

Methodology for Modeling Savings for Home Energy Management Systems

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ABSTRACT

Home Energy Management Systems (HEMS) are part of a quickly expanding product market that provides homeowners with the ability to control energy consuming devices through monitoring and feedback, programmed schedules, control logic, and utility signals. The broad range of HEMS product combinations and the high dependence on occupant behavior make it challenging to create modeling algorithms that accurately estimate impacts on energy bills, especially under time-of-use rates. This challenge has been identified by stakeholders as a major barrier to utility program incentives and energy efficiency credits in energy codes.

The objective of this study was to develop a repeatable and defensible methodology to analyze the energy savings for a HEMS that meets the minimum certification requirements under ENERGY STAR® Smart Home Energy Management System (SHEMS) Version 1. Mandatory connected loads include a smart thermostat, two smart lights, and one smart power strip or outlet. Control strategies must include feedback to occupants through an in-home display, user programming, occupancy sensor-based controls, and responsiveness to utility signals such as demand response programs.

Several occupant behavior patterns were selected to quantify the range of energy savings potential for a HEMS with this basic functionality. Realistic room-by-room occupancy levels and usage patterns were established for connected devices. A series of event-driven hourly profiles were created, followed by adjustments based on application of HEMS control strategies to thermostats, interior lighting, and plug load schedules. EnergyPlus modeling was performed using these hourly schedules in three locations (Boston, Houston, and Phoenix) to examine climate dependence of energy savings.

Introduction

HEMS are part of a quickly expanding product market that provides homeowners with the ability to control energy consuming devices through monitoring and feedback, programmed schedules, control logic based on occupancy sensors or weather data, machine learning, and utility signals. Two recent studies by See Change Institute and CLEAResult indicated that 21 percent of consumers owned at least one HEMS product and approximately 32 percent of households had products that could be controlled by a smartphone (Hendron et al. 2020). The broad range of HEMS product combinations and the high dependence on occupant behavior make it challenging to create modeling algorithms that accurately estimate impacts on energy bills, especially under time-of-use rates. This inability to quantify the benefits of HEMS has been identified by stakeholders as a major barrier to utility program incentives and recognition by energy codes (Hendron et al. 2020).

In 2021, Frontier Energy completed a study for the National Energy Renewable Laboratory (NREL) to address these data gaps and recommend a savings estimation methodology which could increase demand for ENERGY STAR certified SHEMS by increasing

consumer confidence in the likely range of energy savings (Hendron et al. 2021). It is also an important step toward a flexible and repeatable method for predicting the energy savings of any theoretical combination of HEMS capabilities, connected devices, and occupant behavioral patterns. The analysis leveraged previous work performed by NREL in support of the Building America House Simulation Protocols (HSP) (Wilson et al. 2014), along with more recent studies of energy savings for HEMS control strategies to simulate the range of expected energy and cost savings for a HEMS that minimally complies with the ENERGY STAR SHERMS Version 1 certification requirements (EPA 2020a). The relevant requirements are summarized below:

- Connected End Uses
 - Heating and cooling via ENERGY STAR Smart Thermostat (EPA 2017)
 - Two smart lights (EPA 2020b) or fixtures (EPA 2019)
 - One smart power strip/smart outlet
- Control Methods
 - Occupant feedback (energy use and recommended behavioral actions)
 - User-established rules/schedules
 - Occupancy sensor-based response
 - Grid signals (demand response, possible load shifting)

In most cases, the requirements related to connected devices and control strategies are very clear. In other cases, EPA identifies general functionality that can be difficult to quantify in a building energy model. The challenge for this project was to convert those requirements into specific modifications to thermostat settings, HVAC availability, lighting and MELs schedules and peak loads, and other modeling inputs that may be affected by the operation of the HEMS.

The 2014 update to the HSP, combined with the Building America (BA) Analysis Spreadsheets (NREL, 2011), provides much of the information needed to analyze HEMS in a consistent manner. However, the HSP is primarily focused on disaggregation of detailed end-uses, along with standardized hourly and seasonal operating profiles. It does not provide guidance on how controls would impact these profiles, nor does it provide discrete event-driven schedules for individual devices or lamps. The HSP is also somewhat out of date, especially in the areas of lighting and miscellaneous electric loads (MELs) where the market has evolved rapidly over the past 5-10 years. The HSP uses constant thermostat settings of 71°F for heating and 76°F for cooling, which are based primarily on occupant comfort according to ASHRAE Standard 55-2010 (ASHRAE, 2010) and are not necessarily realistic for most households. Finally, most schedules are the same on weekdays, weekends, and vacation days, which is not as realistic as we would like for detailed HEMS analysis.

