Residential ZNE Retrofit EE, DR, IES, HEMS + PV – a Tall Loading Order
Zero Net Energy Home
Design, Development and Implementation

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ABSTRACT

Under a California Solar Initiative's (CSI) Research Development, Demonstration and Deployment (RD&D) Program grant, the team established a suite of Integrated Demand-Side Management (IDSM) elements, retrofitted a 1,278 sq.ft home in Southern California with this package, and is monitoring the different systems and the home's performance. The IDSM suite includes (in loading order), an energy-efficiency (EE) package, appliances and thermostat with demand response (DR) capability, intelligent energy-storage (IES), a home-energy-management system (HEMS) and an innovative low-cost plug and play PV system. The battery-storage system's intelligence and programming functions archive data that provides patterns of energy use to which regular charging and discharging can be programmed to manage recurring loads seen by the grid. The system also has DR-capability to track and moderate demand in real-time, reducing unanticipated peak demand. The various IDSM components came from different manufacturers making integration a challenge, which will be discussed. System costs, including installation were carefully recorded for individual systems, and fully-integrated cost/benefit analyses will be presented. This IDSM retrofit which is also a zero net energy (ZNE) design could also be incorporated into new construction. It has the capability to shape residential loads to virtually any shape desired by the utility for grid optimization, while being totally transparent and unobtrusive to the homeowner. The results of this study may help shape future retrofits in terms of IDSM components (and their capabilities), retrofit package design, and the integration and implementation of ZNE and IDSM in both retrofit and new homes.

1. INTRODUCTION

Driven in part by the California Global Warming Solutions Act (AB 32), the California Energy Efficiency Strategic Plan was developed to provide "Big Bold" goals to reduce energy use in buildings. These "Big Bold" goals include, that by 2020 all new homes should be ZNE and the energy use in the existing home market be reduced by 40%. This places substantial pressure on the residential markets to find marketable methods to improve energy efficiency, and to reduce the costs of residential PVs. Efforts are ongoing in both the new and existing residential markets to design and evaluate ZNE efficiency packages that are practical and as cost-effective as possible. Although not addressed by these two "Big Bold" goals, a parallel and important effort is needed to substantially reduce summer peak electricity demand to address the greenhouse gas (GHG) reduction goals of AB 32. These goals can be achieved through combinations of energy-efficiency improvements, coupled with on-site PVs and significant energy storage, both electrical and thermal.

Electricity generated by PVs both offsets electricity use and can help reduce peak electricity demand; however, typical south facing rooftop PV electricity generation peaks mid-day, that is earlier and out of phase with the system peak which occurs much later. During their mid-day generation peaks, efficient homes with PVs frequently produce more electricity than the homes demand, and they feed the excess generation back into the grid when not needed by the homes. When this excess generation is fed back into the grid on community-scales, it can result in reduced grid efficiency as the grid has not been designed to handle this two way flow of energy in large amounts. Alternatively, the excess energy can be stored in the homes as thermal and/or electricity storage (batteries), as well as at the local distribution system level. Thus both utilities and homeowners benefit from a "loading order" of Energy Efficiency measures, Demand Response (DR), Energy Storage and controls that have higher priority in the design process than PV or other on-site generation.

2. ZNE RETROFIT DESIGN AND DEVELOPMENT

The ZNE test home is sited in the inland Southern California region. A set of efficiency measures or "package" was selected to improve the envelope efficiency, space heating and cooling systems efficiencies, water heating efficiency, and most of the kitchen appliances (which were both DR and high efficiency). The package of Energy Efficiency (EE) measures was the result of an iterative approach to optimize the mix of measures that achieve ZNE.

The development of the ZNE package measures optimized (a) the natural gas-fueled EE appliances to garner the large source energy (b) savings provided by gas verses electrical. Fuel-neutral envelope measures included in the ZNE package were ceiling insulation, high efficiency windows, solar hot water systems, hot water recirculating systems, and envelope sealing to produce low air leakage. The final choices for efficient space cooling and water heating include an 18 SEER AC and a 2.8 COP heat pump water heater (HPWH). The final element of the ZNE package was on-site generation, a PV array sized to produce sufficient source energy to offset the annual energy use of the efficient home. The GE Retrofit Solar PV Kit installed on this home comes in system sizes of 2.4kW steps; considering the home and the EE-retrofit package, the most appropriate PV system size was a 4.8kW.

