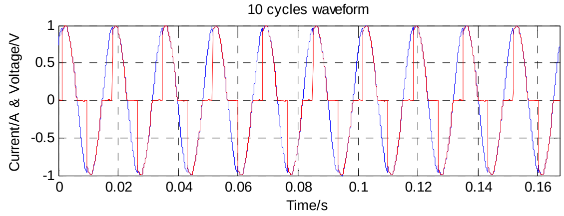
Figure 28: (a) The conceptual front-end circuit of linear power supply; (b) Normalized steady state voltage and current waveform of linear power supply.

Phase Angle Controllable Circuit Category (Category-PAC)

PAC controller is widely used for LED lightings, heaters, fans, and other appliances that require continuous voltage adjustment. Figure 29 (a) illustrates a typical PAC circuit. The load current can be adjusted continuously by controlling the firing angle of the thyristor. Figure 29 (b) shows a typical normalized current waveform of a PAC circuit.



(a)



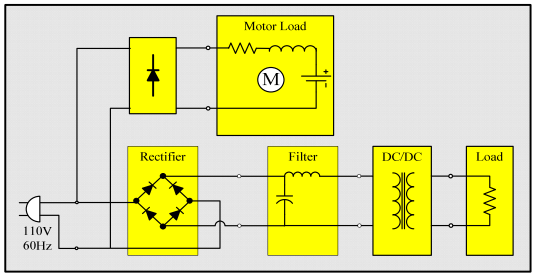
(b)

Figure 29: (a) The conceptual front-end circuit of PAC controllable load; (b) Normalized steady state voltage and current waveform of PAC controllable load.

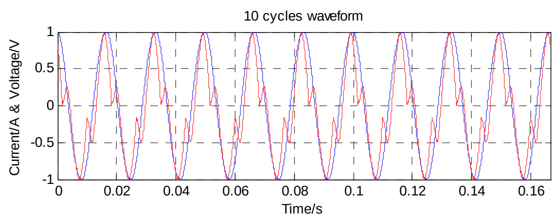
Complex Structure Category (Category M)

The appliances in Category M refer to those loads with multiple circuits supplied by independent front-end power supplies. Figure 30 (a) gives an example of a complex structure load, in this case a microwave oven. It is a combination of Category X and Category NP. Usually, there are two or more parallel power supplies at the load front-end. As a result, the load current appears to be composed currents from one or more of the above six categories. Figure 30 (b) shows a typical waveform of a microwave oven.

Different loads in Category M will have different waveforms since they are composed of different category structure. This diversity can be beneficial for the second level classification. At the same time, it increases the difficulty in extracting some common features in the first level classification. Besides, it is possible that the current waveform of loads in Category M is similar to the other six categories since some category's circuit structure may dominate the front-end topology. Some more sophisticated steady feature extraction methods are needed.



(a)



(b)

Figure 30: (a) The conceptual front-end circuit of complex structure load; (b) Normalized steady state voltage and current waveform of complex structure load.

In summary, the plug-in load study has resulted in a purely model-driven taxonomy of typical plug-in loads in buildings. This hierarchical taxonomy is depicted in Figure 31. The first level, i.e. Level-I shown, consists of seven load categories: resistive loads (R); reactive predominant loads (X); electronic loads with power factor correction circuit (P); electronic loads without power factor correction circuit (NP); linear power supply using transformer to boost voltage (T); phase angle controllable loads (PAC); and complex structures (M). The majority of Resistive Loads (R) are used for heating, cooking, and lighting. The representative loads include space heaters, coffeemakers, and incandescent lamps. For Reactive Loads, the appliances often consist of compressors, motors, or chillers. The motors commonly used for appliances are often small DC motors. The typical loads in this sub-category are fans, washers, refrigerators and shredders, etc.

The next two big groups of appliances are all electronic loads, denoted as categories P (Power Factor Correction) and NP (without Power Factor Correction). The typical electronic loads include personal computers, projectors, TVs/monitors, and small electronic devices, such as cellphone chargers, portable DVD players, and adaptors of portable printers, etc. Loads in Category T refer to those low power appliances that use linear DC power supplies with a small transformer at the front-end. Battery chargers, paper punchers and staplers are representative loads in this category. Devices such as light dimmers that use Thyristor phase angle voltage control are listed in the PAC category. Category M consists of appliances that often have high power consumptions, and multiple electrical systems. For instance, microwave ovens and laser printers are all classified into this category.

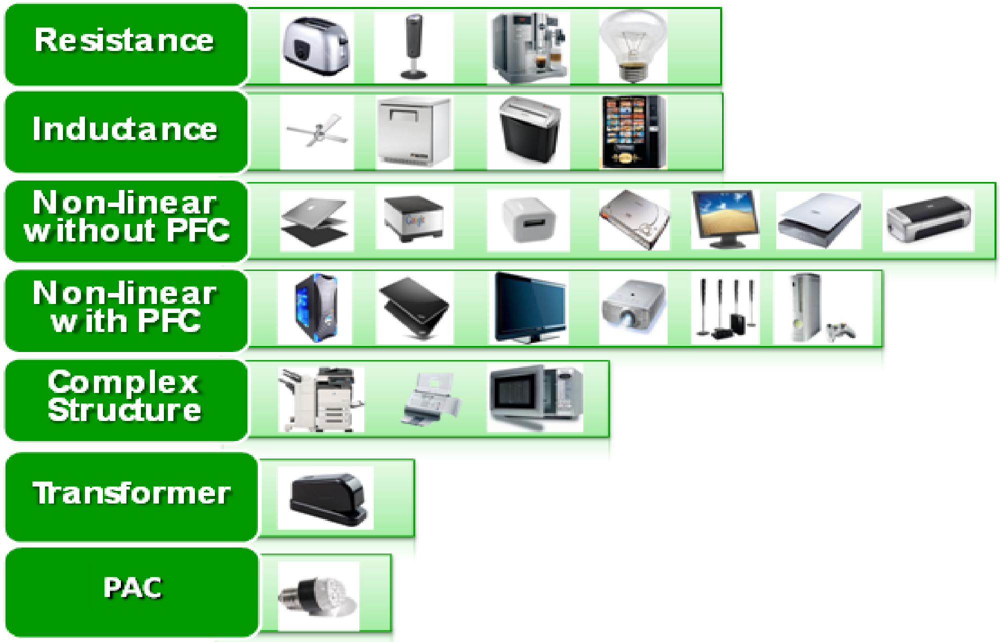


Figure 31: Hierarchical Taxonomy of Plug-in Loads.

3.3.3 Plug-in Load Data Collection and Database Construction

<u>Database Construction</u>

One of the main outcomes of the appliances research and modeling is to help construct a database for every load under study. Many papers have developed the taxonomy of plug-in loads that are typically found in commercial buildings, and have prioritized them based on their total contribution to building energy consumptions and energy saving potentials. This work uses the taxonomy suggested in [26] as the guideline to define the scope of appliances under study.

Table 9 and Table 10 show the database structure for two load types, a space heater and a portable printer, which are used merely as an example. The database describes every load type in five categories: 1) Load Type; 2) Brands (with top five market share); 3) operating characteristics; 4) Front-end Circuit Topologies; and 5) operating states. To date, a total of 42 load types, and 5 to 7 brands per type, have been selected and studied. To obtain a more generalized load space, several standards including 80 PLUS, Energy Star, CECAER, and IEC 61000-3-2 were considered in the selection process [27]. The constructed database covers over 90% of electric appliances used in commercial and residential buildings.

Through the progress of the project, numerous load current and voltage raw waveforms have also been collected to construct a plug-in load V/I waveforms database. The raw voltage and current (V/I) waveforms of all the load models selected have been collected under all the applicable operating states. This includes startup, steady, standby (or other low power states), and particular working states for some loads (e.g., printing states for printers).

Table 11 provides a summary of tested plug-in loads and applicable operating status. Each set of V/I waveform are sampled at 30.72 kHz sampling rate for at least one minute. A total of 627 sets of data have been recorded. A data-preprocessing-engine has been developed in MATLAB environment to process and analyze all the collected data, including V/I waveforms plot, V-I trajectory, FFT analysis, power factor, real power, reactive power, and apparent power calculation. The provides a user-friendly interface to access the database, as well as to display the signal analysis results, as shown in Figure 32. The plug-in load V/I waveforms database has been expanded continuously through the development process every time there was new test conducted. The waveforms in this database have been utilized to verify the updated algorithm performance through offline analysis.

Table 9: A Snapshot of Database Structure – Brands, Work Types, and Topologies

Load Type	Brands	Work Types	Power Supply Topology
Space heater	1.Holmes	1.Ceramic	1.Pure Resistive adjunction
	2.DeLonghi	2.Quartz	2.Inductive adjunction
	3.Honeywell	3.Oil filled	3.SCR controllable
	4.Lasko	4.Heater fan	
	5.Pelonis		
Portable Printer	1.Brother	1.Laser	1. Switch Power Supply without PFC with Front-End EMI
	2.Canon	2.Inkjet	
	3.Dell	3.All-in-one	
	4.Epson		
	5.HP		

Table 10: A Snapshot of Database Structure – Brands, Work Types, and Topologies – Load Operations States

Load Type	State	Work State	Data Description
Space heater	t.s	1.Startup	1.Start from Plugging actions
	s.s	2.Low Taps	2.Working Steady State
		3.High Taps	3.Working Steady State
		4.Fan	4.Working Steady State
		5.Standby	5.Switch closed without using
Portable Printer	s.s	1.Standby	1.Start from Plugging actions
		2.Energy Saving	2.On w/o thermal component
	t.s	3.Startup	3.On with thermal component
		4.Printing	4.Working Transient State
		5.Copying	5.Working Transient State
		6.Scanning	6.Working Transient State
		7.Doubleside	7.Only Printing State

Table 11: Tested Plug-in Loads and Operating Status

Load Types	Operating Status
Compact fluorescent lamps (CFL)	Steady
FLs	Steady
Incandescent lamps	Steady
TVs	Steady, standby, sleep
PC monitors	On, screen saving, local OFF
Cell phone chargers	Charging, fulled charged, disconnected
DVD players	Steady, standby
Set-top box	TV On, TV Off, not connected to TV
Microwaves	Heating, defrost, plugged in
Printers	Steady
heaters	Heat, Fan
fans	Steady
laptops	Active, charging, standby, energy saving
Laptop charger	Charging, disconnected
desktop CPU	CPU + Monitor ON, CPU ONmonitor OFF
projectors	Projection, no connection to PC
fax machines	Transmitting/receiving, standby
multifunctional equipment	copying, printing, scanning, energy saving,
camera battery chargers	charging, fully charged, no battery
hard drive adapters	Data transfer, standby, plugged
refrigeratorsr	Steady
electronic boards	page change, printing, standy
network camera	Active, standy
shredder	steady, standby
water dispenser	Heater ON, Cooler ON, Heater OFF + Cooler OFF
beverages vending machine	steady
coffee machine	Heater ON + Coffee, Heater OFF + Coffee
bread toaster	steady, standby
energy saving power strips	steady

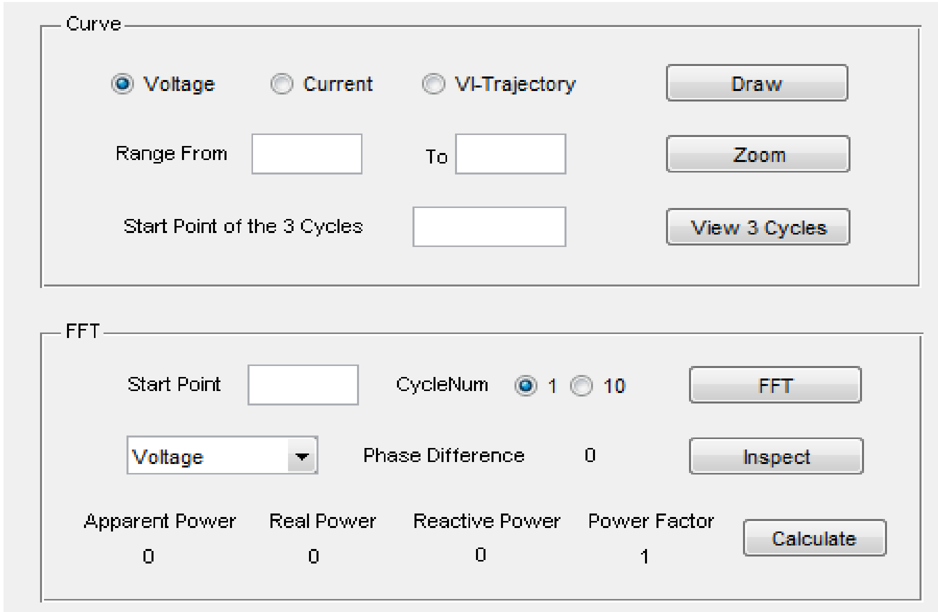
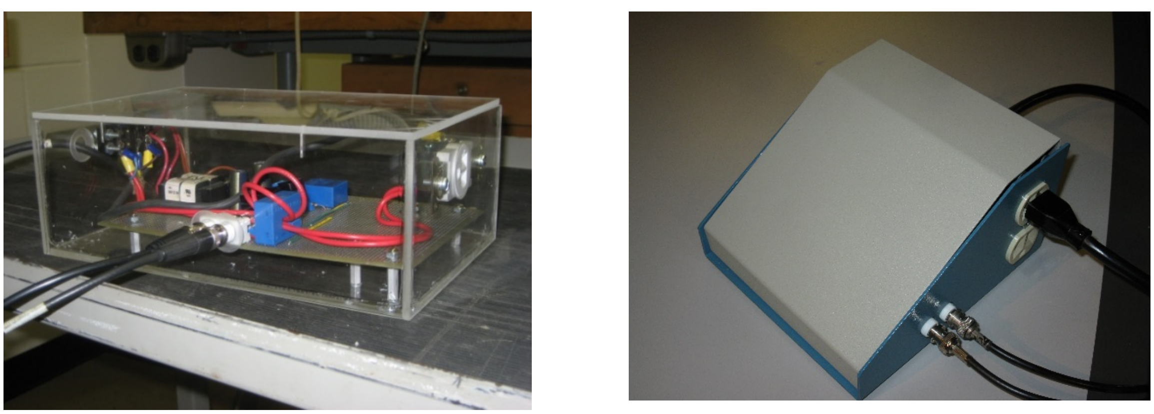


Figure 32: Plug-in Load Database User Interface

Plug-Load Voltage/Current Waveforms Data Collection

Prototype plug-load voltage and current (V/I) data acquisition (DAQ) modules have been developed and built both in Eaton and Georgia Institute of Technology during the first phase of the project. The DAQ modules shown in Figure 33 have been used to support the current and voltage waveform measurement of any single phase plug-in loads. These DAQ modules are self-powered, and portable. The output signals are regulated to +/-15V voltage signals that are compatible to most of the data-logging devices with BNC interface. It supports two outlet voltage levels, i.e. 120 V@ 60Hz and 230 V @50 Hz, and has been tested and used in Eaton facilities, and the Georgia Institute of Technology laboratory.



(a) (b)

Figure 33: Plug-load V/I Sensing Module: (a) GT DAQ Module; (b) Eaton DAQ Module

3.3.4 Nonintrusive Load Identification Algorithm Development

The major activities under the load identification algorithm development include,

- Defining a Plug-in Appliances taxonomy and identification target;
- Plug-in Appliances modeling and feature analysis/extraction;
- Hierarchical Load Identification algorithm development

Plug-in Load Appliances Taxonomy and Identification Target

There are numerous types of plug-in loads/appliances on market. The amount of various plug-in appliance types available on the market today can go up to 1000. It becomes technically challenging, almost a "mission impossible" to identify and distinguish all the plug-in appliances from one type to another. This triggers an important question to be answered, in particular, at the beginning of the project, i.e., what is a plug-in appliances taxonomy that drives a meaningful and valuable load identification development target. Answering this question becomes essential to help frame the technology development focus as well as to analyze and assess the technical feasibility during the course of the project.

Plug-in appliances can be categorized in many different ways depending on the motivation of a segmentation/categorization. The following list provides a few examples of how plug-in loads can be segmented, and the significance of such a segmentation.

- ID#1: By power consumption per unit.
    - For instance, plug-in appliances can be ranked by how much power is consumed by appliances of same type, e.g., PCs; Monitors; Task Lightings; Printers/scanners/MFDs; Other electronic loads, and so on.
    - Segmentation by power consumption can help users immediately recognize the largest energy hawks in buildings.

- ID#2: By load front-end topology, as presented in Section 3.3.2;
    - Segmentation by circuit topology can help define the technical feasibility for load identification algorithm development.

- ID#3: By load operation type or pattern;
    - For instance, plug-in appliances can have any of the following operation types,
        - Type-I: Plugged-in loads that are triggered to operation primarily by a power switch, and have relatively constant power consumption;
        - Type-II: Computer with continuous power fluctuation after it is powered to operation;
        - Type-III: Imaging equipment, a microwave, or any other loads that can be triggered to operation by a manual-button/action other than a power switch.
        - Type-IV: Refrigerator, or any other loads that can be switched ON/OFF automatically through a built-in sensor.
    - This segmentation can also help define the technical feasibility for load identification algorithm development, as well as standardize a test procedure to verify identification algorithm performance.

- ID#4: Banned Loads in building vs. Others.
    - For instance, some plug-in appliances, i.e., space heaters, are not allowed being used in a building.

- This segmentation helps facility managers to define and regulate building policies.

- ID#5: By controllability (Controllable Loads vs. Always-ON Loads).
  - For instance, some appliances, e.g., computers, require SOFT-SHUNDOWN stead of depriving power directly from outlets. Some networking devices need to be continuously ON. These Always-ON loads can also be referred as Critical Loads.
  - This segmentation is usually driven by safety and security concerns.

- ID#6: By operation modes.
  - For instance, any loads can be categorized by whether they are in an operating mode (or functioning modes), a standby mode, a sleep mode, or a parasitic mode.
  - This segmentation can help define utilization of assets in buildings, and/or identify demand response opportunities.

- ID#7: High Efficient Loads vs. Low Efficient Loads.
  - For instance, an incandescent lamp can be defined as low efficient lighting load, and a LED lamp is a high efficient light load.
  - This segmentation can help drive procurement decisions for lower consumption alternatives of appliances in buildings.

It is safe to say that the values drive different categorizations of plug-in loads, and consequently drive different load identification targets. Consolidating the outcomes from the market study presented in Section 3.2, as well as the results from plug-in load appliances topology and operating principle research, a Plug-in Appliances Taxonomy with Load ID target with prioritization has been established under this project, as shown in

Table 12. This developed hierarchical taxonomy is primarily driven by the value proposition developed from market study and the feasibility study from plug-in load research. It plays a very important role in the algorithm development, which has been used to frame up a model-driven, hierarchical load identification algorithm; to enable an optimized, simple load ID solution; and to drive the technology development focus through the project.

Table 12: Plug-in Appliances Taxonomy with Load ID target

Level 1 - Load Category	Level 2 - Load Sub-Category (Target Granularity)	Load ID Prioritization
R: Resistive Loads	PR1: Task lights (Incandenscent lamps)	H
	PR2: Space heater	H
	PR3: Other resistive loads: Coffee makers; tea pot, etc.	M
X: Reactive Loads	X1: Task lightings (FL lamps)	H
	X2: Refrigerator, water dispensor, etc	M
	X3: Microwave Oven	M
	X4: Personal Fans; Humidifier; others	
T: Nonlinear w/ TXM	T1: Small electronics (e.g. computer speakers; USB hubs; AA battery chargers;, etc)	M
P: Nonlinearw/ PFC	P1: PC (Desktop/Laptop) (>75W)	H
	P2: Big TVs/Monitors (LCD/LED/CRT) (>75 W)	H
	P3: Portable MFD/Scanner (>75 W)	H
	P4: Projectors; other office equipments	
NP: Nonlinear w/o PFC	nP1: PC (Desk/Laptop) (<75 W)	H
	nP2: PC Monitors; small TVs; CRT Monitors	H
	nP3: Portable MFD/Printer/Scanner (<75 W)	H
	nP4: Task Lightings (CFL/LED lamps)	H
	nP5: Oher small electronic devices: computer peripherals; chargers; adapters	M
PAC: Nonliear w/ Phase Angle Control	PAC1: Lighting or heater loads with Dimmer	H
M: Complex Structure	M2: Large Printer/Copier/Fax Machine/MFD	H
	M3: Co-located multiple loads on one outlet	H

<u>Load Identification Critical Performance Requirements</u>

Another key question during the load identification development is how to translate the value proposition and the Key Success Factors as discussed in Section 3.2 to a meaningful and measurable load identification performance metrics. The definition of these metrics is important to determine the development focus and target.

The technology development and its target has been driven by DFSS (Design for Six Sigma) methodologies. The load identification performance requirements are identified and quantified. The performance requirements flow down depicted in Figure 34 shows how the identification performance requirements are related to various value elements, and eventually drive the success factors in a system level.

It is noted that, sensitivity and precision of load identification form the core performance requirements, which can be different for different groups of loads to drive the different values of the developed technology. As a highlight, the criteria are summarized as below:

ID Sensitivity 85%~ 90% for all the Device Classes as defined in

- Table 12
- ID Precision > 90% for Critical loads and Operating Mode

The first performance requirement mainly drives to improve the visibility performance and saving performance of the plug-in load control and management solution; and the second performance requirement mainly drives to minimize or reduce the negative impact to users from the plug-in load control and management solution

Value = Max. Saving Potentials * Participation Rate (i.e., Compliance Rate)
- Productivity Loss (due to Nuisance Trips and Re-calibration)
- Maintenance Cost (due to commissioning and re-commissioning)

Value Elements	Description	Key CTQs
Boost Energy Savings Potential	Visibility to Energy consumption by load category Controllable loads are turned-off during after-hours; Prohibited loads are identified and flagged Offending devices are to replace or remove; Controllable loads are included into demand response.	**80%~90% of max. saving potentials** (→ ID Sensitivity > 85% for Level-2 Categories)
Increase Participation Rate (Compliance Rate)	Continuous user feedback and automatic verification that identified device categories are appropriately used and controlled	**90% accurate classification of load by Device_Dlasses** (→ ID Sensitivity > 90% for Level-2 Categories)
Reduce Nuisance Trip (Productivity)	Accurate determination of users' occupancy while turning-off loads; Minimize productivity loss to end-user through control algorithms tailored to workflow and device type	**Nuisance trip (turn-off) less than 5%** (→ ID Precision > 85% for Critical Loads and Operating Mode)
Reduce Maintenance	Reduces cost of (re)commissioning by automatically reporting on compliance with regard to use and control of identified device types	**Auto-verification of plug-in loads management policies compliance** (→ ID Sensitivity > 85% for Level-2 Categories)

Figure 34: Load Identification Performance Requirements and Flow Down

Feature/Signatures Extraction, Analysis and Optimization

Plug-in Appliances Feature Space Assessment and Challenge Discussion

With reference to literature that has been studied,

Table 13 lists the most commonly used and proposed features and signatures of plug-in appliances. The different load features/signatures in three areas have investigated, as follow.

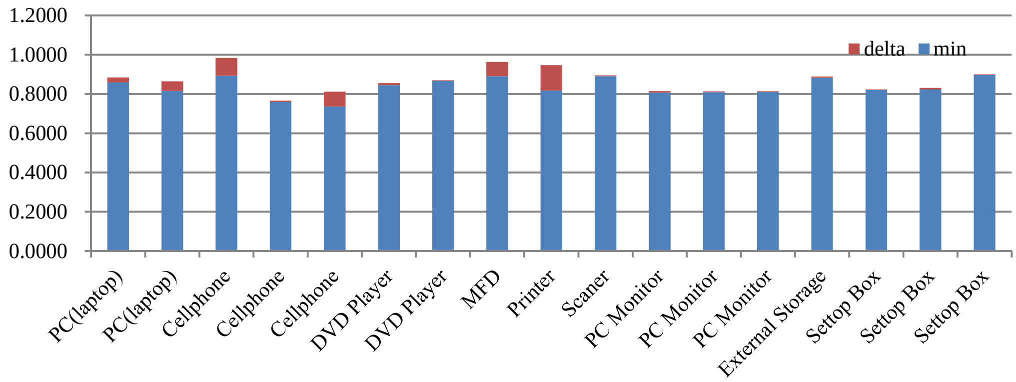
- Steady state current waveform and power quality related quantities
- The voltage-current trajectory graphical representation under start-up and steady-state conditions.
- Transient state characteristics of load current, including short-term harmonic contents, transient power contents, etc.
- Load event detection, operating status profile, operating modes patterns, etc.

Table 13: Extracted Features/Signatures of Tested PELs

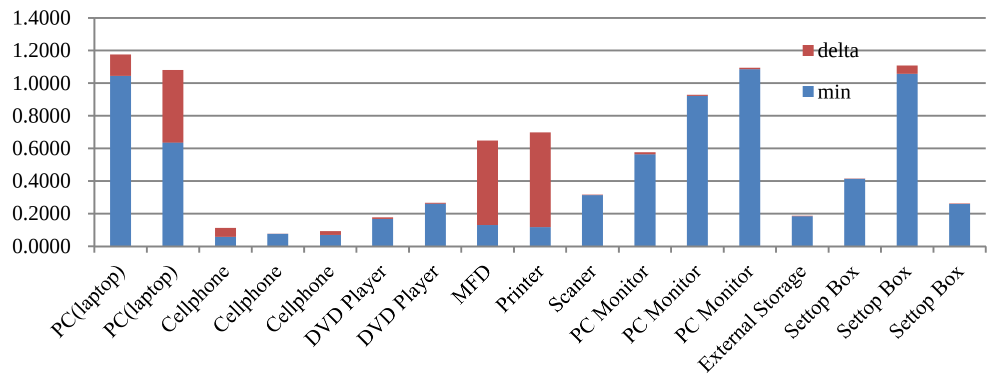
Steady State	V/I Trajectory	Transient State	Event Detection
Current/Voltage RMS values;	Area;	Transient Peak;	Load ON/OFF
Active/Reactive power;	Eccentricity;	Rise time, Peak time;	Operating status changes
Current Crest factor;	Thinness Ratio;	Damping ratio;	
Total Harmonic Distortion (THD);	Slope and length of middle segment;	Settling time;	
K-factor;	Polynomial Coefficients	Transient Peak ratio;	
Power factor:		Transient Power	
True PF;			
Distortion PF;			
Harmonics: 3rd, 5th, 7th, …			
Normalized admittance			

Traditional steady-state features are often one-cycle feature, i.e. the features can be extracted from a one-cycle waveform. The usual feature metric contains RMS current value, average displacement power factor, average total harmonic distortion of current, average power factor, and third and fifth harmonics of the current waveform. A feature range analysis based on the data in Appendix A is conducted and a typical invalid feature and typical valid feature are presented respectively in Figure 35. A range analysis intuitively proves the validity and invalidity of the features in original feature space. Figure 35 (a) illustrates that all the loads in this category have the same value of the third harmonics current, moreover the derivation of the third harmonics current is also small. Therefore the third harmonics current feature has limited value. Figure 35 (b) illustrates that the working power is greatly different for various kinds of loads. For laptops and printers, the derivation of the RMS is corresponding to the working characters and circuit principles of these two types of loads stated in Section III. Based on this analysis, an optimized feature space is proposed, shown in Table 14.

