Field Evaluation of Long-Term Performance of Energy-Efficient Homes

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ABSTRACT

Energy efficiency in residential construction has accelerated over the last decade. Efficiency is "by design" using simulation programs, but long-term performance-data to evaluate performance of design tools is missing because of the difficulty and expense of monitoring needed volumes of different homes and their designs. The current initiative, led by EPRI and conducted by BIRAenergy, with support from Salt River Project (SRP) and Meritage Homes, examines the differences in performance of different levels of energy-efficient homes after a few years of operation. The performance of these homes is measured using advanced metering infrastructure (AMI) data and is compared to the design efficiency, embodied in design HERS ratings. The homes providing the data for this study were built, sold and occupied between 2007 and 2014.

Meritage Homes, who built all of the homes providing data for this study, was establishing their corporate commitment to energy-efficiency and resulting design goals. During the seven-year time during which candidate homes were built, Meritage's energy-efficiency design goals improved in four steps, including homes designed and constructed to (1) International Energy Conservation Code (IECC) 2003 code, (2) Energy-Efficient, ENERGYSTAR, (3) energy-efficient solar homes, and (4) one Zero Net Energy homes. The homes were selected from two adjacent communities in the Gilbert, AZ area, a suburb of Phoenix and served by Salt River Project (SRP). The results show that the improved designs and construction practices did result in improved energy performance in the homes, but fell short of the efficiency improvements predicted by the HERS scores.

Project Background

Recently, low energy homes and low energy-use communities have become a majority of new homes built in Arizona as homebuilders have adopted energy efficiency as a strategy to battle against foreclosures. Over the last few years, many of the large national home builders such as Meritage Homes, Shea Homes and KB Home have brought homes to market with HERS scores less than 40 with only a small percentage increase in price for the efficiency upgrades compared to a code home with a HERS score of 80 - 100. The higher efficiency homes are also eligible for utility incentives to defray the cost of the efficiency and generation measures. Builders can also offer no-down leases for PV systems, reducing first-costs to zero but with decreased economic return over time. The reported uptake for the ZNE option was about 5% of all solar buyers. Since building their first ZNE home in Lyons Gate, Meritage has constructed more than 100 ZNE homes around the country, as an option in multiple markets, as well as working with EPRI and BIRAenergy on California's first ZNE neighborhood currently nearing completion in Fontana, CA, in collaboration with Southern California Edison.

Utility incentives for energy-efficient new homes are typically based on improved modeled performance. But without significant information regarding the occupants and their behaviors, existing models use default occupancy schedules and values for home operation that can have profound impacts on total energy use, including occupancy schedules, thermostat settings and general operation, and Miscellaneous Electric Loads (MELs). Without good occupant energy-use data, the HERS scores will likely not be accurate predictors of actual use. Further, the divergence between HERS scores and actual performance will increase in new, more efficient homes. This will occur both because plug loads are increasing and because as the energy use for space conditioning and water heating decrease, the fraction of total energy use effected by occupant behavior and the plug loads become an increasingly larger fraction of the energy use. A couple advantages of evaluating production homes is that the groups of homes have consistent efficiency designs and implementation, and the occupant population may not be "self-selecting", i.e., the data is not biased by people focused on energy conservation. The project aims to evaluate the relative accuracy and thereby the potential usefulness of HERs ratings in differentiating energy performance of the homes; it also aims to show the importance of occupant operation and MELs behaviors on energy use in new homes. The project will aim to measure the gap between modeled and actual performance so that models can be adjusted to take into account the impact of behavior and plug loads.

Projected Benefits of project

This project will inform utilities, governments, and other stakeholders of the relative value of HERs ratings on actual and/or relative home performance, and the magnitude of potential impacts of actual home schedules, operational practices and the amount, type, and use of MELs on actual energy performance. The results are intended to provide foundational data that will guide future residential program design and load research. Identifying whether low energy homes do indeed perform to expectation will have implications for both utilities and for the larger public and homebuilders.