In addition to the EE and PV systems, this ZNE-retrofit home includes kitchen and cloths washing and drying appliances that are both efficient and DR-enabled, and an intelligent battery system. The battery system is programmable and the GE DR-appliances and PV system are connected to the GE Brillion Nucleus that could provide energy-use information to the homeowners (occupants) as

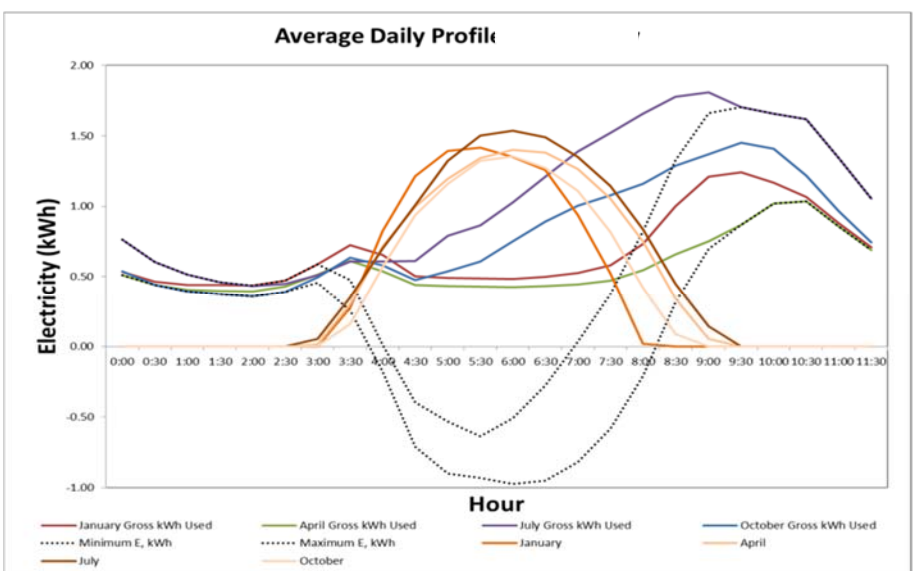

Fig. 1: Simulation results of a BEopt E+ v1.3 model of the CSI RD&D ZNE test home were used to determine the average daily electrical use profile, indicating both gross and net electrical consumption. The average hourly solar generation for the region of California Climate Zone 10 is also shown.

well as connect to the utility DR system either through the smart meter or via the web, as described below.

Building energy-use simulations were performed throughout the design of the ZNE package. These included an initial base-line, used for development of the ZNE package, a calibrated base-line, and post-ZNE retrofits based on the package measures and the calibrated base-line. The calibration of the base-line simulations included improved information regarding the use of the home and of energy-using appliances and equipment in the home. Some of the simulation parameters were based on a questionnaire filled out by the homeowner, such as thermostat set point temperatures, an inventory of plug-in devices, the existence of a second refrigerator in the garage, etc.). This as-built simulation provided a very good baseline for the home prior to the efficiency retrofits.

