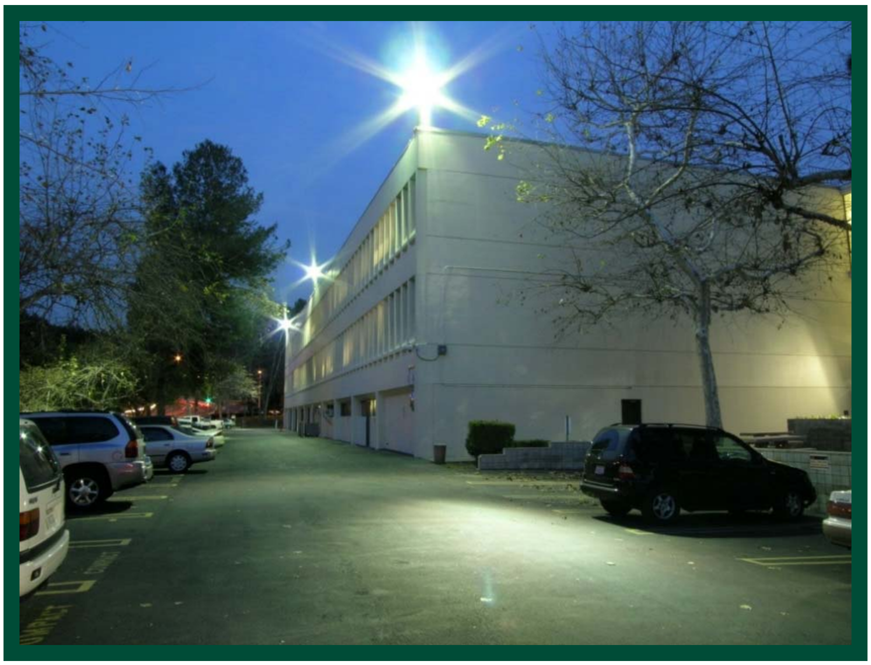
Evaluation of Residential Room Air Conditioner Control with Smart Plugs for Peak Load Reduction

DR12.21 Report



Prepared by:

Emerging Products
Customer Service
Southern California Edison

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EXECUTIVE SUMMARY

PROJECT GOAL

Demand Response (DR) capabilities have been introduced into the marketplace to control room air conditioners (ACs) using “smart plugs”, controllable outlets that ACs can plug into. The objective of the study is to field trial a sample of smart plug technologies to understand and verify their demand reduction capabilities, among products commercially available in the marketplace.

Project goals included conducting laboratory evaluation of selected technologies in order to assess 1) demand savings, 2) accuracy of power usage reporting of the technologies, and 3) impact of room AC fan speed settings on results.

TECHNOLOGY DESCRIPTION

The smart plug device chosen for evaluation is called a Thinkeco Modlet. The modlet is designed specifically for controlling existing room air conditioners in response to demand response (DR) events. The modlet comes with a separate remote controller that has a built-in thermostat for reading indoor temperature. The thermostat provides the ability of the modlet to control ACs plugged into the modlet, based on indoor temperature conditions. Both Wifi and Zigbee versions of the modlet are commercially available for establishing connectivity in the home. The Zigbee version requires a separate gateway connected to a router, while the Wifi version establishes connectivity to an existing home router using Wifi. A Friedrich Kuhl room air conditioner with Wifi connectivity was selected for lab testing under control by the modlet, and without the modlet as well.

By enabling existing room ACs operating during critical times to respond to DR events, smart plugs like the modlet offer potential for automated peak load reduction to utilities. The technology also offers remote control convenience and thermostat-based control in support of system load balance. By augmenting existing room ACs with DR capability, the technology does not necessitate new investment in connective window ACs in order to support utility DR programs.

PROJECT FINDINGS

Among the dozens of smart plug products reviewed, the ThinkEco Modlet was the only one that demonstrably supported responsiveness to DR events among the products evaluated. Other products could be scheduled to operate on and off based on times schedules or were in the midst of product development to demonstrably support automated response to DR events. At the time of evaluation the modlet already supported a rich set of DR functionality for both DR participants and DR program administrators. Its basic operational design is described in a state diagram included in this report, depicting conditions under which the modlet switches an AC between on and off states.

The modlet was first field tested to control existing air conditioning units of customers before being lab-tested with a connective window air conditioner. The field trial identified different types of impacts achieved with ACs under modlet control. Types of impacts included: full impact (ACs cycled off throughout a DR event); reduced duty cycles; delayed cycling; partial impact; or no impact achieved (due to user override and/or lack of AC utilization during a DR event).

Overall the modlet was observed to perform as described by manufacturer marketing literature. Product features target maximal DR event participation and AC response, within bounds of customer-designated indoor temperature comfort. Features supportive of peak load reduction include: automated power cycling (within user-designated comfort set-points) governed by indoor temperature conditions; device sweeps to re-engage participation mid-way during each DR event; and randomization to stage initiation of response going into a DR event and stage restoration of power coming of a DR event.

A Friedrich Kuhl room air conditioner with Wifi connectivity was tested under modlet control as well as without modlet control. The tables below summarize findings for demand reduction achieved during two separate lab tests conducted during disparate seasons of the year. Due to differing baseline testing conditions during the spring and summer seasons, results are not intended to be compared across the two tables.

TABLE-ES 2. SUMMARY OF DEMAND REDUCTION WITH MODLET (SPRING LAB TEST)

	POWER CONSUMPTION (KW)	DEMAND REDUCTION (KW)	AVERAGE POWER CONSUMPTION (KW)	AVERAGE DEMAND REDUCTION (KW)
Baseline (Setpoint at 72°F)	0.23	-	0.23	-
Modlet Setpoint at 75°F-78°F	0.10-0.12	0.11-0.13	0.11	0.12

TABLE-ES 4. SUMMARY OF DEMAND REDUCTION WITH FRIEDRICH WINDOW AC (SUMMER LAB TEST)

	POWER CONSUMPTION (KW)	DEMAND REDUCTION (KW)	AVERAGE POWER CONSUMPTION (KW)	AVERAGE DEMAND REDUCTION (KW)
Baseline (Setpoint at 72°F)	.21	-	0.21	-
Friedrich Setpoint at 75°F-78°F	0.16-0.18	0.03-0.04	0.17	0.036

Lab testing revealed the modlet platform reporting instrumented values for power consumption, whereas the Friedrich platform always reported a constant value despite varying indoor and outdoor conditions tested. The modlet power measurements were within 4% of EPRI's independent lab measurements and were biased lower. On the other hand, the Friedrich AC platform reported a static value for power consumption based on the window AC model's power rating.

There was little difference in power draw between the three fan speeds of the Friedrich AC. At low, medium, and high fan speeds and different outdoor temperatures, the power draw stayed within ±4% of average.

PROJECT RECOMMENDATIONS

Smart plug technologies can be installed and commissioned by customers, without requiring utility or professional truck rolls. They have the potential of achieving demand savings, and at lower deployment costs than traditional programs that require professional installation. However, for easier installation it is recommended that manufacturers improve the self-registration process for users by minimizing the need for manual entry of registration keys and codes.

The products initially evaluated and field trialed performed as described by the manufacturers. However, details of how products operate, if at all, to support DR are generally left undocumented in marketing literature to the consumer. It is recommended that manufacturers further document product features and capabilities supportive of demand response, as well as provide power consumption details and indications of accuracy, should a user desire to reference such information.

Economic rationale for mass market consumer adoption of DR-enabling technologies is generally incentivized by programs encouraging demand (kW) savings, whereas the average residential electric bill incentivizes energy (kWh) savings. Therefore, the market for room AC control using smart plugs is generally utility-driven. As a method to enhance further adoption, utilities can highlight technology features of plug load control devices (e.g., consumer convenience via remote control; comfort through thermostatic control, etc.) that are supportive of lifestyle needs. By conveying a clear rationale for consumer participation in DR programs based on product capabilities that also address lifestyle needs, utilities can increase engagement in DR programs and expand deployment of DR-Ready devices like smart plugs for room AC control. A pilot program is recommended as a next step to evaluate demand savings in real-world situations with a sufficiently large number of customers to establish statistically meaningful results. Integrated control with available house fans (e.g., whole house fan) could augment the pilot investigation.

ABBREVIATIONS AND ACRONYMS

AC	Air Conditioner
APS	Advanced Power Strip
DBT	Dry Bulb Temperature
DR	Demand Response
EE	Energy Efficiency
EMS	Energy Management System
EPRI	Electric Power Research Institute
HVAC	Heating Ventilation and Air Conditioning
HEMS	Home Energy Management System
OpenADR	Open Automated Demand Response
PLEMS	Plug Load Energy Management Systems
SCE	Southern California Edison
WBT	Wet Bulb Temperature

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INTRODUCTION

Plug loads today are predominantly under manual control by consumers, who manually switch their end-use devices on and off. Many plug loads remain always on such as electronic plug loads manufactured with internal sleep modes. A very small portion (less than 1%) of plug loads today are being managed externally with smart plugs as part of a plug load energy management system.