Customer Recruitment and Analysis Strategy

An intent of the project was to evaluate energy use in homes with different levels of built-in energy efficiency. Prior experience of the authors in working with homebuilders led us to the Lyons Gate community in Gilbert, AZ. The Lyons Gate community was launched in 2011 as a solar standard community, one of the first in the nation. It was also one of the first to include deep energy efficiency as a standard feature. A very important innovation was the incorporation of spray foam insulation as a standard component of these homes, both for the walls and to create conditioned attics by insulating the underside of the roofs. Figure 1 shows a bird's eye view of the community with a 1.8 – 2.2 kW system on every home[1]. Some of the homes in Lyons Gate do not have rooftop solar because the program switched to solar being optional in 2012.

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[1] These solar systems are unique in that they are a hybrid-combination PV and Thermal systems. The thermal portion consisted of recovering waste heat from PV by pulling outside air through channels formed by the vertically-oriented racking system under the PV modules, which has the additional benefit of slightly improving PV production in hot areas

Figure 1. Meritage Homes at Lyons Gate – one of the first solar[2] standard communities. View from space via Google Earth; the dark areas on most roofs are the solar roof-top systems.

Figure 2 shows three homes with the PV/Thermal solar system, two with a standard 2 kW system (9, 225 W modules) and one a ZNE home with 5.4 kW (24, 225 W modules) of PV. These homes had Home Energy Rating System (HERS) scores in the 30 range for standard solar homes and with additional PV panels, the HERS rating could be driven to zero for the ZNE homes. The ZNE was offered as an upgrade option by the builder for these communities.

Baseline data required homes built to a low, but standardized construction, and with similar demographics and home sizes. The precursor community to Lyons Gate, Desert Valley, located in neighboring Mesa, AZ, about 3 miles away fit this need. Lyons Gate was built from 2011 to 2014, while Desert Valley was built with similar floor plans from 2007 – 2009. Desert Valley was built with gas heating and water heating, while Lyons Gate was all electric, planning ahead to a zero site-energy homes[3]. Hence, the winter electric energy use of Lyons Gate is substantially higher, but the summer peaks are expected to be quite a bit lower. Between the two communities, there is a total sample of nearly 393 homes, 223 from Desert Valley and 160 from Lyons Gate that can provide AMI data for this study.

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[2] The solar systems in Meritage Lyons Gate are also unique as a hybrid-combination of PV and Thermal systems.

[3] The switch from gas heating and cooking is not considered to present any problems in comparing energy use in the homes because the efficiency levels are known and all energy is site. Thus conversions are for energy only; transmission and distribution losses are not pertinent to the comparisons.

