EFFECTS OF HOME ENERGY MANAGEMENT SYSTEMS ON DISTRIBUTION UTILITIES AND FEEDERS UNDER VARIOUS MARKET STRUCTURES

Mark RUTH, Annabelle PRATT, Monte LUNACEK, Saurabh MITTAL, Hongyu WU, Wesley JONES
National Renewable Energy Laboratory – USA
mark.ruth@nrel.gov, annabelle.pratt@nrel.gov, monte.lunacek@nrel.gov, saurabh.mittal@NREL.gov, hongyu.wu@nrel.gov, wesley.jones@nrel.gov

ABSTRACT

The combination of distributed energy resources (DER) and retail tariff structures to provide benefits to both utility consumers and the utilities is not well understood. To improve understanding, an Integrated Energy System Model (IESM) is being developed to simulate the physical and economic aspects of DER technologies, the buildings where they reside, and feeders servicing them. The IESM was used to simulate 20 houses with home energy management systems on a single feeder under a time-of-use (TOU) tariff to estimate economic and physical impacts on both the households and the distribution utilities. Home energy management systems (HEMS) reduce consumers' electric bills by precooling houses in the hours before peak electricity pricing. Utilization of HEMS reduce peak loads during high price hours but shifts it to hours with off-peak and shoulder prices, resulting in a higher peak load.

INTRODUCTION

Electricity distribution systems are being upgraded for many reasons: assets nearing retirement, additional customers, changes in load requirements, and increased penetration of distributed energy resources (DER). One key example is photovoltaic (PV) solar which motivates upgrades due to problems with stability; excessive reverse power flow; overvoltages; increased difficulty in voltage control; increased power losses; increased reactive power requirements; and difficulty in islanding detection [1]. A second key example is a desire to upgrade to smart grid technologies to reduce power outages; increase efficiency of energy delivery; and manage DER, including electric vehicles and solar PV technologies [2].

A possible alternative to feeder upgrades is operational management of distributed resources such as storage, responsive loads including smart appliances, and using energy management systems; however, the total variable renewable penetration that can be supported is not currently known [3]. For operational management to support the distribution system, the utility's consumers (e.g., homeowners) need to be provided financial incentives. Historically, demand-response programs have involved either paying customers to reduce energy use during high demand periods or paying customers on a periodic basis for the ability to shut off high-load devices such as air conditioners [4]. Tariff structures including real-time pricing, time-of-use (TOU) pricing, and others are being implemented [5].

The capability to simulate and test the effects of various tariff structures is useful to understand their potential and compare benefits of various combinations of technologies and tariff structures. Ideally, the simulations include generation, loads on the feeder that are managed by people or energy management systems, tariff structures and how they economically incent consumers, and the physical performance of the components on the distribution feeder. Also, recent studies have indicated that steady-state peak-time analysis is, in some cases, insufficient for distribution simulation. Instead, the increased level of detail of dynamic and time-varying analysis is necessary to capture the effects of DER technologies on the feeders [6].

In this paper, we report on the Integrated Energy System Model (IESM) that is being developed to test retail tariff structures and distributed technologies to estimate benefits to both households and retail utilities. Specifically, we report here on its use to simulate home energy management systems (HEMS) that control house cooling under TOU pricing and show results on the economic and physical impacts of this technology. Economic impacts include cost savings to the households and potential revenue losses for the utility. Physical impacts include potential discomfort for people in the houses and potential reduced wear on distribution system components for the utilities.

Other models have been developed to address potential impacts of distributed resources on the grid. One is the Agent-based Modeling of Electrical Systems (AMES) test bed which has been used to simulate the impact of price-responsive residential thermostats on both the retail and wholesale markets under a simple real-time pricing scenario, consisting of a cost adder to the wholesale price [7]. While a distribution system power simulation tool, GridLAB-D [8], is used to generate load profiles for all loads other than the HVAC system, custom code was developed to simulate and optimize the HVAC system. The optimization uses a model predictive control approach, which takes into account energy cost and occupant discomfort, as well as weather and price forecasts, improving upon earlier work which arrived at a setpoint based on only the current price [9]. The optimization is run only once a day, and is idealized in that it uses the same HVAC model for the optimization as for the simulation.