EMERGING TECHNOLOGY PRODUCT

Plug load energy management systems (PLEMS) are provided by vendors that are typically distinct from building energy management system and lighting control system vendors. PLEMS platforms monitor and control plug loads with advanced power strips (APS) or plug-in wall modules, and offer energy management for devices plugged into them. Examples are shown in Figure 1. Some of these devices may also offer surge protection.

PLEMS typically utilize web-based software to present the information collected on plug-load status and electricity usage through graphical summaries and reports designed to help users make improved energy decisions. Some platforms are capable of monitoring usage of individual plug loads (not just aggregate usage), and can also automate plug load control based on time schedules, plug load usage levels, or other configurable conditions, alerting users to potential faults detected through real-time device monitoring to identify anomalous conditions.

Advanced platforms provide insight using data aggregation and reports to enhance understanding of plug load usage by device type or groups. Insights offered may include quantified base-load reduction, peak-load avoidance, and opportunities for employing demand-response in the operation of select plug loads.

Figure 1: Smart Power Outlets (Dual and Single Outlet Modules and Power Strips)

PLEMS solution offerings are typically tailored to specific customer segments. For example, some solutions target commercial office buildings and/or research laboratories while other solutions target residential room air conditioner control or home theatre control. Platforms designed for commercial building plug load energy management may include preventative maintenance features and reports to improve understanding of building occupancy.

In the commercial sector, building energy management systems control about half of the building energy load due to larger electrical systems like HVAC. However, a large remaining percentage (e.g., 25-30% of overall commercial building usage) stems from plug load energy usage (e.g., electronic office equipment, miscellaneous loads in break rooms, and vending machines).

Title 24 building code is requiring plug load management for new commercial building construction and major renovation projects. Consequently, emerging solutions for commercial building wall-outlet control are being advanced to meet latest code requirements for controllable outlets.

The California Energy Code, and in particular the 2013 version of Title 24, Section 130.5 discusses requirements for controllable outlets. Existing code explains how controllable outlet requirements may be satisfied by switching the outlets to operate similarly to lighting system control. Beyond code requirements, technical advancement in control algorithms can lead to more intelligent controls governing operation of controllable outlets in commercial buildings. Future advancements could enable greater energy efficiency and demand response tailored to occupant preferences; while offering building owners and energy managers added options for enhancing energy savings with plug load control to better achieve future zero net energy goals for new construction and major remodels.

ASSESSMENT OVERVIEW AND OBJECTIVES

The overall project objective was to select and conduct a trial of Demand Response-Ready (DR-Ready) technologies supportive of SCE's demand response objectives. Only commercially available mass market plug loads and plug load control systems (or smart outlets) were considered. At project onset, specifics of technology selection for field trial was guided by direction established through group consensus across SCE's organization[1].

End-use device categories of interest were selected based on support for the primary objective of peak load reduction. Device categories included room air conditioners and smart power strips capable of controlling plug loads like office equipment. Based on scanning the technology horizon for commercially available end-use devices with DR capabilities, a structured list of commercially available DR-Ready end-use technologies was developed, identifying possible candidates for product evaluation.

The primary objective focused on lab and field trial of window air conditioner plug load control for peak load reduction. Goals included performing technology assessment on product capabilities to assess potential demand savings, and recommend any improvements. A secondary objective was to assess the accuracy of power consumption reported by the selected devices, and any impact of window AC fan speed settings on results.

[1] At project start, an online questionnaire was developed to formally survey SCE's organizational objectives for using DR-Ready technologies. Findings revealed peak load reduction as SCE's primary objective for using DR-Ready devices in the short-term.

TECHNOLOGY SELECTION FOR EVALUATION

TECHNOLOGY REVIEW

A technology short list was assembled to identify commercially available connective and controllable products in the categories of interest (i.e., room air conditioners and smart power outlets) with potential to support peak load reduction. The sponsoring utility SCE clarified a preference to enable existing room ACs to support peak load reduction. Consequently, the project direction was refined to conduct field trial of smart power outlet technologies capable of controlling existing room air conditioners, as opposed to installing new connective room air conditioners.

The matrix shown in Table 5 was developed for quick comparison of functional capabilities supported by different smart power outlet products. Both multi-outlet "smart strips" and single-outlet "smart plug" modules are included in the matrix. The matrix summarizes manufacturer, product name, device capabilities, and standards supported, at the time of initial investigation in 2014.

Functions and Capabilities

		Stand-alone			Applications												Access			
Supplier	Product	Requires Vendor Gateway	Interoperates with EMS product suite	Local (non-cloud) software option	Measured Power Usage	Off-premises on/off control	Schedulable control	Configurable rules-based automation	Demand Response	Power Usage Reporting	Real-time feedback	Temperature-sensing control	Current-sensing Control	Occupancy-sensing Control	Local remote for control	Surge suppression	Online app	Smart phone/tablet app	Local PC app	Communication
Homewerks	Smart Plug		■		■	■	■	■	■	■	■					■	■	■		Wifi, OpenADR
Homewerks	Smart Strip		■		■	■	■	■	■	■	■			■ *		■	■	■		Wifi, OpenADR
Boss Controls	Power Strip 600 and Smart Plug 110		■		■	■	■	■		■	■					■	■	■		Wifi
Enmetric	PowerPort and Bridge	■			■	■	■	■		■	■		■				■			Wifi-like
ThinkEco	Modlet	■			■	■	■	■	■	■	■	■			■		■	■		Zigbee HA
GreenWave Reality	PowerNote (1-port or Multi-port)	■	■		■	■	■	■		■	■						■	■		ZigBee, Z-Wave
Lowes Iris	Smart Plug	■	■		■	■	■			■	■						■	■		Z-Wave
Ecobee	Smart Plug	**	■		■	■	■	■	■	■	■	■					■	■		ZigBee
JetLun	JIM (EMS + Smart Plug)	■	■	■	■	■	■	■	■	■	■	■		■	■ ***	■	■	■	■	HomePlug, ZigBee
Visible Energy	UFO Power Center				■	■	■	■		■	■						■	■		Wifi
Tricklestar	Energy Monitor (Smart Plug)						■				■					■				
Tricklestar	Advanced PowerStrip (7 or 12 outlet)												■			■				
Belkin	WeMo Switch and Motion (Smart Plug)						■				■			■				■		Wifi
Belkin	Conserve Energy-Saving Surge Strip														■	■				
Belkin	Conserve Socket with Energy Saving Outlet												■			■				
Watt Stopper	Smart Power Strip IDP-3050													■		■				
Bits Limited	SUG7 Wireless USB Surge Protector												■		■					
Niagra Conservation	Energy Saving Smart Surge Protector												■			■				
Embertec	EmberCeptor AV Series Power Saver (Smart Strip)														■	■				

Table 5: Smart Plug and Smart Strip Comparison

DOWN-SELECTION THROUGH INITIAL EMPLOYEE TRIAL

Three vendor products were selected for initial trial in EPRI and SCE offices to verify vendor statements of support for DR functionality. The products installed at EPRI and SCE employee facilities included ThinkEco modlets, Enmetric powerports, and Homewerks smart plugs and strips. Distinguishing features of each product are summarized below.

- ThinkEco Modlet
  - Remote control with thermostat built-in
  - Support for full range of plug types (15/20A, 110/220V)
  - Vendor mention of DR capability
- Enmetric Powerport and Bridge
  - Designed for office environment (15A devices: laptop, monitor, printer)
  - Configurable rules-based automation (current-sensing, schedulable)
  - Vendor mention of DR capability
- Homewerks Smart Plug and Strip (powered by Cloudbeam)
  - Wifi-enabled and priced for residential application
  - Vendor mention of DR capability (via OpenADR 1.0)

Among the three, only the ThinkEco and Homewerks smart plug products were found with functional capability to respond to DR events. In contrast, the Enmetric smart strip product lacked ability to respond to a DR signal at the time of evaluation, but could be scheduled for switching operation (e.g., based on TOU rates).

Besides verifying vendor assertions about device functional capabilities, the products were also installed to examine ease of provisioning. Although each product was provisioned successfully, the EPRI and SCE project managers noted installation issues (e.g., error messages during installation process) can arise when older internet routers are used that are incompatible with current technologies. Moreover, ways to improve the user installation instructions were noted for the Homewerks products. In addition, user operations that could result in disruption in data acquisition (e.g., placing a computer in sleep mode) were also noted. The findings informed selection of product options (e.g., stand-alone gateway versus USB gateway) and customer sites.

The outcome of the initial employee trial was the selection of the ThinkEco platform for field testing at customer sites. This platform exhibited more mature functional capabilities to support DR programs, as well as consumer self-installation without a professional truck roll to assist.

DESCRIPTION OF MODLET OPERATION

The state diagram in Figure 2 depicts modlet operational design. The state diagram describes normal modlet behavior as well as modlet operation during and after a DR event.

Distinct states of operation are illustrated for the modlet controlling power supplied to a window AC unit via a switching relay inside the modlet.