For the load sub-categories/types in the Level-II, the transient information, such as startup or special working states, are the major potential features to be utilized. Figure 36 gives an example of representative start-up profiles for three different load types, i.e. personal computers, monitors, and printers. Besides, every Level-I category needs to have its individual set of features, so that the feature selection for each category has its own focus of interests when considering the physical characters within that category. This process potentially drives an optimized and simple feature selection for the entire load space.



(a)



(b)

Figure 35: (a) The range of 3rd harmonic normalized current waveforms; (b) The range of RMS of the current waveforms

Table 14: A List of OFFICE Electronic Loads and the Optimized Original Features

Name of Loads	Power	Deriviation of Power
PC (Laptop) (<75 W)	> 45W	Medium
Cellphone Charger	< 10W	Small
DVD Player	< 20W	Small
Set Top Box	> 30W	Small
MFD/Printer/Scanner	> 45W	Large
PC Monitor	> 45W	Small
Hard Drive	< 15W	Small

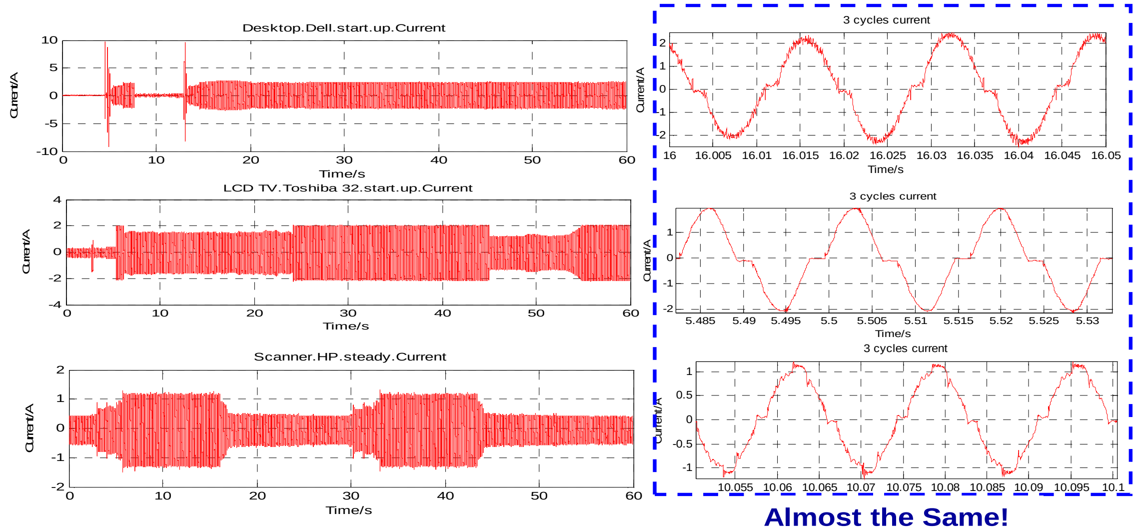


Figure 36: Startup Profiles of Typical Electronic Loads

<u>Plug-in Appliances Feature Analysis and Optimization</u>

The feature analysis and optimization process has been a continuous effort during the entire technology development cycle. The process is usually triggered by new failure cases being identified.

The steady-state features that are commonly used for NILM can be classified into three groups, i.e., time-domain features, frequency-domain features, and V-I trajectory graphical features. Typically, the dimension of these three feature spaces in literatures is often on a scale of 10 to 15 to ensure a satisfactory result [18] [19] [20]. There is no guideline to drive an optimized feature selection. For example, the most commonly used frequency-domain features include the first 10 to 15 harmonics and the phase angle displacements between voltage and the third and fifth order current harmonics. Even though all the above features are utilized, it is still difficult to distinguish and identify loads with the granularity as defined in Level II (depicted in Table III). Therefore, a multilevel classification structure us used to drive the feature set selection. The proposed structure divides a complex problem into several simple problems. Moreover, as the development of the structure is supported by a complete power supply market study, it drives a more generalized solution, and is easy to extend.

When the NILM problem is divided into a multilevel classification problem, the feature space can be analyzed in two steps as given in Section II. If only the Level-I categories are considered in the first step, all the loads present very distinct characteristics from one category to another. A set of three features in frequency domain, i.e., normalized fifth order current harmonic component, fundamental phase angle displacement and the total RMS high frequency content, has proved, as shown in

Table 15. It is much simpler than the original feature space without sacrificing identification performance in this level.

Table 15: Feature Forms of Frequency Analysis

Category [n]	$5^{th}/1^{st}$ [%]	High Frequency [0/1]	Phase Angle [º]
1	0	0	0
2	0	0	[45,90]
3	[60,100]	1	[0,10]
4	[0,10]	0	[0,10]
5	[10,60]	0	[45,90]
6	[10,60]	1	[10,35]
7	[10,60]	1	x

For the second level of classification, the problem becomes more complicated for the following reasons. First of all, using steady state features alone cannot completely distinguish the loads in the Level II. Secondly, every Level II category needs to have its own individual set of features. Therefore, the feature selection for each category has its own focus due to the physical characteristics of the devices within that category. This process can result in an optimized and simple feature selection for the entire load space. The NP category (DC converter without PFC) is taken as an example to elaborate the challenges as well as the opportunities.

In previous research, the corresponding identification performance and effectiveness for loads with similar electronic front-ends (i.e., the Level-II sub-categories/loads in the same Level-I category in

Table 12, e.g., NP-category loads) have often been overlooked. It has been recognized that most of the steady state features currently used cannot further drive a meaningful load identification solution with Level-II granularity no matter how sophisticated the algorithms. Consider the NP-category. The main circuit structure of all the NP loads are almost the same with only limited differences caused by the component selection when the DC/DC converters and voltage/current regulators are designed. Even though the topologies of voltage or current regulators are different from one load to another, relatively small changes have been observed in those features that are commonly adopted in the literature. This is because the features were not selected to address the important subtle differences.

Taking the three types of filter topologies utilized in NP-category loads as an example, there are small but explicit differences between the three current waveforms as a result of a circuit discrepancy, as shown in Figure 24. These small differences are difficult to distinguish using FFT analysis or V-I features. A set of Level II features that are specifically selected and applied to distinguish between the above variations for NP loads is desired. Note that, even though this set of features may not be applicable to classify loads in other categories, it is optimized for this NP load space. Combining Level II features with the first three frequency-domain features, results in a feature vector based on a multilevel structure that is simpler and more efficient.

While only the NP-category was used as an example, the transient information, such as startup or special working states, are the major potential features which can be utilized in all of Level II.

The main objective of feature extraction and optimization under this project is to select a hierarchical, high-dimensional load feature space. Through the course of the project, there are about 500 plug-in appliances that have been tested, and investigated via analyzing the collected PELs V/I waveforms.

The major activities include,

- Feature extractions for all the appliances that have been tested.
- The features investigated include all the features that have been learned in the literatures.
- Conduct the Principle Component Analysis (PCA) to investigate the independence and correlation between any of the features. Keep the features that show the most statistical independence, and remove the features with the most correlations to the independent features.
- Conduct the Distance Matrix analysis to further optimize the selected features.
- Conduct a preliminary distinction performance analysis to test on the failure and successful cases for all the loads tested.
- Extract the failure cases and setup these failure cases as the next round feature analysis focus.
- Investigate and develop new features that can address the previously identified failure cases.
- Cycle the process back to step two for the Principle Component Analysis to (re-)select and (re-) optimize the feature space.

Because the hierarchical identification approach is adopted for the technology development, the feature analysis and optimization has been conducted also in a hierarchical fashion.

One of the most important advantages of topology research in a classification problem is to reduce the complexity of the feature space. Another contribution of topology research is to extract new features and furthermore to distinguish the loads sharing the same circuit structure or even the same circuit topology. The feature selection based on the topology research establishes a meaningful and generalized connection between the load signatures and its front-end circuit. Therefore, when the loads are discussed in this paper, new time domain waveform features are proposed and have preliminarily proved to be useful to differentiate the above variations.

- This hierarchical structure for feature analysis and optimization can be scaled and updated individually.
- The optimization process can be conducted independently without relying on other part of the system.
- This ensures an optimized performance locally for each of the levels and categories with interests.

Hierarchical Load Classification and Identification Algorithm Development

Once the optimized feature set is selected, the next has activity focused on the classification and identification algorithm development.

Classification Algorithm Evaluation and Selection

An optimized feature space helps to establish a foundation. Meanwhile, a high-dimensional classifier is essential to ensure a desired performance of the load classification and identification.

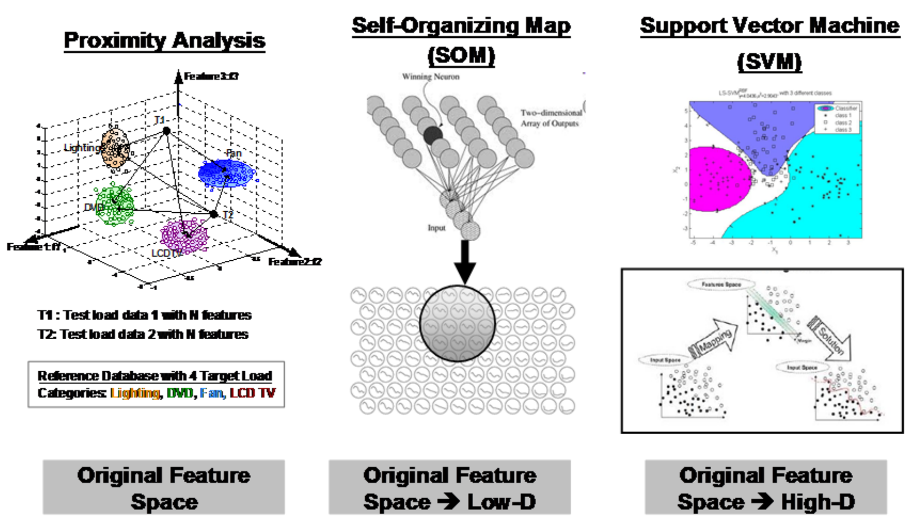
With the load models and load signatures developed and identified from previous subtasks, several intelligent load identification and classification algorithms have also been investigated to automatically identify the type of loads being plugged in as the initial load ID algorithm development effort during Phase I. To date, three load identification algorithms have been initially investigated and developed: Proximity Analysis; Self-organizing Map (SOM); and Support Vector Machines (SVM), as depicted in Figure 37. The comparison of the three developed load ID methods is summarized in

Table 16.

Proximity Analysis is a load classification/identification approach, where the likelihood of the test load is evaluated by the distance (Euclidean, Canberra etc.) for selected set of signatures between the reference load types in a Load Feature Reference Database and test loads.

Self-Organizing Map (SOM) is a computational method for the low-dimensional (2 or 3-D) visualization and analysis of high-dimensional data. As an unsupervised, competitive neural network, SOM implements the winner-take-all function for self-clustering, and uses a neighborhood function to preserve the topological properties of the input space. The implementation of SOM enables an optimized Load Feature Reference Database. It provides a convenient 2-D or 3-D representation of load feature database, and allows the fast and simple real-time implementation of load classification/identification.

Support Vector Machine (SVM) uses kernel functions to perform separations with complex boundaries, and performs classification by constructing a high dimensional hyper plane that optimally separates data into categories. The main advantage of SVM is to transform data from low dimension to high dimension as separation becomes easier in higher dimensions, which, however, increases the computational burden.



(a) (b) (c)

Figure 37: Developed load identification algorithms: (a) Proximity analysis; (b) Self-Organizing Map; (c) Support Vector Machine.

Table 16: Comparison of Load ID Methods

	Proximity Method	Self Organizing Map (SOM)	Support Vector Machine (SVM)
Pros	1.Direct raw data analysis 2.Provides "Confidence level" criteria	1.High to low dimension (2 or 3). ➔ faster execution speed for online identification 2.Self-clustering/organizing feature similarity; 3."Other" unrecognized types automatically defined 4.Easy to visualize and interpret the results	1.Uses kernel functions to perform separation with complex boundaries
Cons	1.computation time also increase, as number of loads increases	1.Clusters of same type will get split. 2.Existing distance metric not good enough to construct an effective classifier 3.No confidence level criteria	1.Supervised training ➔ predetermined number of clusters; 2.Limitation on speed and size in both training and testing 3.High dimensional space ➔ increased memory for reference database 4.No confidence level criteria

At the beginning of the project, the performance of the developed load ID algorithms has been initially tested for 14 loads, and initial results show the successful identification rate is approximately above 90%. Table 17 summarizes the testing results by load types and algorithms.

Table 17: Comparison of Results: Percentage of Successful Identification

Tested MELs	Proximity Method		SOM	SVM
	Squared Euclidean	Canberra		
	(%)	(%)	(%)	(%)
CFL	100.00	100.00	98.25	100.00
FL	99.57	100.00	95.65	100.00
Incandescent	100.00	100.00	100.00	100.00
Fan	99.48	100.00	100.00	100.00
PCMonitor	98.33	98.33	100.00	100.00
Printer	98.94	99.47	86.81	99.47
CellPhoneCharger	99.52	100.00	91.35	99.04
DVDPlayer	98.66	99.67	74.25	89.63
Heater	98.32	100.00	100.00	100.00
LCDTV	100.00	100.00	100.00	97.49
LEDTV	100.00	100.00	100.00	100.00
Microwave	99.83	100.00	99.13	88.58
PlasmaTV	95.76	100.00	95.76	93.22
SetTopBox	97.64	100.00	100.00	100.00

The main focus and intention for this stage of the development is to assess the performance difference of various approaches above, and evaluate the potential computation burdens that are needed accordingly. As one of the major goals in this project is to demonstrate the feasibility of the developed technology in a cost-effective, embedded environment, one of the algorithm focuses is to have a better understanding on the potential computation requirements.

Through the analysis and comparison among the various classification methods investigated above, the Self-Organizing Map and Bayesian Classifier stands out by considering the resultant performance, complexity of the algorithm and requirements for memory space.

<u>Hierarchical Load ID Classification Development</u>

A hierarchical load ID structure has been established to help define the load categorization by different levels of granularity, and also used as guidance for feature selections. This structure helps divide a complex problem into several simple problems. Moreover, as the development of the structure is supported by a complete power supply market study, it drives a more generalized solution, and is easy to extend. Figure 38 depicts a flow diagram of the developed hierarchical load identification algorithm.

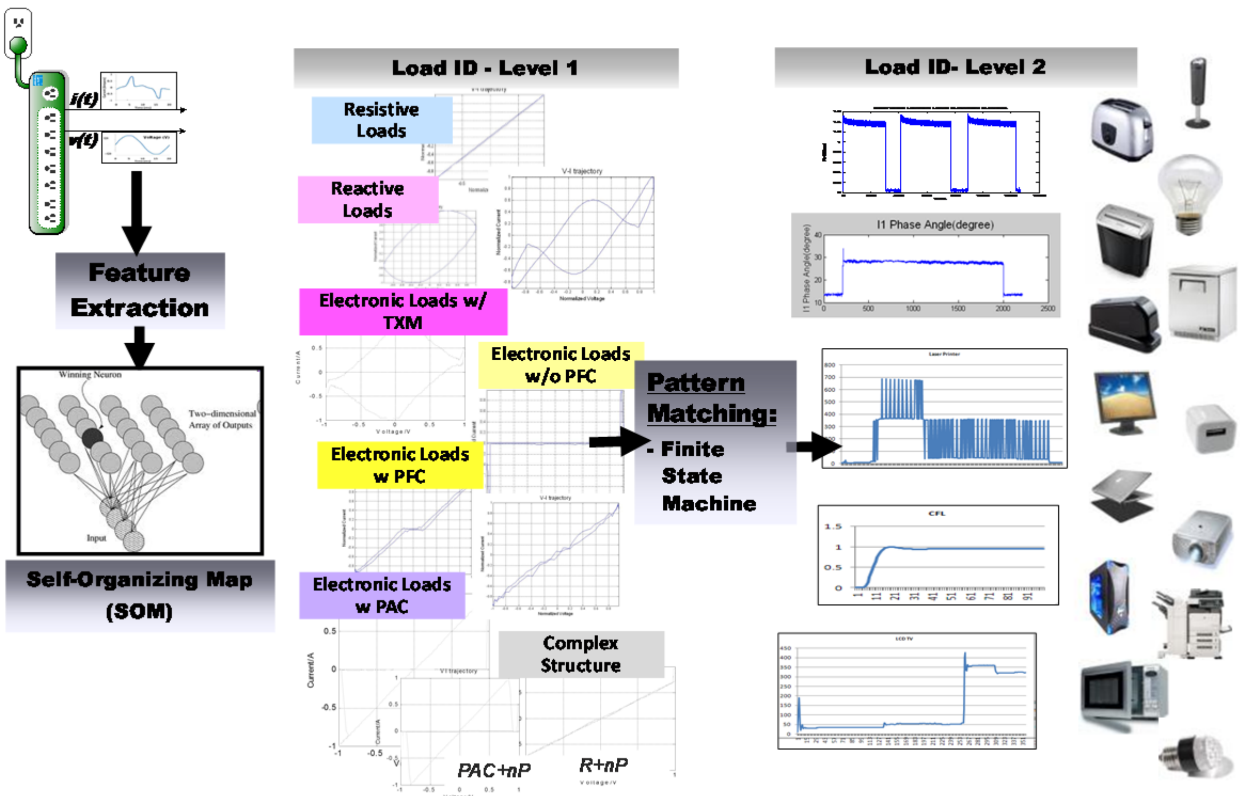


Figure 38: Hierarchical Load Identification.

Level-1 Load Category Identification and Validation Results

A simple set of steady state graphical features has been extracted and analyzed for the Level-1 identification. This level of load category identification requires very low sampling rate, i.e., 1.92 kHz, of data, but still remains the satisfactory performance of categorization. The computational requirements for the proposed algorithm have also been analyzed with a comparison to the traditional approaches based on time-domain and frequency-domain features. The analysis demonstrates a great computational advance with the computational burden reduced by half, and memory space requirement reduced almost by 90%.

Level-2 Load Sub-category/Type Identification and Validation Results

For the second level classification, the problem becomes more complicated. Only steady state features can hardly distinguish all the loads in the Level II granularity, particularly for the loads with standard DC power supply as the front-end (e.g., NP- and/or P-category loads as depicted in

Table 12**).** The front-end circuit topology analysis presented above shows that the main circuit structures of all the electronic loads (P/NP-category loads) are almost the same with very limited differences caused by the component selection when the DC/DC converters and voltage/current regulators are designed. Even though the topologies of voltage or current regulators are different from one load to another, the changes that have been observed in those features that are commonly adopted in literatures are relatively small. Besides, the selection of the front-end topologies is not necessarily associated to the load types themselves.

Several time-series classification techniques have been investigated for Level-2 load sub-category identification based on load start up profiles. The start-up profiles have also been modeled by a concept of state machines, where four element patterns have defined the long-term load behaviors.

The classification for electronic appliances (i.e. P- and NP-category loads) present the most challenge when the higher granularity identification is required. This is mainly caused by the highly diversified start up behaviors of electronic appliances, such as printers, multi-functional devices, personal computers, etc. The optimized reference profiles have been selected for the P- and NP-category load space. The major failure cases are being evaluated by investigating additional profile-related features. The initial analysis results show that more than 80% of accuracy can be achieved for major electronic appliances, including TVs, monitors, projectors, printers, fluorescent lamps and desktop computers.

<u>Important Practical Issues Handlings for Real-time Implementation of Load ID</u>

There are a few important practical issues that have been learned through the literature survey and the algorithm development process, whose importance was not recognized and understood initially at the beginning of the project. These two issues are directly related to the actual users' behavior, and consequently, to the effectiveness of real-time implementation of the developed load identification algorithm.

Plug-in Load Appliances Mode Detection and Validation Results

As one of the major tasks for load ID algorithm development, a reliable detection and identification for actual operating status of the plugged-in devices also brings a lot of development interests and challenge.

In the context of plug-in appliances, the definition of the operating status is as follows:

- M1 Load Operating Mode
- M2 Load Low Power Mode (Standby, hibernating, or energy-savings)
- M3 Parasitic Mode (when the load is locally switched-OFF, but still connected to mains and still consuming small powers)
- M4 No load plugged on PS-Outlet
- M0 PS-Outlet Switched-OFF Mode
- M00 Entire Power Strip Plugged-Off or Switched-OFF

The significance of an effective detection and distinct of the above various operating status lie into the following several aspects:

- It provides customers the visibility of the load energy/power usage by Operating Modes. In a networked plug-in load system, this information is particularly important to provide the aggregate energy/power consumption with a differentiation/segmentation between the energy that is really in use; and the energy that is consumed but really neglected by users, e.g., parasitic/vampire mode. This information provides a direct visibility to the potential saving opportunities to customers.

- It provides important prerequisite information for a reliable Event Detection (presented in the sub-section as follows), and consequently to enable the load ID algorithm at the right moment for the real-time implementation.
- A reliable Operating Mode detection also ensures reliable control (or a safe turn-OFF) of plug-in loads, in particular, the critical loads, with minimized potential damage to the devices and negative impacts to users. In another words, it helps to minimize the unnecessary nuisance trip when the plugged-in loads, especially critical loads, are to be turned-off.

Via traditional approach, operating status is justified simply by a power threshold. For instance, when the power level is larger than a threshold, say 5W, the plugged-in load is said being in an Operation status; when the power level is less than this threshold, the load is said being a non-operating mode. The major issue for this approach is that using only this condition as criteria overlooks the potential difference among various plug-in appliances (refer to NREL report, over 1000 types of plug-in appliances available on market.). For instance, a lot of large electronic devices, e.g., big TV screens, or computers, on market usually draws power up to 15 watts at their parasitic mode. On the other hand, a lot of small electronic loads only draw around 8~9 watts even when they are in the real operating mode. This overly simplified condition has proved to be not sufficient enough to justify the actual operating status of a load. This has also been observed as one of the main reasons that cause the nuisance tripping from the Load-sensing based Advanced Power Strips available on the market.

Under this project, a more effective Operating Mode Detection algorithm has been developed to address the issues discussed above.

Plug-in Load Appliances Event Detection Significance

Event detection is very critical in addressing the uncertainties and varieties caused particularly by the various users' behaviors.

The Event Detection intents being designed to detect the moment when a plug-in appliance is put in use, i.e., a plugged-in appliance is drawing power for the actual operation. For instance, a PC is powered ON for booting up; a Monitor is given power for displaying; a space heater is switched ON to generating heat, etc.

By definition, a plug-in appliance in use is different from when it is simply given power but as in a standby mode, or a parasitic mode.

The significance of a reliable Event Detection is that the moment defined by a detected "Event" helps frame up the right moment to enable the Load ID algorithm. As part of the developed algorithm and extracted features rely on the startup profile of a plugged-in device. The moment or duration when the corresponding profile is utilized is crucial to ensure a trustful and reliable load identification.

The potential complication involving in Event Detection is that many plug-in appliances have large power fluctuation during the actual operating status. This unexpected power fluctuation may trigger the unnecessary "Events", and consequently, the unnecessary implementation of

Load ID process. These unnecessarily triggered Load ID processes may potentially provide the incorrect Load ID results, as the captured power profile does not necessarily contain the representative signatures as in its startup profile.

Examples of various actual use scenarios that may trigger events include,

- A load is plugged into the outlet with an actual operating started;
- A load is plugged into the outlet settled to parasitic mode;
- A load is switched ON to a standby mode;
- A load is switched ON to an actual operating mode;
- A load is later (i.e., after powered up) triggered to an operating mode by a user;
- A load is later (i.e., after powered up) triggered to an operating mode by an internal sensor.

Note that only some of the above use scenarios intend to trigger a Logical Event, and consequently, enable the Load ID process. How to differentiate the above scenarios for a reliable Event Detection, and how to mitigate the impact to the algorithm performance if an unintended event is detected, has been included as one major research and development effort. The importance and challenge has not been recognized at the very beginning of the project, but only being established through the firmware implementation and verification by when developing SPS Gen-1 prototype to ensure the reliability of the developed technology.

This can also be treated as one of major outcomes under the project development.

Unknown and/or Uncertain Results Handling

As any type of identification and classification problem, the result shall be justified with a certain confidence level as soft decision.

For the results with very low confidence level, the resultant ID shall be retained at the level where the confidence is fairly high. For instance, if a tested PC monitor cannot present a level 2 result with reasonably high confidence level, (e.g., >50%) then the result would only show the tested load as an undefined electronic load. This result is not able to specify the ID down to the device type level, but it still presents that the load is an electronic load, instead of a resistive load or a reactive load. For some use cases or applications, even this level of load identification information has proved to be useful, particularly, from improving visibility perspective.

This type of progressive display of load identification result has been considered as a feasible and meaningful load identification approach, particularly when handling some unknown or uncertain situation. The identification result only convey to a point/level where the information is available and certain.