Another study of the impact of residential HVAC control on the distribution grid was conducted using a Java framework that integrates GridLAB-D, model predictive controllers and custom reduced-order building models [10]. The model predictive controllers were also only run once per day, and a real-time price was provided as an input, based on historical CAISO prices and weather.

In this paper, we describe the IESM's structure. We then define the scenario used in the analysis; report results on the impact of HEMS technology on a feeder; and provide conclusions and propose future work.

INTEGRATED ENERGY SYSTEM MODEL

The Integrated Energy System Model (IESM) is being developed to analyze interactions between multiple technologies within various market and control structures, and to identify financial and physical impacts on both utilities and consumers. Physical impacts include both consumer comfort (e.g., difference between actual and desired temperature) and distribution feeder operations including voltage profiles and equipment loading. In addition, the IESM will be dynamically integrated into hardware in the loop (HIL) testing of technologies in the National Renewable Energy Laboratory's (NREL's) Energy Systems Integration Facility (ESIF) by providing market signals to technologies and equipment.

To meet these objectives, the IESM is being designed to perform simulations of a distribution feeder, end-use technologies deployed on it, and a retail market or tariff structure. The IESM uses co-simulation, wherein multiple simulators with specific modeling capabilities co-operate towards a common objective of bringing the capabilities together in a shared execution environment, and manages time and data exchange between component models. The co-simulation execution is performed on a high-performance computer (HPC).

In the current version, GridLAB-D, which performs distribution feeder, household, and market simulations, is co-simulated with Pyomo [11], which implements a HEMS for each household. GridLAB-D is an agent-based, open source power system simulation tool developed by the Pacific Northwest National Laboratory. It performs quasi-steady state simulations for distribution feeders, including end-use loads such as heating-cooling systems, water heaters and electric vehicles. It also manages retail markets and responses to market signals [8]. Similar to [10], the wholesale market is not included.

The IESM can include both price responsive thermostats, responding to the current price, and model predictive controllers which can be run several times during the day, which models the operation of such devices more realistically. In the reported case, the IESM utilizes HEMS, implemented in Pyomo, minimizes its house's cooling cost using a model predictive control approach and sets the cooling setpoint to a calculated optimal value while constrained by an envelope around the desired temperature [12]. No custom HVAC model was developed for the HEMS, instead, through the IESM's co-simulation structure, models available in existing software simulation packages are accessed.

Ultimately, the IESM will utilize an internal discrete event coordinator that operates on abstract time and an enterprise message bus as shown in Figure 1. The scheduler is expected to manage GridLAB-D's simulation of distribution feeders; actual or simulated loads and DER either in experimental hardware, GridLAB-D, or another simulation package such as Energy Plus [13]; and simulation of technologies, such as HEMS, markets, and consumers. Component libraries allow the creation of comprehensive scenarios, including different types of houses and market structures in a plug-and-play component-based manner.

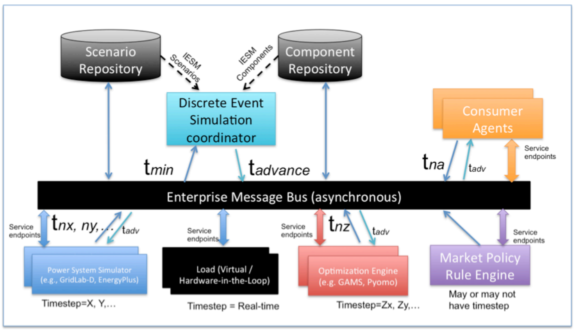

Figure 1. Integrated Energy System Model (IESM) architecture

SCENARIO DEFINITION

A scenario was created for a distribution feeder in the state of North Carolina in the Southeast of the United States in the summer for the month of July when air conditioning use is high. A distribution feeder based on the IEEE 13-node test feeder is used and about 3% of the load is replaced with houses in order to provide a price-responsive, varying load component [14].