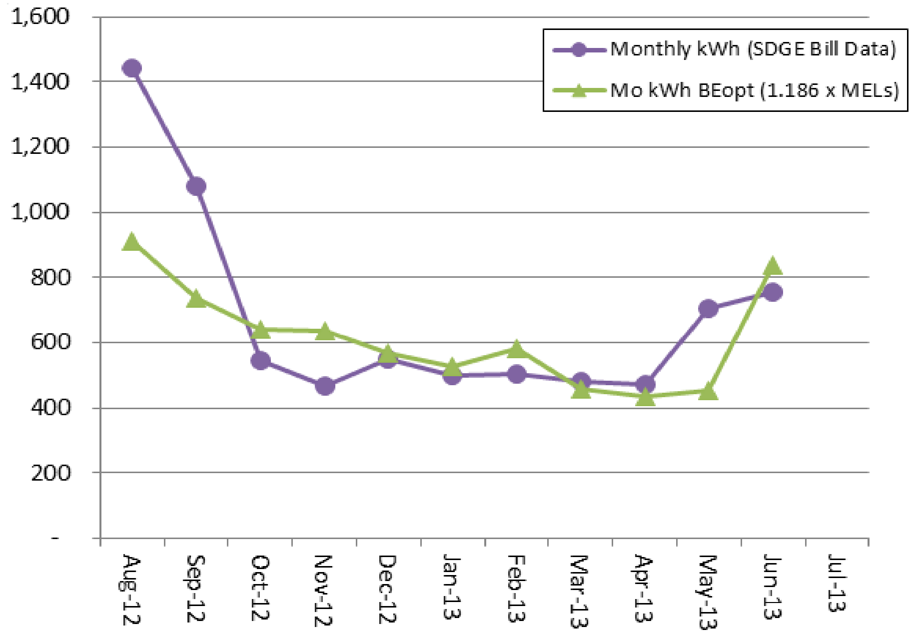

Fig. 2: Baseline data - actual monthly actual energy use from SDG&E bill data and BEopt simulation results for the Santee home. This data is from the 10th of each month labeled in the abscissa to the 10th of the next month (SDG&E meter-reading intervals). The beta-test PV system was installed in Oct 2012, and the generated electricity is accounted for in the SDG&E data.

To develop the ZNE package, energy-efficiency measures were individually simulated over the base-case, providing a basis for comparing individual measures and developing packages of measures. Different packages were evaluated based on the individual simulations and experience. Finally, based on cost-effectiveness, availability, and practicality of installation and/or use, a final ZNE package was developed, emphasizing cost-effectiveness and whole-house energy savings. The final ZNE package (in the absence of PVs) is predicted to provide an annual savings of about 32% source-energy compared to the as-built base-case. This ZNE home has been retrofitted with EnergySTAR appliances (DR-capable, donated by GE), R-49 attic (with new HVAC ducts buried in the attic insulation), a radiant barrier attached to the bottoms of the rafters, building envelope sealing (to 3.0 SLA), 100% LED lighting, dual-pane low-e windows, and 18 SEER air conditioner coupled with a 95% AFUE furnace. The addition of 4.8 kW of PV make this home a Zero Net Energy Home, on a Source-Energy basis. Using the default costs in BEopt from NREL, this package, including PVs would cost the homeowner $34,370. The average daily use profile of the home, as shown in Figure 1.

3. ZNE EVALUATION

Baseline data for the ZNE home was derived from past utility bills provided by SDG&E, going back about a year. SDG&E provided data from August 10, 2012 – Oct 10, 2013. The PV system was installed in two, 2.4kW sets. The first 2.4kW GE Solar PV Kit was installed in October 2012 and the PV system output was monitored from installation onward, allowing the exact PV production to be added back to the bill data to calculate whole-house energy use from August 10, 2012 – July 2013, when the retrofits were installed. Thus, the baseline data did not include any direct effects of PVs or EE retrofits, and there is nothing apparent in the data used for baseline to indicate that there were any indirect, behavioral changes due to the beta-testing of the PV system, or anticipation of the EE upgrades.

Figure 2 is a plot of the energy use of the pre-retrofit ZNE home by month, comparing the actual energy use to monthly simulations. Figure 2 shows both the actual energy use monthly for a year, and the BEopt simulations of the

continues from the baseline data on from July 2013, when the retrofits were done, with bill data through November 10 (labeled October for the period October 11 – November 10), the last available data.

Figure 3 shows the BEopt simulations for both continued under baseline conditions and including the retrofit changes in efficiency and generation. The fit of the simulations to