Technical Approach

A literature review was conducted focused on leveraging field studies that could provide direct modeling inputs, such as studies of thermostat settings with and without a smart thermostat, or a specific fraction of lights that are regularly turned off when rooms are unoccupied. Studies that provided energy savings for one technology, or a bundle of technologies, were used as a calibration point for approximating reasonable behavioral changes that would result in comparable energy savings. In a few cases, no field data were available to support specific modeling inputs and engineering judgment was applied to make reasonable assumptions about likely operational changes following the installation of a HEMS.

The starting point for all operating conditions were those documented in the HSP and associated spreadsheets. These hourly profiles, representative of average occupancy characteristics, encompass all loads within a category (e.g. lighting or plug loads) and as a result are smooth. Therefore, these schedules were converted into more realistic step functions based on specific devices turning on and off at certain times of day. Specific occupancy levels were established in each room at each hour of the day, including unoccupied periods. This use of discrete behavioral patterns and operation of specific devices was necessary to make realistic adjustments to loads based on HEMS operation and grid signals.

Modeling inputs were developed for four combinations of behavior before and after HEMS installation, as shown in Table 1. For the baseline cases without HEMS, the “Not Energy Conscious” (NEC) case represents fairly high use occupants that generally don’t take actions to minimize energy use, while “Very Energy Conscious” (VEC) occupants employ thermostat set-back/set-up and usually attempt to turn off lights and electronic devices when not in use. In cases with HEMS, the “Somewhat Engaged” household makes limited use of HEMS features and sometimes overrides demand response signals. The “Highly Engaged” household uses all features and does not override demand response or other signals except in unusual circumstances, such as during a dinner party.

Table 1. Matrix of occupant behavior with and without HEMS installed

Without HEMS	Not Energy Conscious (NEC)
	Very Energy Conscious (VEC)
With HEMS	Somewhat Engaged (SE)
	Highly Engaged (HE)

EnergyPlus was used for modeling. The HSP new construction building envelope characteristics were applied to a typical 2-story, 3-bedroom, 2150 ft² single-family house prototype with a minimum efficiency gas furnace and air conditioner. Assumptions for all uncontrolled end uses were based on the HSP. Because discrete occupancy levels were required for the purpose of applying control logic, we assumed three occupants instead of the HSP default of 2.6. Models were evaluated in Boston, Phoenix, and Houston. The three locations provided for variation in heating, cooling, and lighting operation; however, it’s recognized that this doesn’t cover all climate considerations in the United States and is intended to provide a sample of results and proof of concept. Energy costs were calculated using a typical national time-of-use rate schedule developed by Frontier Energy for another project (German and Hoeschele 2014). The peak cost from 4pm to 9pm year-round was \$0.30/kWh and the off-peak cost all other times was \$0.10/kWh. A national average rate of \$1.0135/therm was used for natural gas as reported by the U.S. Energy Information Administration (EIA) for 2019 (EIA 2021).

Analysis Methodology

Occupancy

The occupancy profiles were developed by creating a narrative for the three occupants of the house on weekdays and weekends, aligning occupancy as closely as possible with targeted

“typical” overall occupancy levels aligned with the Codes and Standards Enhancement (CASE) Report for the Title 24, Part 6 energy code¹ on plug loads and lighting (Rubin et al. 2016) for weekends and weekdays. The targeted total occupancy levels were 48 person-hours on weekdays, 54 person-hours on weekends/holidays, and 0 person-hours during vacation periods. Narratives for the three occupants on weekdays and weekends are shown in Table 2. Adult #1 works full time outside the home, while Adult #2 works part time. The Teenager goes to school most of the day but does some schoolwork at home in the afternoon. The family has dinner together, and sometimes participates in family events together. The rest of the time, family members generally act independently.

These narratives are representative of the activities in which typical members of a household would engage and were carefully selected to align as closely as possible with data points from the literature review. The narratives were applied consistently across all four types of energy use behavior described in Table 1.

Table 2. Weekday occupancy narrative

Hour	Weekday			Weekend			
	Adult #1	Adult #2	Teenager	Adult #1	Adult #2	Teenager	
1	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	
2							
3							
4							
5							
6							
7							
8	Bathroom	Breakfast	Breakfast	Breakfast	Breakfast	Breakfast	
9	Work	Bathroom	Bathroom	Bathroom	Cleaning	Video games	
10		Work	School	Yardwork	Yardwork	Yardwork	
11		Home for lunch		TV	Bathroom	Music	
12		Work		TV	Lunch/errand	Shopping	Friends/ soccer
13				Reading	Cleaning		
14			Cleaning	Homework	Soccer practice	Soccer practice	
15		Reading/TV	Music	Nap	Reading	Homework	
16		Long walk	Shopping				
17		Dinner	Dinner	Dinner	Dinner	Dinner/ dishes	Dinner
18	Out to movies	Out to movies	Out to movies	Pay bills	TV/video games	Video games	
19				Shopping		Music	
20	Reading/ TV	Reading/TV	Video games	Reading		TV	
21			TV	Ice cream	Ice cream	Ice cream	
22							