3.3.5 Laboratory Load ID Demonstration Platform

To facilitate the load ID algorithm testing and validation in real-time at an early stage of the project, a PC-based load identification demonstration platform based on National Instrument LabView VI program has been set up at Eaton labs in Milwaukee, USA and Pune, India. As the very first Load ID development and demonstration platform, it is also known as SPS Prototype Gen-0.

The major goal of SPS Prototype GEN-0 is to enable a Quick Load ID algorithm development in MATLAB and validation in a semi-real-time environment. The system diagram is depicted in Figure 39 below. The GEN-0 platform consists of

- Data acquisition module, with power supply, V/I sensing and signal conditional circuitry;
- NI LabVIEW H/W Interface Modules;
- PC with LabVIEW S/W Development System.

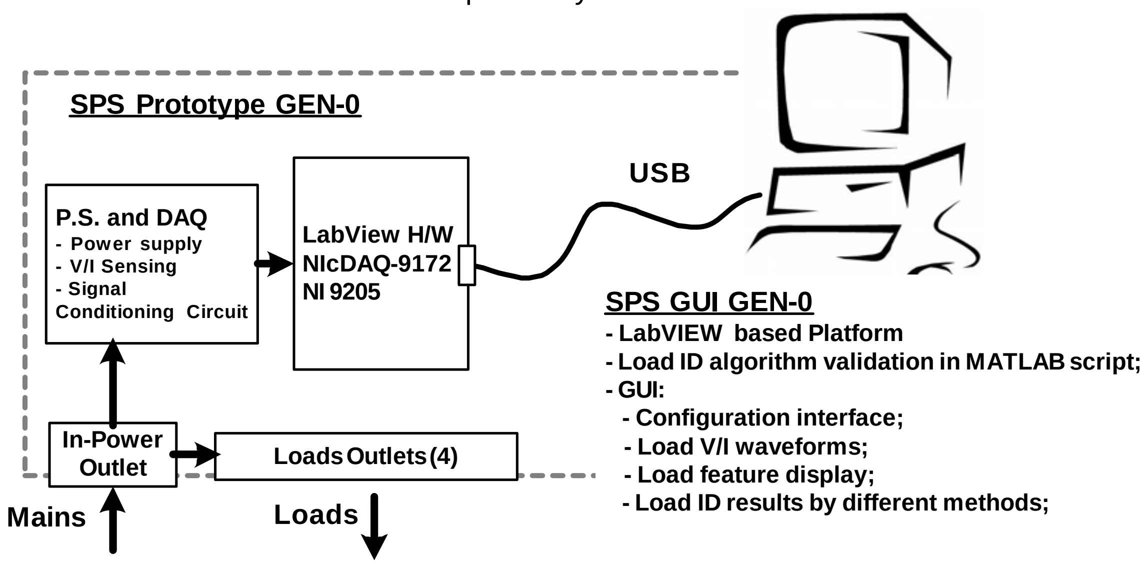
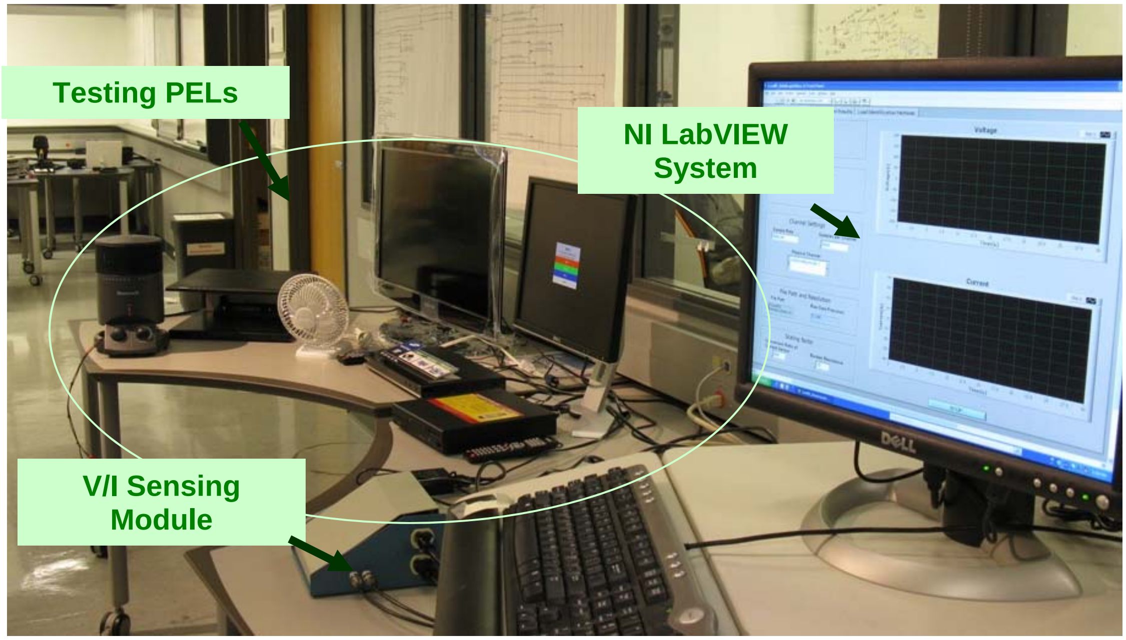


Figure 39: System Diagram of SPS Gen-0 Prototype

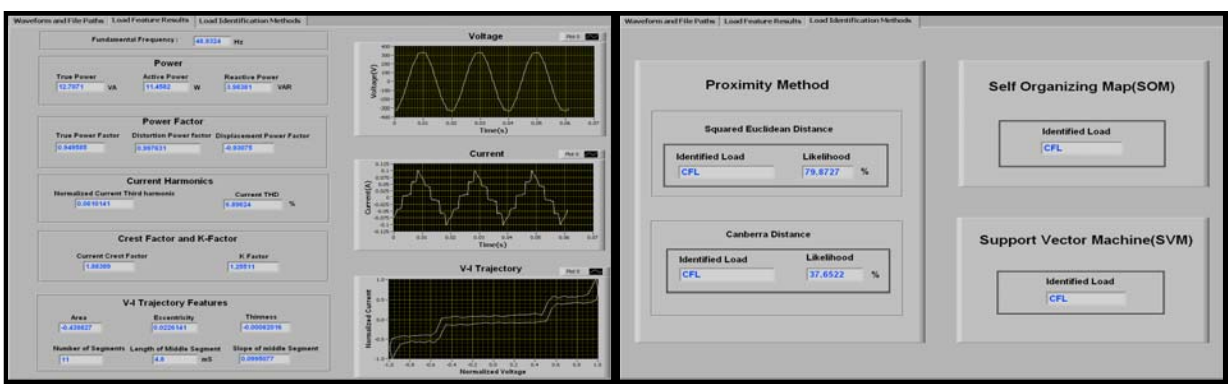
The DAQ system is used to connect the V/I sensing module (as introduced in the previous section) to a host PC where the LabView VI software program has been developed to log the load waveforms measured from the DAQ system for further signal analysis, to validate real-time identification performance, and to display results. The laboratory plug-load V/I DAQ platform is shown in Figure 40, with two snap-shots of the developed LabVIEW VI user interface.

This platform has been to support Load ID algorithm development throughout the whole program, to validate real-time identification performance in lab environment.



(a)

(b)



(c)

Figure 40: (a) Load ID Demonstration Platform Laboratory setup in Eaton; (b) NI cDAQ-9172; (c) LabVIEW VI User Interface

3.4 Smart Power Strip/Receptacle Prototype Development

The development of Smart Power Strip prototype is essential to demonstrate the feasibility of the developed technology in a cost-effective, embedded environment, as well as to demonstrate and verify the value proposition of the proposed Smart Power Strip concept.

With reference of the identified Key Success Factors as discussed in Section 3, the prototype development has been targeted to fulfil and implement those feature requirements, including, Automatic load identification, outlet (i.e., device level) monitoring, Adaptive Control, and Self-configuration.

The major activities under this task include,

- Established a Smart Power Strip prototype development road map;
- Smart Power Strip Gen-1 design and development;
- Smart Power Strip Gen-2, also called as Smart Receptacle, design and development;
- Smart Receptacles (SRs) Network + Remote Energy Management System (REMS) development.

3.4.1 Smart Power Strip prototype development road mapping

A multi-generational prototype development roadmap has been established to facilitate the requirements and development focuses at different phases of the project. Consolidating the outcomes from the business value proposition and development effort, the team has conducted a product concept generation session during the second phase of the project by characterizing the Key Success Factors for the targeted Smart Power Strip concept. The main requirements include,

- Monitor and report load use status, including load types, operating mode, and power consumption/quality, etc., of plugged loads at outlet level;
- Turn ON/OFF controllable outlets manually and/or automatically;
- Support wireless communication to a remote device;
- Provide user interface to allow outlet control configurations as needed.

Additional requirements are also included to facilitate development, testing and debugging purposes including:

- Have direct access to internal parameters of the SPS prototype through a remote device with refresh rate of at least every one second;
- Have means to log current/voltage waveforms, load identification results, and other algorithm related information of plugged loads for performance assessment and post-analysis.

Three generations of the SPS prototype have been developed through the project development process. Table 18 below highlights the goals, requirements, and expected outcomes of each prototype generation, as well as the time frame.

Table 18: SPS Multi-Generational Prototype Requirements and Expected Outcomes

Gen-1: Smart Power Strip Box	Gen-2: Smart Receptacle	Gen-3: SRs Network + REMS
Goals		
Embededed system implementation and validation of Load ID algorithm	**Validation of Load ID aglorithm with larger load set in a real building environment**	**Plug-in load control and management platform to demonstrate Load ID values in a**
Fundamental Load ID real-time validation in an embedded system platform, mainly for engineering debugging/ performance/ demonstration	Extended l Load ID real-time validation in an embedded system platform, mainly for engineering debugging/demonstration/field	Web-server based user interface, known as Remote Energy Management System (REMS), to support remote access of multiple SR devices in the network
PC user interface (hard-wired) to visualize the functionality as defined in functional requirements	Web-server based user interface to support remote access of individual SR devices	
Functional Requirements		
Identify loads that are plugged into outlets	Identify loads that are plugged into outlets	Automatically discover multiple SR devices in the network
Report Load ID, Operating Mode, power consumption with power quality associated	Report Load ID, Operating Mode, power consumption with power quality associated	Aggregate and report power usage of plugged in loads in the work broken-down by Device Classes,
Control individual load manually	Control individual load	Allow users to configure policies
Accuracy of load identification for critical loads to 80%	Report load use compliance status	
	Data logger to retrieve field data	
Expected Outcomes		
MATLAB code ported to DSP	Integrated SR electronic board	Functioning SRs Network + REMS that meet above requirements
Software Kernel well defined	Standalone/portable SR	
Well understood Load ID computation requirements	Well understood Load ID computation requirements	
Demonstrate SPS Gen-1 to meet above requirements	Demonstrate SR to meet above requirements	

3.4.2 Smart Power Strip Gen-1 Prototype Development

To facilitate an embedded system implementation and validation of the developed load identification algorithm, the Smart Power Strip Gen-1 prototype was developed and set up in both the electronic labs at Eaton facility in Milwaukee, USA and Pune, India.

The major goal of SPS Gen-1 prototype is to implement and validate fundamental Load ID functions and performance in an embedded system platform, mainly for engineering debugging/ performance/ demonstration purpose. The system diagram is depicted in Figure 41 below. The Gen-1 platform consists of,

- Data acquisition module, with power supply, V/I sensing and signal conditional circuitry;
- DPS Evaluation Board (off-shelf);
- 6 outlets + current sensor and relay/switch circuitry per outlet;
- A serial communication interface to a Host PC;

- Host PC with a simple GEN-1 user-interface, mainly to provide GEN-1 function visualization, interfaces to display real-time load use status, including load ID results, status, and power consumption, etc., as well as to manually control individual outlet as needed.

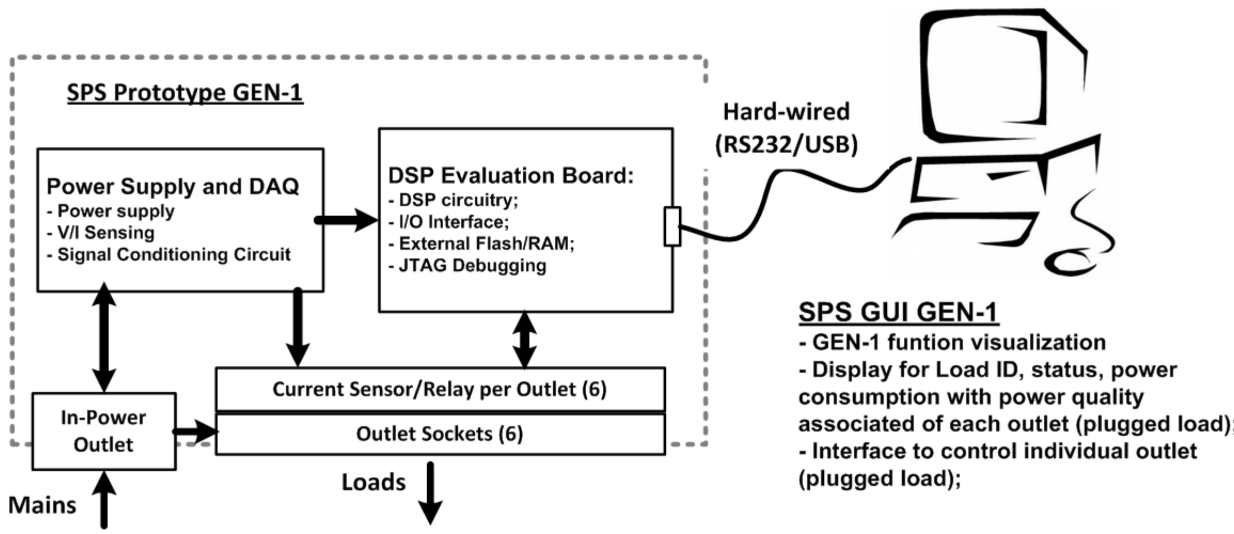
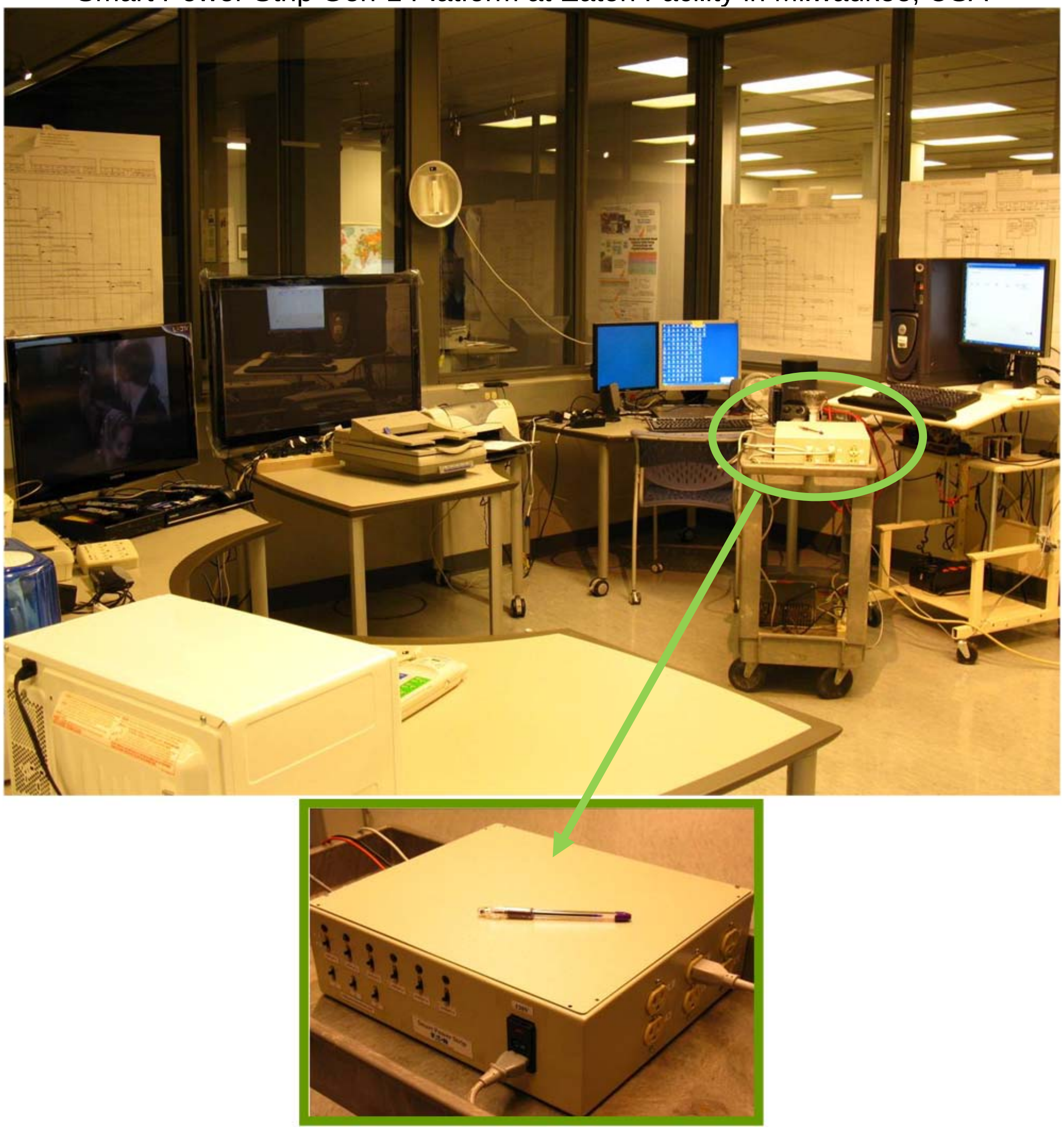


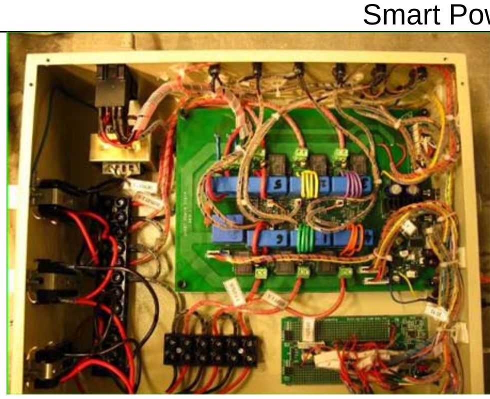
Figure 41: System Diagram of SPS Gen-1 Prototype

Figure 42 shows the laboratory set up in Eaton facility’s electronics lab. Two snap-shots of the SPS GUI Gen-1 are presented in Figure 43.

Smart Power Strip Gen-1 Platform at Eaton Facility in Milwaukee, USA



Smart Power Strip Gen-1 Prototype

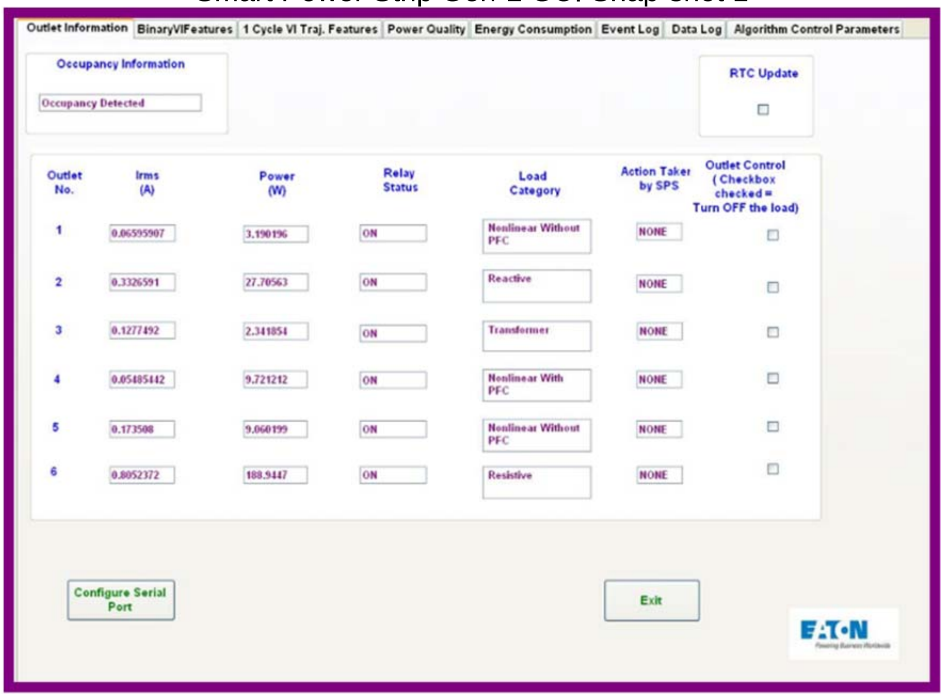


Sensor and Actuator Board

EVAL KIT FOR TMS320F28X
(TMS320F28069)

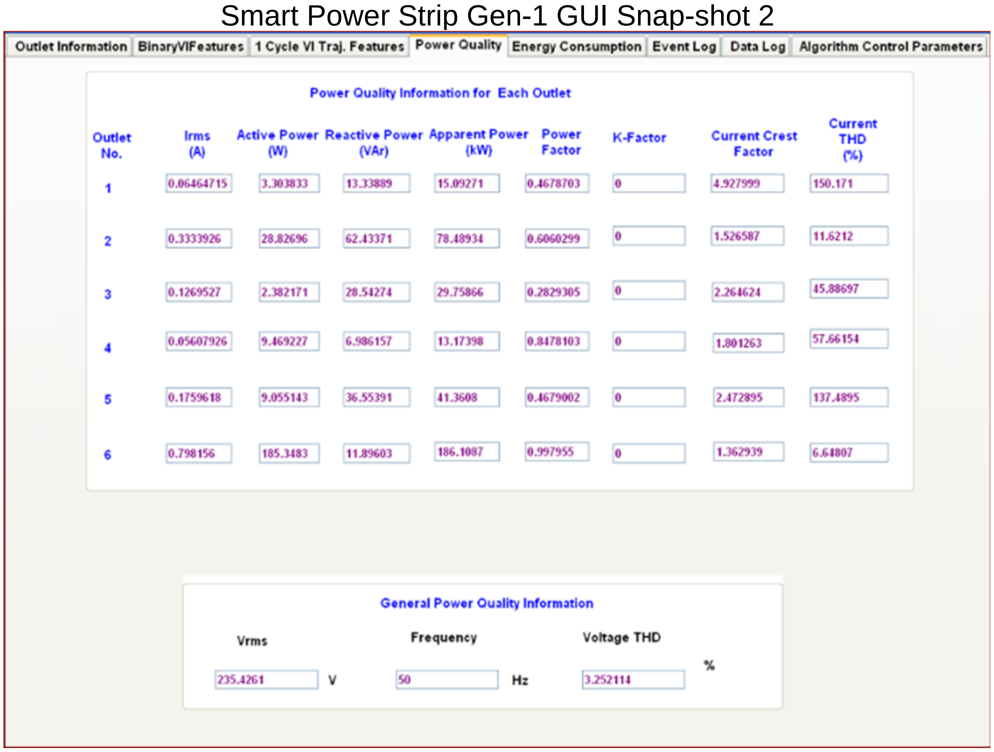
Figure 42: Smart Power Strip Gen-1 Prototype at Eaton, Milwaukee lab

Smart Power Strip Gen-1 GUI Snap-shot 1



(a)

Smart Power Strip Gen-1 GUI Snap-shot 2



(b)

Figure 43: Smart Power Strip Gen-1 Prototype User Interface Snapshots

The GEN-1 platform mainly serves for embedded system validation of load ID algorithm. The major takeaways from GEN-1 include,

- Well defined Load ID kernel architecture;
- Well understood load ID computation requirements.

This lab setup served as the embedded system platform used for the load identification algorithm testing and validation throughout the entire project.

3.4.3 Smart Power Strip Gen-2 Prototype Development

The major goals of SPS Gen-2 prototype, also referred as “Smart Receptacle (SR)”, are to facilitate the portable load identification validation and testing in a larger load set especially during the field test in a real building environment, including,

- Demonstrate that the Eaton’s developed load identification functionality and other technical attributes can be implemented in an embedded platform, i.e., the developed Smart Receptacle;
- Demonstrate the Smart Receptacle can be accessible by a remote device, e. g., personal computers, smart phones, etc., via WiFi communication;
- Support to demonstrate the value proposition of the proposed solution, e.g., increasing plug-in loads energy savings through the use of Smart Receptacles by users.

The Smart Receptacle (SR) prototype integrates embedded Load ID, plug-in loads control and management strategies, WiFi communication, and web-service-based user interface. The system diagram is depicted in Figure 44 below. The Gen-2 platform consists of:

- Integrated SR electronic board, including self-sustained power supply; V/I sensing/signal sensing and conditioning at outlet level; DSP circuitry; and WiFi RF module, etc.;
- Distribution of power to downstream plugged-in devices similarly to any regular power strips or receptacles on market, but with pre-designated ALWAYS-ON-Load-Outlet (ALO) and Controllable-Load-Outlet (CLO) with relay/switch circuitry. (120 V @ 60 Hz; 230V@ 50Hz)
- Web services to support remote access of SR devices;
- GEN-2 user-interface, including real-time load use status display, remote control of CLOs, and PiLMC configuration, etc.
- Mini-SD Card to support data logging.

The design and development focus for SR prototype is the electronic hardware development with a customized receptacle packaging to a small, portable, and more commercial looking form. The Smart Receptacle prototype is shown in Figure 45.