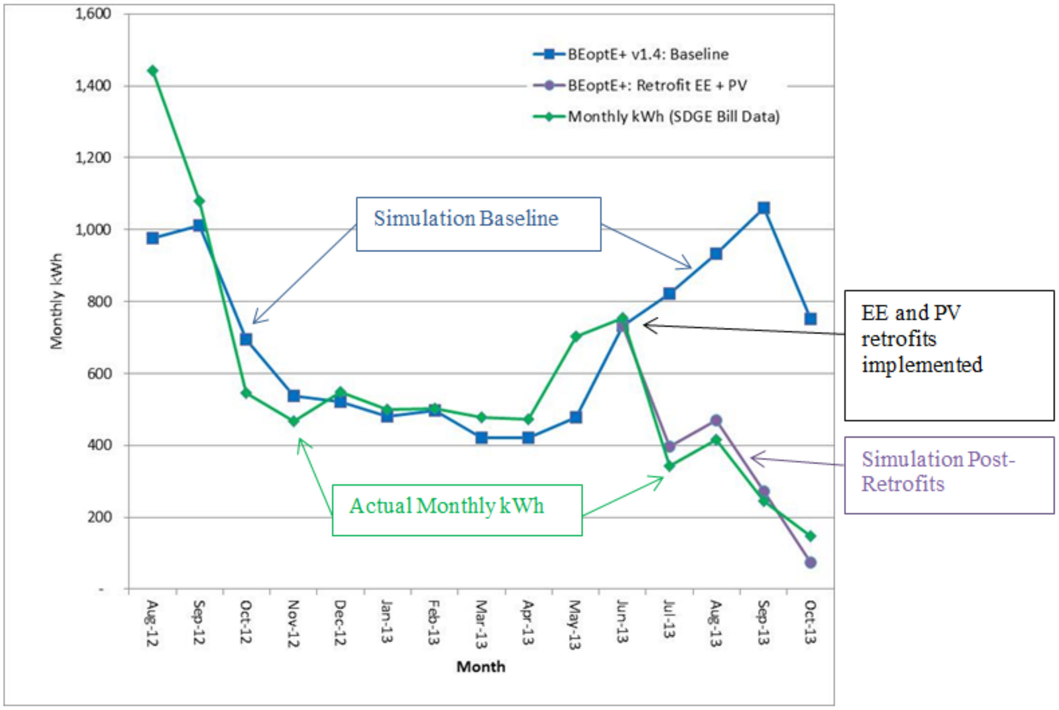

Fig. 3: Baseline and post-retrofit electricity use in ZNE home. Monthly kWh from SDG&E Bills are plotted in in green, and BEopt simulation of the baseline electricity use are plotted in blue (pre-retrofit, and the baseline continuing post-retrofit). BEopt simulations of post-retrofit electricity use are plotted in purple, starting the month before the retrofits were performed (June) for continuity in the graph.

ZNE home and the resulting monthly electrical energy use. The BEopt simulations include calculations of the miscellaneous electric loads (MEL), which were derived from a detailed survey of the devices that produce the MELs including an older refrigerator/freezer in the garage. Other than the months of August and September, the BEopt simulations and actual energy use are quite similar. The differences in the two summer months could be due to air conditioning running all day for the mother and two little children.

The data plotted in Figure 3 include the same data as in Figure 2, but continues through September 2013 up to November 10, 2013, the last date for which bill data was available. In Figure 3, the baseline conditions are as in Figure 2, through July 10, 2013 (labeled June, the monthly period being June 11 – July 10); however, Figure 3

the actual electricity used is very good for both the baseline, and the post retrofit. The differences between the BEopt baseline simulation continuing post-retrofit, and the post-retrofit bill data show the estimated impacts of the retrofits on electricity use. The EE and PV retrofits were performed in July, and the impacts of these retrofits are readily apparent as the difference between the BEopt baseline and actual kWh, as well as BEopt simulations of kWh post-retrofit, starting in July.

There are only four months of post-retrofit data (that is, post retrofit of PV and EE; the battery system was not on-line until October 2013), so the strength of quantitative conclusions from the data in Figure 3 are open to debate; however, qualitatively, the retrofits have a clear and strong impact on the electricity drawn from SDG&E. This limited data set shows a reduction in electricity use over the four-month period from July 10 – November 10 of over 70%. This includes changing the water heater from gas to heat-pump, and the kitchen range from gas to electric, both of which increase the number of electrical loads.