¹ Title 24, Part 6 is California’s statewide Building Energy Efficiency Standards.
<https://www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards>

23	Computer			TV	Reading	TV
24	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep

	Out of the House
	Master Bedroom
	Second Bedroom
	Master Bathroom
	Second Bathroom
	Dining Room
	Living Room
	Office

Demand Response Events

Representative demand response events were derived from the 2020 Southern California Edison (SCE) signals for the Smart Energy Program (SCE 2020) and are shown in Table 3. The 14 events from SCE occurred primarily on the hottest days and were often clustered together during a heat wave. TMY3 data was reviewed to select the hottest 14 days for each of the three modeled sites and the demand response events were applied in sequence to those 14 TMY3 days. This is a simplification of the true range of demand response events that occur under different programs for different electric utilities around the U.S., which may have cold weather events and morning events.

Table 3. Demand response events for modeling

Event #	Start Time	End Time
1	07:00PM	08:00PM
2	05:00PM	09:00PM
3	07:00PM	08:00PM
4	07:00PM	08:00PM
5	07:00PM	08:00PM
6	06:00PM	08:00PM
7	07:00PM	08:00PM
8	05:00PM	09:00PM
9	03:00PM	07:00PM
10	06:00PM	08:00PM
11	03:00PM	07:00PM
12	02:00PM	06:00PM
13	05:00PM	08:00PM
14	04:00PM	08:00PM

Thermostat Settings

Thermostat settings vary significantly across the day, for different day types, and for the different behavioral scenarios. Figure 1 illustrates temperature set points recommended in various studies reviewed by the project team. From this, comfort preferences were chosen for this study (“Frontier”) of 68°F for heating and 76°F for cooling.

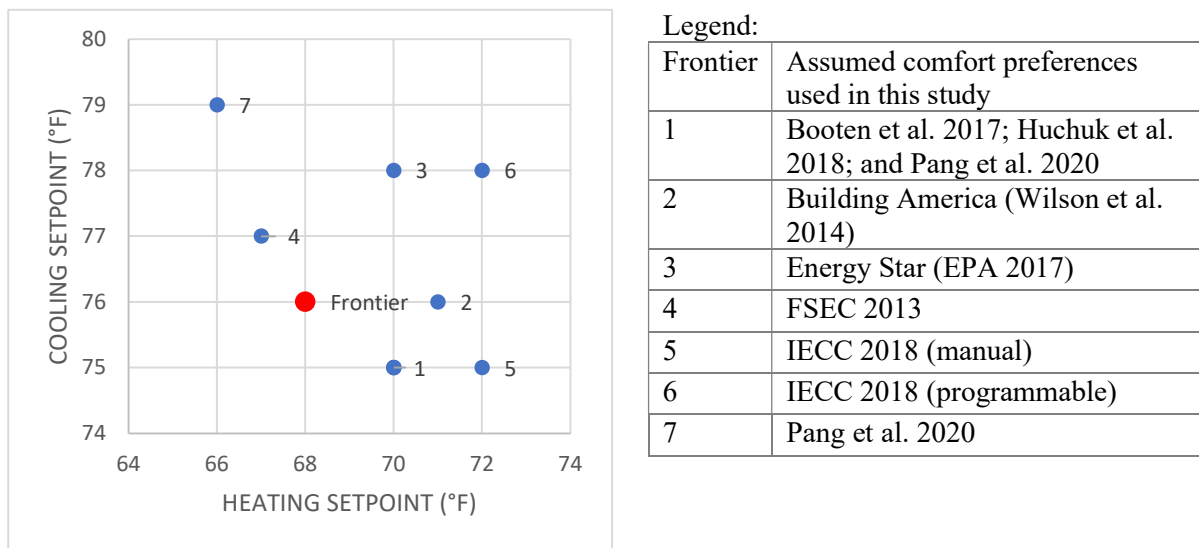


Figure 1. Thermostat comfort set point comparison.

The nominal baseline comfort settings were adjusted for each of the different behavior scenarios and throughout the day each unique day type. There were no adjustments to thermostat settings based on geographic location. Heating and cooling seasons were established based on the HSP default. For the thermostat schedules, the home's occupancy matches that assumed for the other end uses. The parameters used to define the thermostat schedules are described below.