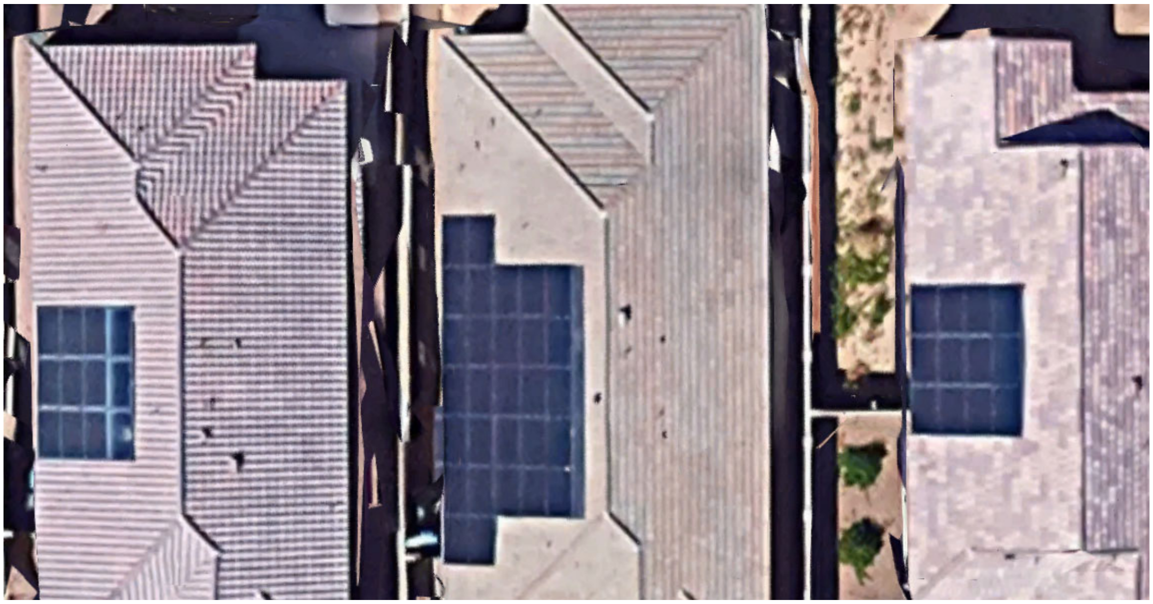

Figure 2. Standard Solar homes and Zero Net Energy homes with PV/T system

Data Sources and Objectives of Data Analytics

Data for 16 homes were collected from two sources, AMI data (from the local utility, SRP), and home energy design data, in the form of HERS scores based on the homes' designs as determined by a respected home energy rating firm and provided by the builder. The analysis of these energy efficient homes was conducted to achieve the following main objectives:

1. Understand actual performance of energy efficient homes compared to the simulated, design performance, and evaluate its potential value in comparing energy-efficiency performance across new homes.
2. Evaluate performance differences between standard homes and energy efficient homes.
3. Observe differences in the energy use and peak demands of homes likely due to different operational behaviors resulting in larger loads such as air conditioning and water heating as well as MELs in actual operation of homes.
4. Understand the impact of solar on overall load profiles to better plan for distribution grid management.

To this end, the homes in the study were divided into four categories: standard efficiency Baseline (code) homes, ENERGYSTAR homes, solar homes, and a ZNE home. The number of homes in each category varied with the available housing stock for our study and willingness of homeowners to share this data. There were more homes in the standard efficiency and solar homes, while there were two Energy Star and one ZNE home. This information is tallied in Table 1.

Table 1. Numbers of homes in each energy-design category, and range and average of HERS index values for each group.

	Baseline	Energy Star	Solar	ZNE
# Homes	8	2	5	1
Ave HERS	100	60	42	0

AMI Data Analytics

After approval by the utility of the methods for data handling and the intermediary subcontractors for data handling and access, AMI data for these homes were provided by SRP for analysis through a highly secured transfer in which the homes were coded and all personal data removed by an intermediary. The AMI data was provided in 15-minute interval-data extending for the period from 5/1/2014 to 3/1/2016 for all these homes except the ZNE home, which was occupied and started to provide data 10 July 2014. The data set is massive and almost beyond management in Excel.

Figure 3 is a scatter-plot of the 15-minute AMI data summed to provide daily total electricity through the meters of all the homes. The main things to notice in this figure is the consistently low energy use from the ZNE home (bright yellow), and to compare both the general spread of data from the other homes, as well as the overall spread of data from this set of homes. This scatter-plot shows the energy use in less efficient homes in comparison to a net zero energy home with a solar and code base home. It has to be pointed out that the difference in total energy use between the baseline and the solar homes is substantial during the summer. However, during the winter, the electric energy use of the baseline home is substantially lower due to gas heating vs. electric heating and water heating (with solar thermal) in the solar homes. Even in the winter, the ZNE and the solar homes use much less energy than the code homes. During the summer, the ZNE homes peak around 37 kWh a day, the solar homes hit 82 kWh, while the code base homes peak at greater than 100 kWh a day, at 134, 135 and 168 kWh a day.