The Sunverge solar integration system (SIS) intelligent battery, electricity storage device went on-line in early October. The intent was to demonstrate the ability to reduce peak loads, and to flatten the electricity load curve as much as possible. The SIS has substantial programming capabilities that can be used to optimize its performance, even to doing some limited load tracking. However, there were both technical and time difficulties in implementing and testing these capabilities. Most importantly, the SIS is designed to work with a PV_{dc} system, and is not currently set up to work directly with a PV_{ac} system as was installed on the retrofit ZNE test home. This situation will be rectified over the coming year with continued monitoring and evaluation. For this study, the SIS was initially programed based on Sunverge technical experience as opposed to actual experience with this home and its electric loads.

The initial SIS programming in the ZNE home was simple and seemingly straightforward - the SIS was to charge and discharge during pre-defined periods that, for charging should be periods of low-load and high PV production, and SIS discharge during pre-defined high-load, low PV production periods. This initial programming worked quite well over the limited duration of this test, other than there was an inadvertent time-shift on weekend charging of the SIS, as shown in Figure 4. This was corrected late November. Other than correcting that programming error, the SIS programming was not changed for the duration of ZNE testing and evaluation detailed in this report. Figure 4 shows the average weekly activity of the SIS and the PV system, all the data coming from the SIS: the yellow areas represent periods of solar generation, and the green areas represent periods of charging the batteries in the SIS (areas above the zero axis) and periods during which the SIS batteries were being discharged (areas below the zero axis). As illustrated in Figure 4, other than for weekends where there was a timing error in the programing, SIS battery charging was done using electricity produced on-site by the solar system. The data show that nearly all the battery charging occurred during periods of good solar generation and therefore came from the solar generation. This is not

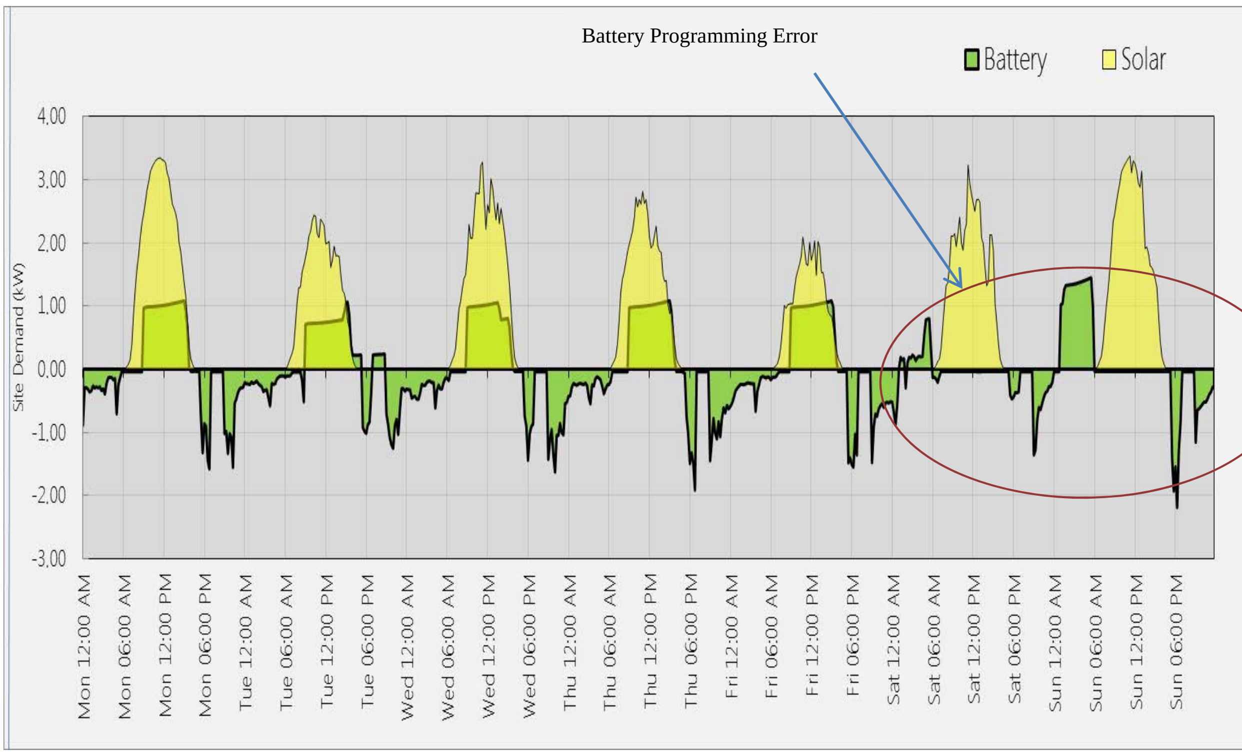

Fig. 4: Solar and battery activity. These data are weekly averages for the solar generation and battery charging and discharging during the month of November 2013. The green shaded area is the battery charging (above zero) or discharging (below zero) to meet home loads.