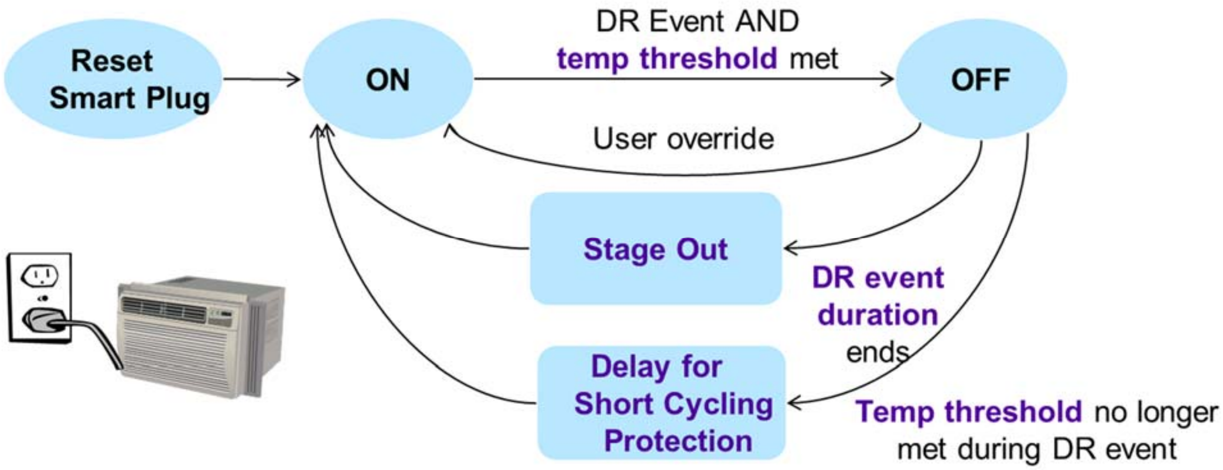


Figure 2: State Diagram Description of Modlet Operation of Window Air Conditioner (Source: EPRI)

As the figure depicts, at initial power-up the modlet by default enters “reset” state before immediately transitioning to “on” state, in which the relay inside the modlet is closed, allowing energization of the window AC. The modlet remains in this “on” state during normal operation (i.e., outside of DR events) when the window AC is not subject to control.

The modlet subjects the window AC to switch between “on” and “off” during DR events, in the following manner. The modlet remains in normal “on” state until an established temperature threshold is met (e.g., three degrees above the user’s normal temperature set point). When the specified setback temperature is reached during a DR event, the modlet enters into “off” state, de-energizing the window AC. The modlet remains in “off” state until either: 1) the indoor temperature threshold is no longer met (signifying need for cooling), or 2) the DR event concludes.

In the former case, the modlet transitions to “on” state after a minimum cycling delay is met, required for short-cycling protection of the window AC compressor. Throughout the DR event, the modlet continues to transition between “on” and “off” states based on actual indoor temperature relative to setback temperature settings. This switching operation may be prematurely interrupted by a user-override (e.g., through adjustment of thermostat settings during a DR event).

At the conclusion of a DR event, the device transitions back “on” after a coordinated or random delay occurs to stage out of the DR event. The Stage Out function helps prevent a spike in electrical demand caused by powering many window ACs at the same time.

Field Trial of Smart Plugs for Room Air Conditioner Control

Field Trial Overview

The field trial deployed six Thinkeco modlets (or smart plugs) at select SCE residential customer sites having broadband and Wifi access. The modlets were located near existing room air conditioners and physically plugged into a wall outlet, in order to control the nearby room air conditioner. Each modlet was provisioned at the customer site and usernames and passwords were established for each customer through an online self-registration process on the ThinkEco platform.

The data collection plan included tracking:

- Power consumption per room AC participating during DR events
- Indoor temperature conditions
- User override per event
- Air conditioners (ACs) that were on during events

Summary Findings

Although six modlets were installed at customer sites in SCE service territory for field trial, historical data revealed that only four out of the six deployed devices participated in a series of DR events. The remaining two modlets were reportedly installed on switchable wall outlets enabling control by wall switches. This physical configuration is not compatible for continuous data collection by the modlets, since the modlets require being continuously powered.

For the four ACs powered by modlets, connectivity and response characteristics were observed during test events conducted in September and October 2014. Data was collected through the ThinkEco cloud. DR test events were initiated on September 11, 15, 17, and 19 and again issued across days in October. Resulting data analyses reveal response outcomes can be grouped into the following five types:

1) Demand impact achieved (due to setback temperature relative to indoor temperature)
2) Partial impact achieved (due to customer override during the course of a DR event)
3) Impact achieved in the form of delayed cycling (or cycling suppression during DR event)
4) Impact achieved only from 10-minute forced off “feature” at start of DR event
5) No impact (since the AC was not on at start of DR event, the DR setback temperature was lower than the actual indoor temperature, and/or customer overrides occurred at start of DR event)

The days of impact occurred on the highest temperature days when test events were conducted. These days occurred in September, as identified below.

TYPES OF RESPONSE OUTCOMES

Data collected during DR test event periods are graphed in this section. Each graph depicts actual indoor temperature measured by the modlet (in blue), indoor setpoint temperature (in orange), and measured power draw (in purple) across one day. DR event periods are demarcated in vertical shades of orange. The entire duration of DR events extended for two to four hours each. The graphs are grouped below by response outcomes exhibited.

1) Type 1: Impact achieved from temperature setback during DR event

Figure 3 through Figure 5 provide examples of normal modlet operation for cycling a connected window AC during a DR event. The figures illustrate AC power consumption relative to indoor temperature and setpoints during test events conducted with select modlets on the dates noted.

The power consumption plot in Figure 3 depicts a window air conditioner (AC number 2) shutting off throughout each of two contiguous 2-hour test periods, and resuming continuous operation immediately at the conclusion of the overall DR event. Since the setback of the remote thermostat at the start of the test period caused the indoor temperature set-point to exceed the actual temperature throughout the DR event, the AC cycled off and only cycled back on at the conclusion of the event when the normal thermostat setpoint was restored. This led to a 213W reduction in power consumption and 852Wh savings in energy consumption across the four-hour test event.

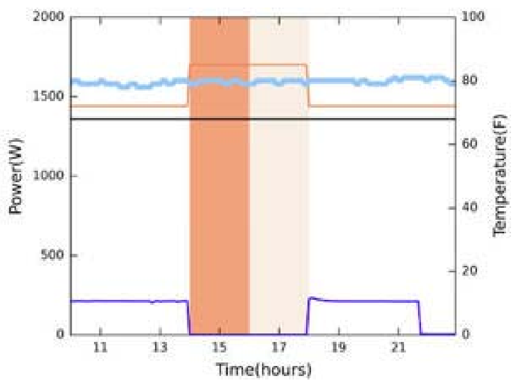


Figure 3: Impact with AC2 on (10/5)

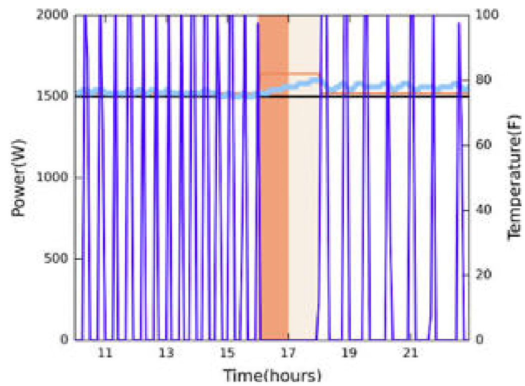


Figure 4: Impact with AC4 on (9/15)

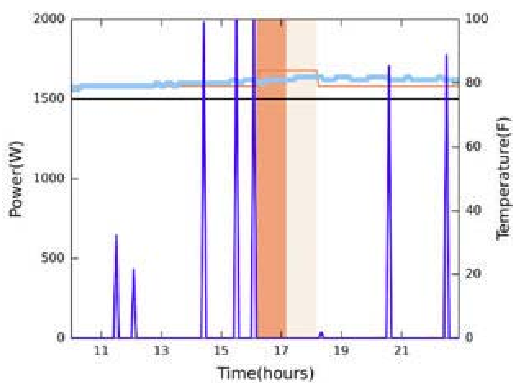


Figure 5: Impact with AC4 on (9/17)

Figure 4 and Figure 5 illustrate cycling of another window air conditioner (AC number 4) during two DR test events in September. As the power consumption plots illustrate, the cycling time of the particular air conditioner was more rapid than AC2 due to the type of technology (a portable evaporative cooler) being controlled by the modlet and the high rated power capacity of the cooler (about 2.1 kW).

Figure 4 depicts a 33% AC cycling pattern leading up to the DR event on September 15. A 33% duty cycle for a 2.1 kW AC that is suppressed off across a two hour DR event, saves approximately 1.39 kWh. For the DR event on September 17, depicted in Figure 5, a 20% duty cycle is observed for the 2.1 KW AC leading up to the DR event. A 20% duty cycle for a 2.1 kW AC that is suppressed off across a two hour DR event, saves about 0.84 kWh.