- Not Energy Conscious (NEC):
 - Comfort Setting: It's assumed that in this scenario occupants only engage with the thermostat when they feel uncomfortable and therefore, they don't regularly achieve the optimal comfort preferences. Fixed thermostat settings of 72°F for both heating and cooling were assumed. This is a worst-case assumption, but one that is probably a reality for many homes that are not paying any attention to energy conservation.
 - Setback: The occupants do not adjust their thermostats for nighttime setbacks, or when leaving the home for brief absences or vacations.
- Very Energy Conscious (VEC):
 - Comfort Setting: Occupants in this scenario engage more with the thermostat than those in the NEC scenario and therefore get closer to the defined comfort preferences. Occupied period set points were 69°F for heating and 75°F for cooling.
 - Setback: There is a 9°F setback for heating and 5°F for cooling at night and during vacation periods. There is no setback for regular vacancies during the day nor brief absences.
 - Schedule: The thermostat time periods are not correctly set, and the system starts an hour earlier in the morning and prior to returning home and runs an hour longer than necessary after going to bed or leaving for the day.

Smart thermostats affect the occupants' choice of temperature set point and can help to minimize HVAC energy use or shift peak demand while maintaining comfort. Various functional capabilities were analyzed to consider how they would affect the temperature set points throughout the day and were combined to develop an assumed thermostat set point schedule for modeling the impact of a smart thermostat in conjunction with a HEMS.

- Somewhat Engaged (SE):
 - Comfort Setting: The settings reflect the true comfort preferences with occupied period set points of 68°F for heating and 76°F for cooling.
 - Setback: There is a 9°F setback for heating, and 5°F for cooling during nighttime, vacations, regular daytime vacancies, and periodic unexpected absences. However, the occupancy sensors only detect about half of the unexpected vacancies.
 - Schedule: The thermostat time periods are a closer reflection of optimal daily schedules, but still not perfect. The system starts an hour earlier in the morning and prior to returning home, and it runs an hour longer than necessary after going to bed or leaving for the day.
- Highly Engaged (HE):
 - Comfort Setting: The settings reflect an occupant who wants to take full advantage of the HEMS capabilities and sets the thermostat set point a bit beyond their base comfort preference and overrides it anytime they find themselves uncomfortable. The occupied period set points are 66°F for heating and 78°F for cooling. For one or two hours a day they override this setting and set the thermostat temporarily at the comfort preference.
 - Setback: There is a 9°F setback for heating, and 5°F for cooling during nighttime, regular daytime vacancies, all periodic unexpected absences, and vacations.
 - Schedule: The thermostat time periods are an exact reflection of actual daily schedules, due to learning algorithms and vacancy detection.
 - Demand Response: Any time a demand response event is called based on the DR event schedule described previously, the thermostat set point is adjusted by 3°F, regardless of time of day, day type, occupancy, or vacation status. The resulting set points vary, but for occupied hours, tend to be 81°F for cooling. For comparison, the 2019 Title 24, Part 6 code requires an occupant controlled smart thermostat to have a default demand response set point in cooling mode of 82°F, and heating mode 60°F (CEC, 2019).

Smart Lighting

To meet SHERMS certification requirements, two ENERGY STAR certified smart lamps or smart fixtures must be controlled. The project team assumed that the overhead fixtures in the living room and master bedroom are connected to the HEMS based on a study that indicated the rooms most likely to include smart lamps and fixtures are living rooms and bedrooms (Applied Energy Group, 2020). In most homes, these fixtures will have LED lamps with manual on/off controls and no dimming capability. Smart fixtures connected to a HEMS are assumed to have a small continuous standby power, dimming capability, and programmable timing for security purposes. Additional characteristics of the assumed light fixtures and controls are summarized in Table 4, along with the reference or other basis for the assumption.

Table 4. Connected lighting assumptions

Lighting Attribute	Without HEMS	With HEMS	Basis
Fixture type	Overhead	Overhead	Judgment
Lamp type	LED	LED	Judgment
Number of lamps	LR: 4, BR: 2	LR: 4, BR: 2	EPA 2021
Hours of useful light	3	3	Based on Rubin et al. 2016
Fixture power	LR: 12 W, BR: 6 W	LR: 12 W, BR: 6 W	EPA 2021
Standby power	0 W	LR: 1 W, BR: 0.5 W	EPA 2019
Dimmed power	N/A	LR: 6 W, BR: 3 W	Judgment
Controls	On/off	Occupancy, dimming, voice activation, demand response	EPA 2020a

Source: Hendron et al. 2021

Assumed operation of connected lighting in the living room and bedroom varies for each of the four categories of energy use behavior, as shown in Table 5. Key differences include how often and for how long lights are left on after leaving the room, use of dimming capability, frequency of overrides, enrollment in demand response programs, and use of programmed scheduling.