The feeder is populated with 20 well-insulated houses with identical parameters, which are connected through four 25 kVA single-phase, center-tapped transformers – each serving 5 houses. The air conditioner in the house is modeled explicitly, and the rest of the household loads are modelled as a lumped ZIP load with a time-varying base power profile. The desired cooling temperature profile is motivated by EPA's Energy Star Recommendations [15]. The desired profile for each house is different, as shown in Figure 2. Each house has a desired daytime temperature between 72° and 77° F (22.2-25.0°C) that is set at uniformly distributed random time between 4:00 AM and 8:00 AM. The desired daytime temperature is constant for 16 hours and is set back by 3°F (1.7°C) at night for 8 hours. Each household's ZIP load base power profile has the same shift in time as the desired temperature.

Two retail electricity tariff structures that are currently in place for households in North Carolina are used. The first has a flat structure with a constant electricity price of \$0.093587/kWh and a monthly service fee of \$11.80 [16]. The TOU rate structure is shown in Figure 3. It has a varying electricity price with peak, shoulder, and off-peak rates and a monthly service fee of \$14.13. The peak, shoulder, and off-peak rates are \$0.2368/kWh, \$0.11961/kWh, and \$0.06936/kWh, respectively. Summer peak hours are 1:00 PM to 6:00 PM, Monday through Friday and shoulder rates are in effect during the two hours before and after the peak hours [17]. All weekend hours are off-peak. Vertical shaded areas in this and other figures indicate peak and should pricing time periods.

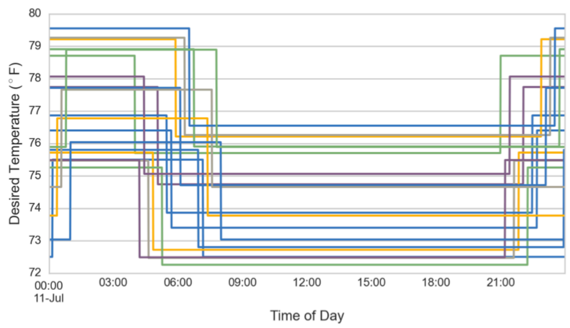

Figure 2. Desired temperature profile for each of the houses in the simulation. Daytime temperatures are randomly distributed between 72 and 77° F (22.2-25.0°C), set at a random time between 4:00 and 8:00 AM. After 16 hours, the desired temperature increases by 3°F (1.7°C).

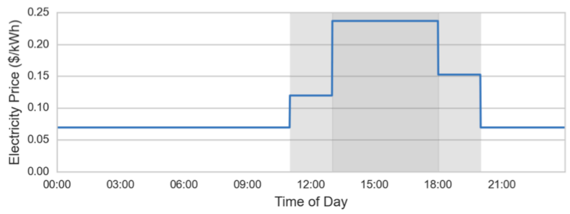

Figure 3. Time-of-use pricing profile for weekdays. All weekend hours are off-peak and have the lowest price

Three HEMS penetrations (0%, 50%, and 100%) are simulated to show how IESM can be used to evaluate the physical and financial impacts of distributed technologies, such as HEMS, in the presence of different markets or tariffs, on the system. Each house's HEMS uses model predictive control to adjust the cooling setpoint from the desired temperature to minimize cost. The HEMS does not allow the setpoint to be above the desired temperature, but does allow it to be down to 5°F (2.8°C) below the desired temperature so that the house can be precooled before peak electricity prices.

RESULTS

Figure 4 shows the range of electricity expenses for the households in the population. Those expenses vary because of variations in desired temperatures and their profiles between houses. For the time period analyzed, the uniform tariff has a lower cost than TOU due to high demand for cooling and other loads during peak hours. Presumably, that load will not be as large at other times of the year and bills under TOU tariffs will be lower during those seasons. Under TOU tariffs, bills are about 5% lower when HEMS are used to manage cooling.

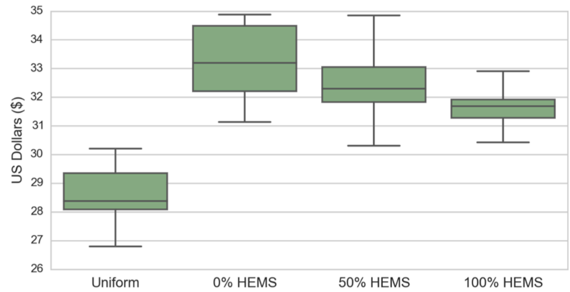

Figure 4. Box plot of the population's electricity bills over the time period from July 7-17, 2012. Use of HEMS reduces each household's bill by about 5%.