2) Type 2: Partial impact due to user override

Figure 6 and Figure 7 depict impact on modlet operation due to user override. The power consumption plots in the graphs illustrate power usage of two window ACs during DR test events, and the indoor temperature plots indicate instances of user override.

In particular, Figure 6 depicts a window air conditioner (AC number 2) responding to setpoint adjustments at the start of a DR event, comprised of four consecutive 1-hour test periods. At the start of the first and second test periods at 6pm and 7pm, respectively, the indoor temperature plot indicates immediate user override resulting in temperature setpoint adjustments back to normal levels. At the start of the third test period at 8pm, the temperature is setback again (per modlet design at the start of each test event), and no longer overridden for the remainder of the DR event. However, since the actual temperature exceeded the setback temperature, the AC cycled on during the third test period. Similarly, during the start of the fourth event period at 9pm, the AC was forced to shut off for ten minutes (per modlet design) and cycled back on afterwards due to high indoor temperature conditions relative to the setback temperature. Consequently, partial impact was achieved.

Figure 7 also illustrates user override impacting results. The particular DR test event consisted of a series of four test periods lasting one hour each, as indicated by the four vertical orange shaded bands. As indicated by the indoor temperature setting (orange plot), the indoor temperature dips sharply towards the end of the second test period, caused by user override. Consequently, the window AC (AC number 1) ran towards the end of the second test period, up until it is forced off at the beginning of the third test period.

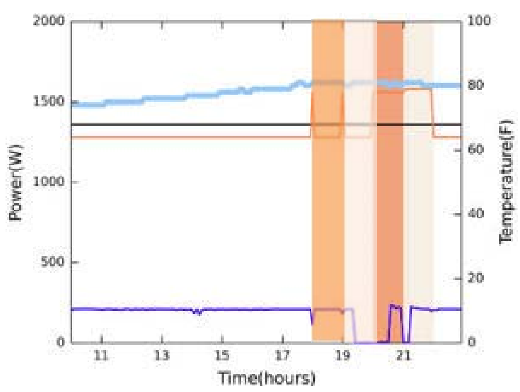


Figure 6: Impact until Override at AC2 (10/19)

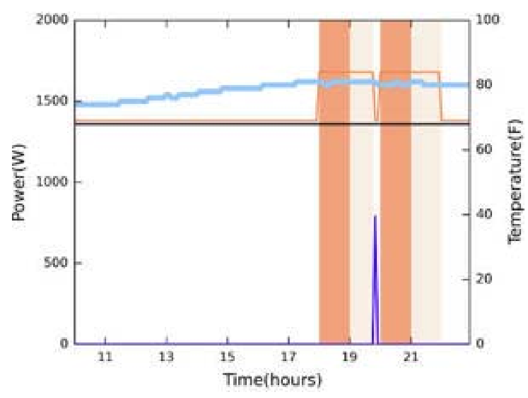


Figure 7: Impact until Override at AC1 (10/23)

3) Type 3: Impact through delayed cycling

Figure 8 and Figure 9 depict modlet control of window ACs resulting in delayed cycling during DR test events (on the dates noted). These two examples depict the possibility of limited impact from modlet operation in terms of only achieving delayed cycling of a window AC during a DR event.

Figure 8 illustrates the window air conditioner (AC number 3) in off state before the start of the DR event. During the first test period of the event at 4pm, the AC remains off until mid-way through the one-hour test period, and is shut off at the start of the second test period for ten minutes, per modlet design. Due to user override during the second test period, the AC cycled back on before the conclusion of the DR event scheduled through 6pm.

Similarly, Figure 9 also illustrates the window air conditioner (AC number 3) delayed in cycling on during the first test period of a DR event. At the conclusion of the DR event the AC immediately cycles back on, upon restoration of the normal temperature settings.

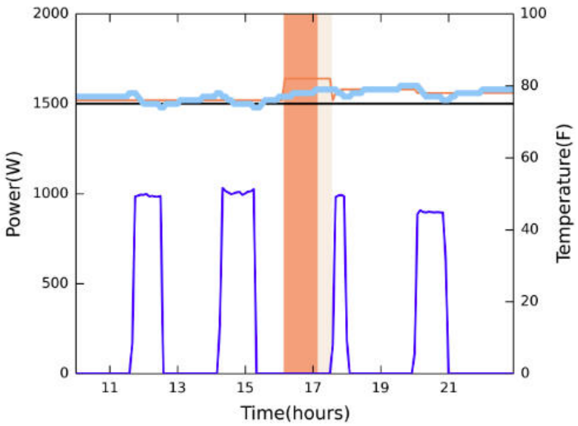


Figure 8: Delayed Cycling of AC3 (9/15)

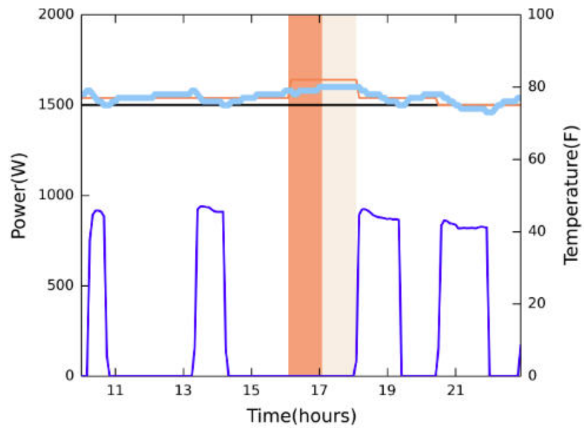


Figure 9: Delayed Cycling of AC3 (9/17)

4) Type 4: Impact only from 10-minute forced off feature

The modlet is designed with a 10-minute forced off “feature” that dictates AC operation at the start of each DR event period. Figure 10 through Figure 12 depict modlet control of window ACs only achieving cycling off during the start of a DR test period (on the dates noted). Figure 10 illustrates the window air conditioners (AC number 1) on before the start of the DR event. During the first test period of the event, the AC is cycled off for ten minutes, and runs continuously throughout the DR event, except at the start of the second test period when it is forced off again for ten minutes.

Similarly, Figure 11 and Figure 12 exhibit the same response pattern, wherein the impact achieved is only from the modlet design featuring forcing the AC off during the first 10 minutes of each test period.

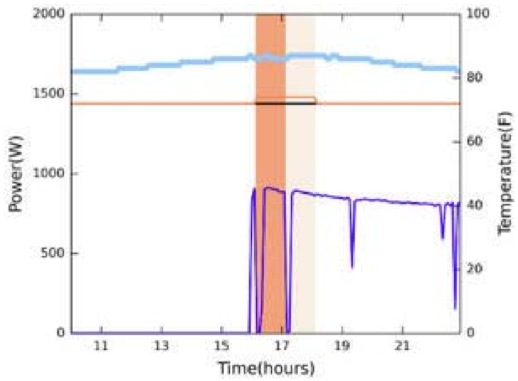


Figure 10: AC1 Forced Off at Event Start (9/3)

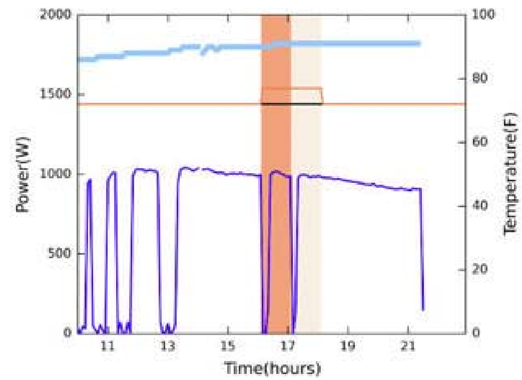


Figure 12: AC1 Forced Off at Event Start (9/15)

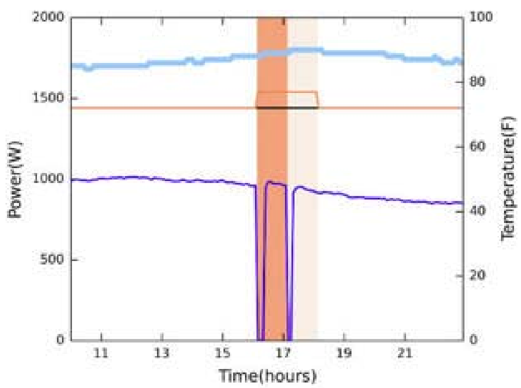


Figure 11: AC1 Forced Off at Event Start (9/17)

5) Type 5: No or virtually no impact

The final type of response outcome observed from data analyses is no impact or virtually no impact. This occurs when air conditioners are turned off when entering into a DR event, as illustrated in Figure 13 and Figure 15 for a window AC (AC number 2). This condition is readily apparent since the indoor temperature setpoint (orange plot) before the DR event falls below the actual indoor temperature (blue plot), but the AC draws no power to condition the space.