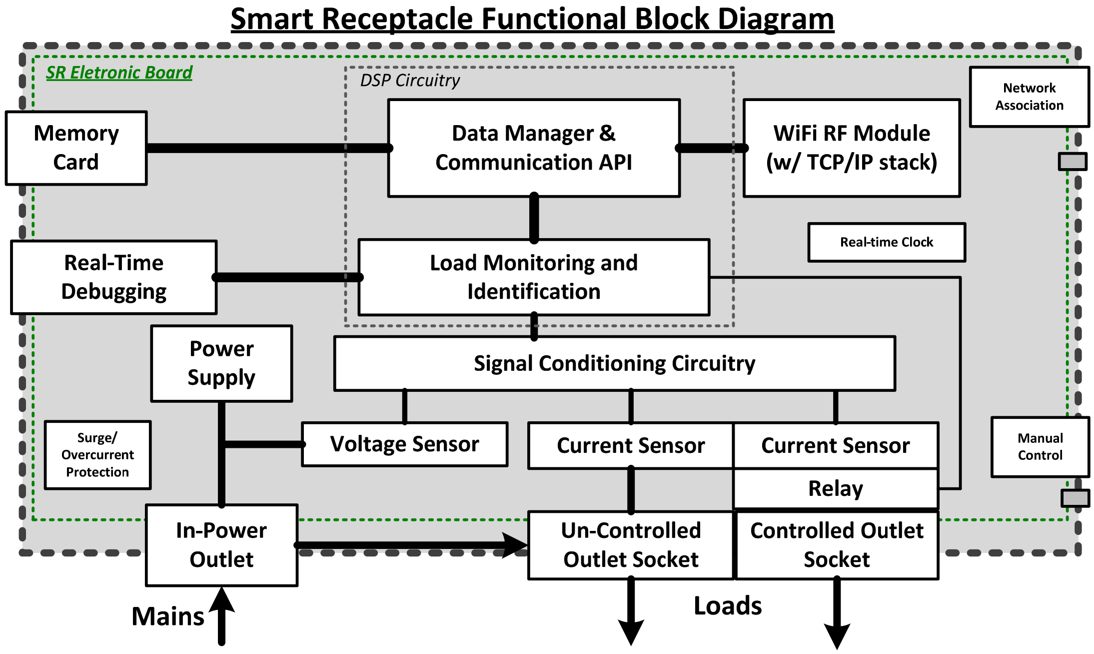


Figure 44: System Diagram of SPS Gen-2 Prototype, i.e., Smart Receptacle

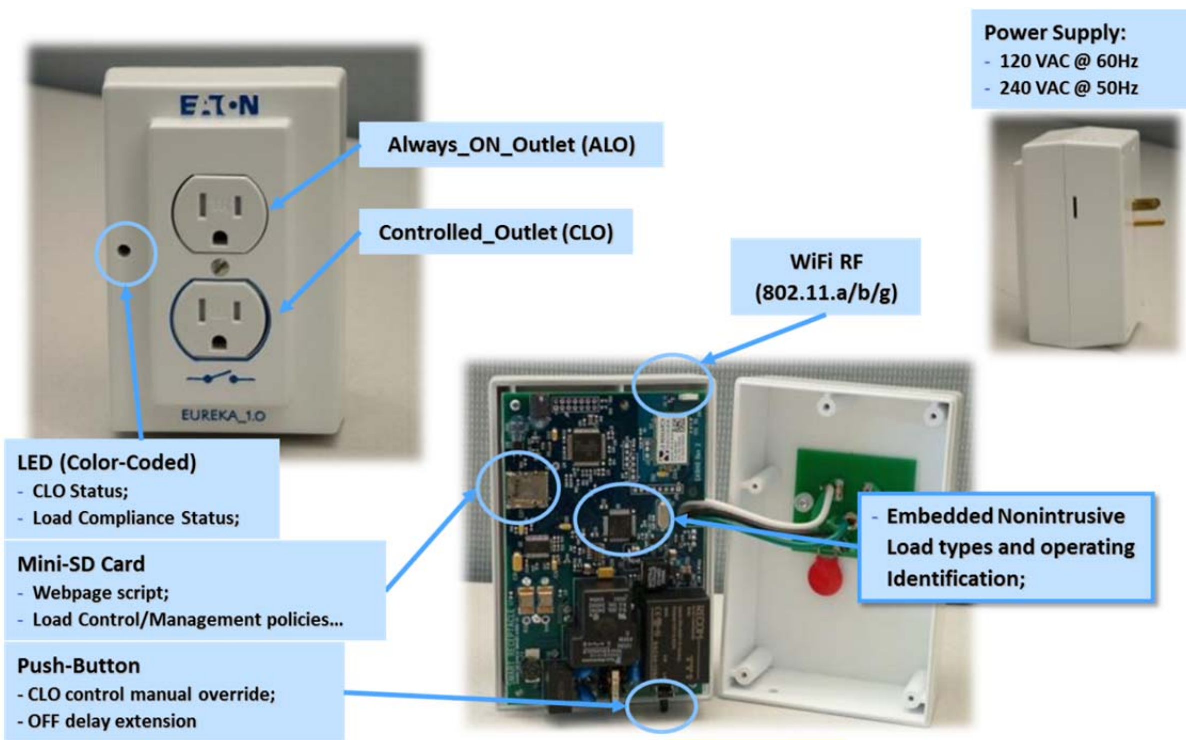
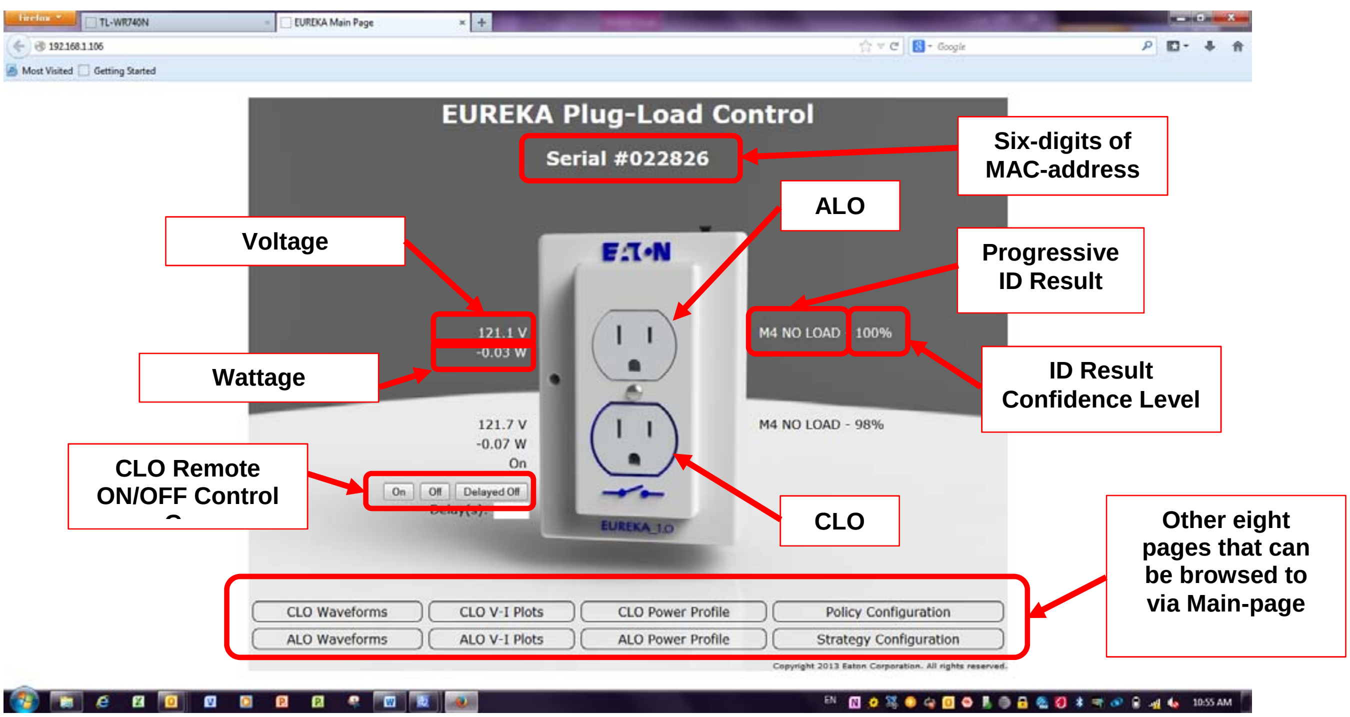


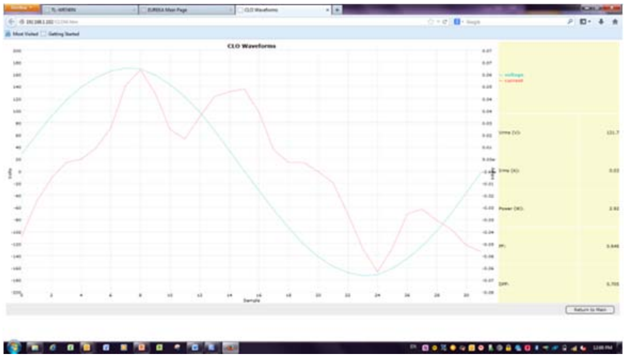
Figure 45: Smart Power Strip Gen-2 Prototype

The SR's assembly is designed in a consumer-electronics type packaging with the dimensions of 5" (H) x 3" (W) x 2" (D). The design of the SR prototype also includes the consideration for potential safety and environmental impact. The outer packaging is designed to cover and eliminate all potential live electrical parts from human contact, and comply with standard electrical creep age and clearance standards for 120 VAC and 230 VAC. The SR assembly is also designed to directly plug in to one outlet of standard commercial or residential receptacle, and maintain its position when plugged in. Isolation, spacing, and grounding is also designed by including some UL standards into consideration, for instance UL61010-1 and UL498A. The prototype is designed for the residential and commercial environment, with temperature range: 0-40^{o}C. Twenty SR prototypes have been built and tested at the Eaton electronic labs in Milwaukee, USA.

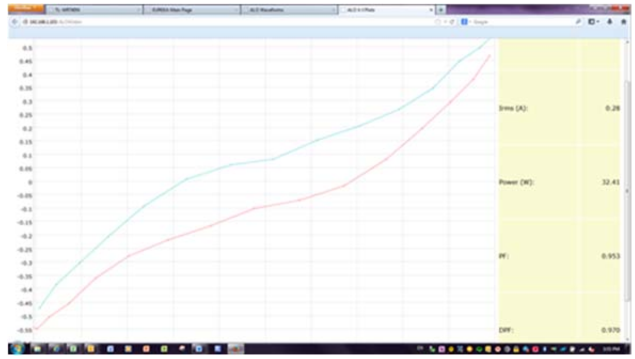
The SR prototype has demonstrated the fidelity of the hardware assembly, and software support for embedded load identification to support continuous monitoring of plugged-in devices (including power consumption, device type, and operating status, etc.); WiFi communication; data management/storage; and web services. The integrated SR prototype is able 1) to monitor the power (quality) values of the plugged loads; 2) to report the load ID results (including operating status, Level 1_ID, Level2_ID and final device class ID). The SR is WiFi compliant with WPS association, and supports HTTP/FTP protocols. Any WiFi device that supports web-browsing, e.g., iPhone, smart phones or PCs, can have the remote access to SR devices and display the status of appliances that are plugged into the SR devices in the network. The snap-shots of the web-service based graphical user-interface (GUI) are presented in Figure 46 below.



(a)



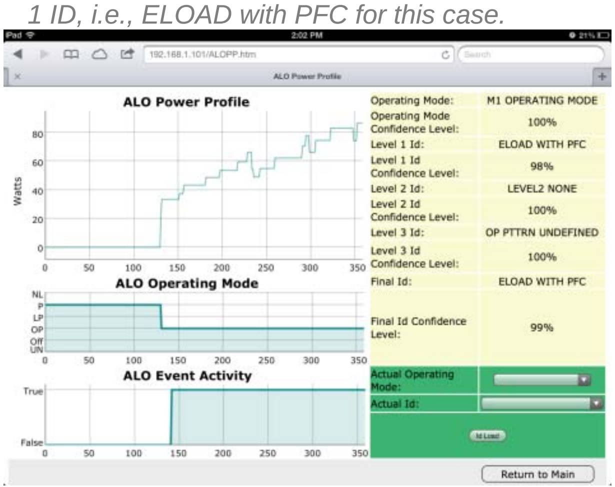
Voltag/Current Waveforms



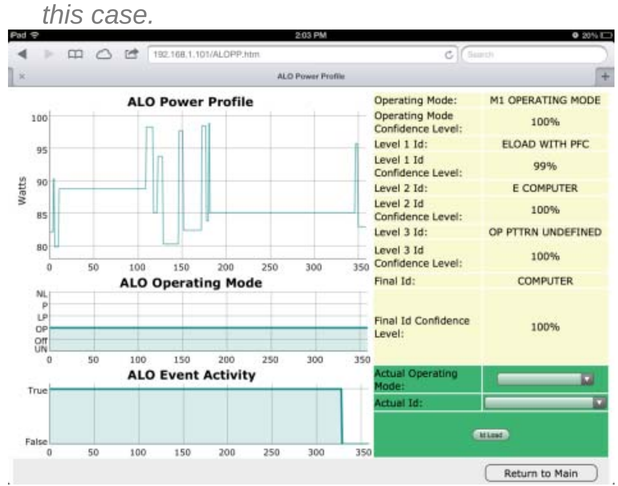
V-I Trajectory

(b)

1)A snapshot a few seconds after an event is detected. Note that, at that moment, there is only Operating Mode and Level 1 ID is available. Therefore, the Final ID only conveys up to Level 1 ID, i.e., ELOAD with PFC for this case.



2) A snapshot at one minute after an event is detected. Note that, at this moment, Level 2 ID is also available. Therefore, the Final ID only conveys up to Level 2 ID, i.e., a Computer for this case.



(c)

Figure 46: SR Web Service based GUI Snapshots: (a) main page; (b) voltage and current waveforms; (c) Load power profile with hierarchical ID results

The developed SR prototype also supports data logging of the status of the plugged-in loads in real-time. Two types of logging files are supported: 1) continuous long-term logging for the load status with a refreshing rate of one second; and 2) short term logging upon event detection (e.g., a new load is plugged into the outlet). The logging files are continuously stored to the mini-SD card, shown in Figure 47 below, in real-time.

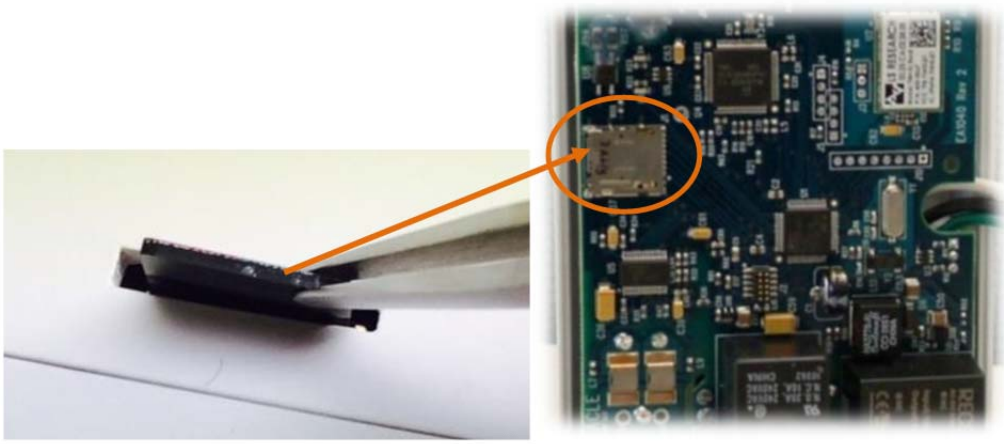


Figure 47: Mini-SD Card for data logging and webpage script storage

A Push-Button, as shown in Figure 48 below, is designed to allow users to manually turn ON/OFF the CLO relay locally. The CLO relay can also be controlled remotely through the web service based GUI.

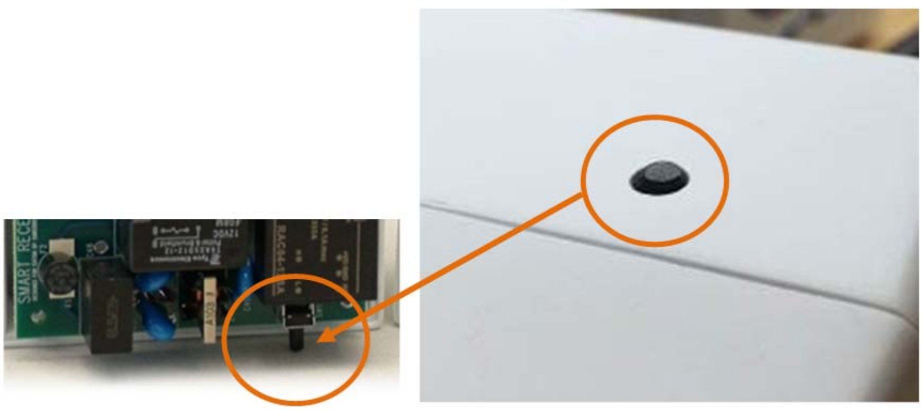


Figure 48: Manual Push Button

The GEN-2 platform mainly serves for the portable load identification validation and testing in a larger load set especially during the field test in a real building environment

3.4.4 SRs Network + Remote Energy Management System (REMS) Development

This project is to address an effective plug-in load control and management solution accomplished through effective load identification. While the development of SR prototypes is to demonstrate the device level capability, including individual load monitoring, ID and control/management, the SRs Network + Remote Energy Management System (REMS) has been developed as a plug-in load control and management platform to demonstrate the values of the developed technologies. This phase is also referred to as SPS Gen-3 development.

With reference to the discussion in Section 3.2, the major values of load identification have been recognized with the three aspects: avoid disruption/frustration; simplify set-up/commissioning; and simplify plug load characterization and monitoring. The major focus in this phase is to develop a Remote Energy Management System (REMS), a PC-based web-server, which is used to discover a Smart Receptacle network, aggregate and display real-time information stream from multiple SR devices in the network. The key functions include,

- Discovering the SRs network;
- Aggregating and consolidating the load use status from all the SRs in the network;
- Reporting aggregated power usage of plugged loads in the network broken-down by (with refresh rate of 5/10 seconds),
    - o Device Classes (up to 25 classes, aligned with the definition in Phase-I);
    - o Outlet Controllability (CLO; ALO);
    - o Operating mode of plugged loads
- Allowing the users to personalize/customize control and management policies/strategies configuration that matches to the actual use scenario, which ensure a flexible and effective management of plug-in loads in residential and commercial building environments.

Figure 49 depicts the developed SRs Network + REMS system, with which individual SRs still work as stand-alone devices for required local load monitoring/ID/control. Users still have the same level of access and control over individual SRs as introduced in a previous section.

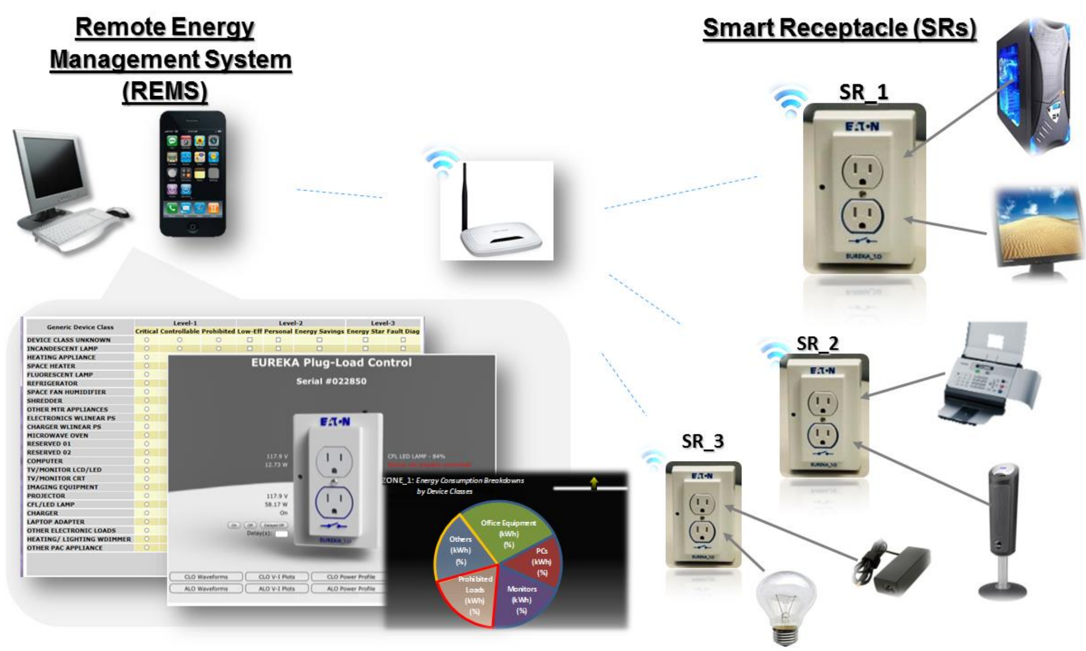


Figure 49: Smart Receptacle + Remote Energy Management System

The effective plug-in load control and management in buildings can be ensured via load management and control policies including:

- SR Outlet (Relay) Control Strategies refer to the conditions when to automatically turn-ON/OFF the outlet relays, e.g., time scheduling, load sensing, or occupancy sensors.

From an outlet control perspective, the SR prototype also integrates an advanced Load-Sensing based automatic outlet control function to enable improved energy savings with reduced nuisance tripping and disruption of existing workflow of users.

The SRs Network + REMS system also reports aggregated plug-in load usage by Device Classes; Controllability; and Operating Mode. There are up to fifteen SR devices installed in Eaton's facility in Milwaukee for a long-term demonstration and measurement. There are 19 plug-in appliances plugged into the SRs network. They are dispersedly placed in multiple working stations, private offices, and a printing room in the testing area. Section 3.5 presents detailed information to demonstrate how the developed system facilitates an enhanced visibility to plug loads usage with actionable information in buildings.

The SRs Network + Remote Energy Management System (REMS) has been developed as a plug-in load control and management platform to demonstrate the values of the developed technologies, in particular, load identification technology, in a network and building level. This platform can also be extended and scaled up with additional functions to enable and demonstrate other benefits, e.g., demand respond. It was also designed with a simple interface that provides the potential to integrate to other building level energy management systems in the future.

3.5 Technology Validation

This group of tasks is aimed at a field validation of the developed technologies in real office building environment. This project is focused on effective plug-in load control and management for commercial buildings, accomplished through effective load identification. The developed Smart Receptacle (SR) prototypes and the Remote Energy Management System (REMS) has been used for various field tests to evaluate the developed SPS prototype and its associated algorithms, application software, and user interface.

The technology validation has been focused on the following three aspects:

1) Verifying the performance of the developed load identification algorithm performance in a less controlled environment and a larger load set; and to further enhance the accuracy and reliability of the developed models and algorithms;
2) Providing the basis to assess the energy saving opportunities from plug-in load usage, and the potential energy savings;
3) Collecting and analyzing the user's feedback regarding the direct experience with the developed prototype, developed algorithms and its associated application software.

In the test plan, the corresponding performance objectives were set forth as summarized in

Table 19 below.

Table 19: Summary of Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
Quantify the developed load identification algorithm performance from field-testing the developed Smart Receptacle prototypes	Sensitivity and Precision by the hierarchical levels, and operating status	The resultant hierarchical ID results that are recorded in the mini-SD card.	**>=85% sensitivity rate** for Level 1 and Level 2 identification **>=90% precision rate** for critical loads operating mode detection
Quantify energy savings from deploying the developed Smart Receptacle prototypes	Energy Savings (% reduction) by space type and occupant type	Receptacle-level power and load use status with a refreshing rate of no less than every 5 seconds, and an accuracy of ±5%. Baseline energy consumption measured with no control that is used as a reference to quantify energy savings from the Smart Receptacle devices.	**10% Energy Reduction** **10% Nuisance turn-off Reduction**
Qualitative Performance Objectives			
User's acceptance and satisfaction with the demonstrated Smart Receptacle	Degree of satisfaction	Live demonstration; direct user's experience; Survey	**75% satisfaction rate**

During technology development, numerous plug-in appliances were tested and load data was collected from the following four locations:

- Eaton Facility @ Milwaukee, Wisconsin
- NREL Research Support Facility (RSF) @ Golden, Colorado
- Georgia Institute of Technology campus @ Atlanta, Georgia
- University of Wisconsin, Milwaukee (UWM) campus @ Milwaukee, Wisconsin

Three sites are selected to facilitate long-term field tests with a coverage as depicted in Table 20.

Table 20: Coverage of Field Test Sites

	Eaton	RSF	UWM
Irregular Work schedule			+
LEED building	+	+	
High efficient building		+	
	Mainstream building	High efficient building	Education Environment

3.5.1 Load Identification Algorithm Performance Validation

The objectives of the Load Identification Algorithm Performance Validation include:

- To verify the algorithm performance in a larger load set in a less uncontrolled environment;
- Improve the algorithm performance based on the collected data.

<u>Testing Scope and Sampling Protocol</u>

The plug-in appliances under testing shall have the coverage as defined by the hierarchical load identification target (targeted Device Classes) presented in Section 3.3. The following Table 21 summarizes the appliances device classes by their operation types.

Table 21: Load Categorization by Operation Types

Device Classes	Operation Types	Priority (1~5; 5: Highest)
INCANDESCENT_LAMP	Type-I	5
HEATING_APPLIANCE		5
SPACE_HEATER		5
FLUORESCENT_LAMP		5
REFRIGERATOR	Type-IV	4
SPACE_FAN_HUMIDIFIER	Type-I	4
SHREDDER	Type-III	3
OTHER MOTOR BASED APPLIANCES		3
SMALL_ELECTRONICS_WLINEAR_POWERSUPPLY	Type-I	4
CHARGER_WLINEAR_POWERSUPPLY		4
MICROWAVE OVEN,	Type-III	4
COMPUTER,	Type-II	5
TVMONITOR _LCD_LED	Type-I	5
TVMONITOR _CRT		2
IMAGING_EQUIPMENT,	Type-III	5
PROJECTOR		4
CFL_LED_LAMP	Type-I	5
CHARGER		4
OTHER_ELECTRONIC _LOADS		3
LIGHTING_HEATING_LOAD_WDIMMER		2
OTHER_PAC_APPLIANCE		1

It is noted that most of the Device Classes contain more than more types of plug-in appliances. For algorithm validation, at least three different types of appliances were tested.

