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We Need to Talk… Developing Communicating Power Supplies to Monitor & Control Miscellaneous Electric Loads

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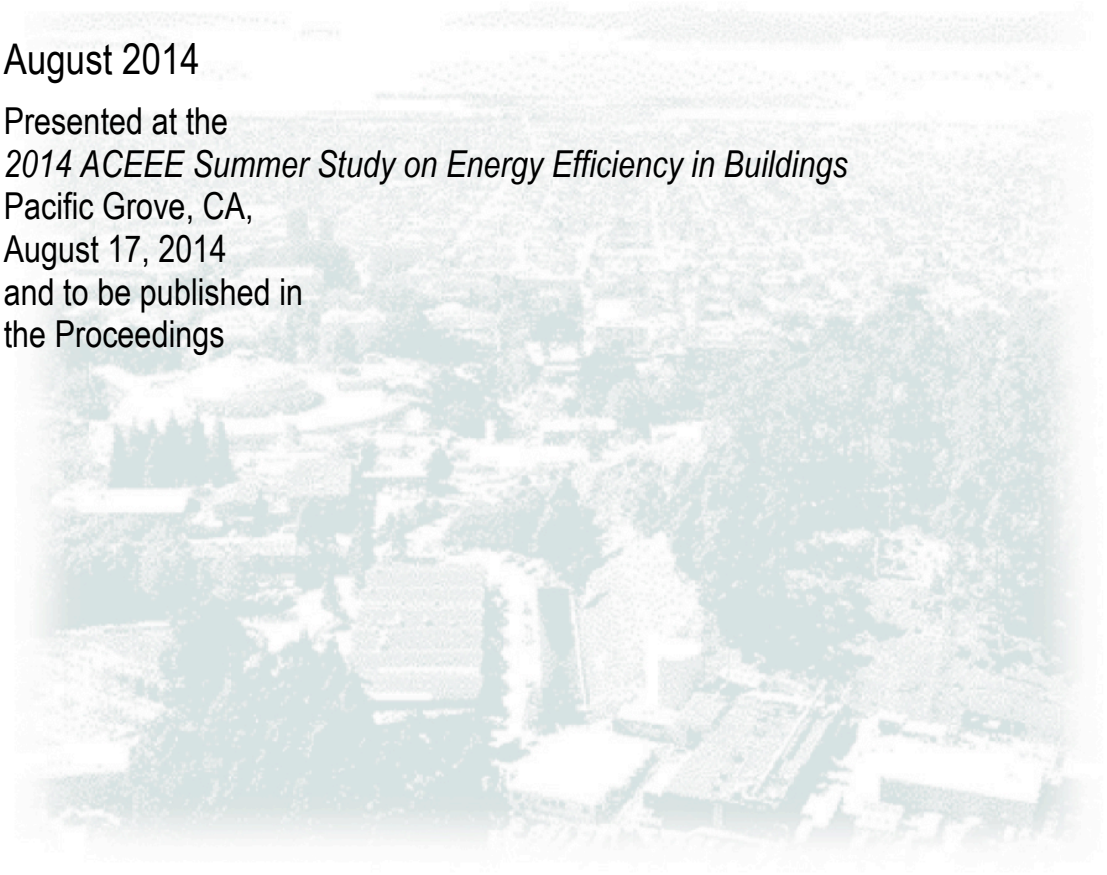

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ABSTRACT

Plug loads represent 30% of total electricity use in residential buildings. Significant energy savings would result from an accurate understanding of which miscellaneous electric devices are using energy, at what time, and in what quantity. Commercially available plug load monitoring and control solutions replace or limit the attached device's native controls - forcing the user to adapt to a separate set of controls associated with the monitoring and control hardware. A better solution is integration of these capabilities at the power supply level. In this paper, we demonstrate a method achieving this integration. Our solution allows unobtrusive power monitoring and control while retaining native device control features. Further, our prototype enables intelligent behaviors by allowing devices to respond to the state of one another automatically. The CPS enables energy savings while demonstrating an added level of functionality to the user. If CPS technology became widespread in devices, a combination of automated and human interactive solutions would enable high levels of energy savings in buildings.