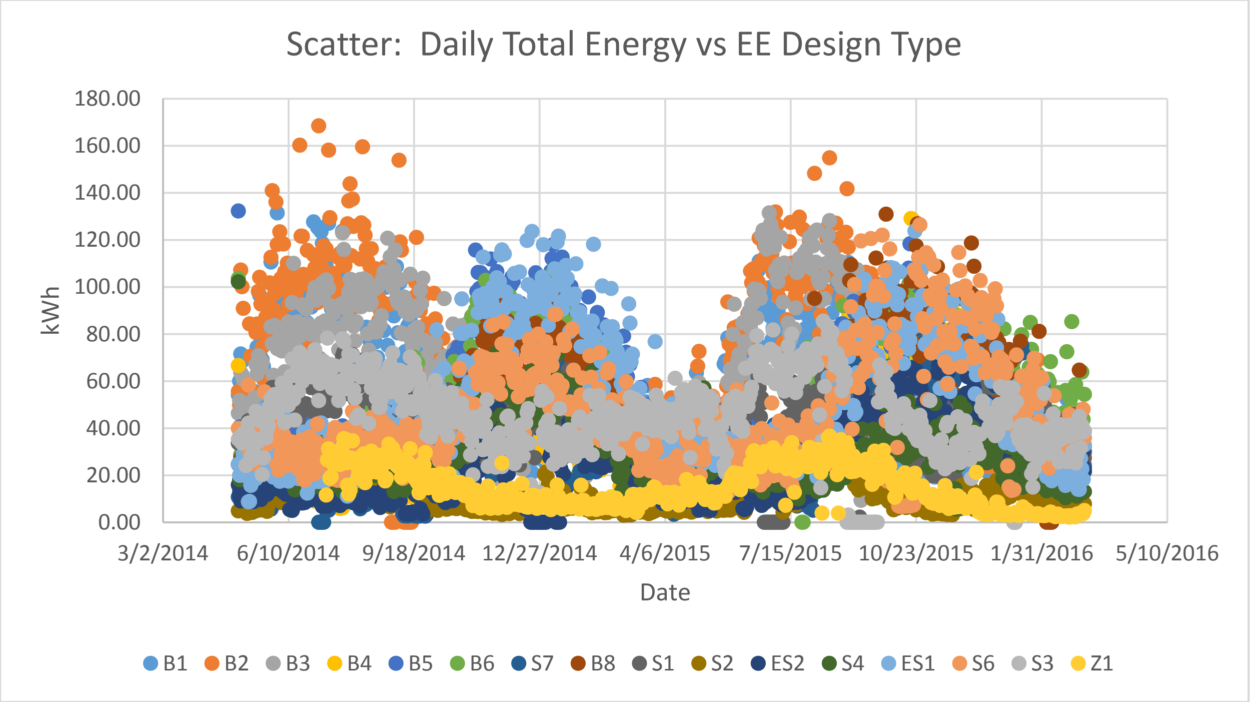

Figure 3. Daily energy use comparisons of all homes. Data is 15-min AMI data summed for each day - each colored dot represents the amount of electricity used on that day. Note the consistently low energy use of the zero energy home (yellow), the general summer-winter pattern of and overall variance in daily energy use and code base homes.

Figure 4 shows the same data as in Figure 3, averaged for each of the four home types. While there is only a single ZNE home in the current data set, it clearly has a low and consistent energy use. The ZNE home is all-electric, so all external energy used by the home enters and excess exits via the AMI. Based on the AMI data, the home is not performing at the designed zero net level. More detailed monitoring is planned and will help define whether the overall energy use is higher than anticipated in the original modeling, or, as we expect, there are specific end uses that the computer modeling under-predicts, MELs for example, and/or whether the controls strategy used for space conditioning do not represent this home. Both additional homes and specific end-use monitoring is planned for this study and will be reported in the future once additional data and circuit-level data become available.