Another situation in which no impact is achieved occurs when the temperature setback is too low to cause the setback temperature to exceed the actual indoor temperature read by the modlet throughout the DR event. This situation is depicted in Figure 14 for a window AC (AC number 4).

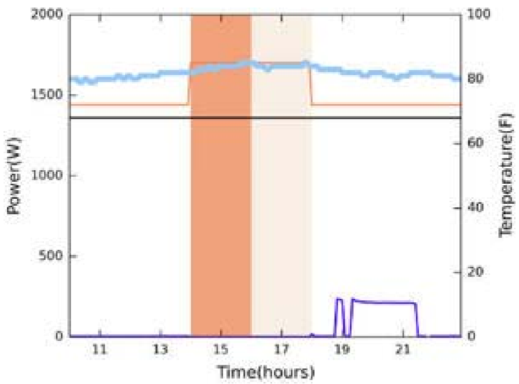


Figure 13: No Impact with AC2 off (10/6)

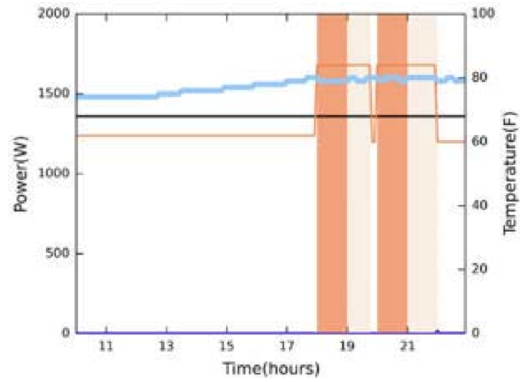


Figure 15: No Impact with AC2 off (10/23)

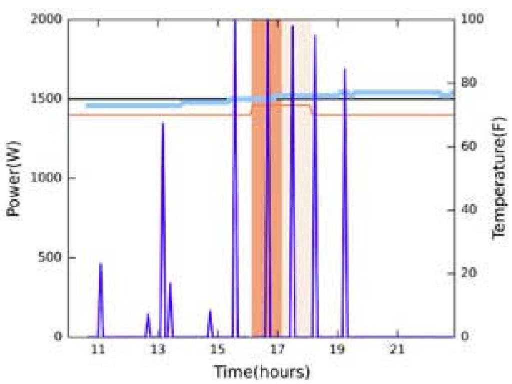


Figure 14: No Impact with AC4 on (9/3)

RECOMMENDATIONS

In order to develop recommendations for possible improvement of the products tested, EPRI interviewed the modlet manufacturer to understand details of device operation per design involving indoor temperature reading. The modlet is reportedly designed to measure, report, and act on measured indoor temperature as follows.

- The thermostat remote control takes indoor temperature readings about every 10 minutes.
- A temperature reading is also taken every time the thermostat remote is awakened by a button press on the remote.
- Measured temperatures are reported to the server within one minute of being read.
- The modlet possesses the thermostat logic and decides when to switch the AC according to:
    - If measured temperature hits set point + 2°F, then the AC is turned on
    - If measured temperature hits set point - 2°F, then the AC is turned off
    - There is an additional timing constraint ensuring at least 8 minutes have passed between state changes (switching operations), except when the customer adjusts settings on the remote to change the temperature setpoint manually (since manual setting changes are allowed anytime).
- The default dead band is set to +/-2°F. However, the customer may be allowed to set the dead band to +/-1 or 2. (The manufacturer has an API to configure it between +/-1°F to +/-4°F, but was not using that feature at the time of the interview in 2015.)

Considering existing design, the following design improvements were identified and shared as recommendations with the modlet manufacturer to inform future product design evolution and improvement.

- It is recommended to tailor temperature set-backs based on participation history of each customer. This is in contrast to existing practice of employing a one-size-fits-all approach for all participant setbacks. For example, customization by basing setbacks on latest indoor temperature condition for individual customers, can result in improved participation while better maintaining user comfort.
- The modlet is designed to automate ACs off at the beginning of each DR event. This automated off-cycle sweeps previously opted-out devices back into DR participation in order to attain greater peak load reduction per device. This automated off-cycle makes DR event initiation obvious to users running their ACs, even those who have opted out. However, in order to minimize user disruptions, it is recommended to support the ability to turn off the automated off-cycle.

Additional recommendations address issues observed during device provisioning and operation.

- The device provisioning process was a non-trivial task, requiring manual entry of Wifi keys and user registration codes. Moreover, older browsers and operating systems presented opportunities for smart plug platform incompatibilities, impeding device installation. Consequently, an automated process is recommended for user self-registration that does not require manual entry of key codes.
- Potential loss of device wireless connectivity is a reality. Therefore, ample local data storage is a good practice for preventing significant data loss upon prolonged

connectivity loss. Device memory storage capacity of at least several weeks' worth of data is recommended, in case measured data cannot be uploaded in a more timely fashion for archival purposes (e.g., upload to a vendor's cloud platform).

REMARKS

The field trial was useful for examining device operation under different circumstances encountered under real-world conditions, including temperature conditions and user override. Based on data collected and analyzed, the modlet was observed to operate consistent with manufacturer design, according to the state diagram in Figure 2.

The field trial identified different types of impacts on ACs under modlet control. These types of impacts included: full impact (ACs cycled off throughout a DR event), reduced duty cycles, delayed cycling, partial impact, or no impact achieved (due to user override and/or lack of AC utilization during a DR event).

Considering the DR test events were initiated in the field during the fall season, after the summer season had passed, field data collected revealed a general lack of AC usage at customer sites during many DR test events. Consequently, the project was extended in 2015 with a lab trial to assess power savings from modlet-controlled cycling. The lab trial is described in the next chapter.

LABORATORY TESTING

LAB TESTED TECHNOLOGIES

Two technologies for room air conditioner control were tested in EPRI's Knoxville, Tennessee laboratory facility. These technologies are illustrated in the figures below. Figure 16 depicts a Wifi-connected room air conditioner, and Figure 17 depicts the modlet that was the subject of customer field trial.

The goals for lab testing were three fold. Namely, to determine:

1) impact of a Window AC's fan speed on power draw,
2) power draw reporting accuracy of the ThinkEco modlet in comparison to a Wifi-connected Window AC (by Friedrich), and
3) demand savings achievable by a modlet-controlled window AC at select setback temperatures.

The lab trial also served to inform the development of recommendations for smart plug product enhancements to better support utility peak load reduction objectives with connected devices.

Figure 16: Friedrich Kuhl Window AC

Figure 17: Thinkeco Modlet and Thermostat Remote Control

POWER DRAW TESTS

TEST PROCEDURE

For determining power draw, a lab test procedure was developed for controlled device testing in a climate chamber. The climate chamber is equipped with instrumentation capability as well as configurable settings for establishing test conditions, such as indoor and outdoor temperature and humidity levels.

The test conditions under which power draw measurements were taken are summarized in Figure 18. The table identifies both indoor and outdoor temperature conditions examined along with fan speed settings of the Window AC. Each test was ran at standard humidity conditions of 51.5 indoor relative humidity.

At each indoor and outdoor temperature condition tested, the following test procedure was followed.

- Outdoor temperature held constant (via chamber temperature control)
- Indoor temperature and relative humidity held constant (via chamber temperature and humidity control)
- Window AC ran for two hours at high fan speed before collecting data (for an average of 30 minutes of collected data)
- Change fan speed to medium, followed by low after having collected data at high speed (for an average of 15 minutes of collected data at each speed)

Outdoor temp	Indoor temp
75F	75F @ 51.5% H, / H,M and L fan speed
85F	75F @ 51.5% H / H,M and L fan speed
95F	75F @ 51.5% H / H,M and L fan speed
105F	75F @ 51.5% H / H,M and L fan speed
115F	75F @ 51.5% H / H,M and L fan speed
Outdoor temp	Indoor temp
75F	80F @ 51.1% H / H,M and L fan speed
85F	80F @ 51.1% H / H,M and L fan speed
95F	80F @ 51.1% H / H,M and L fan speed
105F	80F @ 51.1% H / H,M and L fan speed
115F	80F @ 51.1% H / H,M and L fan speed
* Run the chamber 2 hours before starting the data recordings	*Collect data for fan speeds- 30 min/H, 15 min M, 15 min L