Introduction

Identifying and reducing plug load energy waste is challenging due to the difficulties in identifying when these loads are consuming energy, and in what quantity. We do know that the number of individual plug loads and their aggregate energy use in buildings is increasing. In homes and commercial buildings, plug loads represent 30% of total electricity use (Lanzisera 2013, Srinivasan 2011). Moreover, the amount of electricity used by plug loads is growing faster than any other load category in both sectors (Comstock 2012). Electricity metering is important for understanding energy efficiency tradeoffs and advanced methods of grid and renewable energy integration, but metering has proven expensive and complicated thus far (Lanzisera 2013).

A large fraction of these plug loads are miscellaneous electronic devices (MELs) such as TVs and associated entertainment equipment, phones, and printers. These devices usually have either internal or external AC to DC switching power supplies. In this paper, we demonstrate a method for integrating wireless metering and control hardware into these power supplies. This technology represents a significant opportunity to better understand energy consumption in buildings, and to curb that consumption through intelligent devices behaviors.

Many common electronic devices such as televisions, game consoles, and computers ship with the ability to connect to the Internet. This capability makes these devices ideal candidates for networked energy monitoring and control. However, nearly all of these devices lack the ability to measure and report their energy use, or receive control signals. They cannot yet participate in systems to improve whole building energy use.

To address these shortcomings, and enable energy-saving behaviors in these devices, we are introducing the concept of a communicating power supply (CPS). A CPS adds electricity metering, computation and communication to electronic devices – all embedded in the device's power supply.

Our solution adds metering and control capabilities by utilizing the properties of the ubiquitous switching power supplies present as part of virtually every electronic device and does so at very low incremental cost. These power supplies switch voltage and current through a transformer which allows us to cheaply measure the power being handled by the power supply. Adding the basic measurement capabilities to a power supply costs roughly $0.10, and adding the microprocessor and communications (if they do not already exist for other applications) adds modestly to the overall device cost. These very low costs place electricity metering and reporting in the reach of very cheap devices like compact fluorescent or light-emitting diode (LED) lamps and battery chargers.

This paper introduces the communicating power supply and presents an example implementation of a CPS ecosystem. In Section II we discuss the overall concept. Section III contains a survey of related work on energy aware devices as well as on communicating energy information on local area networks and the Internet. Section IV contains a review of our proof of concept demonstration and sample applications. In Section V we provide a perspective on the widespread deployment of this technology from a consumer, energy policy, and energy efficiency standpoint.

System Concept

To date, addressing plug load efficiency has been handled primarily through regulatory processes. Voluntary energy efficiency programs like the U.S. EPA's ENERGY STAR program have successfully engaged with manufacturers to reduce the energy use of plug load devices. Involuntary national energy efficiency standards have also played a role. Unfortunately, policy-based solutions have trouble keeping pace with the rapid advance of these technologies.

Hardware-based solutions to the problem of monitoring and controlling plug loads are now available on the market. These commercially available products are installed in between the outlet and the device being monitored. This plug-through approach comes with a unique set of advantages and drawbacks. The main advantage is flexibility with regards to the devices monitored and/or controlled. One monitor can be used with a wide range of devices. A major downside of the plug-through approach is the loss of native controls. Native controls include remotes, switches, or other interfaces with which the user is familiar Plug-through monitoring and control only works as expected if the monitored device is in the 'on' position. This allows the plug-through device to control the device's state (on, off, etc.). Not all users are receptive to the loss of native controls. Users expect devices to retain their familiar user interfaces, and keeping track of which control method is currently active leads to frustration and rejection of the control technology (Katipamula 2012).

Our solution has the benefits of these plug-through devices, while retaining the familiar native controls of the electronic device. The CPS measures device energy use, and reports this information along with the device's identity over a network to a central entity. The CPS also receives control information from users or other devices. The user is still able to control the

device's power state manually, if desired. This concept is shown in Fig. 1 where three electronic devices are powered by CPSs.