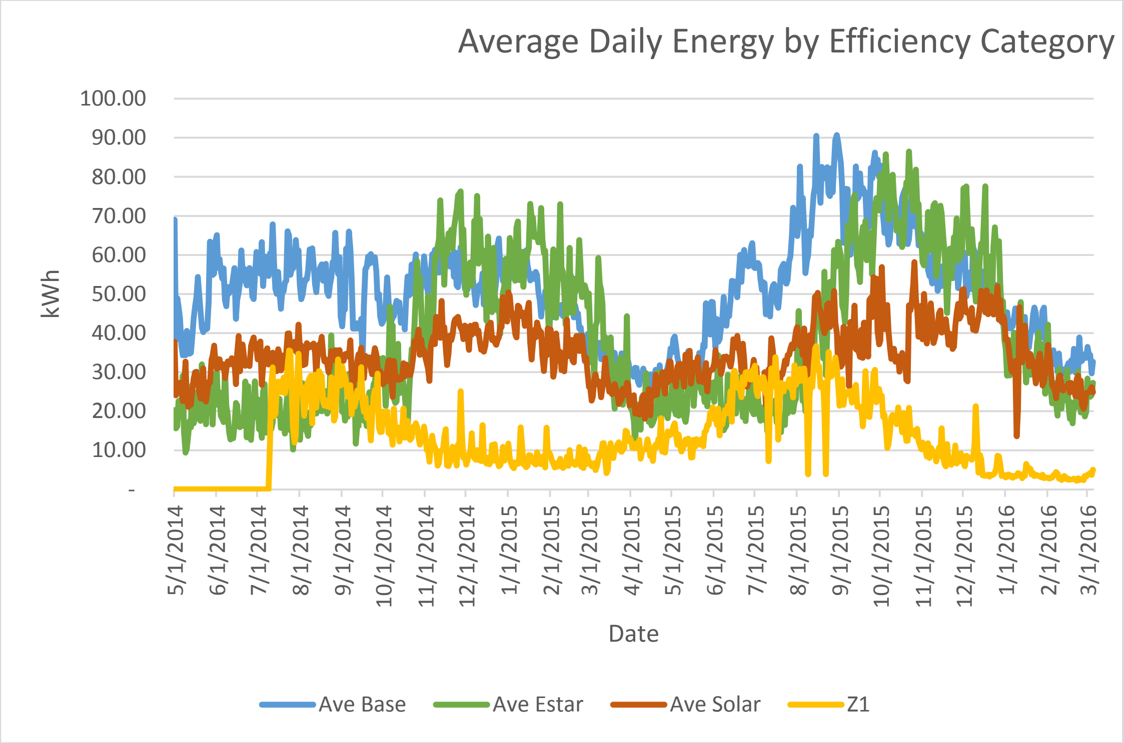

Figure 4. Daily AMI meter data for the four different groups of energy-efficient homes. This is the same data as in Figure 3, but in this graph the data has been averaged for each of the 4 sets of homes. Note that the ZNE home, while not at zero is clearly below all the other groups of homes.

Load data during a hot summer day is illustrated in Figure 5. Data from a single day, 14 August 2015 is shown. Temperatures that day in the Gilbert AZ area peaked at 113°F; the minimum temperature for the day was 91°F. These day-long hot temperatures produce flatter load curves than where night cooling occurs. Nonetheless, the ZNE demonstrate a huge 5 to 10+ kW difference in afternoon demand (!), and 1 – 3 kW lower demand than the solar homes.

While the ZNE home produced the very large reductions in peak demand, the AMI data does not show any negative demand as one would expect from a ZNE. Neither figures 5 nor 6 indicate any current flowing from the home through the meter to the distribution system, resulting from net excess generation. It is possible, in fact likely, that the AMI meter does not register current direction or that it is converted to a zero current to the home, a possible explanation for no reverse current flow during a hot summer day. The lack of reverse current flow through the meter in in Figure 5 is due, at least in part to the blending of winter and summer load profiles to produce the average curves. For the single day in Figure 6, this lack of overproduction is also at least partially due to the hot temperatures throughout the day, the outdoor temperatures ranging from 91°F low to 113°F high, indicating that the air conditioner is running throughout the day, consuming much of the electricity generated by the PV system.