SR units Installation and Testing Procedure

During algorithm verification testing, Smart Receptacles worked as portable devices. A tester took one SR device, or as many as desired, to the loads being tested. After a SR device was powered up, the load under test was plugged into either ALO or CLO of the SR device. The tester operated the load in a way as the load is actually in use. The load identification results are available one minute after a load is put in an operating (or working) mode.

Because the load identification algorithm is implemented based on the assumption that there is only one appliance plugged in one outlet at a time, the algorithm performance test shall be conducted one after another. The load identification results can be observed directly via any remote device, e.g., a PC, or a smart phone, with web browser for the tester's immediate verification. An Actual ID drop down list also allows the tester to select the Actual ID and log this information into the mini-SD card.

All the ID results and intermittent results, e.g., extracted features etc., were also logged into the mini-SD card for every test conducted. The above logged Actual ID provides the developers a comparison to the ID results while conducting for post processing. The current and voltage waveforms can also be logged into the SD card with real time stamped. This logged information is particularly useful during the field test, where the testers are usually not in the same location as where the algorithm developers are. For those failure cases, where detailed post processing was needed, the logged information enables an easier communication between the tester and the developer.

With reference to Section 3.3, the algorithm is designed in a way that load identification is only triggered by a detected event, the test procedures for loads with different operation types need to be different in order to ensure all the relevant and sufficient events are created for the algorithm performance verification. Table 21 provides a guideline to develop and standardize a testing procedure. This procedure is particularly helpful when a large scale of load testing was conducted, which provides a guideline for all the testers, and ensured all the tests conducted are relevant and sufficient. The following series of figures provide a few examples of how the remote web page displays the testing results and the tester can utilize the information to facilitate the testing procedure.

When there is no load connected, only the Operating Mode is available. For instance, as shown in Figure 50, a computer is plugged onto the ALO without being switched ON. The identification result shows the load is in Parasitic Mode.

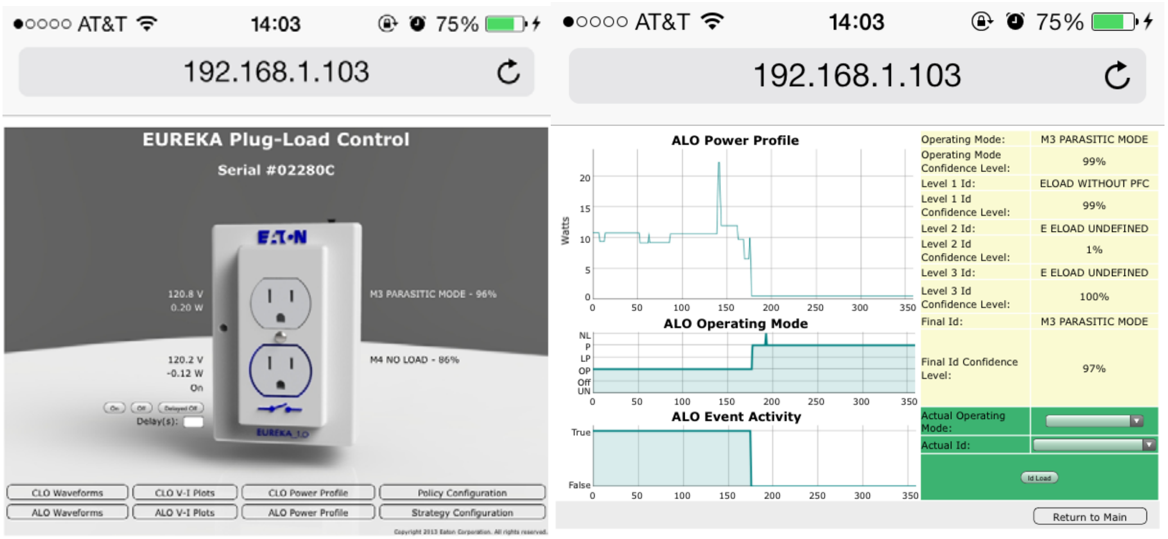


Figure 50: Load ID Results Display – Before a plug load is switched ON

After a load is switched ON and triggered into operation, an event is triggered with Load ID process enabled. Within one minute upon the event detection, only the Level 1 ID is available. Given the same example, the Operating Mode shows the load is in M1 Operating Mode, as shown in Figure 51.

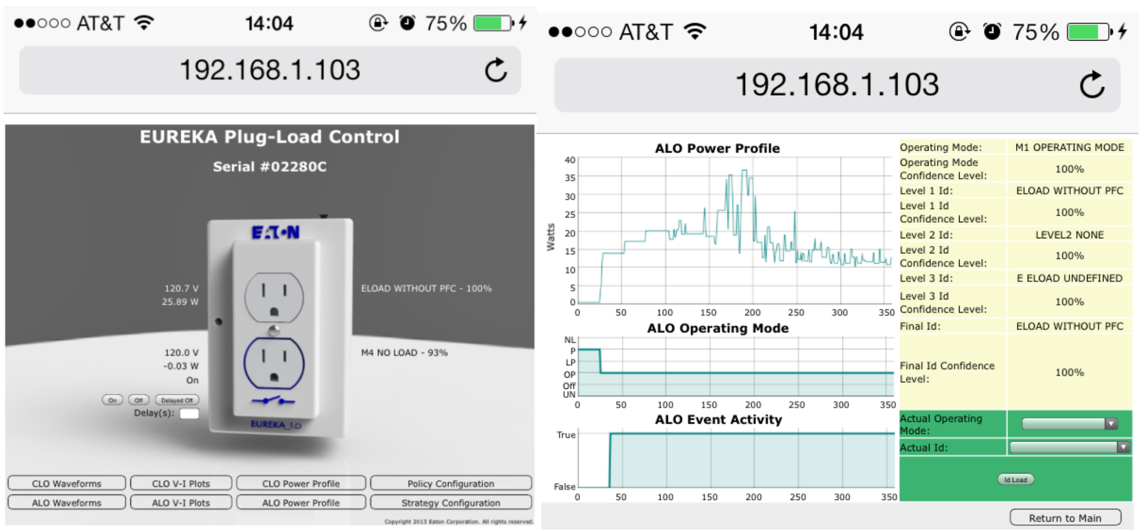


Figure 51: Load ID Results Display – Within One minute after a plug load is switched ON

When a load is switched ON into operation for more than one minute, Level 2 ID and Final ID is available. Given the same example, the load is identified as Computer, as shown in Figure 52.

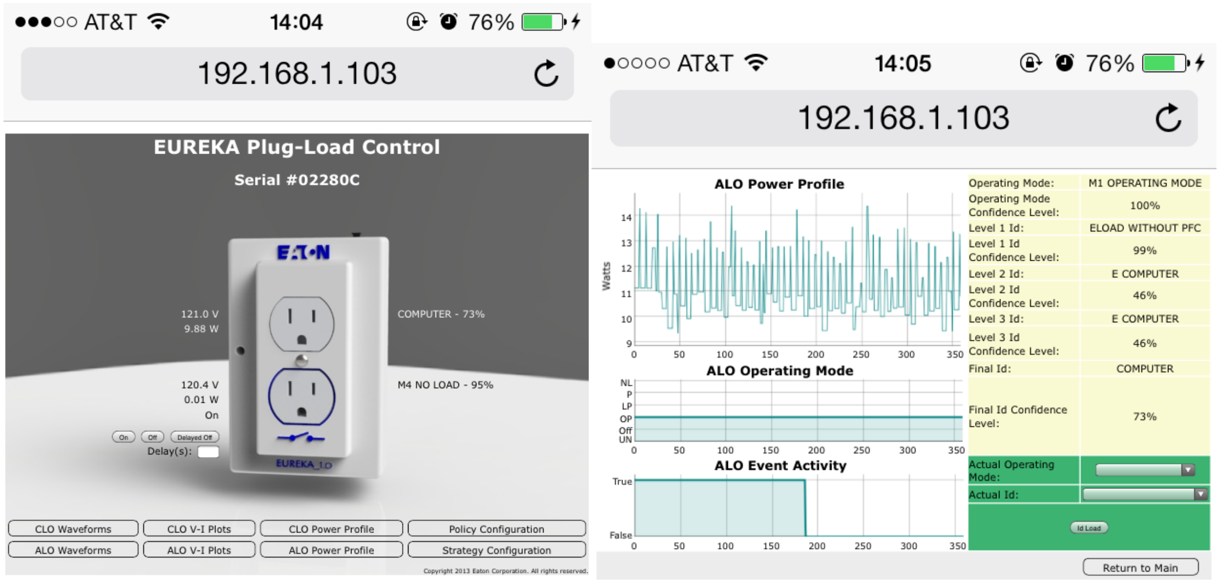


Figure 52: Load ID Results Display – One minute after a plug load is switched ON

Large power fluctuation potentially triggers another event, and consequently another Load ID process. The load remains in Operating Mode, and the Level 1, Level 2 and Final ID is updated continuously in real time, as shown in Figure 53.

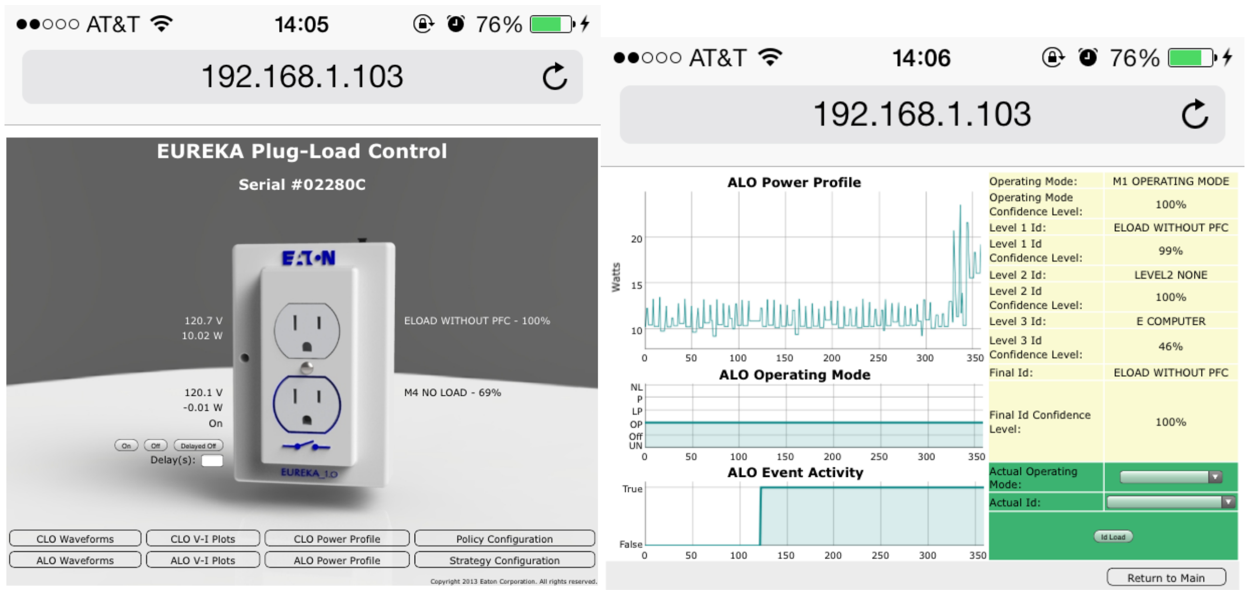


Figure 53: Load ID Results Display – Before a plug load is switched ON

<u>Technical Performance Analysis and Assessment</u>

With reference to the discussion in Section 3.3, the load identification performance requirements are summarized as below:

The identification granularity (Device Classes) target is defined in

- Table 12;
- The Device Class ID Sensitivity shall be larger than 85%;
- The Critical Load and Operating Mode ID Precision shall be larger than 90%;

The SR units have been tested for the load identification algorithm performance in multiple locations, including three of Eaton's facilities, NREL RSF facility, and UMW Milwaukee campus. Around forty types of plug-in appliances (up to 237 load models, with 4~7 models for each load type) have been tested. Most of the appliances have been tested at least three times to verify the repeatability of the identification performance. Around 900 tests have been conducted. Refer to Appendix C for the distribution of tested plug-in appliances by load categories.

The following tables provide a summary of the Sensitivity and Precision performance in the various levels of the hierarchical load identification structure. Level 1 load identification performance assessment includes 2,566,839 counts of cycle-based data. The testing results, as summarized in Table 22, demonstrate the performance of the Level 1 load category identification with the accuracy of more than 90% in average. The major failure cases are from some Resistive loads (e.g., small incandescent lamps with high frequency components), PAC (α<90^{o}C), and Reactive loads with small phase angles.

Table 22: Sensitivity and Precision in Level1-ID

Level-1 Load Category	Counts of Data Points	Sensitivity	Precision
R-load	421382	0.957	0.99
X-load	324744	0.945	0.932
NP-load	835601	0.973	0.997
P-load	720512	0.994	0.969
M-load	129152	0.826	0.909
T-load	25621	0.873	0.415
PAC-load	27965	0.597	0.662

The Level 2 load identification development for the resistive loads (R); reactive predominant loads (X); electronic loads with power factor correction circuit (P); electronic loads without power factor correction circuit (NP); linear power supply using transformer to boost voltage (T); phase angle controllable loads (PAC); and complex structures (M) have been completed. The corresponding validation results are summarized in Table 22 through Table 25 with Sensitivity and Precisions performance of ~90% in average.

Table 23: Sensitivity and Precision in R-Load Level2-ID

Level-2 Device Classe	Counts of Test Points	Sensitivity	Precision
Incandescent lamp	18	1	1
Heating appliances	46	1	1

Table 24: Sensitivity and Precision in E-Load (i.e., P- and NP-Load) Level2-ID

Level-2 Device Classe	Counts of Test Points	Sensitivity	Precision
Computer	349	0.957	0.982
Imaging Equipment	279	0.968	0.954
Projector	64	0.984	1.00
LED lamp	52	1.00	1.00
Monitor/Screen	232	0.991	0.990

Charger	115	0.965	0.771
E-others	115	0.667	0.571

Table 25: Sensitivity and Precision in X, T, and M-Load Level2-ID

Level-2 Device Classe	Counts of Test Points	Sensitivity	Precision
Florescent lamp	26	0.962	0.962
Power Adapter	12	1	1
Fan/humidifier	13	0.923	0.75
Microwave	29	1	1
Refrigerator	190	0.942	1
Shredder	15	0.933	0.824
X-others	12	1	0.75

Operating Mode detection performance assessment includes totally 1718906 counts of cycle-based data. The testing results, as summarized in Table 26 demonstrates that the algorithm can successfully distinguish the normal operating mode, parasitic mode, and unplugged mode with success rate up to 95% in average.

Table 26: Sensitivity and Precision of Operation Mode Detection

Level-2 Device Classe	Counts of Test Points	Sensitivity	Precision
M1: Operating Mode	1367964	0.995	0.983
M3: Parasitic Mode	195671	0.911	0.959
M4: No Load	155271	0.927	0.97

3.5.2 Load Identification Value Validation – Quantitative Analysis and Assessment

<u>Objectives</u>

With the load identification algorithm development and validation as the major focus of this project, the objectives of prototype development and field tests have also been targeted on demonstrating and proofing the values of the developed load identification technology.

With the reference to the value proposition that drives an effective plug load control and management solution discussed in Section 3.2, the net value of load identification can be expressed by,

> Net Value = Energy Saving Gains – Setup/Configuration cost – Negative Impact to Productivity Loss.

Where,

- Energy Saving Gains can be achieved by,
  - 1.1 Automatic outlet level control to reduce/cutoff the energy consumption that is not in use;
  - 1.2 Improved visibility to plug load usage with actionable information that drives further reduction of energy consumption (This aspect of energy saving requires users' participation, and its effectiveness highly depends on the users' acceptance and involvement.)
- Setup / Configuration cost can be reduced by,
  - 2.1 Automatic association between the controlled and monitored outlets and plugged-in appliances;
- Negative Impact to Productivity Loss can be reduced by
  - 3.1 More accurate and reliable determination of actual load status, to prevent nuisance tripping.

The field tests presented in this sub-section have been conducted to validate the points 1.1 and 3.1 of the above value propositions with quantitative analysis and assessment. The related field tests and validation for the points1.2 and 2.1 is presented in the following sub-sections.

<u>Testing Scope and Sampling Protocol</u>

As discussed in Section 3.2, the management and control of plug-in loads is challenging mainly because of the diversity of plug-in loads, as well as the variations in users' behavior. Field tests and validations have been designed based on the application scenarios by the dimensions as follows:

- Existing plug load devices;
- Job functions of occupants/users;
- Space types;
- Time of use.

<u>SR Units Installation and Testing Procedure</u>

For load ID value demonstration and validation, the tests were conducted to support long term measurement of load usage in a few selected locations that intend to cover the representative use scenarios by occupants and space types as listed above. The existing power strips or receptacles were replaced by the developed Smart Receptacle prototypes. The Smart Receptacles can work both as a standalone and networked device. For each selected site, e.g., a workstation, private office, or printing room, two to three Smart Receptacle prototypes were installed to measure the plug load power consumption, operating status, and load types of individual devices at outlet level. The applicable data was collected for a one- to two-week period to capture the typical usage pattern of the tested site, and thus to build sufficient information for an effective values assessment. The Load Use Status at each outlet, including current, power, operating mode, as well as the load ID results, is updated every one second and stored into mini-SD card continuously during the long term of measurement. The logged data was stored in a data folder with the device ID (MAC address) automatically attached. This arrangement is beneficial for the remote data transfer from other testing sites.

To measure the baseline energy consumption as well as to verify the performance of the installed SR units, the CLO automatic control was disabled, i.e., CLO remains being ON during the long term measurement test.

Note that, the function of CLO automatic control has been tested individually for up to 100 various testing scenarios to validate the effectiveness of the CLO automatic control. Its specific control function during long term testing was then simulated through offline analysis. The corresponding offline analysis and beneficial assessment is introduced in the following subsection.

During installation, the only equipment calibration is to program the SR's real-time clock to the system clock before they are installed in place. The calibration only requires pressing the "Set Time" button through the \Setup.htm web page after the SR is connected to the network. Once SR's real-time clock is set, there is no further need to maintain the time, unless the SR device was left unpowered for fairly long time, say three to four days.

All the logged data was post processed to remove the discrepancies that were caused by loss of communication signals, or incorrect data, etc. This post process is important to provide equal comparison of data sets collected from different location, and during different research phases.

Load ID Value Demonstration with Quantitative Analysis and Assessment

Table 27 through

Table 29 depict testing sites at three field locations including space types, number of test sites, testing duration, and connected appliances. Appendix D summarizes the power profile of all appliances connected for long term tests.

Table 27: Long Term Tests at Eaton Facility

Space Type	No. of Test Sites	Testing Duration (workdays/ weekends)	Connected Appliances
Private Office	1	12 (8/4)	Monitors (2); Laptop Computer (1); Printer (1); DVD Player (1) HDMI Adapter (1); Electronic white board (1); Shredder (1)
Work Station	2	10 (6/4)	Monitors (2); Laptop Computer (1)
Printing Room	1	4 (4)	Multifunctional Device (1); Shredder (1); Heat sealer (1); Electric puncher (1)
Kitchen Area	1	2 (2)	Microwave (4); Ice Machine (1); Vending Machine (3)

Table 28: Long Term Tests at NREL RSF Facility

Space Type	No of Test Sites	Testing Duration (workdays/ weekends)	Connected Appliances
Private Office	2	16 (12/4)	Monitors (1); Computer (1); Laptop Computer (1); Charger (1)
Work Station	2	11 (7/4)	Monitors (2); Laptop Computer (1); LED lamp (1)

Table 29: Long Term Tests at UMW Campus

Space Type	No of Test Sites	Testing Duration (workdays/weekends)	Connected Appliances
Private Office	1	12 (8/4)	Desktop Computer (1); Monitor (1); Scanner (1); Printer (1)

Operational Testing and Analysis with CLO Automatic Controls

In order to demonstrate the difference of various automatic control strategies, a CLO Auto_Control module was designed to implement the automatic CLO control. With reference to the discussion in Section 3.1, typical control strategies applied by traditional APSs include,

- Time Scheduling;
- External Sensor, e.g., occupancy sensors, or;
- Load Power Level Sensing;

In this project, a Load ID based CLO automatic control scheme has also been developed and implemented. The selection of various CLO control approaches can be configured by users.

For the field tests validation, modeling and simulation was conducted to examine the impact on the energy savings and the potential negative impact to users through automatic CLO control. To establish a fair comparison among various control approaches, as well as their impacts, the simulation study based on three different control approaches was conducted,

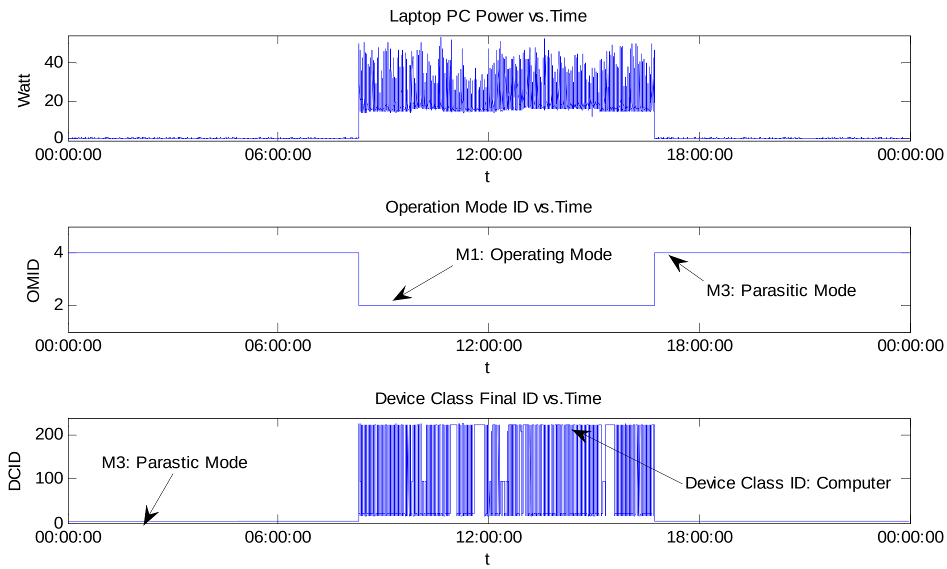
- Time Scheduling based;
- Load Power Sensing based;
- Load ID based.

Because external occupancy sensor based CLO automatic control relies on another occupancy sensor in place, its control reliability depends heavily on the performance of the selected sensor itself. Besides, the additional cost involved with the sensor adds another dimension to the benefit assessment. These additional dimensions of analysis are not relevant to the key points to be proved in this project. Therefore, in the validation process, only three control approaches were included in the analysis.

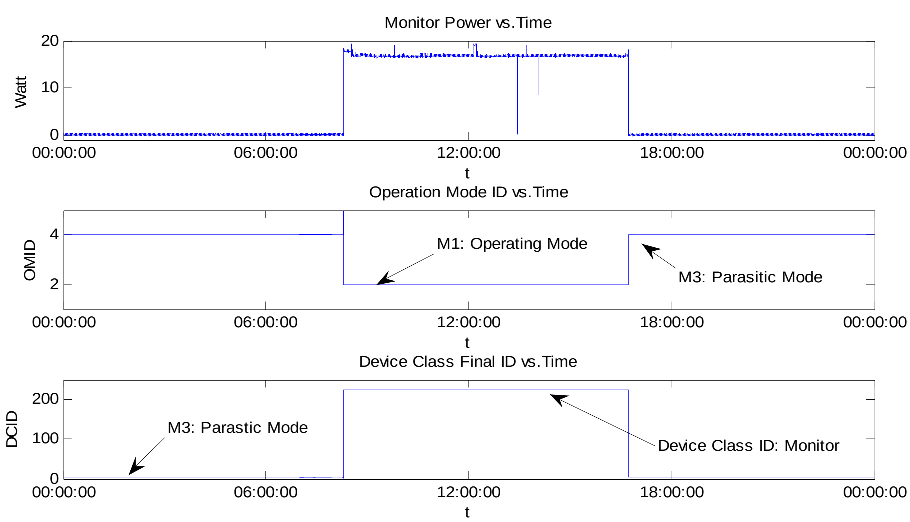
For each long-term test conducted, the power, operating status and load ID results profiles were generated for the entire testing duration. These three profiles are used as the inputs to the CLO_Auto_Control module. The module was implemented based on the three automatic control approaches to generate the corresponding CLO control signals. The following two aspects were assessed with the resultant control signal,

- The resultant energy savings through the three CLO automatic control approaches;
- The comparison between the actual occupant status, and the corresponding CLO automatic control signals (Note that, the disagreement between the actual occupant status and actual CLO turn-ON/OFF decision is the main reason that causes Nuisance tripping of CLO relay, which consequentially results in potential interruption of user's work, potential damage of devices, loss of productivity, etc.).

Figure 54 gives an example of the measured daily profiles of load power consumption, operating mode, and corresponding load ID result for the laptop PC at the private office in an Eaton facility.



(a)



(b)

Figure 54: Load Power Profiles with Operation Mode and Load ID Results of a Workstation at Eaton's Facility: (a) Computer; (b) Monitor

For Time Scheduling control approach, the default ON schedule, if the occupant did not request an alteration, was 6 a.m. to 6 p.m. weekdays. In other words, Smart Receptacles were configured to energize the plugged-in appliances only between 6:00 am and 6:00 pm on weekdays. The schedule based controls were expected to reduce plug level energy use during weekend and nighttime hours when equipment was not in use, therefore reducing building energy consumption without impacting the building occupants. Compared to the baseline energy consumption, the Time Scheduling based control approach helps reduce the average power of a tested site by 6% to 34.8% (Refer to Table 32,

Table 33 and Appendix H). As observed from use profiles of each tested site, the power consumption can be reduced further if the time schedule can be adjusted or configured to match the user's work schedule instead of a general 6:00am to 6:00pm, Monday to Friday schedule.

From the nuisance tripping perspective, because most of the occupants under testing have working hours less than 9 hours during work days, there is very few nuisance tripping observed under the Time Scheduling based control approach. This non-nuisance tripping performance is compromised by the less energy savings as discussed above.