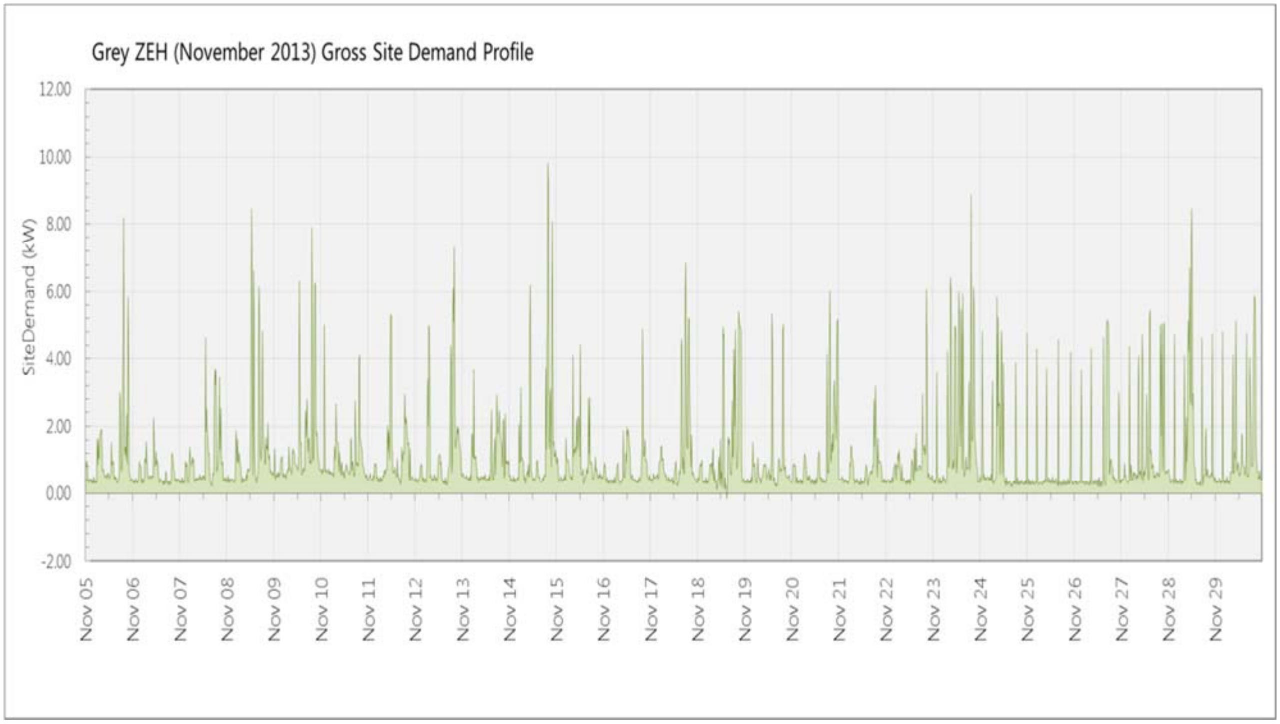

Fig. 5: Electric Load Profile of ZNE Home for most of November 2013. This data is post-ZNE retrofit, and the home is very efficient.

the case for weekends, due to a programming error for the timing of SIS charging on weekends, as shown in the circled area on the graph. This programming error was identified and easily corrected in late November.