Table 5. Targeted light fixture operational behavior before and after HEMS installation

Behavioral Attribute	Without HEMS		With HEMS		Basis
	NEC	VEC	SE	HE	
Lights on in unoccupied rooms	1-2 hours after occupancy, 2/3 of the time	1 hour after occupancy, 1/3 of the time	Occupancy sensor override 1/2 of the time	No occupancy sensor overrides	Judgment based on Urban et al. 2016
Vacation	Always on in LR, off in BR	Always off	Always off	2 hours/day on in LR (for security), off in BR	Judgment
Dimming	Not available	Not available	Used 1/3 of the time	Used 2/3 of the time	Judgment
Demand response	Not available	Not available	Not enabled	Enabled, always off	Based on Applied Energy Group 2020

Source: Hendron et al. 2021

Application of these behavioral patterns to the connected lighting features and the occupancy schedules resulted in hourly connected lighting energy for weekdays, weekends, and vacation periods. An example profile is shown in Figure 2 for weekends. These profiles were adjusted for time of year and latitude using HSP guidelines. In creating these profiles for the EnergyPlus models, the total lighting energy in the HSP was reduced by 70% based on the Title

24 CASE report (Rubin et al. 2016). See the NREL report (Hendron et al. 2021) for additional details.

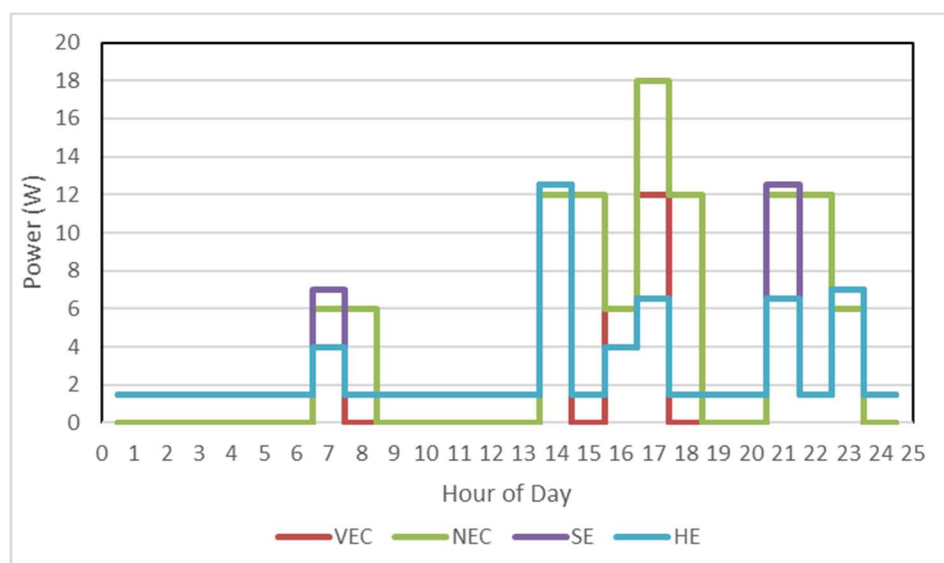


Figure 2. Weekend lighting profiles. *Source:* Hendron et al. 2021.

Advanced Power Strip

ENERGY STAR SHERMS requires one connected smart power strip or smart outlet. For this analysis, a Tier 2 Advanced Power Strip (APS) was selected controlling the primary entertainment system, including a TV, set-top box, and video game system. A Tier 2 APS has advanced sensing capabilities with sensors that detect both occupancy and infrared signals from remote controls. It was also assumed that the APS was controlled through voice activation, programmed using the HEMS interface, and disabled in response to grid signals during demand response events. A summary of the attributes of connected plug loads is provided in Table 6, along with the reference or other basis for the assumption. Hourly profiles were developed for weekday, weekend, and vacation days after applying these behavioral patterns to the occupancy narratives. See the NREL report (Hendron et al. 2021) for additional details.

Table 6. Targeted plug load assumptions

Lighting Attribute	Without HEMS	With HEMS	Basis
Connected devices	N/A	Entertainment center: primary TV, set-top box, video game system	Valmiki and Corradini 2016
Connected load	N/A	200 W	NREL 2011
APS standby power	N/A	1 W	Wei et al. 2018
TV power	169 W active, 1 W standby	169 W active, 1 W standby, 0 W off	Rubin et al. 2016