The only two exception observed is the Private Office measured at UWM campus. The occupant holds a relatively irregular working schedule, and has been observed staying in office until 7:00 or 8:00 pm during workdays, and coming to office during weekends. If the default ON schedule is applied to this test case, nuisance trips are encountered.

Figure 55 below shows an example with this scenario.

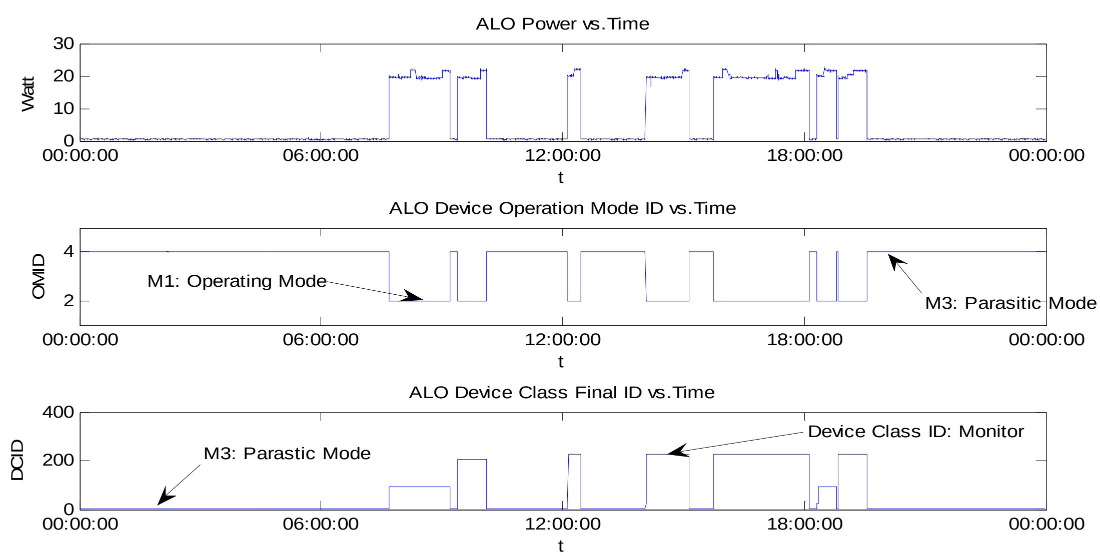


Figure 55: A Load Power Profile with Operation Mode and Load ID Result of a Workstation at UWM Campus

For Load Sensing based control approach, the power level threshold is selected to be 2W~5W according to common practices applied to traditional load sensing-based APSs. In other words, this Load Sensing based control approach senses when a plug-in load changes from an operating mode (or in-use state) to a parasitic mode (or a low power state), i.e., when the sensed power changes from a power level less the above said threshold. When this transition is detected, the power strip deprive power from all the CLOs.

Compared to the baseline power consumption, Load Sensing based control approach helps reduce the average power of a tested site by 5.4% to 20.8% (Refer to Table 32,

Table 33 and Appendix H). Even though this control approach is designed being better tailored for the actual usage pattern of plugged-in loads and the occupant use behavior, and it shall offer more saving opportunities and less nuisance tripping compared to the Time Scheduling based control approach, the reality is not as ideal as expected. The performance, however, highly relies on the selection of an appropriate power level threshold to determine the ON and OFF moment of the CLO. If the power threshold is selected with a low value, e.g., < 2 W, this control solution offers less nuisance tripping. However, the energy savings are compromised, because many appliances are observed having power consumption of more than 5W even in their idle/parasitic mode, and are not turned OFF during afterhours. On the other hand, if the power threshold is a relatively high value, e.g., 5 W, the energy savings are better optimized to the maximum saving potentials. However, more nuisance trips are observed, because many loads, particularly high efficient electronic appliances, have low power consumptions even in their active modes. The actual performance based on the field test data shows that a power level threshold is an overly simplified CLO control condition, and needs to be calibrated carefully. Figure 56 below provides two examples that show a simple power level threshold is not sufficient enough as a CLO control condition to ensure a maximized energy savings and, at the same time, a minimized nuisance tripping. For instance, if a threshold of 10W is selected. The printer shown in Figure 56 (a) can never be switched OFF, and on the other hand, the scanner shown in Figure 56 (b) will also always be switched OFF.

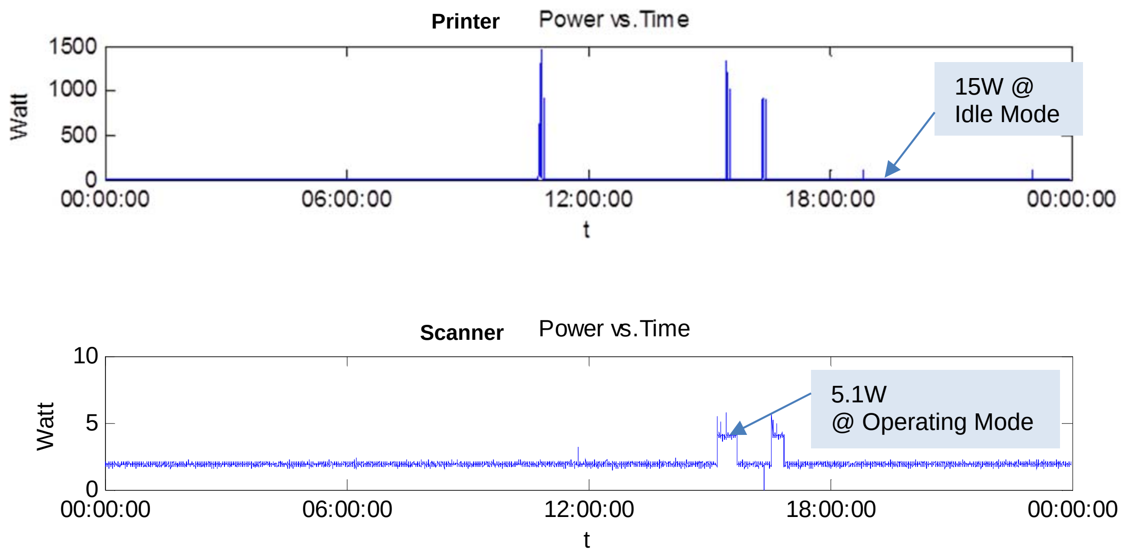


Figure 56: Power Profiles for (a) A Printer; (b) A Scanner

For Load ID based control approach, the detected Operation Mode, Load ID result, and real-time serve as the inputs to determine the CLO automatic control signal. This approach can be considered as an advanced Load Sensing based approach, which is also designed to be better tuned for the actual pattern of loads and occupant use behaviors. Instead of using only a power level as the threshold, however, this approach utilizes the resultant Load ID and Operation Mode information to determine the ON/OFF moment to control CLO. The performance assessment for all the test sites have demonstrated an improved performance from both the energy saving and nuisance tripping perspectives (Refer to Appendix H).

It is worthwhile pointing out that the performance of Load ID based control approach is closely related to the performance of the developed load ID algorithm. As discussed in previous sections, the Precision of Critical Load Operating Mode detection directly drives the performance of CLO automatic control.

In order to assess and compare the performance based on the three control approaches, the energy consumption (with reduction percentage) and the observed nuisance trips have been evaluated for all the long term field tests conducted. It is noted that the performance analysis and assessment is on a per-unit (or a per-site) basis, i.e., as per working station, private office, etc. Table 30 and Table 31 provides the power consumption profiles of two private offices at Eaton facility in Milwaukee and UWM campus respectively.

Table 30: Power consumption profiles in one Private Office at Eaton Facility in Milwaukee

	Power Consumption (Watts)		
Load Types	Active	Idle	Parasitic
Monitors (2)	18.5	-	0.2
Laptop Computer (1)	35.4	-	0.2
Printer (1)	54.7	4.3	-
DVD Play (1)	5.8	0.5	
HDMI Adapter (1)	3.4	-	0.5
Electronic white board (1)	51.2	-	0.2
Shredder (1)	278.6	-	0.2

Table 31: Power consumption profiles in one Private Office at UWM Campus

	Power Consumption (Watts)		
Load Types	Active	Idle	Parasitic
Desktop Computer (1)	51	-	1
Monitor (1)	20.7	-	0.5
Scanner (1)	5.1	2	-
Printer (1)	600	15	-

Table 32 and

Table 33 below give two examples of the assessment results for one workstation at Eaton Facility and one private office at UWM campus. This two examples represent two scenarios with relatively low and high energy savings. Refer to Appendix H for the assessment results for all other test sites.

Table 32: Energy Savings and Nuisance Turn-OFF Performance Assessment at UWM Campus

Private Office				
	Baseline	**Time Scheduling based Control**	**Load Power Sensing based Control**	**Load ID based Control**
Energy Consumption Total (kWh/week)	9.283	6.056	7.356	5.591
Energy Consumption Work-hours (kWh/week)	5.436	5.436	5.436	5.436
Energy Consumption Afterhours (kWh/week)	3.848	0.62	1.92	0.155
Weekly Reduction Percentage (%)	-	34.8%	20.8%	39.8%
Nuisance trips Occurrences rate (%)	-	25%	16.3%	8.1%

Table 33: Energy Savings and Nuisance Turn-OFF Performance Assessment at Eaton Facility

Private Office				
	Baseline	**Time Scheduling based Control**	**Load Power Sensing based Control**	**Load ID based Control**
Energy Consumption Total (kWh/week)	4.302	3.644	4071.9	3.552
Energy Consumption Work-hours (kWh/week)	3.521	3.521	3.521	3.521
Energy Consumption Afterhours (kWh/week)	0.781	0.122	0.55	0.030
Weekly Reduction Percentage (%)	-	15.3%	5.4%	17.4%
Nuisance trips Occurrences rate (%)	-	0	16.3%	8.1%

The benefit analysis and assessment shows that, in average, the developed Load ID based CLO control approach demonstrates a moderate energy saving performance compared to Time Scheduling based approach; and results in less nuisance trip occurrences compared to Load Sensing based approach. The tables below summarize the benefit analysis and assessment by occupant and space types.

Table 34 and Table 35 summarized the performance of energy savings by space types and occupant types

Table 34: Percent Energy Savings by Space Type

Open office – Work Station	Private Office	Kitchen Areas	Printing Rooms
6.8% ~ 23.8%	9.3% ~ 39.8%	36.7%	2.2%

Table 35: Percent Energy Savings by Occupant Type

Technical Staff	Management Staff	Professor
6.8% ~ 23.8%	9.3% ~ 17.4%	39.8%

Compared to baseline energy consumption, **the developed Load ID based control approach demonstrates a reduction by 6.8% ~ 39.8% depending on the existing plug-in load applied and usage behavior of occupancy.** This result matches the literature and market study discussed in Section 3.2 showing the energy savings from plug-in loads in buildings are uncertain and diversified, closely dependent on the existing usage pattern and behavior.

The significant outlier with the lowest savings is printing station where a multifunctional device needs to stay on 24/7 to allow users to remotely operate the load, e.g., printing, etc. The case with the highest savings is the private office at UWM campus. The main reason is that older models of computers and printers are used in this office, and the user does not set up to push loads to energy saving mode when loads are not in use. Therefore, this case presents the most energy saving potentials. On the other hand, computers, monitors and other office appliances are all relatively new models at Eaton facility and NRE RSF facility. Besides, almost all occupants take their computers away with them afterhours. This results in that most energy usage comes from parasitic power consumption during afterhours. The energy saving potential itself is relatively low. However, it is observed that, **around 10% of energy savings still can be achieved even for cases with low energy saving potentials**.

3.5.3 Load Identification Value Validation - Qualitative Analysis and Assessment

Objectives

With reference to the list of load identification values presented in the previous subsection, the field tests and validation presented in this subsection is focused on the points 1.2 and 2.1, i.e.,

- Improved visibility to plug load usage with actionable information that drives further reduction of energy consumption (This aspect of energy saving requires users' participation, and its effectiveness highly depends on the users' acceptance and involvement.)
- Automatic association between the controlled and monitored outlets and plugged-in appliances to reduce the time and cost on system setup and configuration.

As the corresponding benefits and values are not quantifiable under the scope of the project, the tests and validations have been designed to facilitate mainly qualitative analysis and assessment.

Testing Scope and Sampling Protocol:

As the above said value elements require the participants /actions from users, it would be difficult to obtain a quantifiable value assessment without a large-scale, long-term deployment of the devices, which is beyond the scope of this project. In this project, tests and validations have been conducted only to a point where the function is demonstrated to the potential users, and/or have a few volunteers experiencing the prototypes for a week or so. The benefit analysis and assessment has been conducted through a collection of user experience feedback.

Through the course of project development, particularly during the final phase of the project, numerous live demonstrations were conducted to groups of audiences who hold roles/positions ranging from standard end-users (or building tenants), energy service providers, research and development engineers, sustainability provokers and process managers, facility managers, product line engineering and marketing managers, etc. Some Eaton colleagues also volunteered to take the developed SR prototypes back home for some period of personal use and experience.

A survey form was prepared to obtain feedback based on user's direct experience with the developed prototypes. The survey is designed to understand the usability of the developed prototype, their acceptance level, and their perception of potential savings and impacts achieved through use of the Smart Receptacles.

Load ID Value Demonstration with Qualitative Analysis and Assessment

As discussed in Section 3.4, besides the automatic load identification function, a few additional features have also included a Smart Receptacle (SR) prototype and Remote Energy Management System (REMS) development, including,

- Deprive power when unoccupied via CLO Automatic Control;
- Monitor, aggregate, and display energy consumption of plug level loads by device classes to help locate the potential savings in future;

Improved visibility to plug load usage with actionable information

There are up to eleven SR devices installed in Eaton's facility in Milwaukee, WI to demonstrate the capability for an improved visibility of plug load usage in a network level. There are 19 plug-in appliances plugged into the SRs network. They are dispersedly placed in multiple working stations, private offices, and a printing room in the testing area. Table 36 summarizes the SR device's IDs with their MAC addresses, and the actual appliances that are plugged in as reference.

Table 36: Smart Receptacles and Plug Loads Connection at Eaton's Facility in Milwaukee, USA

SR Mac Address	CLO	ALO
02:28:41	NO load plugged in	Samsung 32" TV
02:28:55	Dell Monitor	HP Laptop
02:27:E5	HP Laptop	Dell Monitor
02:27:EF	Incandescent Lamp 100W	LED Lamp
02:28:0C	Relay Off	HP Printer
02:28:11	Monitor	Desktop
02:28:30	Fan	Incandescent Lamp
02:22:C5	No load plugged in	Laptop
02:28:40	Monitor	Laptop
02:28:16	Incandescent Lamp	Fan
02:28:51	Monitor	Desktop

The first set of figures below shows a snapshot of the developed webpages at the moment when almost all the appliances/loads are in their operating mode during work hours.

The main page shown in Figure 57 lists all the SR devices that have been discovered in the network, as well as the use status of all the plugged-in loads in the network. The appliance use status includes real-time power; the types of appliances that are plugged into that outlet; as well as the operating mode indication. Note that, all SR devices are also automatically labeled with their MAC addresses after they are discovered, as shown on the right column.

- Home
- Power Usage
- Always On Oultet Power Usage
- Controllable Oultet Power Usage
- Mode

Smart Receptacle	Controllable	Always On
022841	RELAY OFF (0 W)	TVMONITOR LCD LED (47.41 W)
022855	TVMONITOR LCD LED (25.51 W)	ELOAD WITHOUT PFC (12.69 W)
0227E5	COMPUTER (38.13 W)	TVMONITOR LCD LED (15.88 W)
0227EF	INCANDESCENT LAMP (96.77 W)	CFL LED LAMP (14.67 W)
02280C	RELAY OFF (0 W)	IMAGING EQUIPMENT (90.6 W)
022811	TVMONITOR LCD LED (30.91 W)	COMPUTER (17.71 W)
022830	SPACE FAN HUMIDIFIER (13.08 W)	INCANDESCENT LAMP (36.06 W)
0222C5	NO LOAD (0.05 W)	RESISTIVE (146.34 W)
022840	TVMONITOR LCD LED (27.15 W)	ELOAD WITHOUT PFC (27.93 W)
022816	INCANDESCENT LAMP (14.58 W)	SPACE FAN HUMIDIFIER (22.69 W)

Figure 57: REMS Web Display – Main Page (Work hours)

There are a few highlights that are worthwhile pointing out. With reference to Load ID algorithm introduced in Section 3.2, the load identification results are displayed in a progressive fashion with a different level of granularity depending on the availability of the information. The load type (i.e., device classes up to Level 2) information is available only one minute after the load has been put in operation. Within one minute after a load is put in operation, the resultant load ID information is only down to Level 1, or only reflect the operating mode. If the SR 0222C5.ALO outlet is used as an example, an incandescent lamp was just powered up for a few seconds when the snapshot was taken, therefore, the identification result only shows “Resistive” as the result at that moment.

If the appliance plugged onto SR_022851.CLO was used as another example, it shows “ELoad Undefined” as the result, while a PC monitor was actually plugged onto that outlet. This example demonstrates a scenario when an identification result with a specific device type has low confidence level, e.g., less than 50%. Therefore, the identification algorithm only presents the load as an undefined electronic load, instead of giving a specific ID result.

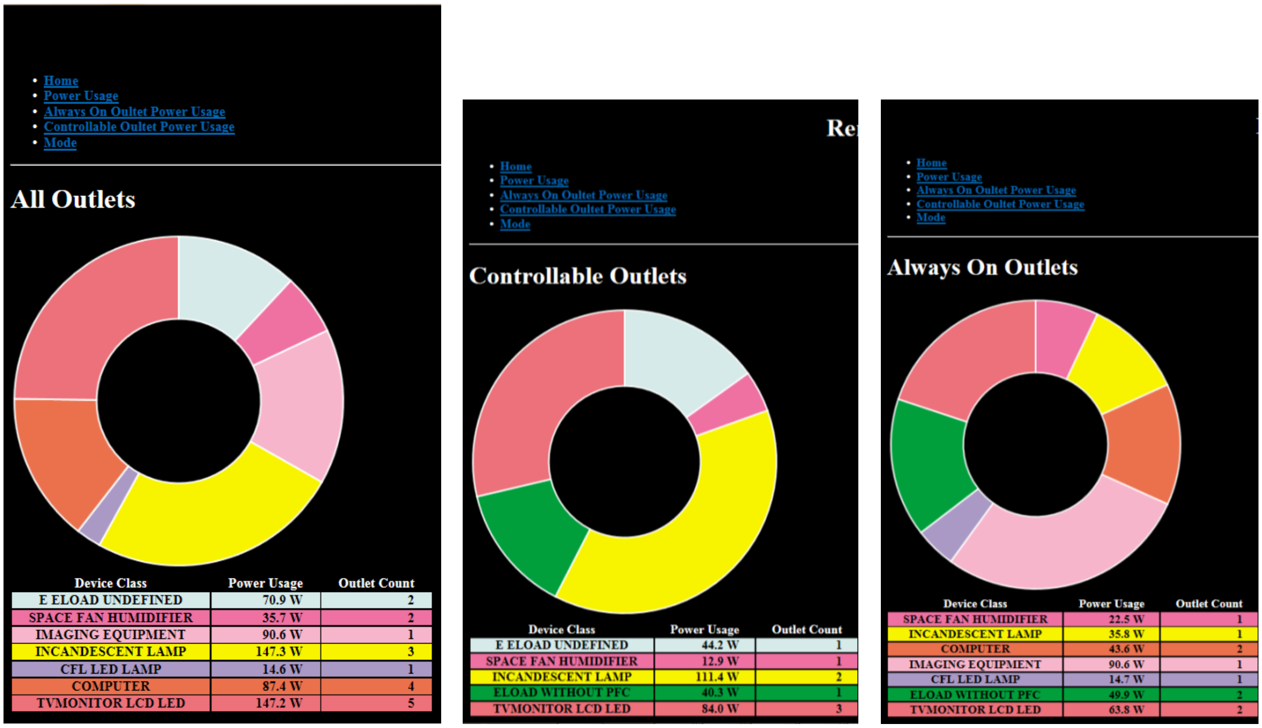
There are also a few other cases, i.e., SR_022841.CLO, SR_02280C.CLO, and SR_0222C5.CLO, where either the relays are open (i.e., OFF) or there is no load connected. The corresponding operating mode results are displayed accordingly.

Finally but not the least, with the automatic load identification, the load connection mapping, as depicted in above figure, can be generated automatically once the appliances are plugged into place. The load connection mapping can also dynamically adapt to any changes of the load connection. For instance, if the user decides to plug a different appliance into the same outlet, the load mapping will be adjusted automatically without any additional manual configuration from the user. In all the existing networked plug-devices on market, mapping load identify to outlet requirements manual configuration, which has been recognized as a very time consuming task. Besides, any changes on the load connection would require the reconfiguration of load mapping. This automatic association between the load identity and outlet device enabled by the automatic load identification greatly helps save money and time on commissioning and re-commissioning of devices, which has been recognized as one of the biggest barriers in Advanced Power Strip adoption on market.

Figure 58 (a) demonstrates another way to visualize the power usage of all the plug-in appliances in the SRs network. Instead of showing the power usage of individual appliance as the traditional plug-monitoring devices do, the developed REMS is able to display the aggregate power usage by device classes. For this test case, there are 18 appliances that are identified in operating mode, and power usage is aggregated together for all the appliances identified with the same Device Class type. The pie chart depicts the power usage breakdown by all the applicable Device Classes in the network. For instance, there are four computers that are identified being in use in the network with a total power consumption of 87.4 Watts. Similarly, there are five TVs/Monitors identified being used with a total power consumption of 147.2 Watts, three Incandescent lamps with total power consumption of 147.3 Watts, and two Space Fans with a total power consumption of 35.7 Watts, etc., in the network. All these appliances are located in different places in the test site, and developed REMS is able to provide an automatic aggregation of power usage with the same Device Class. This solution promotes a totally different view of plug-in loads usage, which is not available via all the existing solutions on market. This solution helps provide a simplified plug-in load monitoring that can help identify high consuming devices with the highest energy reduction potentials from Device Classes perspective. This information is particular useful in a large facility with high plug-in load population. This information can be used to inform awareness programs and possible investments in further procuring plug-in load control and management solutions.

Figure 58 (b) and (c) depict the similar aggregated breakdowns of power usage of appliances by device classes for Always-ON and Controllable outlets respectively. This information would be helpful to identify the potentials and devices that suitable for demand response events.

The total power usage of the SRs network is around 600 Watts. There are around 70 Watts power usage is categorized as undefined electronic loads. From the final Device Class identification perspective, the accuracy of the power aggregation in the Device Class level is 88.2%, and accuracy of the power aggregation in level-1 is then up to 100%.



(a) (b) ©

Figure 58: REMS Web Display – Aggregate Power Consumption by Device Classes and Controllability (Work hours)

Figure 59 below demonstrates the way of visualizing the power usage of all the plug-in appliances in the SRs network by operating modes. The power usage of plug-in appliances is aggregated by the actual operating modes of individual appliances. For this test case, there are 19 outlets that are identified to be plugged with loads that are in operating mode, and one outlet with no load connected, and two outlets with relay switched OFF.

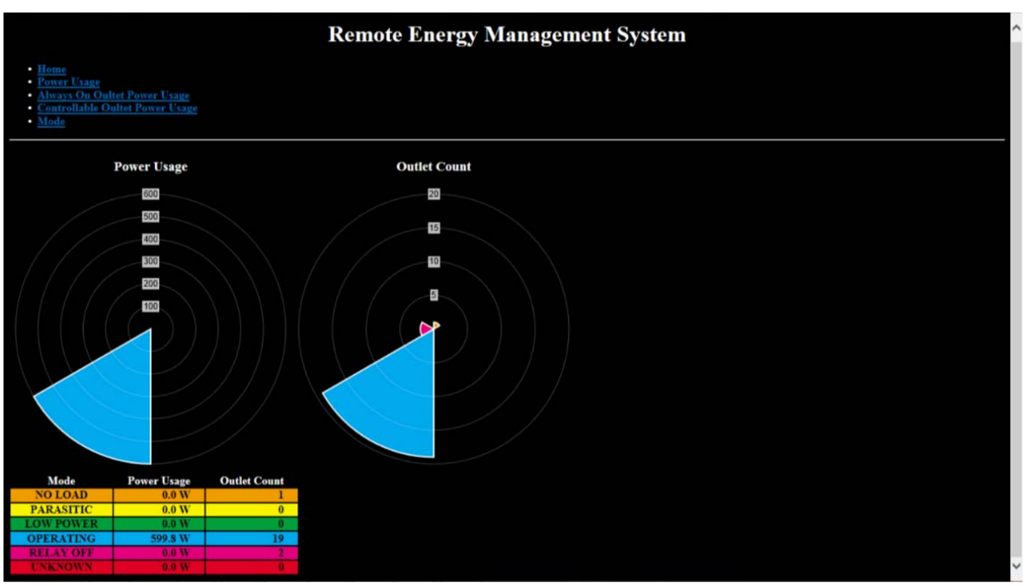
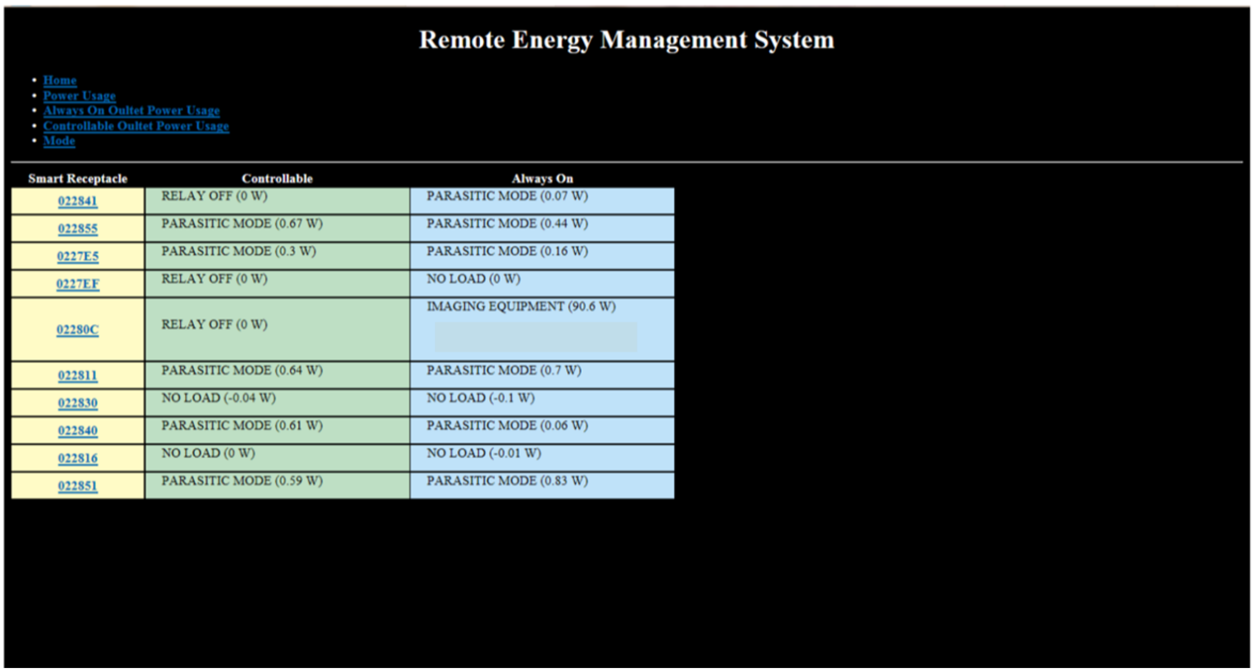


Figure 59: REMS Web Display – Aggregate Power Consumption by Operation Mode

This information is helpful to improve the awareness of plug-in load and outlet utilization, as well as the energy saving potentials during different times of day. This above figure provides the snapshot during working hours when most of the loads are actually in use and in operating mode.