The following features differentiate the CPS solution from existing plug-through technologies:

- Power supply integration (either internal or external to the device).
- Knowledge of the device under control.
- Native controls are retained – no control conflicts.

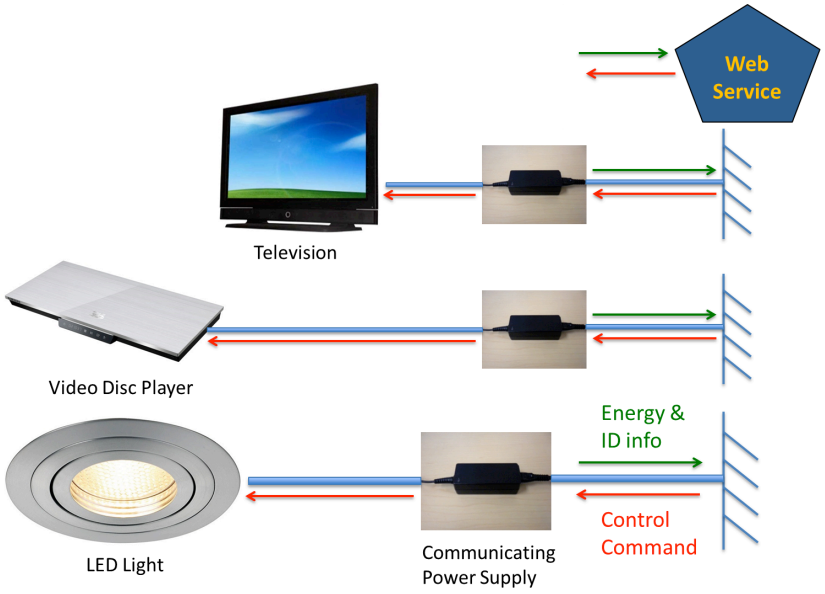

Fig. 1. System concept showing three devices with communicating power supplies that report energy data to a web service and pass control information directly to the device.

Related Work

Measuring and controlling the energy use of devices has seen a great deal of attention in recent years, and there has been activity in the academic literature, the consumer market, and among research organizations. In this section we review existing solutions for measuring and reporting the energy use of devices over a network.

Existing Energy-Aware Consumer Products

Existing commercially available and research-stage solutions for reporting plug load device energy use over the network fall into three main categories: large 'smart' home appliances; plug level energy monitors; and nonintrusive load monitoring (NILM). In addition, some solutions in each of these three categories utilize "middleware" (hardware and software) that facilitates network communication from the device to a central monitoring and control entity. These categories are discussed briefly below.

Smart home appliances

Major appliance manufacturers offer product lines of smart home appliances that can be connected to Wi-Fi and can be monitored and controlled from a computer or mobile device. These are mostly large appliances, such as washers, dryers, refrigerators, and dishwashers. The appliances are high-end models in terms of cost and possess features that may not be desired or needed by a homeowner who is only interested in the addition of energy reporting capabilities.

Plug level energy monitors

Plug-level energy monitors offer monitoring and control capabilities at the wall outlet, as an independent power-strip, or at the circuit breaker panel. These adapters are used to monitor each end-use device. Many brands are commercially available. The devices typically communicate over a wireless network and include dashboard software. Devices in this category typically cost around $50 per device. When the necessary control software and hardware gateway is included, the price of monitoring plug loads in a household or commercial building could escalate rapidly.

In addition to high initial cost, these devices have several important drawbacks. First, they must be individually installed and programmed. If the device is moved, or additional devices are plugged in, then the identification and control aspects are lost. Second, many of the products rely on proprietary communication protocols. This leads to incompatibilities and legacy networks. These drawbacks mean that plug level energy monitors could be adequate for short-term or limited operation but are not well suited for a permanent, scalable, system.