Cost savings are driven by the use of power during off-peak and shoulder times for precooling the houses. Figure 5 displays the total cooling power of all the houses over each day with vertically shaded bars indicating peak-price hours and shoulders. The solid lines display the mean total cooling loads over all 11 days, and the shaded areas indicates a 95% confidence interval. Results for the uniform price distribution are identical to the scenario with 0% HEMS penetrations.

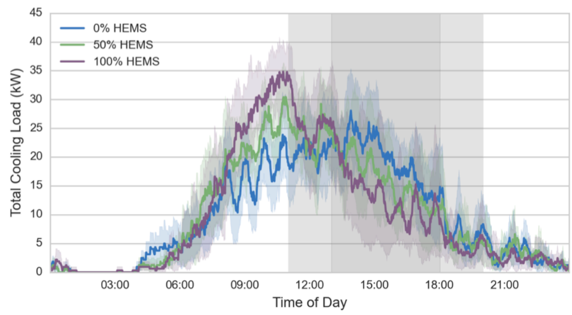

Figure 5. Daily profile of total cooling power load at several levels of HEMS penetrations. When HEMS are present, power use is shifted from peak hours to earlier times when it is less expensive.

When HEMS are present, power use is shifted from times when cost is higher (peak-price periods from 1:00 PM to 6:00 PM) to earlier hours when it is not as expensive. In addition, with the HEMS penetration levels simulated here, the peak is higher during the time period before prices increase than at any time without HEMS. The HEMS used in this study does not adjust any other household loads so they are not shifted due to pricing.

Figure 6 shows the total load on the distribution transformers. The solid line shows the mean and the shaded area shows a 95% confidence interval. The peak load during peak pricing is reduced with the HEMS penetration levels simulated here, but a new, higher peak load is created during the time period before peak pricing. Because the peak load is just shifted, the distribution feeder still experiences peak stress even though the TOU rate structure was likely designed to reduce the peak load.

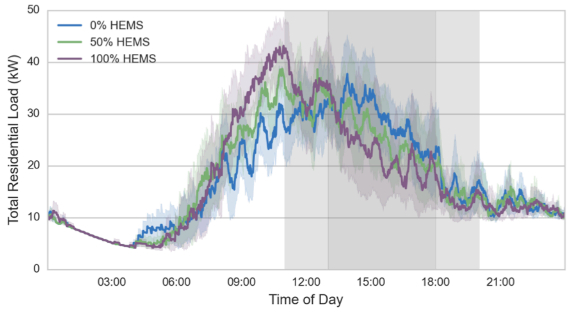

Figure 6. Daily profile of the total distribution transformer load with several HEMS penetrations. Presence of HEMS reduces the peak load during peak pricing but creates a new peak load in the time period before peak pricing is in effect.

Using power to precool intrinsically indicates that the house's temperature setpoint is lower than desired for a time before the peak pricing period. Figure 7 shows the daily profile of the population's average temperature over all days with and without HEMS. The solid line shows the mean and the shaded area shows a 95% confidence interval. The average of the population with HEMS precools by almost 2°F (1.2°C) as compared to the population without HEMS (i.e., without cost optimization). Note that the starting time for cooling is consistent because the two populations have the same time for the initial house's change in desired temperature and, during that time, the setpoint for both is the desired temperature.

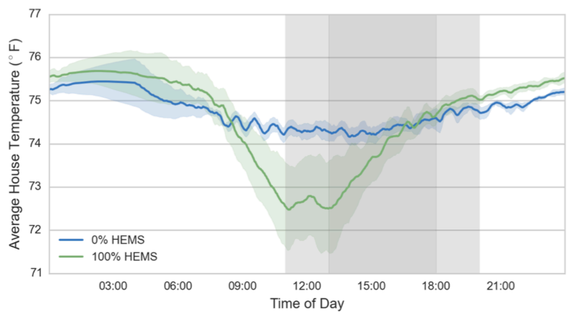

Figure 7. Daily profile of mean household temperature for the population with and without HEMS. HEMS minimize cost by precooling by about 2°F (1.1°C) before peak pricing is in place.