In order to demonstrate the use of this web display and information, another snapshots of the same webpage taken during afterhours are shown in Figure 60 and Figure 61. It can be seen that eleven electronic appliances with soft/electronic power switches turn to Parasitic mode during the afterhours, and five appliances with hard/mechanical power switches turn to NO Load mode. The only exception is the Imaging Equipment, i.e., a networked Multifunctional device, located in the printing room remains active even during afterhours.



Remote Energy Management System

- Home
- Power Usage
- Always On Oultet Power Usage
- Controllable Oultet Power Usage
- Mode

Smart Receptacle	Controllable	Always On
022841	RELAY OFF (0 W)	PARASITIC MODE (0.07 W)
022855	PARASITIC MODE (0.67 W)	PARASITIC MODE (0.44 W)
0227E5	PARASITIC MODE (0.3 W)	PARASITIC MODE (0.16 W)
0227EF	RELAY OFF (0 W)	NO LOAD (0 W)
02280C	RELAY OFF (0 W)	IMAGING EQUIPMENT (90.6 W)
022811	PARASITIC MODE (0.64 W)	PARASITIC MODE (0.7 W)
022830	NO LOAD (-0.04 W)	NO LOAD (-0.1 W)
022840	PARASITIC MODE (0.61 W)	PARASITIC MODE (0.06 W)
022816	NO LOAD (0 W)	NO LOAD (-0.01 W)
022851	PARASITIC MODE (0.59 W)	PARASITIC MODE (0.83 W)

Figure 60: REMS Web Display – Main Page (Afterhours)

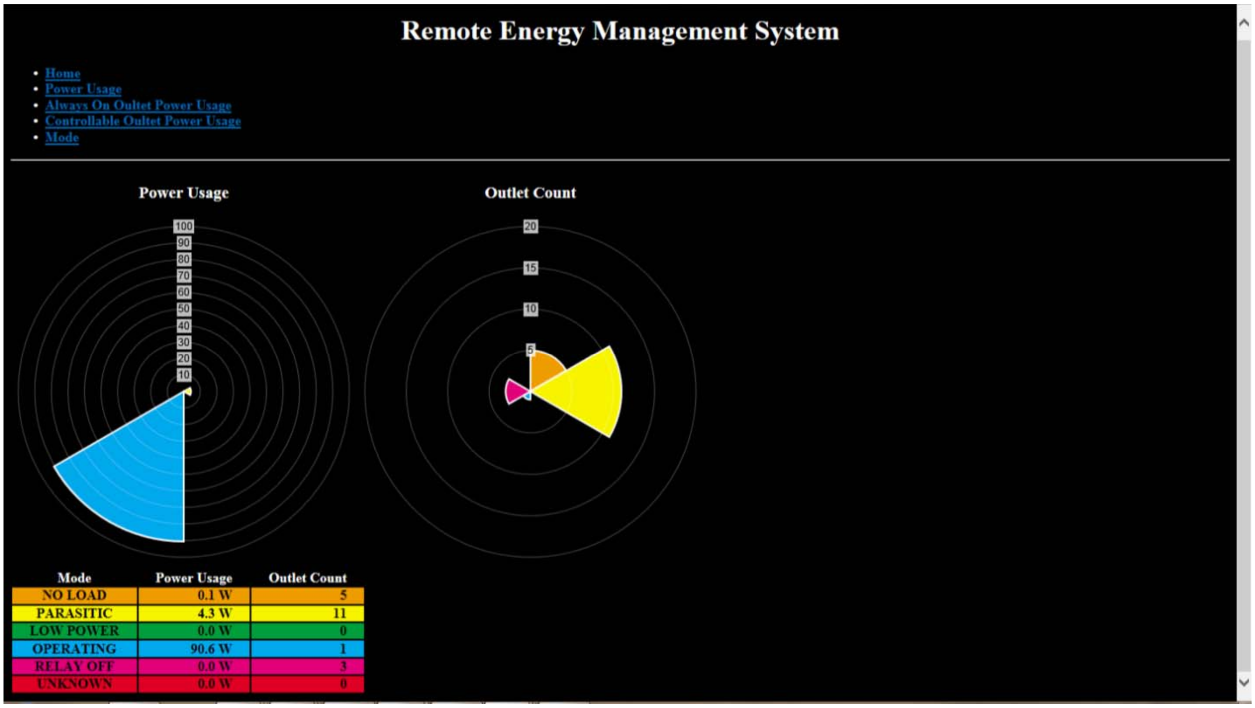


Figure 61: REMS Web Display – Aggregate Power Consumption by Operation Mode (Afterhours)

This second webpage provides a clear visibility to the utilization of the SRs' outlets and plug-in appliances in the network. This information is also helpful to identify the potentials for demand response events.

Easy setup and configuration

With reference to the system diagram of a SRs Network + REMS system shown in Figure 49 in Section 3.4, there are essentially four steps to setup such a system:

- Power up all the Smart Receptacles and set the real-time;
- Plug in all the needed plug appliances and use them as needed;
- Start running the REMS web service on a designated computer to automatically discover all the SR devices in the network;
- Automatically associate the plugged-in appliances to the corresponding SR's outlets.

The first two steps typically take around one minute for each location, e.g., a workstation, a private office, a printing room, etc. These two steps are required by first installation of any types of APSs into place. It usually takes less than five minutes for the REMS web server to discover all the Smart Receptacles in the network. This matches network discovery performance of typical network-based APSs on market.

The major differentiation that the developed prototypes have established under this project lies in the fourth step during the setup and configuration process. As discussed previously, the load identification results for all the plugged-in appliances are available within one minute after they are powered up. These Load ID results provide an association between all the plugged-in appliances to the outlets automatically, and the REMS web service automatically obtains the actual load connection information in the network in real time. With existing network-based APSs, however, this association process requires installers to manually provide the actual load/appliance connection configured for the system. If any load connection changes, the configuration needs to be updated as well. This manual configuration is usually a tedious and time-consuming process, which may take up to couple of hours to set up a system with, say 40 APS devices. This fact has been recognized as one of the major drawbacks from the existing APS solutions.

The experience obtained from various lab and field test demonstrations on the developed Smart Receptacle prototypes, however, suggests that the total setup and configuration of the entire SRs Network + REMS system could take less than half an hour with a deployment scale of 40 SR devices. This greatly simplifies the installation process and reduces the time needed for setup and configuration. The time and cost reduction on initial installation can become more obvious for larger scale of deployment. For instance, manual configuration with existing APSs for a 200 devices network can take up to a day of work. The time needed for automatic appliance-to-outlet association with Load ID information is then independent from the number of devices in the network, but only rely on the availability Load ID results, which is less than a minute. Moreover, there is no re-commissioning and reconfiguration needed, even though load connection changes through time. The load identification information provides automatic updates on the appliance-to-outlet association that minimize the cost for continuous maintenance.

Benefit Assessment and Results

The following individuals provided feedback based on their experience with the developed prototypes and technology through project review discussion and/or answering surveys:

- Eaton’s facility manager who manages a facility of 260,000 ft^2 with around 700 tenants;
- NREL engineers who have experienced various Advanced Power Strips available on the market;
- Eaton’s sustainability and energy service engineer and manager who have strong interests on the sustainability side of a product;
- Eaton’s product line engineering and marketing managers who hold the responsibility of new products development and commercialization;
- University students;
- Eaton’s employees as a regular end-user.

The table below summarizes the resultant average rankings for the four Load ID value elements by four groups of individuals, i.e., facility managers; end-users; energy service engineer/researchers; and product line managers.

Table 37: Load Identification Qualitative Value Assessment

Load ID Value Elements	Facility Managers	End-users	Energy Service engineers/ researchers	Product line managers
Reduce Plug-in loads Energy Consumption	4	3	4	3.5
Avoid disruption/frustration	3	3.3	4.5	4
Simplify set-up/commissioning	5	4.7	4.5	4
Simplify plug load characterization	4	4.7	4	3.5

and monitoring				

In general, the survey shows that the four Load ID value elements have been recognized as valid or even key factors to enable the wide acceptance and adoption of developed plug-in load control and management solution with an average ranking more than 4 out of 5. Facility managers particularly appreciate the improved visibility of plug level loads that provides actionable information with further energy savings potentials. Energy Service engineers think the aggregated energy usage of plug level loads by device classes, operating modes, and their controllability is beneficial in identifying more demand response opportunities. From an end-users' perspective, being aware of load use status and ability to control the load remotely are considered useful features. Besides, minimized nuisance tripping is also considered important.

3.5.4 Summary

Two major goals for the field tests and validations include:

1. Demonstrating and validating load identification algorithm performance with a large load set in a less-controlled environment;
2. Demonstrating and validating values of the developed technology via quantitative and qualitative value assessment.

The successful integration of the developed algorithm into an embedded environment has also demonstrated and proofed the feasibility for a cost-effective plug-in load control and management solution. Over 1,000 tests have been conducted for more than 100 plug-in appliances throughout the course of the project.

- The developed load identification algorithm has demonstrated the performance with the load ID granularity of ten Device Classes.
- The sensitivity performance reaches to up to 85% in average.
- The precisions of operation mode for critical loads can reach to up to 90% in average.

With respect to the validation of value proposition, both quantitative and qualitative analysis and assessments have been conducted during the phase of field tests and demonstration. Quantitative assessment shows that the proposed technology and prototype is able to provide a greater than 10% reduction in plug-level energy consumption through implementation of the SR prototypes. Compared with the existing APSs, the developed Smart Receptacles with integrated load ID are able to obtain moderate improvement of energy savings through automatic control of CLOs under ideal situation.

The major differentiation and benefits that the developed technology essentially brings in are to reduce the offsets and negative impacts from the actual use of the existing solutions. The validated values can be summarized from the four aspects below,

- Improved visibility with actionable information and further saving opportunities identified;
- Reduced negative impact due to potential (perceived) interruption of work flow through 10% reduction of nuisance tripping of SR's CLO control compared to the existing APS control solutions;
- Reduced installation cost by reducing the time spent on initial setup and configuration by at least half. The reduction rate increases further with larger scale of system deployment;
- Reduced ongoing maintenance (re-commissioning) costs due to improved compliance.

3.6 Challenges/Risks Assessment and Mitigation Activities

The major challenges and risks identified under the project include,

- Establish a meaningful plug-in load identification target;
- Load identification algorithm development,
  - particular for electric appliances with similar front-end topologies;
  - Electronic loads with power factor correction and pure resistive loads;
- Understand and establish values of load identification that can add to plug-in load control and management solutions;
- The acceptance of Plug-in loads management to mainstream customers with an attractive financial return.

Table 38 summarizes the identified challenges/risks, activities that have been conducted to mitigate those risks, as well as the major impacts and outcomes. The numbers of associated sections are also highlighted for reference.

Table 38: Challenges Assessment and Mitigation

Challenges and Risks	Mitigation Activities	Impact
Meaningful Load ID target	Market VoC/VoM research to understand the true needs of customers (Section 3.2.2; Section 3.3.2)	Drive the development effort with better focus
Load ID algorithm development particularly for electronic appliances	Plug appliances front-end topology and operating principle study and research (Section 3.3.1); Large scale of current and voltage waveform collection with a focus on electronic appliances. (Section 3.3.3)	Model-driven, hierarchical load identification technology
Load identification value proposition	Market VoC/VoM research to understand the true needs of customers (Section 3.2.2; Section 3.3.2); Literature and market research on existing solutions and current industrial trend to identify the gaps.	Clearly frame out the four value elements of load identification technology for effective plug-in load control and management solutions
Acceptance of plug-in load control and management with attractive financial returns	Drive the development and integration of load identification for a low cost embedded environment (Section 3.4); Lab and field demonstration to audiences with diversified roles (Section 3.5)	Demonstrated cost-effective, functional prototypes;

Eaton's Corporate Research and Technology practices a systematic Project Management process that is applied to all the living projects, including this program, within organization. Risk Assessment and Mitigation planning and execution is one of the key elements within project management process. Eaton's Project Management tools have been effectively deployed to facility efficient execution of the project to meet goals.

4.0 SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary of Findings

According to a variety of referenced reports and our own findings, the energy savings from Advanced Power Strip (APS) usage range from 10-43%. In an office environment where the typical combination of devices consume 1200 kWh per year and the typical electricity rate is $.11/kWh, this translates into $16-57 of annual savings. At $50-$100 dollars per installed APS, this translates into a payback period of 10.5 months to 10 years.

Barriers to APS Adoption for Plug-in Load Control and Management

Other investments/priorities: In isolation, a six year payback on an energy savings measure can appear to be attractive. But in practice such investments must be made in the context of fund limitations and competing spending priorities which often have shorter payback.

Non-energy investments: Building owners and managers, use breakeven time as a metric to screen and prioritize investments. Unless they are particularly motivated by environmental stewardship, business and consumers will evaluate energy savings investments along with other investments such as facilities improvements. Research suggests that typical breakeven hurdles for building investments range from three to five years for commercial entities and four to six years for government entities, well below the results obtained from the use of APSs in many situations.

Faster payback energy efficiency measures: Even if a business is committed to energy conservation, it will sort potential investments based on break-even time. Several energy conservation measures including more efficient lighting and more efficient HVAC equipment currently offer faster return on investment than use of APSs as measured by break-even time.

Competition from alternative plug load energy reduction approaches: In addition to advanced power strips, there are other commonly known means to limit plug load power consumption. In the short run, the energy consumption of existing devices can be managed by techniques including.

- Changing user behavior through awareness programs
- Managing certain devices (such as computers and printers) with network based power management software
- Use of embedded branch circuit controls

None of these techniques require purchase of dedicated hardware.

In the long run, plug load energy can be reduced by improving the devices themselves. The power consumption of computers and displays has been decreasing steadily as result of improvements in semiconductor efficiency and internal power management systems.

Difficulty using current generation of APS devices: Published results, as well as interviews performed by the team, indicate that the current generation of APSs is inconvenient to use. In particular users express frustration with the time required to set up advanced power strips and the work interruptions that result from inappropriate control algorithms and/or inaccurate operation of APS sensors. It does not take much lost work time due to APS use to offset the energy savings from APS. Indeed use case studies by the SPI/Eaton team indicate that lost productivity can offset the estimated energy savings.

These frustrations result in disuse of existing APS as well as negative word-of-mouth which limits adoption.

Uncertain savings: Whereas energy conservation measures such as efficient lighting have predictable outcomes, the savings from use of APSs depend on several factors including the mix of devices attached to each strip, the schedule of the user, and the degree to which the user adheres to use of controlled outlets. As noted earlier, there is wide variation in range of resulting savings and, occasionally, negative savings.

Key Success Factors for APSs

Automated Load Identification (ID): By automatically identifying attached devices plugged into each outlet, installation and commissioning costs would be lower. It would also be an enabler for self-configuration (SC) where installation and commissioning would be fully automated.

Automatic Load identification would also support analysis and building/energy managers by identifying loads that are candidates for replacement or outright prohibition.

Finally Automated Load Identification would support application of appropriate control algorithms to minimize damage to devices and/or loss of end-user productivity.

Outlet Level Monitoring (MON): Outlet Level Monitoring supports Adaptive Control (see below) by accumulating detailed usage pattern information on each device. Outlet level monitoring also has intrinsic value including the ability to monitor devices individually or by class in order to inform energy management usage. Finally outlet level monitoring (combined with ID) supports awareness of devices suitable for demand response.

Adaptive Control (AC): Adaptive control is the concept of striking the best balance of user convenience and energy savings by monitoring and responding to patterns in user behavior. For example, if the user has a pattern of leaving their desk for frequent short breaks during the day, an adaptive control algorithm would avoid shutting down peripherals after a short period of time so as to have all devices available when the user returns to their desk. Load Identification and Outlet Level Monitoring are prerequisites for Adaptive Control. The ability to accumulate time series of energy consumption associated with specific devise type and correlate this information with indicators of user behavior and the energy consumption of related devices would provide the raw data necessary to the development of adaptive control algorithms that are customized to the current behavior of each user. Note that the derivation of Adaptive Control is beyond the scope of this report.

Self-Configuration (SC): Self configuration describes the concept that devices plugged into smart strips could automatically announce their identity (type) and location to a monitoring network and complementary energy management software. This would significantly lower installation costs and inadvertent inconvenience to users based on out-of-date information regarding device types and locations on the network. Note that Automatic Load Identification is a prerequisite for Self Configuration.

Value of Load Identification on Plug-in Load Control and Management

The ability to automatically identify loads promises to overcome some of the barriers to advanced power strip adoption.

Avoid disruption/frustration: In standalone use of APSs, miscellaneous load identification ensures that the appropriate control strategy is applied to each device plugged into the power strip. This avoids inappropriate denial of power to devices which could lead to user inconvenience and/or device damage.

Simplify set-up/commissioning: In networked applications load identification serves to reduce user frustration associated with set-up as there is no need to manually map loads to outlets for the purpose of interfacing with energy monitoring software.

Simplify plug load characterization and monitoring: Time series (Aggregate) information regarding energy consumption by device type could be used to inform awareness programs and possible investments in permanent plug load management hardware. This information can also be used to adaptively modify algorithms to maximize energy savings while conforming to occupant usage patterns. APSs with load identification could also be temporarily installed in a workplace to characterize the install of plug loads and monitor their energy consumption.

Load Identification Technology Development

Plug-in Load Taxonomy and Identification Target: There are numerous types of plug-in loads/appliances on the market. The amount today can go up to 1,000. It becomes technically challenging to identify and distinguish all the plug-in appliances from one type to another. It is very important to establish a plug-in appliances taxonomy that drives a meaningful load identification development target that can provide values to customers.

Moreover, how to translate the value proposition and the Key Success Factors to a meaningful and measurable load identification performance metrics is also critical. The definition of ID target and performance metrics is essential to help frame the technology development focus as well as to analyze and assess the technical feasibility during the course of the project.

Load Identification Algorithm Development: Load identification technology development needs are also being driven by a feasibility and sensitivity study. One of the biggest issues that is not yet addressed by most researchers is there is not a guideline available to drive an optimized feature selection for load identification. Almost all the approaches disclosed in literature are based on a data-driven approach, where the load distinction has only been addressed via a statistical analysis of the available dataset. The connections between the utilized features and the load's physical circuit topology have never been explicitly addressed and analyzed. This particularly presents challenges to ensure a reliable identification performance and effectiveness for loads with similar electronic front-ends, e.g., various office electronic equipment, and/or audio/video equipment, etc.

Therefore, a model-driven, hierarchical plug-in load identification approach has been proposed and developed to enable an optimized and scalable load identification solution. One of the most important advantages of topology research in a classification problem is to reduce the complexity of the feature space.

Load Identification Algorithm Employment: There are a few important practical issues that have been learned through the literature survey and the algorithm development process, whose importance was not recognized and understood initially at the beginning of the project. These two issues are directly related to how the actual users' behavior may consequently impact the effectiveness of real-time implementation of the developed load identification algorithm.

As one of the major tasks for load ID algorithm development, a reliable detection and identification for actual operating status of the plugged-in devices also brings a lot of development interests and challenges. Reliable detection of Operating Mode provides customers the visibility of the load energy/power usage by Operating Modes. This information provides a direct visibility to energy saving potentials as well as demand respond opportunities. It also provides important prerequisite information for a reliable load identification particularly for the real-time implementation. A reliable Operating Mode detection also ensures reliable control (or a safe turn-OFF) of plug-in loads, in particular, the critical loads, with minimized potential damage to the devices and negative impacts to users. In another words, it helps to minimize the unnecessary nuisance trip when the plugged-in loads, especially critical loads, are to be turned-off.

4.2 Benefits Assessment

In the field of plug-in load control and management, users/human interference plays an important role to enable the effectiveness of the offerings. Typically, commercial building occupants are unaware of their energy use. Occupant behavior and equipment are the driving forces behind energy use. Occupants need to be aware of how their energy use affects the building's overall performance. This awareness drives people to eliminate items that waste energy and are unnecessary. This project has been pioneering in looking at the feasible and cost-effective solutions to address this issue, i.e., the effectiveness of a plug-in load control and management solution.

Through field tests and use case studies, both quantitative and qualitative analysis and assessment have been conducted to establish and validate the differentiation that the developed technology can offer. The value assessment has not only focused on the direct energy savings, but also targeted on the convenience of use and users' acceptance. The later factors are essential to enable true adoption and compliance of plug-in load control and management solutions, and consequently enable/improve the *actual* energy savings from plug-in load power consumption.

Quantitative assessment shows that the proposed technology and prototype is able to provide a greater than 10% reduction in plug-level energy consumption through implementation of the SR prototypes. Compared with the existing APSs, the developed Smart Receptacles with integrated load ID are able to obtain improved energy savings through automatic control of CLOs.

The major differentiation and benefits, which the developed technology essentially brings, are to reduce the offsets and negative impacts from the actual use of the existing solutions. The validated value can be summarized per the aspects below,

- Improved visibility with actionable information and further saving opportunities identified;
- Reduced negative impact due to potential (perceived) interruption of work flow through 10% reduction of nuisance tripping of SR's CLO control compared to the existing APS control solutions;

- Reduced installation cost by reducing the time spent on initial setup and configuration by at least half. The reduction rate increases further with larger scale of system deployment.
- Reduced ongoing maintenance (re-commissioning) costs due to improved compliance.

4.3 Conclusions and Recommendations

In response to U.S. Department of Energy (DoE)'s goal of achieving market ready net-zero energy residential and commercial buildings by 2020 and 2025, Eaton partnered with the Department of Energy's National Renewable Energy Laboratory (NREL) and Georgia Institute of Technology to develop an intelligent load identification and management technology enabled by a novel "smart power strip" to provide critical intelligence and information to improve the capability and functionality of building load analysis and building power management systems.

Even though the developed technology is applicable for both residential and commercial buildings, this project focused on effective plug-in load control and management for commercial buildings, accomplished through effective load identification. The project completed Smart Receptacle (SR) prototype development with integration of Load ID, Control/Management, WiFi communication, and Web Service. Twenty SR units were built, tested, and demonstrated in an Eaton lab; eight SR units were in National Renewable Energy Lab (NREL) for one-month of field testing. Load ID algorithm testing for extended load sets was conducted within Eaton facility and a local university campus. A SRs-network + REMS system has been installed at Eaton facility in Milwaukee for a continuous live demonstration.

The major contributions from this project include,

- This project identified the Key Success Factors, and the values of the developed Load Identification technology that enables an *effective* plug-in load control and management solution, which can be widely adopted by customers; A Value Model was established for plug load control and management to quantify the major value drivers. This value model does not only include the direct energy savings, but also considers the convenience of use and users' acceptance.
- This project established a hierarchical plug-in load taxonomy through comprehensive plug-in appliances research, including appliance usability; front-end topology; and operating principles. This taxonomy provides a guideline for a model-driven, hierarchical plug-in load identification development with an optimized and scalable performance. One of the most important advantages of this hierarchical load ID approach is to reduce the complexity of the feature space, and enable a simple, cost-effective, embedded load ID solution.
- This project has developed a web-service based Remote Energy Management System that serves as platform to demonstrate the major values of the developed technologies, in particular, load identification technology, in a network and building level.

There are several areas that are worthwhile being investigated as recommendations for future work.

Load ID Challenges: The developed load identification technology has demonstrated its performance meeting the requirements, however, there are still several challenges and open issues that need to be further investigated. One of the biggest challenges is to handle new plug-in appliances that continuously enter the market. If continuous updates of the embedded load ID software is required frequently, this potentially compromises the user's acceptance to the solution. As one potential solution, a certain self-learning mechanism, by which contextual cues and temporality of load usage can be obtained, can be included into the load identification algorithm. The algorithm is then updated automatically and subject to any changes with new loads being used.

While Load identification can help to overcome barriers to advanced power strip adoption, the following additional conditions for success need to be further considered.

Price: In order to achieve prevailing hurdles applied by building decision makers, the price of smart power strips must be low enough to result in significantly faster payback times than a typically achieved today. Prices must continue to decline as the efficiency of plug load devices steadily increases, and the savings from control declines. This requires further simplification and optimization of the developed technology.

Ease/simplicity of use: While load identification should help to simplify set-up and apply appropriate control strategies, it is not clear that this would reduce enough lost time to make smart power strips an attractive investment. Prescriptions for achieving sufficient ease-of-use are beyond the scope of this study. Suffice it to say future APSs with broad appeal will likely reflect the insights gained from a thorough usability analysis. A demonstration project is suggested to champion the technology into several lead users/buildings to further evaluate the functionality and features developed and to demonstrate this in a less controlled environment with larger sets of diversity.