It is also interesting to see in Figure 5 a rippling in the shape of the demand curves, indicating a cycling of demand of about 2 kW, probably due to air conditioner cycling. This cycling does not occur during the late afternoon in the S1 and the ZNE homes. The likely explanations are that the many or most of the homes have oversized air conditioners, whereas the air conditioners for the ZNE and possibly the solar homes have been downsized from typical, forcing them to run full-out during the hottest part of the day, which is optimal for energy use and for air conditioner life.

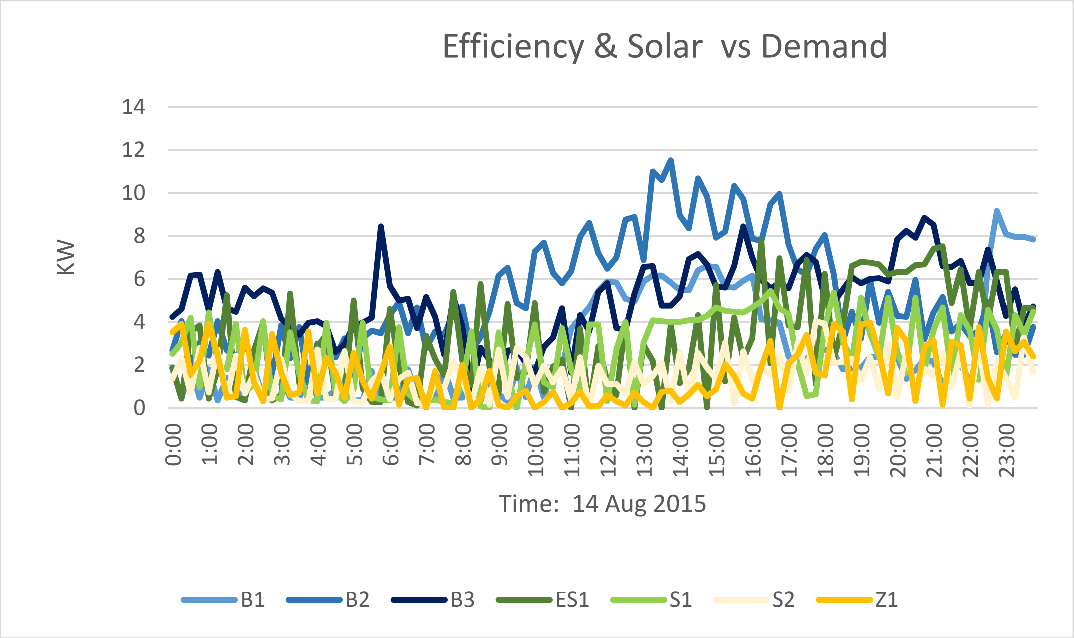

Figure 5. Hot summer day (14 Aug 2015) 24 hour load profiles for single homes on a single hot day. The peak temperature that day in the surrounding area was 113°F.

The data presented in this paper show clear reductions in the amount of electricity used by the newer homes of the group (see Figure 3), as well as the demand during peak hours (see Figure 5). The homes were completed and first occupied during the period from 2007 to 2014 (the ZNE was the most recently finished home in this study). The reference homes for this study are the oldest and were designed to meet the 2003 IECC. All the homes in this study were built by Meritage Homes, providing consistency in workmanship at least among the 4 groupings of homes. All the HERs ratings were determined and provided by the same energy-efficiency firm who has a good reputation for quality work.

The consistency of builder and HERs vendor throughout the study provide a reasonable basis for evaluating the HERS rating as an accurate indicator of energy efficiency performance that could be expected by the average or typical homebuyer. Thus we explore the question: How trustworthy is the HERS rating as an indicator of the relative energy efficiency of new homes, given a consistent process and method for determining the HERs ratings.