Figure 18: Test Matrix Summarizing Climate Chamber Test Conditions

FAN SPEED IMPACT ON POWER DRAW

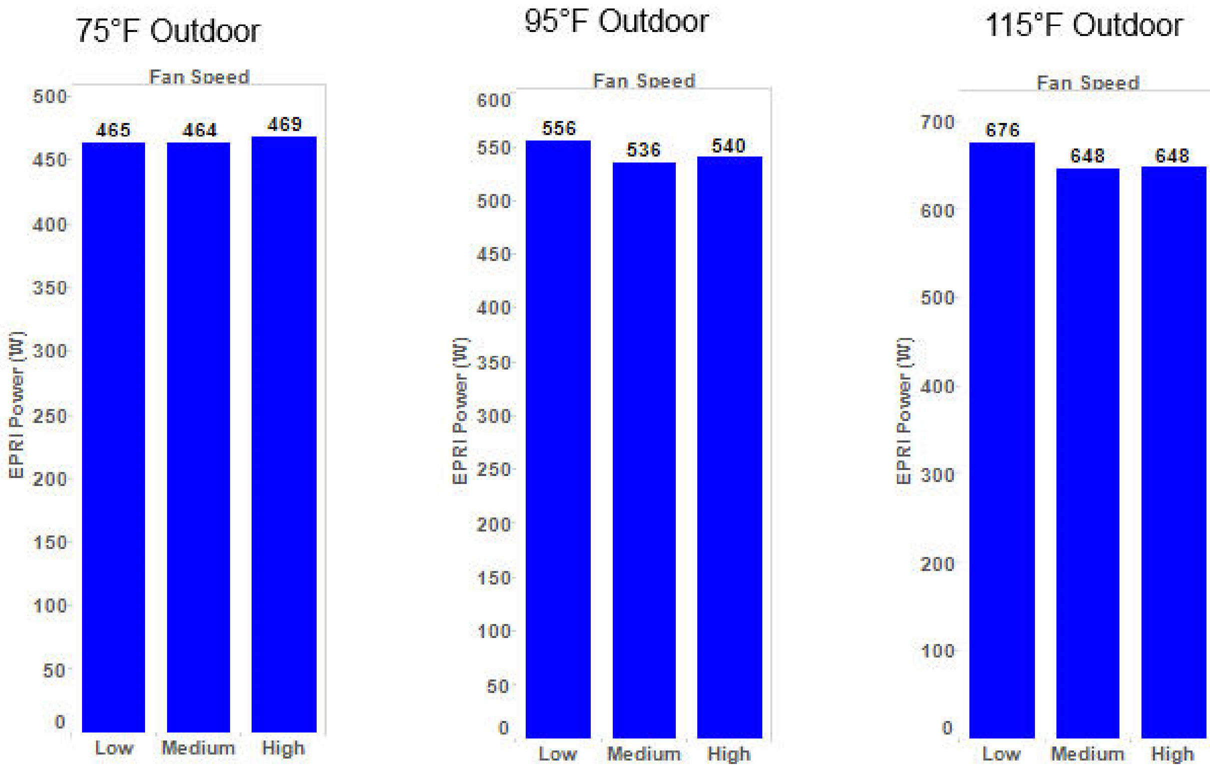


Figure 19: Comparison of Fan Speed Effect on Power Draw

Measured power consumption at low, medium, and high fan speeds are shown in Figure 19 at three different outdoor temperatures (and for the same indoor condition of 80°F dry bulb temperature and 67°F wet bulb temperature). The average power draw at 75°F is 466W and the difference in power draw between the three fan speeds is within ±1%. The average power draw at 95°F is 544W and the difference in power draw between the three fan speeds is within ±4%. The average power draw at 115°F is 657W and the difference in power draw between the three fan speeds is within ±4%.

The 95°F and 115°F outdoor temperature cases resulted in higher power draw at low fan speed than at higher fan speeds. This translates to 2% more power usage at low fan speed than average at 95°F outdoor temperature, and 3% more at 115°F outdoor temperature. Higher power draw at low fan speed seems counterintuitive, but can be explained by the way the window AC works.

Normally in a split system there are two different fan motors; one for the indoor unit and one for the outdoor unit. In the case of a window AC, both the fans (indoor and outdoor) are installed on the same straight shaft on a single motor. When the fan speed is reduced, not only does the internal air flow (on the evaporator) decrease but also decreases on the external fan (condenser). The condenser due to the reduced airflow at low fan speeds cannot reject as much heat as it could with a higher fan speed for the same ambient temperature. This reduction in air flow results in higher condensing pressures making the compressor work hard and hence the higher power. The difference is negligible at the lower end of ambient temperatures (75°F) due to the milder conditions which makes heat rejection easier.

POWER DRAW REPORTING ACCURACY

An additional test was conducted to determine the accuracy of power draw reported by two different vendor platforms (i.e., the Friedrich Window AC and Thinkeco platforms, respectively). Collected data from the lab trial was analyzed, along with data received from the Wifi-connected window AC manufacturer. The power draw data received from Friedrich was not available to the end-use customer at the time of the lab test, but was received from the manufacturer by special request for the purposes of performing an assessment.

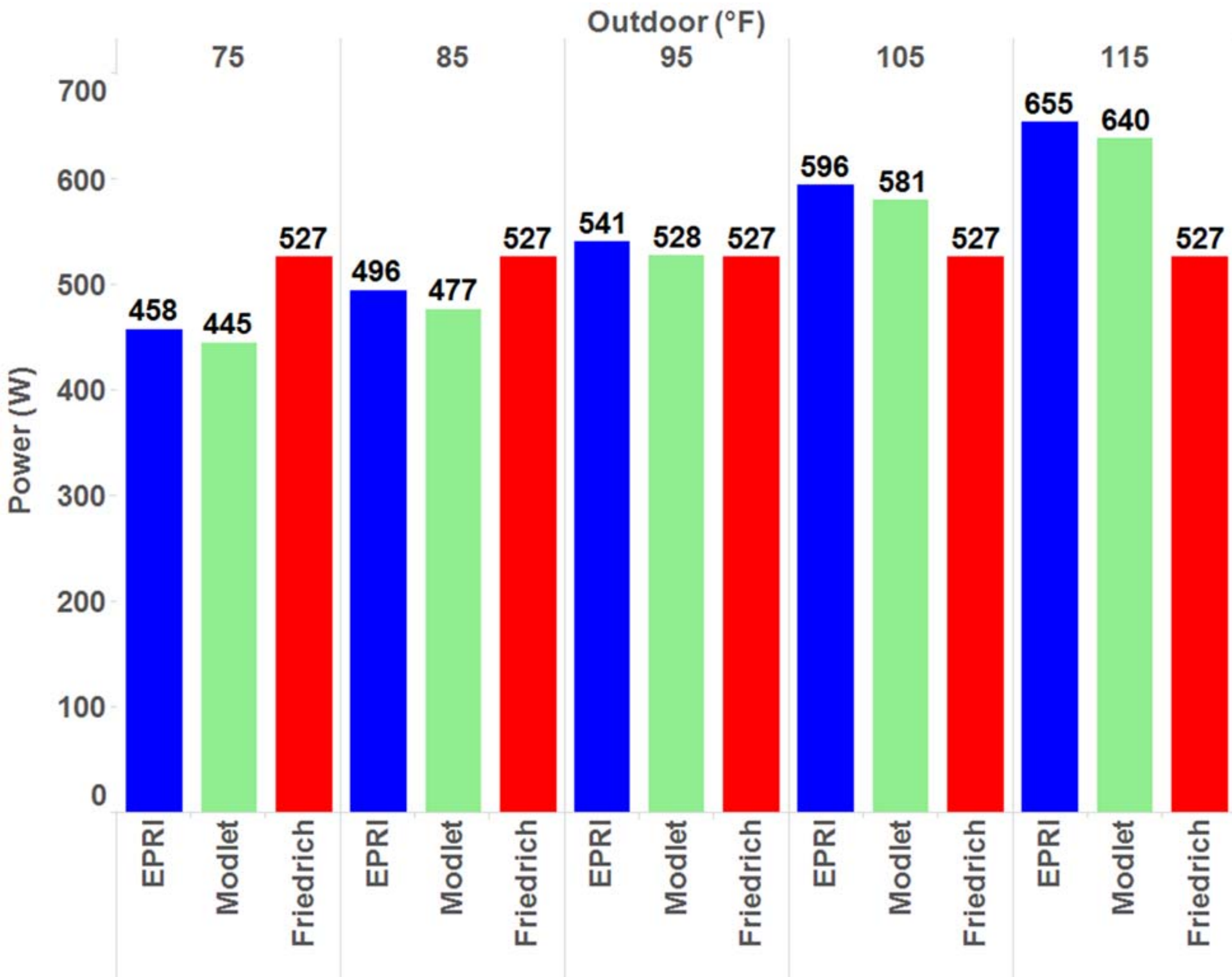


Figure 20: Comparison of Measured Power Draw against Modlet and Friedrich Reported Values

The above graph shows a comparison between power draw reported by three different sources. The reporting devices are a data acquisition instrument located in the climate chamber (for independent measurement and comparison), a modlet, and information provided by the window AC manufacturer through data file transfer to EPRI.

Figure 20 presents power draw reported by the three sources at different outdoor conditions, and for the same indoor condition of 80°F dry bulb temperature (DBT) / 67°F wet bulb temperature (WBT). As the figure illustrates, the information provided by the window manufacturer is a constant value. The value reported is merely the rated power of the AC, which is 527W. The manufacturer platform reported the same power draw anytime the AC is ON.