5.0 PRODUCTS DEVELOPED

Publications:

1. D. He, L. Du, Y. Yang, R. G. Harley, and T. G. Habetler, “Front-End Electronic Circuit Topology Analysis for Model-Driven Classification and Monitoring of Appliance Loads in Smart Buildings,” Smart Grid, IEEE Transactions on , vol.3, no.4, pp.2286-2293, Dec. 2012.
2. D. He, L. Du, Y. Yang, R. G. Harley, and T. G. Habetler, “Electronic Circuit Survey for Office Load Monitoring and Identification”, Energy Conversion Congress and Exposition (ECCE), 2012 IEEE , pp.1228-1232, 15-20 Sept. 2012.
3. L. Du, Y. Yang, D. He, R. G. Harley, T. G. Habetler, and B. Lu, “Support vector machine based methods for non-intrusive identification of miscellaneous electric loads”, IECON 2012 – 38th Annual Conference on IEEE Industrial Electronics Society, pp.4866-4871, 25-28 Oct. 2012
4. L. Du, D. He, et.al, “Self-Organizing Classification and Identification of Miscellaneous Electric Loads”, Power and Energy Society General Meeting, 2012 IEEE, pp.1,6, 22-26 July 2012, San Diego, CA, USA.

Technologies/Techniques:

1. A nonintrusive, intelligent load modeling, identification and prediction technology that can automatically determine the type, energy consumption, power quality, operation status and performance status of plug-in loads, using electric waveforms at a power outlet level. This technology uses Model-Driven, Hierarchical Load Identification technology. a hierarchical model for plug-in loads based on the front-end topology and operating principle research; Developed and implemented an Event-Driven, Hierarchical, Model-based Load Identification technology.
2. Load Identification based Plug-in Loads Control and Management solution that provides an autonomous association between the loads being managed/monitored and product offerings, e.g., Smart Receptacles, or other plug devices.

Inventions/Patent Applications, licensing agreements:

1. "System And Method Employing a Hierarchical Load Feature Database to Identify Electric Load Types of Different Electric Loads", U.S. patent applied in November 28, 2011, U.S. Patent Application Serial No. 13/304,783.
2. "System and Method Employing a Self-Organizing Map Load Feature Database to Identify Electric Load Types of Different Electric Loads", U.S. patent applied in November 28, 2011, U.S. Patent Application Serial No. 13/304,758.
3. "System and Method Employing a Minimum Distance and a Load Feature Database to Identify Electric Load Types of Different Electric Loads", U.S. patent applied in November 28, 2011, U.S. Patent Application Serial No. 13/304,834.
4. "System and Method for Electric Load Identification and Classification Employing Support Vector Machine", U.S. patent applied in August 29, 2012, U.S. Patent Application Serial No. 13/597,324.
5. “Method and System Employing Finite State Machine Modeling to Identify One of a Plurality of Different Electric Load Types”, U.S. patent applied in June 3, 2013, U.S. Patent Application Serial No. 13/908,263.

6. “Method and System Employing Graphical Electric Load Categorization to Identify One of a Plurality of Different Electric Load Types”, U.S. patent applied in June 7, 2013, U.S. Patent Application Serial No. 13/912,819.
7. “System and Method for Instantaneous Power Decomposition and Estimation”, U.S. patent applied in June 18, 2013, U.S. Serial No.: 13/920,602
8. “System and Method Employing a Self-Organizing Map Load Feature Database to Identify Electric Load Types of Different Electric Loads”, U.S, Patent issued on JUNE 17, 2014, U.S. Patent No. 8,756,181.
9. “System And Method To Characterize And Identify Operating Modes Of Electric Loads”, Invention Disclosure.
10. “System Architecture For Embedded Real-Time Implementation Of Hierarchical Load Identification Algorithms”, Invention Disclosure.
11. “Load Identification Based Loads Control And Management In Buildings”, Invention Disclosure.

Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment.

1. Database:
   a. Plug-in Loads Current/Voltage Waveforms and Features Database
   b. VoC/VoM interviews database
   c. Plug-in Load Identification Quantified Value Model
2. Hardware:
   a. NI LabVIEW based DAQ module
   b. Smart Power Strip Gen-1 Prototype
   c. Smart Receptacle Gen-2 Prototype
3. Software:
   a. Hierarchical Load ID MATLAB code for Offline analysis
   b. Hierarchical Load ID firmware code for SR Gen-2 prototype
   c. STM firmware for data management, WiFi communication, and webpage service
   d. Smart Receptacle Webpage JAVA script
   e. REMS PC-based web service software

6.0 COMPUTER MODELING

NA

References

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APPENDICES

Appendix A Load Identification Load Tests Distribution

Total 866 tests.

Load Category	Load Model	No. of Tests
RESISTIVE	27	137
REACTIVE	59	176
TRANSFORMER	13	30
MICROWAVE	10	87
ELOAD_WITH_PFC	31	141
ELOAD_WITHOUT_PFC	94	274
PAC	3	21

Resistive Loads:

Appliances Type	No. of Appliance Models	Target IDs
Incandescent lamp	13	Incandescent lamp
Iron	2	Heating Appliances
Space Heater	6	
Hairdryer	2	
Bread toaster	1	
Electric Skillet	1	
Coffee Maker	2	

Reactive Loads:

Appliances Type	No. of Appliance Models	Target IDs
Fluorescent lamp	13	Fluorescent lamp
Fan/Humidifier	9	Fan/Humidifier

Microwave:

Appliances Type	No. of Appliance Models	Target IDs
Microwave	23	Microwave

Transformer (Small electronic devices with linear power supply)

Appliances Type	No. of Appliance Models	Target IDs
Power Adapter	7	Small Electronics with Linear Power Supply
Charger	1	Charger

P (Electronic loads with power factor correction):

Appliances Type	No. of Appliance Models	Target IDs
Desktop	4	Computer
Laptop	3	
LCD/LED TV	6	Screen
Projector	12	Projector
Printer/copier/multifunctional devices	9	Imagine Equipment

NP (Electronic loads without power factor correction):

Appliances Type	No. of Appliance Models	Target IDs
Desktop	10	Computer
Laptop	14	
LCD/LED TV	15	Screen
LCD/LED PC monitor	32	
CRT monitor	2	CRT Monitor
CFL/LED Lamp	9	Lamp
Charger	3	Battery Charger
Printer/copier/multifunctional devices/scanner	34	Imagine equipment
Speaker	1	E-Others
DVD Player	16	
Set Top Box	2	
Portable hard drive	1	

PAC:

Appliances Type	No. of Appliance Models	Target IDs
Incandescent with Dimmer	3	Dimmer
Heating Appliances with Dimmer	2	Heating Appliances

Appendix B Level-1 Categorization Performance Results

Total Counts: 2566839

R: Total = 421382

Total		421382	2063595		
		P	N		
P’	403812	**403215**	**597**	**0.999**	Precision
N’	2081165	**18167**	**2062998**	**0.991**	PNR
		0.957	**1.000**		
		Sensitivity	Specificity		

FP: **T**
FN: **PAC**

X: Total = 324744

Total		324744	2160233		
		P	N		
P’	329366	**306742**	**22624**	**0.931**	Precision
N’	2155611	**18002**	**2137609**	**0.992**	PNR
		0.945	**0.990**		
		Sensitivity	Specificity		

FP: **P, NP, PAC, T**
FN: **M, P, T**

M: Total = **129152**

Total		129152	2355825		
		P	N		
P’	117381	**106715**	**10666**	**0.909**	Precision
N’	2367596	**22437**	**2345159**	**0.991**	PNR
		0.826	**0.995**		
		Sensitivity	Specificity		

FP: **T, X**
FN: **PAC**

T: Total = 32765

Total		25621	2459356		
		P	N		
P’	53870	**22369**	**31501**	**0.415**	Precision

N'	2431107	3252	2427855	0.999	PNR
		0.873	0.987		
		Sensitivity	Specificity		

FP: **X**

FN: **M, NP, P, R, X**

NP: Total = 835601

Total		835601	1649376		
		P	N		
P'	816157	813381	2776	0.997	Precision
N'	1668820	22220	1646600	0.987	PNR
		0.973	0.998		
		Sensitivity	Specificity		

FP: **P, PAC, X**

FN: **P, X**

P: Total = 720512

Total		720512	1764465		
		P	N		
P'	739174	716348	22826	0.969	Precision
N'	1745803	4164	1741639	0.998	PNR
		0.994	0.987		
		Sensitivity	Specificity		

FP: **NP, T, X**

FN: **NP, X**

PAC: Total = 27965

Total		27965	2457012		
		P	N		
P'	25217	16702	8515	0.662	Precision
N'	2459760	11263	2448497	0.995	PNR
		0.597	0.997		
		Sensitivity	Specificity		

FP: **M, R**

FN: **NP, X**

Appendix C Operating Mode Detection Performance Results

Total Counts: 1718906

M1: Total = 1367964

Total		1367964	350942		
		P	N		
P’	1384697	1361318	23379	**0.983**	Precision
N’	334209	6646	327563	**0.980**	PNR
		0.995	**0.933**		
		Sensitivity	Specificity		

M3: Total = 195671

Total		195671	1523235		
		P	N		
P’	185839	178171	7668	**0.959**	Precision
N’	1533067	17500	1515567	**0.989**	PNR
		0.911	**0.995**		
		Sensitivity	Specificity		

M4: Total = **155271**

Total		155271	1563635		
		P	N		
P’	148370	143864	4506	**0.970**	Precision
N’	1570536	11407	1559129	**0.993**	PNR
		0.927	**0.997**		
		Sensitivity	Specificity		

Appendix D E-Load Level2-ID Results

E-load: Total = 1101 for All Operations

Charger: Total =6

Total		6	1096		
		P	N		
P’	7	**4**	**3**	**0.571**	Precision
N’	1095	**2**	**1093**	**0.998**	PNR
		0.667	**0.997**		
		Sensitivity	Specificity		

Computer: Total = 349

Total		349	753		
		P	N		
P’	340	**334**	**6**	**0.982**	Precision
N’	762	**15**	**747**	**0.980**	PNR
		0.957	**0.992**		
		Sensitivity	Specificity		

Imaging Equipment: Total = 279

Total		279	823		
		P	N		
P’	283	**270**	**13**	**0.954**	Precision
N’	816	**6**	**810**	**0.993**	PNR
		0.968	**0.984**		
		Sensitivity	Specificity		

Projector: Total = 64

Total		64	1038		
		P	N		
P’	63	**63**	**0**	**1.000**	Precision
N’	1038	**0**	**1038**	**1.000**	PNR
		0.984	**1.000**		
		Sensitivity	Specificity		

Lamp: Total = 52

Total		52	1050		
		P	N		
P’	52	**52**	**0**	**1.000**	Precision
N’	1050	**0**	**1050**	**1.000**	PNR
		1.000	**1.000**		
		Sensitivity	Specificity		

Monitor/Screen: Total = 232

Total		232	870		
		P	N		
P’	239	**230**	**9**	**0.962**	Precision
N’	863	**2**	**861**	**0.998**	PNR
		0.991	**0.990**		
		Sensitivity	Specificity		

CRT Monitor: Total = 4

Total		4	1098		
		P	N		
P’	2	**2**	**0**	**1.000**	Precision
N’	1100	**2**	**1098**	**0.998**	PNR
		0.500	**1.000**		
		Sensitivity	Specificity		

E-Others: Total = 115

Total		115	986		
		P	N		
P’	144	**111**	**33**	**0.771**	Precision
N’	957	**4**	**953**	**0.996**	PNR
		0.965	**0.967**		
		Sensitivity	Specificity		

Appendix E R-Load Level2-ID Results

R-load: Total = 64 for FirstTimeOperation

Incandescent Lamp: Total = 18

Total		18	46		
		P	N		
P’	18	**18**	**0**	**1.000**	Precision
N’	46	**0**	**46**	**1.000**	PNR
		1.000	**1.000**		
		Sensitivity	Specificity		

Heating Appliances: Total = 46

Total		46	18		
		P	N		
P’	46	**46**	**0**	**1.000**	Precision
N’	18	**0**	**18**	**1.000**	PNR
		1.000	**1.000**		
		Sensitivity	Specificity		

Appendix F X, T, and M-Load Level2-ID

X-load: Total = 298 for FirstTimeOperation

Florescent Lamp: Total = 26

Total		26	272		
		P	N		
P’	26	**25**	**1**	**0.962**	Precision
N’	271	**1(0)**	**271**	**1.000**	PNR
		0.962	**0.996**		
		Sensitivity	Specificity		

Power Adapter: Total = 12

Total		12	286		
		P	N		
P’	12	**12**	**0**	**1.000**	Precision
N’	286	**0**	**286**	**1.000**	PNR
		1.000	**1.000**		
		Sensitivity	Specificity		

Fan/Humidifier: Total = 13

Total		13	285		
		P	N		
P’	16	**12**	**4**	**0.750**	Precision
N’	281	**1(0)**	**281**	**1.000**	PNR
		0.923	**0.986**		
		Sensitivity	Specificity		

Microwave: Total = 29

Total		29	269		
		P	N		
P’	29	**29**	**0**	**1.000**	Precision
N’	269	**0**	**269**	**1.000**	PNR
		1.000	**1.000**		

		Sensitivity	Specificity		

Refrigerator: Total = 190

Total		190	108		
		P	N		
P’	179	**179**	**0**	**1.000**	Precision
N’	119	**11**	**108**	**0.908**	PNR
		0.942	**1.000**		
		Sensitivity	Specificity		

Shredder: Total = 15

Total		15	283		
		P	N		
P’	17	**14**	**3**	**0.824**	Precision
N’	284	**1**	**283**	**0.996**	PNR
		0.933	**1.000**		
		Sensitivity	Specificity		

X-Others: Total = 12

Total		12	286		
		P	N		
P’	16	**12**	**4**	**0.750**	Precision
N’	282	**0**	**282**	**1.000**	PNR
		1.000	**0.986**		
		Sensitivity	Specificity		

Charger: Total = 1

Total		1	297		
		P	N		
P’	1	**1**	**0**	**1.000**	Precision
N’	297	**0**	**297**	**1.000**	PNR
		1.000	**1.000**		
		Sensitivity	Specificity		

Appendix G Power Profiles of Field Test Sites

Eaton Facility

The Eaton facility has around 270 tenants in the building, where there are around 40 tenants in CRT area. The electricity is at cost of 10.63 cents/kWh. The electricity energy consumption is highlighted in the table below.

Building Segment	Standard/ On-Peak Usage (kWh)	Off-Peak Usage (kWh)	Total Usage (kWh)	Total Electric (Metered) Charges
Average Monthly Consumption - Office	28233	29247	57480	$ 6,114.56
Average Monthly Consumption - Labs	37760	60325	98085	$ 10,826.68
Estimated (25%) GRT Monthly Consumption - Office	7058	7312	14370	$ 1,528.64
Estimated (25%) GRT Monthly Consumption - Labs	9440	15081	24521	$ 2,706.67
Total estimated GRT Monthly Consumption	16498	22393	38891	$ 4,235.31

In the CRT office environment, there is one multifunctional device that is shared by approximately 40 users on average. There are only two workstations that have their own single-user machines. Additional equipment in the previously occupied workstations included task lights, a phone, and miscellaneous items such as cell phone chargers, earphone chargers, lights (decorative or functional, or both), mini refrigerators, coffee ports, electric tea pots, fans, personal heaters, label makers, and radios. It is noted that, in the Eaton facility, almost all the tenants are using laptop computers, and the computers are taken away with users during afterhours. The PC monitors go to sleep mode automatically, when they are not connected to PCs.

In the kitchen area, the Eaton facility offers amenities, including coffee kiosk, ice machines, and vending machines. The coffee machine and water heater are left powered 24/7. The coffee machine had a continuous average load of 1000 W. Multiple glass-front refrigerators are used to store food and cold drinks. Overall, the kitchen area has an average continuous load of nearly 3000W.

Private Office

Load Types	Power Consumption (W)		
	Active	Idle	Parasitic
Monitors (2)	18.5	-	0.2
Laptop Computer (1)	35.4	-	0.2
Printer (1)	54.7	4.3	-
DVD Player (1)	5.8	0.5	
HDMI Adapter (1)	3.4	-	0.5
Electronic white board (1)	51.2	-	0.2
Shredder (1)	278.6	-	0.2

Work Station-1

Load Types	Power Consumption (W)		
	Active	Idle	Parasitic
Monitors (2)	18.4	-	0.2
Laptop Computer (1)	36.3	-	1.3

Work Station-2

Load Types	Power Consumption (W)		
	Active	Idle	Parasitic
Monitors (2)	25.1	-	0.6
Laptop Computer (1)	24.7	-	0.3

Printing Room

Load Types	Power Consumption (W)		
	Active	Idle	Parasitic
Multifunctional Device (1)	492.8	97.1	19.7
Shredder (1)	278.6	1.7	-
Heat sealer (1)	900	-	1.1
Electric puncher (1)	10	-	1.6

Kitchen

Load Types	Power Consumption (W)		
	Active	Idle	Parasitic
Microwave (4)	1485	-	2.2
Ice Machine (1)	1014	4.3	-
Vending Machine (3)	276.6	37.5	-

NREL RSF Facility

The following provides a brief building profile of NREL Research Support Facility (RSF) in Golden, Colorado

- Building Size: 220,000 ft^2 (20, 438 m^2);
- Built Year: 2010;
- Number of Occupants: 1000
- Number of Workstations: 1000
- Accessible rooms: working stations; private offices; conference rooms, print rooms, kitchen areas.
- The facility represents a high efficient building that has practiced very aggressive energy conservation measures.
- LEED building platinum;

In NREL's RSF building, tremendous effort has been made to reduce plug and process loads to achieve load energy office building. As suggested in the report, to meet the building energy goal, Plug-in loads have been reduced by approximately 50%. The methodology and reduction strategy that NREL researchers have developed to identify and reduce plug-in loads include,

- Maximizing space efficiency in shared areas;
- Purchasing high efficient appliances, including LED lights, refrigerators, LCD monitors, etc. and eliminating mechanically cooled drinking fountains;
- Applying power management surge protectors, i.e., an APS;
- Applying energy saving strategies on workstation equipment,
- Applying management and safety policies disallow the use of personal equipment at individual workstations.

Some researchers in the RSF building need to leave their computers powered on during unoccupied hours so they could remotely run simulations. The workstations are configured to use wake-on-local area network functionality. Therefore, their computers are left in standby mode and are accessed remotely.

Private Office - 3

Load Types	Power Consumption (W)		
	Active	Idle	Parasitic
Monitors (2)	11.4	-	0.5
Laptop Computer (1)	31.2	-	0.5
LED lamp (1)	8.5	-	0.4

Private Office - 4

Load Types	Power Consumption (W)		
	Active	Idle	Parasitic
Monitors (1)	6.1	-	0.7
Computer (1)	43.9	-	0.3

Laptop Computer (1)	23.3	-	0.4
Charger (1)	11.81		0.3

Work Station-1

Load Types	Power Consumption (W)		
	Active	Idle	Parasitic
Monitors (2)	18.2	-	0.5
Laptop Computer (1)	30.6	-	0.2
LED lamp (1)	8.5	-	0.4

Work Station-2

Load Types	Power Consumption (W)		
	Active	Idle	Parasitic
Monitors (2)	11.4	-	0.5
Laptop Computer (1)	24.3	-	1.7
LED lamp (1)	8.5	-	0.8

UWM Campus

The team was not able to obtain building profile information for the University of Wisconsin, Milwaukee (UWM) campus in Milwaukee, Wisconsin.

Through the testing process, it has been observed that the UWM facility under test consists of older version of plug appliances compared to the other two buildings under testing. Therefore, the energy saving potentials are relatively higher than the other two field sites.

Private Office

Load Types	Active	Idle	Parasitic
Desktop Computer (1)	51	-	1
Monitor (1)	20.7	-	0.5
Scanner-1 (1)	5.1	2	-
Printer-1 (1)	600	15	-

Appendix H Energy Savings and Nuisance Trips Performance Assessment of Field Test Sites

Eaton Facility

Private Office					
	Baseline	Time Scheduling	Load Power Sensing (1.5W)	Load Power Sensing (5W)	Load ID based Control
Energy Consumption Total (kWh/week)	4.302	3.644	4071.9	3.552	3.552
Energy Consumption Work-hours (kWh/week)	3.521	3.521	3.521	3.521	3.521
Energy Consumption Afterhours (kWh/week)	0.781	0.122	0.55	0.030	0.030
Weekly Reduction Percentage (%)	-	15.3%	5.4%	17.4%	17.4%
Nuisance trips Occurrences rate (%)	-	0	0	16.3%	8.1%

Work Station - 1					
	Baseline	Time Scheduling	Load Power Sensing (1.5W)	Load Power Sensing (5W)	Load ID based Control
Energy Consumption Total (kWh/week)	1.848	1.686	1.664	1.664	1.664
Energy Consumption Work-hours (kWh/week)	1.656	1.656	1.656	1.656	1.656
Energy Consumption Afterhours (kWh/week)	0.192	0.03	0.008	0.08	0.08
Weekly Reduction Percentage (%)	-	8.8%	10%	10%	10%
Nuisance trips Occurrences rate (%)	-	0	0	0	0

Work Station – 2					
	Baseline	Time Scheduling	Load Power Sensing (1.5W)	Load Power Sensing (5W)	Load ID based Control
Energy Consumption Total (kWh/week)	1.618	1.521	1.508	1.508	1.508
Energy Consumption Work-hours (kWh/week)	1.503	1.503	1.503	1.503	1.503
Energy Consumption Afterhours (kWh/week)	0.115	0.018	0.005	0.005	0.005
Weekly Reduction Percentage (%)	-	6%	6.8%	6.8%	6.8%
Nuisance trips Occurrences rate (%)	-	0	0	0	0

Printing Room					
	Baseline	**Time Scheduling**	**Load Power Sensing (1.5W)**	**Load Power Sensing (5W)**	**Load ID based Control**
Energy Consumption Total (kWh/week)	25.117	24.642	24.771	24.576	24.554
Energy Consumption Work-hours (kWh/week)	21.258	21.258	21.258	21.258	21.258
Energy Consumption Afterhours (kWh/week)	3.859	3.384	3.513	3.317	3.296
Weekly Reduction Percentage (%)	-	1.9%	1.4%	2.2%	2.2%
Nuisance trips Occurrences rate (%)	-	0	0	0	0

Vending Area					
	Baseline	**Time Scheduling**	**Load Power Sensing (1.5W)**	**Load Power Sensing (5W)**	**Load ID based Control**
Energy Consumption Total (kWh/week)	117.3	117.06	117.06	116.751	74.117
Energy Consumption Work-hours (kWh/week)	67.6	67.6	67.6	67.6	67.6
Energy Consumption Afterhours (kWh/week)	49.7	49.5	49.5	49.2	42.94
Weekly Reduction Percentage (%)	-	0.2%	0.2%	0.5%	36.7%
Nuisance trips Occurrences rate (%)	-	25%	0	0	0

NREL RSF Facility

Private Office - 3					
	Baseline	Time Scheduling	Load Power Sensing (1.5W)	Load Power Sensing (5W)	Load ID based Control
Energy Consumption Total (kWh/week)	1.316	1.166	1.144	1.144	1.144
Energy Consumption Work-hours (kWh/week)	1.137	1.137	1.137	1.137	1.137
Energy Consumption Afterhours (kWh/week)	0.179	0.028	0.007	0.007	0.007
Weekly Reduction Percentage (%)	-	11.5%	13.1%	13.1%	13.1%
Nuisance trips Occurrences rate (%)	-	0	0	0	0

Private Office - 4					
	Baseline	Time Scheduling	Load Power Sensing (1.5W)	Load Power Sensing (5W)	Load ID based Control
Energy Consumption Total (kWh/week)	2.256	2.072	2.047	2.047	2.047
Energy Consumption Work-hours (kWh/week)	2.038	2.038	2.038	2.038	2.038
Energy Consumption Afterhours (kWh/week)	0.217	0.034	0.009	0.009	0.009
Weekly Reduction Percentage (%)	-	8.1%	9.3%	9.3%	9.3%
Nuisance trips Occurrences rate (%)	-	0	0	10%	0

Working Station - 1					
	Baseline	Time Scheduling	Load Power Sensing (1.5W)	Load Power Sensing (5W)	Load ID based Control
Energy Consumption Total (kWh/week)	1.668	1.55	1.533	1.533	1.533
Energy Consumption Work-hours (kWh/week)	1.528	1.528	1.528	1.528	1.528
Energy Consumption Afterhours (kWh/week)	0.141	0.022	0.006	0.006	0.006
Weekly Reduction Percentage (%)	-	7.1%	8.1%	8.1%	8.1%
Nuisance trips Occurrences rate (%)	-	0	0	0	0

Working Station - 2					
	Baseline	Time Scheduling	Load Power Sensing (1.5W)	Load Power Sensing (5W)	Load ID based Control
Energy Consumption Total (kWh/week)	1.548	1.224	1.381	1.179	1.179
Energy Consumption Work-hours (kWh/week)	1.164	1.164	1.164	1.164	1.164
Energy Consumption Afterhours (kWh/week)	0.384	0.06	0.218	0.015	0.015
Weekly Reduction Percentage (%)	-	20.9	10.8%	23.8%	23.8%
Nuisance trips Occurrences rate (%)	-	0	0	0	0

UWM Campus

Private Office					
	Baseline	**Time Scheduling**	**Load Power Sensing (1.5W)**	**Load Power Sensing (5W)**	**Load ID based Control**
Energy Consumption Total (kWh/week)	9.283	6.056	7.612	7.356	5.591
Energy Consumption Work-hours (kWh/week)	5.436	5.436	5.436	5.436	5.436
Energy Consumption Afterhours (kWh/week)	3.848	0.62	2.176	1.92	0.155
Weekly Reduction Percentage (%)	-	34.8%	18%	20.8%	39.8%
Nuisance trips Occurrences rate (%)	-	25%	0	16.3%	8.1%