TV hours of active use	4 hours/day weekday, 6 hours/day weekend	4 hours/day weekday, 6 hours/day weekend	Based on Bureau of Labor Statistics 2019 and Rubin et al. 2016
Set-top box power	21 W active, 16 W standby	21 W active, 16 W standby, 0 W off	NREL 2011
Set-top box hours of active use or DVR recording	4 hours/day weekday, 4 hours/day weekend, 2 hours/day vacation	4 hours/day weekday, 4 hours/day weekend, 2 hours/day vacation	Judgment based on NREL 2011
Video game system power	10 W active, 2 W standby	10 W active, 2 W standby, 0 W off	NREL 2011
Video game system hours of active use	1 hour/day weekday, 2 hours/day weekend	1 hour/day weekday, 2 hours/day weekend	Based on Bureau of Labor Statistics 2019
APS location	N/A	Living room	Judgment
Controls	On/off (active/standby)	Occupancy, remote control sensor, voice activation, demand response	EPA 2020a

Source: Hendron et al. 2021

Modeling Results

Energy savings for each of the three relevant end uses (HVAC, interior lighting, and plug loads) in each location are shown in Figures 3 through 5. Energy savings are presented for each combination of scenarios. For example, the “NEC-SE” case presents savings for the Somewhat Engaged HEMS scenario relative to the Not Energy Conscious pre-HEMS scenario. HVAC savings are highest in Houston, where both heating and cooling loads are significant. The predicted savings ranges from 12% to 60% of total HVAC energy and depends heavily on how energy conscious the occupants are prior to HEMS installation, to what extent they use the features of the smart thermostat, and the magnitude of the heating and cooling loads.

Savings for interior lighting are much smaller because the connected lamps required by ENERGY STAR represent only a small fraction of total installed lighting, with savings ranging from -2.0% to +2.7%. There are small differences between climates because of variations in the confluence of daylight hours with occupancy and HEMS operation. There is also a risk that certain features of smart lighting (such as voice activation and home security), when combined with significant standby energy, can lead to negative savings. The negative savings for the VEC-SE case are a result of standby energy use of the lamps combined with suboptimal programming of the lighting controls. In other words, a very energy conscious person can do a better job at turning lights off than a control strategy. It should be noted that operating hours are relatively low in the analysis because the field studies indicated that living room and bedroom lights were used only a few hours per day. Some households will begin with higher usage and can expect larger savings when the lights are controlled by a HEMS.

Savings for plug loads is unaffected by climate and range from 1% to 11% of total plug load electricity use depending on occupant behavior before and after HEMS installation. The indirect impact on heating and cooling is captured in the HVAC analysis (Figure 3). There is significant potential for higher savings by using Tier 2 APS to control additional TVs and home offices, instead of focusing exclusively on the primary home entertainment system. However, field studies (Valmiki and Corradini 2016) (Piper et al. 2017) indicate that the application modeled offers the highest energy savings potential for a single APS.

A complete summary of modeled electricity and gas use for each occupant behavior, connected end use, and geographic location is provided in Table 7. A comparison of the results to existing field studies demonstrated that the range of modeled savings is reasonably consistent with savings measured in actual homes. Energy savings for lighting and plug loads are relatively independent of climate, but HVAC energy and cost savings vary significantly based on space conditioning loads.

Differing assumptions can lead to very different results, which is why the assumptions applied in this analysis are documented in detail. Spreadsheets illustrating the application of our assumptions to the behavioral narratives is available from the authors upon request. These spreadsheets have been automated to the extent practical, allowing relatively straightforward generation of new results using different assumptions.

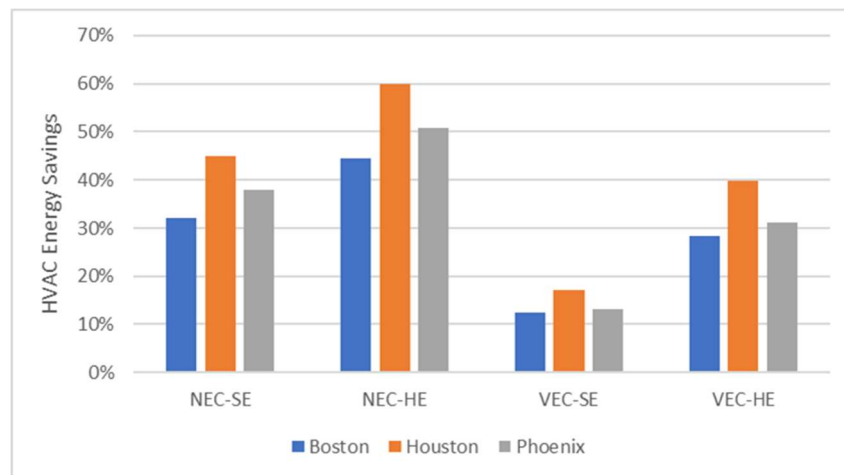


Figure 3. Percent HVAC energy savings for ENERGY STAR SHEMS. *Source:* Hendron et al. 2021.