Nonintrusive load monitoring

An alternative to plug level energy monitors are nonintrusive load monitoring (NILM) systems. NILM systems consist of one energy meter to monitor whole building energy consumption and use signal processing to disaggregate the individual end use loads. Multiple groups have published algorithms to optimize the disaggregation analysis (Beckel 2012, Marchiori 2009, Figueiredo 2012, Marchiori 2009). This technique is still largely a research effort, with groups investigating various techniques to disaggregate end use loads via methods such as machine learning. There are currently no commercially available products on the market.

This technique is effective for large (over 150 Watt) loads that operate in discrete levels (e.g., on/off, high/medium/low) but does not work as well for low powered loads or loads with large number of variable states, such as the dishwasher or electric stove. Continuously varying loads like dimmer switches on lights or adjustable speed drives on motors may not be suitable for monitoring without implementing rather expensive feature detectors. Multiple sources of inaccuracy arise from heterogeneity in meters, load profiles, and appliance types (category, make, size, and manufacturer). Low-power consumer appliances, such as miscellaneous electronics (MELS), exhibit similar power consumption characteristics. This property makes the

recognition task even more challenging. NILM does not currently achieve the same level of accuracy as direct metering at the end use.

Communicating Power Supply Demonstration

To illustrate the advantages of the CPS concept compared to current technologies, we prototyped several CPSs and implemented the technology in three standard electronic devices. In this section we detail the principles of operation, the software and hardware implementation, and provide example energy saving applications.

Principles of Operation

The CPS takes advantage of the standard operational characteristics of modern AC to DC switching power supplies. These power supplies switch the input current through a magnetic device at high speed in order to maintain a stable output voltage while efficiently converting input power to output power. Power supplies modulate both the duty cycle and the frequency of the switching to minimize wasted energy and maximize overall performance (Jinwen 2004). Due to the relationship between duty cycle and power output, the duty cycle can be used as a proxy for the power (Watts) passing through the supply at a given input voltage.

Fig. 2 shows a simplified schematic of a switching power supply with added CPS components and connections shaded in red.

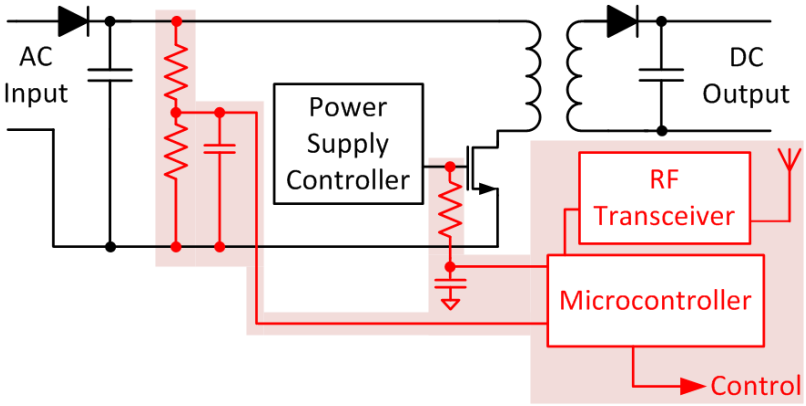

Fig. 2. Simplified schematic of a communicating power supply where shaded components are added for a complete CPS and unshaded components are part of the original power supply design.

The prototype CPS uses a microprocessor to measure the power supply's duty cycle. The microcontroller also measures the value of the input voltage. These two values are applied to a lookup table to map duty cycle and voltage to a power level. After determining the power level, the measurement is sent over the network wirelessly using an integrated RF transceiver. All CPSs in the network communicate with a central hub at regular intervals. The network is able to dynamically change wireless frequency when communication is broken or becomes unreliable.

Hardware Implementation

This hardware demonstration utilized commonly available prototype hardware (mbed-based)[1] with open-source software libraries for nearly all components. The only system components that were custom made for this demonstration were the power supply modules and the circuit boards that contained various interface components. The power supplies were built by Power Integrations, a company that designs power supply controller chips. These power supplies had the switching output and input voltage available as extra wires fed out of the power supply.