Figure 8 shows the daily profile of the primary voltage of the distribution transformer at node 652. It serves five houses. The solid lines display the mean and the shaded area indicates a 95% confidence interval. With HEMS, the lowest voltage is experienced at an earlier time in the day, coinciding with the peak transformer load moving earlier due to precooling. The minimum voltage is lower in this case, due to the fact that the peak transformer load is higher with HEMS than without. Overall the voltage variation is small due to the fact that only a small percentage of the load at this node is replaced with houses that provide a time-varying load component.

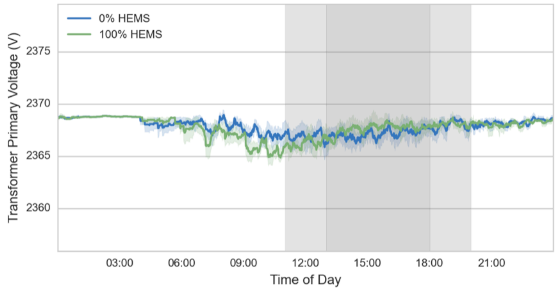

Figure 8. Daily profile of primary voltage of the transformer at node 652 and serving five houses. Use of HEMS shifts time of low voltage to coincide with new peak introduced by HEMS.

Utility net revenue is calculated as the difference between income from the household electricity bills reported above and the wholesale cost of the electricity provided. The wholesale cost of the electricity is calculated as the product of the total electricity demand for the feeder and the Midcontinent Independent Service Operations hourly real-time locational marginal prices for a hub in North Carolina (price node 746136) and are assumed to be unaffected by the modelled changes in the load.

Table 1: Comparison of household expenditures and utility net revenue between scenarios

	Sum of household expenditures	Utility net revenue
Uniform rate	$573	$470
TOU rate – 0% HEMS	$665	$562
TOU rate – 50% HEMS	$650	$547
TOU rate – 100% HEMS	$632	$530

Table 1 shows the utility net revenue and the total household expenditure for the four scenarios. Utilizing HEMS reduces the sum of household expenditures by $33 in the time period analyzed, but only reduces the utility net revenue by $32. Where bulk power prices are unaffected by load, utility net revenue is reduced by approximately the same amount as household expenditure reductions; thus, indicating that the TOU rate structure provides similar net revenue at all times.

CONCLUSIONS AND FUTURE WORK

This paper presented results from a specific scenario simulated using a co-simulation platform, the Integrated Energy System Model (IESM), under development to study the physical and economic impact of distributed technologies under different markets or tariff structures.

The results reported here show that the combination of time-of-use (TOU) pricing and Home Energy Management Systems (HEMS) controlling residential cooling systems reduces peak load during high price hours but moves the load peak to hours with off-peak and shoulder prices. This situation would be further exacerbated with HEMS that are able to shift the operation of multiple loads within a household in response to price, compared to this scenario where only the cooling load is shifted. Those results indicate that, if the key objective of TOU pricing is to flatten the peak on a distribution feeder, a successful tariff structure will be related to the penetration of HEMS and other price-responsive systems and adjust as that penetration increases. Use of HEMS saves consumers money by reducing their electricity bill, but reduces utility net revenue equivalently. Tariff structures need to be designed carefully to ensure the utility sufficient revenue to stay solvent. There exist opportunities for aggregator services to manage loads in a coordinated way so as to ensure both cost savings to consumers and load profile improvements for utilities.

We plan to continue the development of the IESM and to perform the following key tasks: increase the number of HEMS penetration levels in the analysis; extend simulations to realistic feeders where all loads are explicitly modelled; extend simulations to realistic house stocks where the houses vary in size, insulation, and other parameters; add various penetration levels of distributed energy resources (DERs), such as rooftop PV; utilize a HEMS that optimizes across multiple objectives, including comfort, energy use, and peak load in addition to cost [18]; develop an aggregator agent that optimizes energy use across multiple homes and supports the feeder; investigate other tariff structures including real-time pricing and critical peak pricing; and simulate multiple feeders and link to a bulk power market model.

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