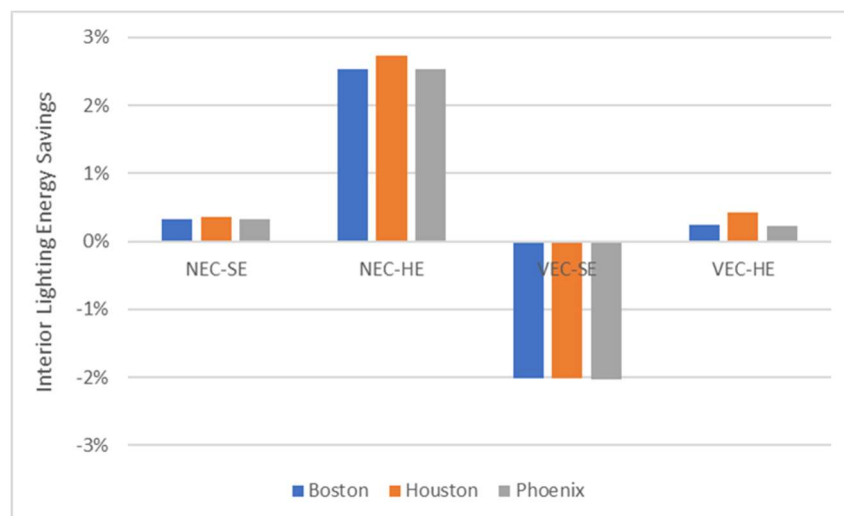


Figure 4. Percent interior lighting energy savings for ENERGY STAR SHEMS. *Source:* Hendron et al. 2021.

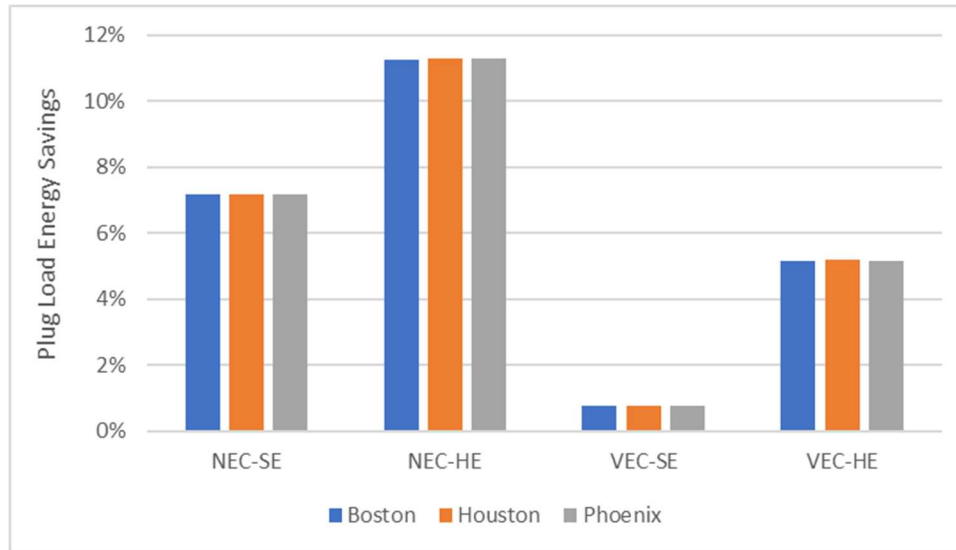


Figure 5. Percent plug load energy savings for ENERGY STAR SHERMS. *Source:* Hendron et al. 2021.

Table 7. Predicted annual energy use for ENERGY STAR SHERMS

Behavioral attribute	Without HEMS		With HEMS		Savings (avg HEMS vs. avg non-HEMS)
	NEC	VEC	SE	HE	
<i>Boston</i>					
HVAC electricity (kWh)	2,187	1,428	1,184	864	43.3%
HVAC natural gas (therm)	944	742	651	536	29.6%
Interior lighting electricity (kWh)	351	343	350	342	0.3%
Plug load electricity (kWh)	2,756	2,578	2,558	2,445	6.2%
Whole house total energy cost (\$)	2,421	2,076	1,954	1,771	17.2%
<i>Houston</i>					
HVAC electricity (kWh)	6,294	4,622	4,000	3,157	34.4%
HVAC natural gas (therm)	223	133	104	68	51.7%
Interior lighting electricity (kWh)	348	340	346	338	0.6%
Plug load electricity (kWh)	2,756	2,578	2,558	2,444	6.2%
Whole house total energy cost (\$)	2,330	1,960	1,836	1,659	18.5%
<i>Phoenix</i>					
HVAC electricity (kWh)	9,838	7,882	7,137	6,020	25.8%
HVAC natural gas (therm)	135	68	48	26	63.5%
Interior lighting electricity (kWh)	354	346	353	345	0.3%
Plug load electricity (kWh)	2,756	2,578	2,558	2,445	6.2%
Whole house total energy cost (\$)	2,851	2,470	2,329	2,109	16.6%

Source: Hendron et al. 2021

Conclusions

This study applied behavioral data gathered from published field studies to model the range of expected energy savings for a HEMS that meets the minimum certifications requirements of ENERGY STAR SHERMS. Analysis results found whole-house site energy savings ranged from a low of 7% (in Phoenix going from VEC to SE) to a high of 35% (in Houston going from NEC to HE) depending on location and occupant behavior before and after HEMS installation. Energy cost savings ranged from 6% to 29% of total utility bills, or \$123 to \$670/year. Savings varied more based on the occupant behavior scenario than the location.