Figure 5 shows the electrical demand profile from the whole house for most of the month of November without either generation or battery influences. The home has the optimized energy efficiency measures and the rooftop GE Solar Retrofit PV system which are designed such that their combination should result in a net-zero amount of electricity used by the home over the course of a year. Nonetheless the home has substantial electricity peak demands, some in excess of 8kW, and many exceeding 5 kW in November. Despite the fact that November is not a month when home electrical demand stresses the grid, and is not a month when system peaking is typically a problem, clearly significant peaks in electrical demand are common but short-lived. Presumably in summer cooling months the peaks would be much longer in duration, showing as wider on a similar graph. Even though these peaks are short in duration, the combination of solar charging the SIS, and good initial programing of the SIS, these peaks were well managed by the home and the vast majority not passed through the meter to the distribution system, and those demands that did go through the meter were suppressed in magnitude. These impacts are evident in Figure 6.

Figure 6 is an average across the weeks in November, and is a compilation of solar generation (yellow), SIS (green) charging and discharging and the resulting home electrical load (red). Figure 6 contains the same whole-house demand data as in Figure 5, and clearly shows the moderating effects on the load curve due primarily to the SIS, which is charged primarily by the PV system. As can be seen in Figure 6, there were only two incidences of peak demands on the distribution system that were near 8 kW, and only about a dozen at or above 4 kW. With the exception of a few spikes on weekend evenings, the load on the distribution system (red) was maintained below 3kW, a vast improvement over the irregular, highly variable demands produced by the home (Figure 5) that were mitigated by the combination of the PV system and SIS (Figure 6). This illustrates the solar, and the solar + SIS working to mitigate the otherwise transient nature of home electricity demands on the distribution system, and the resulting, relatively smooth net loads on the distribution system.

The substantial improvement in the load shape of electricity demand on the distribution system produced by the SIS, which is charged primarily by the PV system, does not come at a significant cost in system efficiency. The data collected from the SIS, evaluated here for the month of November, produced the following statistics regarding the functioning of the SIS:

Greatest demand reduction:	3.4 kW
Total energy used by SIS to offset site loads	194 kWh
SIS energy consumption and efficiency losses	52 kWh
Round-trip efficiency losses	13 kWh
SIS system efficiency	93%
Energy exported to grid if Solar Only	246 kWh
Total actually exported to grid	166 kWh
PV energy shifted by SIS	81 kWh
% reduction in PV energy exported to grid (shifted by SIS)	33 %

As previously described, these data and results from the SIS are from the initial setup conditions. The SIS performed quite well in reducing peaks, flattening the load curve, and shifting PV energy from being exported to the grid when not needed, for use in the home when needed, or potentially exported to the grid if needed.