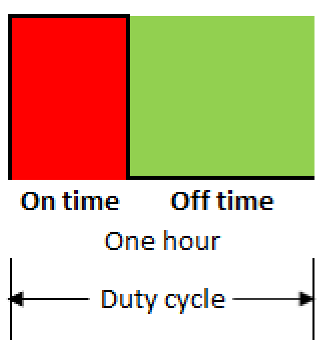
In contrast, the EPRI power measurements were taken with instrumentation equipment that meets ANSI C12.20 and IEC 62053-22 (0.2%) accuracy classes. The modlet power measurements are within 4% of the EPRI measurements and biased to the low side. The accuracy of the modlet power measurement is reportedly ± 5%, as dictated by internal components within the device.

DEMAND SAVINGS TEST

TEST PROCEDURE FOR ASSESSING DEMAND SAVINGS

In order to determine demand savings of a modlet-controlled window AC at select setback temperatures, a test procedure was devised to assess device behavior in steady state under baseline conditions as well as under select temperature setback conditions. The test procedure below was developed and conducted in EPRI's Knoxville, TN lab facility in a controlled climate chamber. The same chamber used to conduct the prior test was used to conduct the test procedure outlined below.

1. Establish baseline conditions for testing
    a. Set outdoor temperature at 95°F
    b. Run the indoor climate chamber with fan only (and no heating).
    c. Establish the Friedrich Window AC set point temperature at 72°F
    d. Set the AC fan to auto fan
    e. Measure the duty cycle[2]
    f. Adjust the indoor chamber heating until achieve roughly 60-80% duty cycle. Note: The duty cycle measurement is in one hour cycles as illustrated below.



2. Run test for the first temperature setback condition
    a. Set the modlet target temperature to 75°F.
    b. Ensure the Friedrich Window AC set point temperature is low enough to enable the AC to always run (e.g., set well below the modlet target temperature)
    c. Set outside thermal chamber temperature to 95°F

[2] The duty cycle is taken as on-time / (on-time + off-time)

   d. Apply approximately the same units (in watts) of heat as was applied inside the indoor thermal chamber during baseline testing
   e. Energize and allow the modlet-controlled AC to cycle for about two hours
   f. After verifying the AC in the chamber has settled to steady state cycling (after about two hours), start data recording and continue recording for at least two complete on and off cycles.
3. Run test for the second temperature setback condition
   a. Set the modlet target temperature to 78°F
   b. Ensure the Friedrich Window AC setpoint temperature is low enough to enable the AC to always run (e.g., set well below the modlet target temperature)
   c. Set outside thermal chamber temperature to 95°F
   d. Apply approximately the same units (in watts) of heat as was applied inside the indoor thermal chamber during baseline testing
   e. Energize and allow the modlet-controlled AC to cycle for about two hours
   f. After verifying the AC in the chamber has settled to steady state cycling (after about two hours), start data recording and continue recording for at least two complete on and off cycles.

WIFI CONTROL BOARD ISSUE RESOLUTION

During the lab test, initial baseline testing (under Step 1 of the test plan) proved problematic. The Friedrich Window AC never turned off despite its target temperature setting being well exceeded during the baseline test. Upon consultation with the manufacturer of the Window AC, settings were adjusted and the root cause was determined to be a faulty Wifi control board inside the unit. The control board was removed, and a series of test runs conducted as outlined in the test procedure.

CYCLING REDUCTION

The power consumption measured for each test run is graphed below. Analysis of the collected data reveals a baseline test duty cycle of about 64%; plus a duty cycle of approximately 26% for each of the two target temperature setback conditions of 75°F and 78°F, respectively.

Figure 21: Power Consumption for Baseline Case (AC set to target temperature of 72°F)

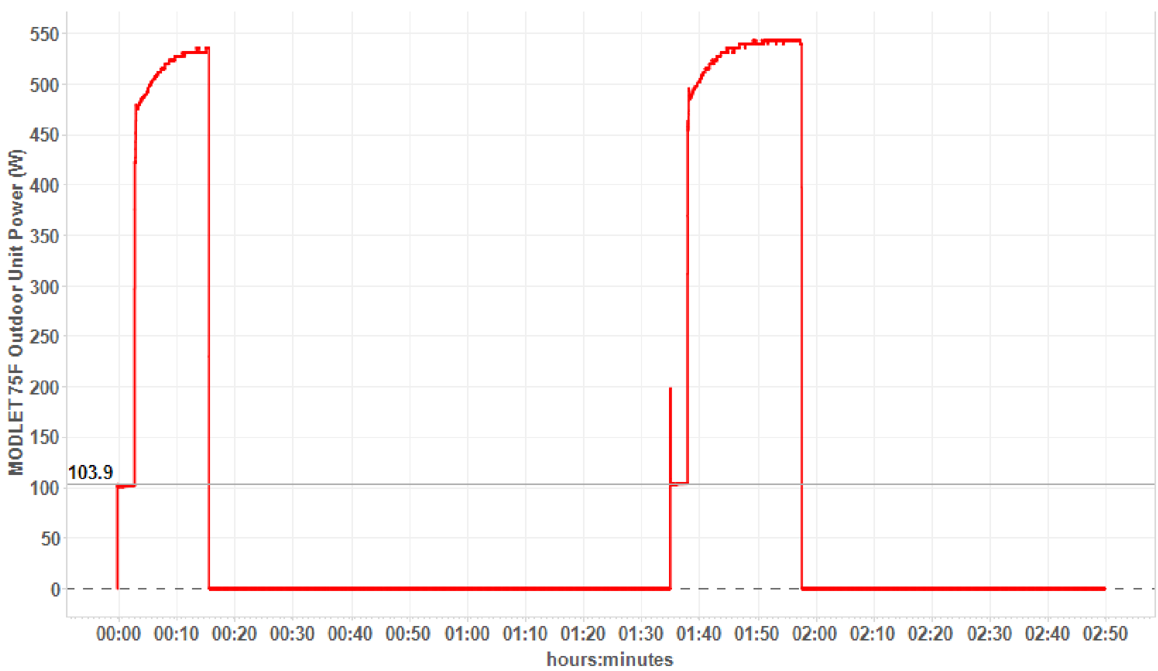


Figure 22: Power Consumption for 75°F Setback Case (Modlet with target temperature set at 75°F)

Figure 23: Power Consumption for 78°F Setback Case (Modlet with target temperature set at 78°F)

Indoor temperature data was received from the modlet manufacturer to help interpret test results. Although indoor temperatures read by the modlet are not normally available to the end-use customer, the data was received from the modlet manufacturer by special request for the purposes of performing an assessment.

Average power consumption was computed across two power cycles of the modlet for each test run. Based on the data graphed in Figure 22 and Figure 23 above, the 75°F setback case resulted in an average power usage of 104W, compared to 121W in the 78°F setback case. That is, the 75°F setback case resulted in lower average power usage than the 78°F setback case. This counterintuitive result can be explained through examination of the plots of indoor temperature collected by the modlet in each setback case.

Figure 24 and Figure 25 below plot modlet manufacturer-delivered data for indoor temperature next to instrumented data taken in the climate chamber during each test. Close examination reveals specific times when the modlet detected indoor temperature changes compared to actual indoor temperature conditions measured in the climate chamber.

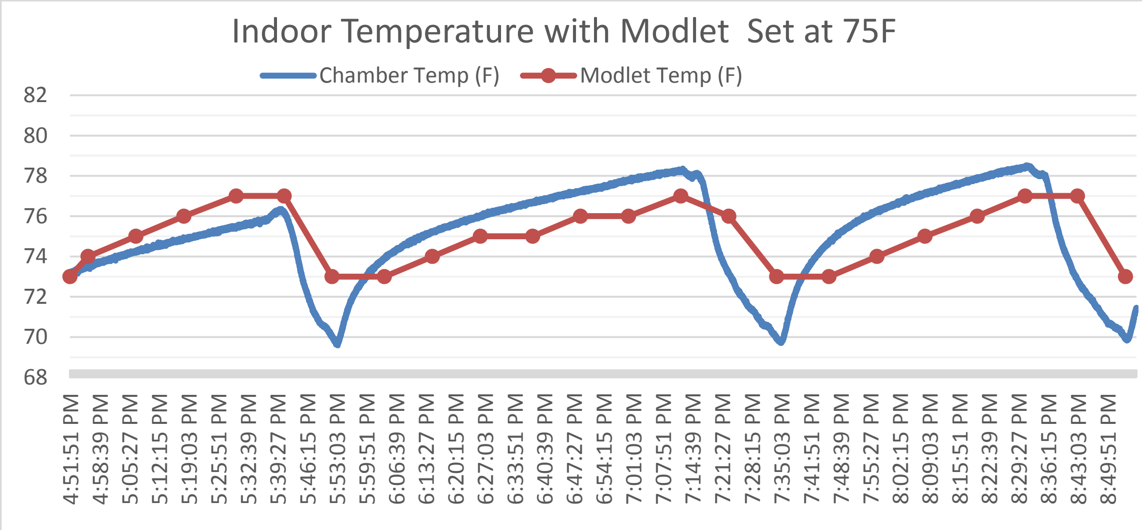


Figure 24: Indoor Temperature vs. Modlet Reported Indoor Temperature for 75°F Setpoint