A photograph of a prototype CPS including the power supply, the processor module, the radio module, and ancillary components is shown in Fig. 3. This hardware fully implements the schematic shown in Fig. 2.

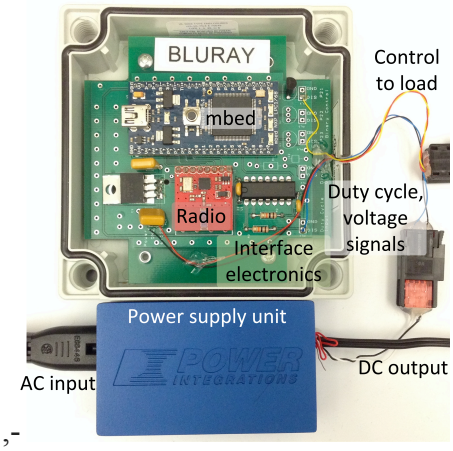

Fig. 3. Photograph of a prototype communicating power supply. In Fig. 2. the microcontroller is the ARM mbed and the unshaded components make up the power supply unit. Wired connections between sub-units also shown.

Controlling devices connected to the CPS requires basic understanding of the product's existing user interface. For example, device on-off operation is often controlled via a button press. The CPS emulated button presses using a MOSFET transistor in parallel with the user controlled switch. In the case where an analog signal for control was needed, we used a digital-to-analog converter on the microcontroller and an op-amp to drive the required signal. This design allows the CPS controls to operate in parallel with the controlled device's existing user interface.

System Demonstration Architecture

The prototype CPSs were used to control three devices: an LED lamp, Blu-ray player, and a television (TV). For the demonstration each device was monitored in real time, and the resulting data were uploaded to the Internet immediately after each measurement. The energy use information was displayed on a dashboard. The user could also manually control each device from the dashboard. Each device retained the use of its native control interface (e.g. remote for

[1] https://mbed.org/

the TV and Blu-ray, and dimmer switch for the LED lamp), allowing the user to seamless switch between web-based and direct-device controls.

Each device was monitored and controlled with the hardware shown in Fig. 2. Thesedevice-level CPSs communicated with a central 'hub' that controlled the local network traffic. Both CPSs and the central hub were based on mbed rapid prototyping hardware. The network control hub was in turn connected to a local server implemented on a Linux microcomputer (Raspberry Pi) connected to the Internet. This server handled interactions with the web service and dashboard running in the cloud.

Fig. 4 shows an overview of the system used in the demonstration.

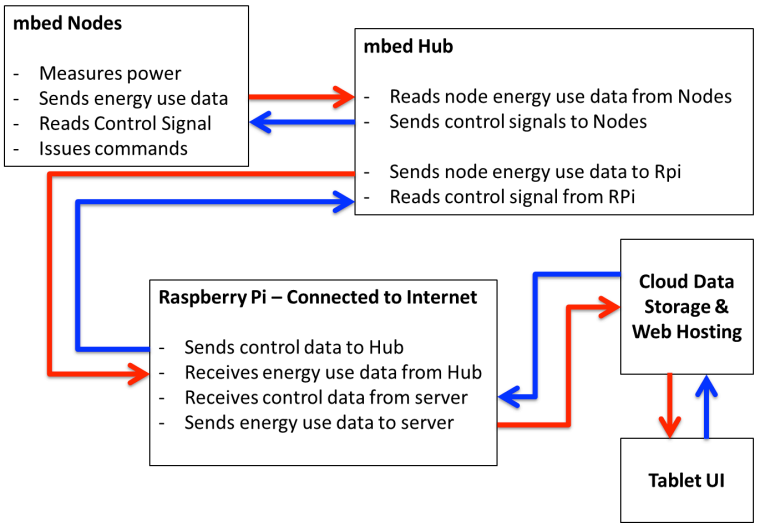

Fig. 4. Functional diagram showing components and communication links of demonstration system. There are multiple mbed nodes and one hub in the network.