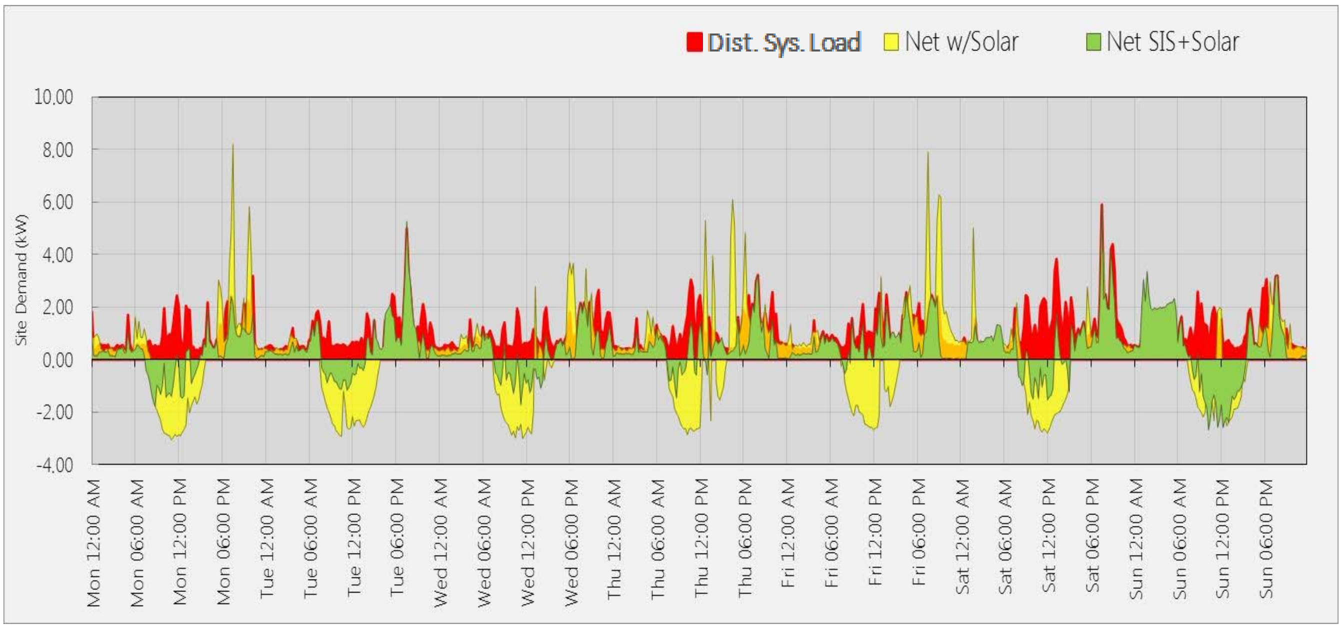

Fig. 6: Compilation of solar and battery impacts on home electricity loads. This graph is an average across the weeks in November.

The SIS is designed to be flexible in its operation, and programmable to function in different modes with different priorities. It also has load tracking capabilities that could be quite useful. There is considerable tuning and experimentation that could be done with this home to determine the real value of combining energy storage with efficiency, not to mention DR and HERS, both of which exist in this home but have not yet been enabled.

4. CONCLUSIONS: ZNE PERFORMANCE AND NEXT STEPS

Evaluation of this ZNE home has been funded for an additional year via a grant from the CSI RD&D Program. The home has already provided valuable data regarding the actual performance of a ZNE retrofit, including both energy-efficiency and peak-reduction, as predicted. This home has produced significant energy savings from the retrofitted efficiency package. The house was also retrofitted with DR-capable GE appliances and controller (Nucleus). The Nucleus recognizes some of the DR appliances, but to-date it has not recognized or communicated with non-GE devices (e.g., the electric meter) or other systems, such as the Sunverge intelligent battery system; thus the DR-capable appliances cannot, as yet, provide DR. The homeowners have yet to be trained in the use of the Nucleus or Sunverge, either as DR controller or a Home Energy Management system. Over the coming year, the team will attempt to implement communications between devices so that DR capabilities and occupant home energy management can be implemented, tested, and evaluated. In addition, the Sunverge electricity-storage, battery system is quite sophisticated. There are many different programing and operational states that should be tested and evaluated, to determine optimal system-configurations for this home, as well as the range of configurations that could be more or less useful in other homes with different systems and occupants – these need to be further tested and evaluated.

The 4.8 kW PV system on the roof has micro-inverters on each panel, making the system ac rather than the typical dc. Ac systems should be less sensitive to shading, a significant limiting factor of the PV market potential in California (3), tests could be performed on this system to evaluate the benefits of ac modules when shading occurs on parts or all of one or more panels in an array. Initial results showed a peak reduction of 3.4 kW in the ZNE home due to the SIS Further evaluation is needed to fully evaluate the potential of the SIS system, including: how to program them, where to put them, how to make them compatible with different types of PV systems (dc and ac, at a minimum), and to evaluate their value to utilities and the consumers. This project has developed and begun to test the integration of efficiency, DR, storage, HEM, and PV systems. In a very limited time, with a relatively small amount of data, this home has already produced some very interesting, and valuable results. Over the coming year this home should produce extremely valuable data regarding equipment and technology integration, homeowner use, and performance evaluation of all the elements in the energy-reduction loading order.

5. ACKNOWLEDGEMENTS

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6. ENDNOTES

(1) "Source energy" is the energy required at a generation plant to provide energy at the site; source energy includes generation, transmission, and distribution losses, which account for nearly two-thirds of the source energy used to produce and provide electricity used by the home.

(2) The term "optimize" used to describe the development process for the energy-efficiency package components. Optimization was not limited to efficiency only, but also included consumer preference for fuel type (gas or electric), efficiency levels, availability and reliability, and cost.

(3) Rob Hammon and Hogan, I.C.H, Market Potential for Residential Rooftop PVs in LA County, Project Report, 2012