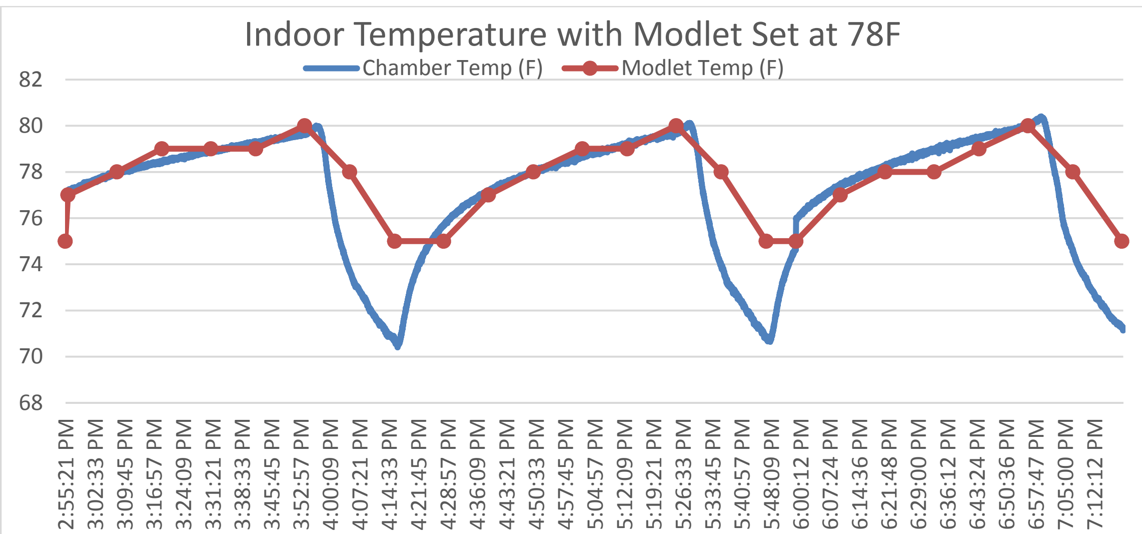


Figure 25: Indoor Temperature vs. Modlet Reported Indoor Temperature for 78°F Setpoint

Operating by design, when set to a target temperature of 75°F or 78°F, the modlet-controlled AC ran until the target temperature was exceeded by two degrees (i.e., fell to 73°F or 76°F), at which point the modlet cycled the AC off. The AC remained off until the modlet detected a temperature rise of at least two degrees above its target temperature (i.e., rose to 77°F or 80°F), at which point the modlet interrupted power to the AC.

The two figures above reveal the modlet reporting measured indoor temperature every 11-12 minutes during the experiments. The slow rate of reporting can result in met temperature threshold conditions being detected in a substantially delayed fashion compared to actual conditions.

For example, during the 75°F experiment, the modlet incidentally sampled indoor temperature soon after the threshold were actually reached. In contrast, detection of threshold conditions being met was substantially delayed in the 78°F experiment. This led to about an 8 degree swing between temperature threshold conditions in the 75°F case compared to about a 10 degree swing in the 78°F case. Consequently, the 78°F case resulted in higher average power usage than the 75°F case, due to the overshoot phenomena described.

DEMAND SAVINGS RESULTS

The tables below tabulate outcomes of lab trial of the modlet as well as the Friedrich window air conditioner under the baseline and setback conditions noted in the tables. Results were collected following the described test procedure.

Test results are noted below in Table 6 for each test run (conducted on the dates indicated). Each row of the table represents a test run with the modlet and/or Friedrich window AC, and results are summarized in the columns. Results summarized include the computed average power draw, the measured indoor temperatures when the AC unit cycled off and then cycled back on, and the maximum and minimum indoor temperatures observed during each test run. The last column contains the computed difference between the maximum and minimum indoor temperatures listed in the previous two columns.

	Average Power (W)	Unit Turns OFF at (°F)	Unit Turns ON at (°F)	MAX T (°F)	MIN T (°F)	DELTA T (°F)
No Modlet (5/13/15)	232	70.7	71.05	72.01	70.11	1.9
Modlet 75°F (5/13/15)	104	69.75	78.36	78.36	69.59	8.77
Modlet 78°F (5/14/15)	121	70.52	80.05	80.12	70.4	9.72

Table 6: Comparison of Results from Additional Test Run with Modlet Setback Temperatures

For comparison purposes, additional test runs were conducted with the Window AC at different setback temperatures. Results are summarized below in Table 7.

The additional test runs were conducted during the summer season following the initial lab test that occurred in the spring. The differences in seasons led to disparate heating and duty cycling conditions during the summer baseline test compared to the spring test, even though the Friedrich window AC was set to 72°F under both tests.

	Average Power (W)	Unit Turns OFF at (°F)	Unit Turns ON at (°F)	MAX T (°F)	MIN T (°F)	DELTA T(°F)
Friedrich 72°F (7/2/15)	206.3	72	71.12	72.54	70.74	1.8
Friedrich 75°F (7/2/15)	163.4	76.13	75.97	76.57	75.35	1.22
Friedrich 78°F (7/6/15)	177.1	79.76	79.72	80.18	79.35	0.83

Table 7: Comparison of Results from Test Run with Window AC Setback Temperatures

Following the same test procedure outlined for the modlet, the Summer lab test involved setting back the Friedrich Window AC to two different indoor temperatures setpoints, following an initial baseline test with the AC set at 72°F target temperature. Findings from the summer test are shown in Table 7.

Average power consumption in the 78°F setback case exceeded that in the 75°F setback case. This may similarly be explained by the oversizing of the Window AC unit relative to the room space of the climate chamber within which the tests were conducted.

VENDOR REMARKS

Upon review of the findings from lab testing, the vendor shared the following remarks:

- The vendor is aware of possible overshoot phenomena when an AC is oversized for a room.

In the event a very powerful AC is installed relative to the size of room being air conditioned, then the vendor's current system design may not sample fast enough to avoid the overshoot phenomena. However, if the AC were sized reasonably for the cooling capacity of the room in which it were located within, then the current designed sampling and reporting rate of indoor temperature data is sufficient to respond well.

- Usually an AC is undersized for a room, especially when hot. So a drastically oversized AC can be uncommon to encounter in the field.
- Good thermostat placement needs to be considered

Good practice is to place the remote control thermostat in a location representative of the temperature in the room and not directly on the AC, in order to achieve good system performance. The vendor generally recommends placing the thermostat remote in the center of the room being conditioned and in the same area as the user.

- Battery life of the thermostat remote also needs to be considered

By default the current sampling and reporting rate for indoor temperature is once every 10 minutes. This equates to battery life extending for 3 years. Conceivably the manufacturer may reconfigure the rate, but would be at the expense of battery life.

CONCLUSIONS

The study evaluated a sample of smart plug technologies with the potential of supporting peak load reduction. The smart plug technologies performed as described in manufacturer marketing literature. Based on field and lab testing of the modlet to control window ACs the following conclusions can be drawn.

Demand savings:

- Impacts observed from field trial of modlet devices varied from reduced power consumption of controlled window AC units (e.g., through cycling achieved during DR events) to no impact (e.g., due to continuous running of the AC).
- Actual outcomes depended on many factors such as room occupancy, consumer override, outdoor temperature conditions and the size of the AC unit relative to the physical indoor space within it is located (e.g., room size and building envelope leakage).
- In a lab test, the modlet achieved 49-55% reduction in average power consumption, with setbacks of 75°F to 78°F, compared to baseline window AC operation at 72°F target temperature and no modlet.
- In a lab test, the Friedrich window AC achieved 14-21% reduction in average power consumption, with setbacks of 75°F to 78°F, compared to a baseline of 72°F target temperature.

Power consumption reporting:

- Reported power consumption values from smart plug platforms can be based on measured values or approximations involving no instrumentation. Consequently, power consumption reported by smart plug devices can vary in accuracy and be biased, impacting assessed demand savings. It is important to distinguish the method of power usage reporting being utilized due to possible wide variation in accuracy of reported values.
- Under lab test, the modlet power measurements were within 4% of the EPRI's lab measurements and were biased lower than lab measurements.
- The Friedrich window AC platform reported a static value for power consumption based on the window AC model's power rating.

Fan speed impact on power consumption:

- Under lab test, there was little difference in power draw between the three fan speeds of the Window AC tested. The average power draw at low, medium, and high fan speeds at different outdoor temperatures was within ±4%.

Market barriers:

- Overall the products field and lab tested performed as manufacturers described in marketing literature. However details of how products operate to support DR are generally left undocumented in normal marketing literature for the consumer.
- Smart plug vendor assertions of product support for demand response capabilities could be better clarified and documented to distinguish support for time scheduling operation of devices (e.g., under TOU rates) from capabilities to receive and process DR event signals.

- The process of self-registration of Wifi devices is a non-trivial task, commonly requiring manual entry of Wifi keys and codes. In contrast, an automated process could greatly simplify the process.