Each node measured the device's power consumption and received control signals. All communication between the nodes and the hub was wireless. A process on both the hub and the nodes ensures that all CPSs are active and connected to the network.

Energy-Saving Applications and Behaviors

Using readily available hardware and a minimum of software development, we demonstrated the potential of unobtrusive load monitoring and control in a CPS. However, our implementation only scratched the surface in terms of demonstrating intelligent device behaviors that could be realized with this type of setup. For example: the system detected when the user had turned off the TV and sent a control signal to the Blu-ray player to turn it off, as well. Similarly, when the Blu-ray player was turned on, the server sent a control signal to the TV to switch it on.

These behaviors add value for the user, and present energy-savings opportunities without introducing inconvenience. Networks of CPSs could be built incrementally, with opportunities for intelligent behaviors, and corresponding energy savings increasing as the network grows. The

largest opportunities for both increased energy-efficiency and user benefits can be found in the ability of these devices to respond to one another, or to other measurement and control devices such as smart thermostats or demand response signals.

Policy and Energy Implications

CPSs such as the one demonstrated in this paper save energy in two ways. First, they provide additional information to encourage energy-efficient behaviors. This information will help prevent unnecessary use and perhaps alert consumers to faults and incorrect operation. Second, the CPS could save energy directly by switching off equipment that would otherwise draw power unnecessarily.

The following discussion is therefore divided into two parts. The first describes savings from improved information and awareness of energy using equipment. The second part surveys and then estimates the energy savings that can be achieved by more precise control of energy-using equipment. Both discussions assume that the CPS ecosystem is fully built out. The 'ecosystem' consists of three elements: 1) communicating power supplies built into a large number of devices in the building; 2) the network to transfer information, and 3) a central entity or server to process the information. The central entity also has the ability to transmit or broadcast commands to individual communicating power supplies. We envision that consumers will be able to track consumption and to issue control commands through a smartphone or computer. In the future, specially designed applications might manage some of the more routine commands. These technologies are already available for some add-on metering/control units.

Energy savings from improved feedback

Management consultant W Edwards Deming once said, "You can't manage what you can't measure." The CPS makes better management possible by providing a means of measuring something that was before not easily measurable.

Several researchers (Kempton and Montgomery 1982) have observed that consumers typically focus on visible energy-using products for energy saving efforts. But many appliances and pieces of equipment in buildings are hidden or the extent of their energy use is not obvious. As a result, it is difficult for an occupant of a home for a manager of a commercial building to easily assess when or how much energy an appliance is using.

Feedback can be provided at varying frequency and degrees of specificity. For example, a Norwegian study showed that consumers reduced their electricity use 10% when the frequency of the utility bills increased from once a year to monthly. More recently, studies examined the impacts of energy consumption when the feedback is offered feedback with greater detail. Darby (2008) surveyed studies of energy saving from improved feedback in homes. She found that the savings ranged from 5 - 15% as a result of direct feedback. Moreover, she found that these savings persisted for a considerable period of time. Most of these studies took place in Europe and the majority of savings were in the form of reduced space heating. It's not clear if these results apply to the CPS since the CPS is primarily suited to electric appliances with power supplies, but similar principles may apply.

Ehrhardt-Martinez et al. (Ehrhardt-Martinez 2010) surveyed energy savings resulting from feedback technologies in the USA. They divided the programs into four categories of

increasing level and speed of feedback. The savings ranged from 3.8% from enhanced billing to 12% for real-time measurement and feedback. The latter category is most appropriate for comparison with the CPS. The authors further estimated that feedback programs, if broadly implemented throughout United States, could save the equivalent of 100 TWh by 2030. Again, these estimates include substantial (though unspecified) savings in space heating, AC, and water heating.