The vast majority, roughly 90%, of savings potential was driven by the smart thermostat, followed by the Tier 2 APS. Savings for smart lighting was very small given the baseline assumption of energy-efficient LEDs with no standby power. In modern homes it is difficult to achieve significant lighting savings unless occupants operate the lights more than a few hours per day. This study was designed to provide a conservative estimate of HEMS potential with a limited number of connected loads. The true potential savings for this technology will be greater and additional work is warranted to quantify the expected savings for HEMS with additional connected end-uses (appliances, hot water system, electric vehicles) or additional devices in the plug load and lighting categories. By including hot water, appliances, Internet of Things enabled devices, and distributed energy resources, a more realistic upper limit for HEMS savings can be evaluated.

Occupant behavior has as much if not greater impact on energy use than installing a HEMS. Over half of the difference between the energy use of the highly-engaged HEMS-using occupant and that of the not-energy conscious non-HEMS occupant is captured by becoming a very-energy conscious user. Simply using an existing thermostat efficiently and turning off devices when not in use can result in very significant savings. This suggests there may be benefits to other behavioral interventions used to complement the installation of HEMS.

This study bracketed energy use and potential savings for four occupant behavior scenarios based on energy consciousness and engagement with HEMS features. The range of savings is indicative of the savings potential, but this study did not estimate average savings for a typical home. If anything is understood well about occupant behavior in homes, it's that it is incredibly variable across the building stock. The lack of a meaningful "average" occupant behavior pattern made it challenging to estimate average energy savings. The use of "narratives" served to tell a story and illustrate the methodology but is not an ideal approach for general application. There is a need for statistically derived data on occupant behavior based on realistic distributions seen in field studies. It is difficult to match energy savings observed in field studies across many houses using a very limited number of scenarios (two behavior types before and after HEMS installation). It would be valuable to estimate savings across a large number of houses by applying stochastic methods to create modeling inputs that represent the true day-to-day and family-to-family diversity in HVAC, lighting, and plug load usage. This more sophisticated analysis would have to be based on a richer understanding of the behavior of HEMS users, as well as the behavior of non-HEMS users. Accurate assumptions for both baseline and improved cases are critical to estimates of savings; however, these are difficult to quantify. For specific households, savings estimates can be improved by applying assumptions specific to the occupants' narrative. The methodology applied for this analysis may be useful to others as a starting point for analysis customized to specific scenarios or other programs or products.

Energy savings were calculated for all control strategies combined because different control strategies are often interrelated or have similar effects (such as voice activation and occupancy sensors, either of which can be triggered when an occupant enters the home). As a result, this study did not attempt to quantify savings for individual control methods and future work could help inform which strategies offer the greatest potential for savings.

Another area for additional work is studying the potential savings for expanded control logic. Advanced controls, beyond those that meet the ENERGY STAR SHERMS minimum requirements, can begin to approach the theoretical maximum energy savings potential without occupant inconvenience. Such controls could include predictive controls, machine learning, tracking of occupant locations inside and outside the house, fault detection and diagnostics, and more advanced energy savings recommendations through in-home displays. Field studies that correlate realized energy savings with the operational behavior of end-users are needed to identify which control algorithms are responsible for most of the potential savings from HEMS. This would be critical for development of energy efficiency programs or codes and standards that aim to provide credit for installation of HEMS that utilize specific beneficial control algorithms.

More detailed analysis of demand response events is needed. This study focused on one typical year of demand response events in SCE service territory. Other utilities in other locations may use very different criteria for issuing grid signals to curtail electricity use. This is an evolving area of research beyond the scope of the current study, but it could provide greater insights into the potential for improving grid resilience through the use of HEMS. Future studies could also isolate the savings from demand response events to better evaluate their impact on energy costs.

The magnitude and range of savings suggest further research is warranted. 35% of whole-house energy savings is a very large opportunity, which should be enthusiastically pursued by energy efficiency programs and codes and standards developers. However, since the savings range is so large (from 7% to 35%) and mostly attributable to differences in the behavior of occupants with and without HEMS, this influence must be better understood before having confidence in expected program savings.

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