Figure 6 provides a visual comparison between HERs design ratings and their measured performance with occupants. Assuming the first set of homes provide a linkage to the HERS baseline (baseline = 100 HERs, ZNE = zero HERS; orange bars). This linkage provides the 100 HERs baseline, allowing us to calculate the energy use expected based on the average energy used by the baseline and the corresponding HERs ratings calculated based on the homes' designs. Thus energy-use expectations could be set using the HERS ratings for our three remaining groups: ENERGYSTAR, solar, and ZNE homes. The results are the grey bars in Figure

6. Discrepancies between the orange and grey bars are apparent, and the standard deviations of the test groups[4] are between 20 and 50% of the design-rating value. Expectations of energy savings are according to the homes' ratings, and there is a near-linear relationship between ratings as the efficiency of the homes are improved, but the slope of the improvement predicted by the HERS ratings is steeper than for the actual homes, with increasing divergence as codes and markets demand more efficient homes. These data indicate that the HERS ratings are well coupled to the increases in new home efficiency, but that HERS ratings are not as good predictors of homes' efficiency as would be desired.

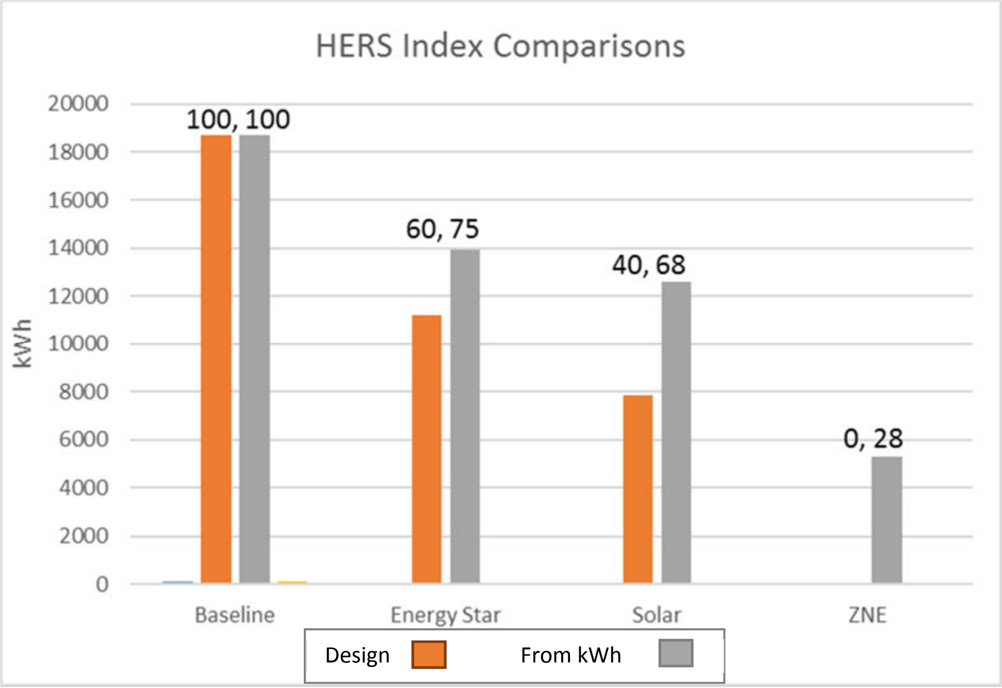

Figure 6. Comparisons of HERs design ratings and actual HERs performance. The design ratings were produced at the close of construction, based on ResNet HERs rules and procedures. "Actual" HERs are estimates based on the baseline homes in this study being equivalent to the HERs baseline, and thus score a 100 HERs rating, and the ZNE would score a zero.