The programs examined by Ehrhardt-Martinez et al. typically employed whole-house meters. It was impossible to track appliance consumption (except, in some cases, heating, AC, or water heating). A CPS can provide real-time consumption data for every device. As a result, it's possible to identify precisely which device is drawing power (and how much). This additional level of precision will simplify problem identification, such as unusually high-energy use or operation when not needed.

Energy Savings from Switching Off Equipment Performing No Useful Function

Meyers et al. (Meyers 2010) estimated that about 3% of total residential electricity use is wasted by electronic products and other small products that are not switched off even though they are not performing useful services. This estimate appears low given results from careful examinations of individual homes and commercial buildings.

Pigg et al. estimated that about 500 kWh/year—5% of total residential electricity use--could be saved by a combination of consumer information and smart power strips. Parker et al. (Parker et al. 2010) measured consumption and savings in two homes with instantaneous power meters designed to provide the occupants feedback. In one home, they installed switches on specific circuits to allow the occupants to switch off appliances with standby power consumption. This arrangement crudely simulated the capabilities of CPSs. The occupants were able to reduce fixed loads in the home 90W, which corresponds to over 800 kWh/year.

Acker et al. (Acker 2012) examined plug loads in several commercial buildings. They estimate that plug loads could be reduced 20% using smart power strips and education of occupants. The CPS would make these savings more likely to be achieved by facilitating both identification and control of unneeded equipment.

National Savings from Communicating Power Supplies

The estimated national electricity savings from communicating power supplies are shown in Figure 5. The savings were calculated as a fraction of each end use based on our estimates of the combined savings fractions attributable from both 1) improved feedback and 2) reduced operation of equipment not performing useful function.

	Primary Electric (Quads)[2]	Estimated Savings (%)	Calculated Savings (Prim. Quads)	Electricity Savings (TWh/year)
Space Heating	1.77	0.5%	0.01	0.9
Lighting	4.65	3.0%	0.14	13.5
Space Cooling	4.60	0.5%	0.02	2.2
Water Heating	1.71	0.5%	0.01	0.8
Refrigeration	2.43	0.5%	0.01	1.2
Electronics	1.94	15.0%	0.29	28.3
Ventilation	1.62	1.0%	0.02	1.6
Computers	1.14	3.0%	0.03	3.3
Wet Cleaning	0.98	0.1%	0.00	0.1
Cooking	0.41	0.2%	0.00	0.1
Other	5.30	5.0%	0.27	25.7
Adjust to SEDS	1.90	0.1%	0.00	0.2
Total	**28.46**		**0.80**	**77.9**

Fig. 5. Savings estimates resulting from widespread CPS deployment

Overall potential savings from the installation of communicating power supplies are about 3% of total building electricity use. The largest contributor to savings – 15%--will occur in the Electronics end use, most of which are plug loads. The CPS will also improve the occupants' ability to monitor HVAC end uses, though not necessarily control them. For that reason, we assumed that very small savings—0.5 % -- would be achieved. This will mostly occur through identification of defective equipment, incorrect schedules, or minor housekeeping.

Conclusion

We demonstrated a proof of concept CPS system capable of controlling and monitoring plug load devices without interfering with those device's native controls. Currently available technology for monitoring and controlling plug load devices introduce control conflicts, and are difficult to use at building-scale. We believe that CPS technology addresses the shortcomings of current technologies, and is the future of energy monitoring for plug loads. Large appliance manufacturers are already embedding networking capabilities in their products. Plug load level monitoring control is a logical next step, with significant as of yet unrealized opportunities for energy savings in buildings.

The CPS concept enables two types of energy savings: feedback related behavior changes, and automated intelligent device behaviors. The potential for both types of savings scales with

[2] From U.S. Department of Energy, 2011 Buildings Energy Data Book http://buildingsdatabook.eren.doe.gov/default.aspx

the number of CPS devices on the network. Most importantly, devices such as a CPS present a value-add to the user, instead of an inconvenience that must be suffered in the name of energy efficiency. This crucial difference between the CPS model and current plug load control devices will enable much wider adoption of this technology than has been realized by solutions currently available on the market.

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