The relationship between the HERs scores and the measured efficiency levels of the groups of homes studied here is not close, in this study. The numbers of homes evaluated is relatively small at 16, resulting in large deviations from the target ratings or target savings. That said, the data used in this analysis of 16 homes is over 100GB, making larger studies using this approach quite cumbersome. Nonetheless, there are more data available for this analysis, and additional analytical methods will be employed in the analysis of this unique data set. This includes breaking whole-house AMI data into constituent end-uses using extensive statistical methods. While the differences between the design rating and the actual measured performance are large, the trend is to increase efficiency and use of renewable energy, in California with a currently aggressive goal to build ZNE homes. This ZNE goal is where the rating and

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[4] Sample sizes are too small for averages and standard deviations to be considered accurate, but they paint a clear picture that the HERs design ratings are likely to be optimistic.

performance are both net zero energy. The HERs rating is going to become a critical tool to allow builders to promote efficiency, and more importantly, HERs ratings provide consumers with a simple method to visualize, understand and quantify the homes they are considering purchasing.

Conclusions

This study has shown that a builder, using HERs ratings as part of their design toolkit has made significant strides in reducing the energy use in their homes. However, these gains are not as large as the HERs ratings predict. Additional research is needed to improve the design tools. The first step should be to determine how the AMI meters deal with energy traversing the meter "backwards" from the home to the distribution system. A quick survey of the raw data from the ZNE home found no negative values when one would expect to find excess production from the relatively large PV system on the roof. To reach ZNE status a home needs a buffer to store and count excess production that offsets any energy from the grid needed when there is no generation (e.g., at night) or when demand is especially high and the banked energy can offset the energy drawn from the grid. The bank can be on-site battery storage or putting the excess back into the grid for use elsewhere – this is net metering.

Whether the design goal of a new home is to meet code or become a zero net-energy home, the tools used in the design should produce a design that will provide the desired performance results, not falling short as found in this analysis. Further, a certification of energy efficient design should equate to both design and actual results. Design and construction of efficient homes on the path to zero net-energy construction, whatever the definition of "ZNE", requires accurate design tools based on simulations from building energy-use models, preferably the same or similar tools that are used to design to code. However, there is little data on the actual performance of these homes against the modeled performance. There are also large questions regarding how to model MELs. There is evidence in the corollary ZNE retrofit analyses reported here that surveys can provide good information to adjust MELs such that the simulations overlay the actual data quite well. It may be possible to collect sufficient information from such studies to statistically characterize MELs, providing modelers with tolerances for MELs, where the MELs could be adjusted within the tolerances to match measured Baseline.

Early research indicates that solar and zero energy homes, while not meeting modeled performance due to various reasons still perform substantially better than code built homes, in both the short and in the longer term. This evaluation requires combining multiple data sources such as utility AMI data, HERS ratings from building permits and circuit level metering. Additional research is underway, following on the results provided herein. These follow-on efforts that extend this project, include the detailed comparisons of measured end-use data with detailed HERs scores to ascertain the information and data gaps needed to inform future residential building modeling and overall research results.

A next step, which is a planned extension of this overall project, is to go beyond using the AMI to provide whole-house data, and to add functionality to the AMI through the use of advanced statistical data analyses to divide AMI whole-house data into its constituent end-uses. This is needed as tool for analyzing AMI data and expanding the results of this study to analyzing design tools and improving their performance, in particular, increasing our understanding and analyses of MELs to develop means and methods to reduce them.

Perhaps more important, the potential use and value of AMI includes methods to produce inexpensive, intelligent hardware add-ons to AMI meters that would make current Home Energy Management systems (HEMs) obsolete, replacing them with practical, easy to use and essentially transparent to the occupants. The mandated adoption of AMI meters provides the basis for rapid adoption of these next-generation HEMs, and will lead to AMI-HEMs becoming ubiquitous. The AMI-HEMs platform will provide the opportunity needed to expand controls and their functionality in optimizing use and function of home appliances and power panels. These expanded function HEMs would assist homeowners to optimize operations of their homes and its electricity-dependent contents. While for some this notion engenders thoughts of “big brother”, a better analogy exists between houses and high-performance cars: Just as drivers of expensive sports and racing cars have come to rely on computer-enhanced driving assistance and accident avoidance, homeowners should expect no less from their homes.