

Grid Integration of Zero Net Energy Communities

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ABSTRACT

Zero Net Energy (ZNE) homes will be the standard for residential construction in California by 2020. The Electric Power Research Institute (EPRI) worked with builder Meritage Homes, the California Public Utilities Commission (CPUC), Southern California Edison (SCE), and BIRAenergy, to design, construct, sell, and monitor a neighborhood of ZNE homes in Fontana, CA. These homes saturated two distribution transformers, to simulate the expected scenario of 2020 when every home would be ZNE. These homes were built to the California code specification of zero TDV (Time Dependent Value) Energy. They utilized electric heating and water heating, with an eye to meeting long term GHG goals through electrification. ZNE homes do not translate to zero energy use on a monthly, daily or hourly basis, and could actually increase the investments required in the transmission and distribution system. Their load profiles mimic the “duck curve”, and at volume upset grid balancing with excess generation during the mid-morning hours and steep evening ramps. The research conducted evaluates potential of controllable loads and energy storage to balance the distribution grid at the transformer, feeder and substation levels. The initial results indicate that grid planning, traditionally based on cooling would need to increase wiring and transformers to accommodate ZNE with newer loads like heat pumps and electric vehicles. The analysis indicated more energy efficiency within ZNE assists both the grid and the builder, while PV is non-coincident. A load aggregation platform that connects and controls loads, battery storage, and PV generation can potentially reduce electrical infrastructure.

Background

The state of California has been the leader in setting ambitious targets for greenhouse gas reduction through landmark bill AB 32. A key component of the pathway to meet the targets of AB 32 is the Long Term Energy Efficiency Strategic Plan, which set the “Big Bold Goal” that all new homes in California be Zero Net Energy by 2020.¹ Extending these goals, the state has further committed to making all new public buildings ZNE by 2025, and all new commercial buildings ZNE by 2030. Initial research efforts have demonstrated technical feasibility and technology pathways. BIRAenergy led an effort to construct and monitor a Zero Net Energy home in Santee, CA, that was one of the first attempts to evaluate battery storage as a way to balance the electric loads. Other significant efforts include the UC Davis West Village, a multifamily community of ZNE buildings, and the 2500 R Midtown project in Sacramento, CA, of single family affordable housing.

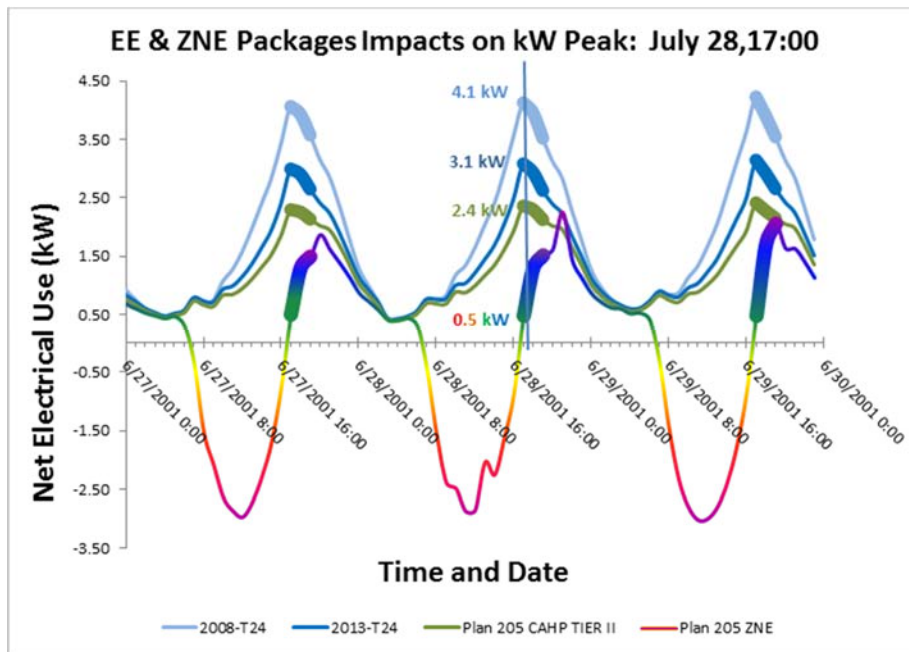
In parallel with California, the European Union has set a target of all new homes to be “Nearly Zero” by 2021 (definition varies by country with many only mandating energy use limits

¹ <http://www.cpuc.ca.gov/NR/rdonlyres/D4321448-208C-48F9-9F62-1BBB14A8D717/0/EEStrategicPlan.pdf>;
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through code). In the Netherlands, ENECO, a local utility, is building 40 near zero homes to assess and demonstrate grid impact of these regulations. But, as 2020 draws near, there is also a more urgent need to scale these efforts across the building industry, and more importantly to engage, educate and bring consumers along to the concept of Zero Net Energy.

This research is conducted as part of the California Solar Initiative RD&D program, and explores the impact of high penetration PV generation. ZNE communities represent the future of high PV penetration as every home can be expected to PV size ranging from 3 to 8 kW varied on EE measures, construction and climate. The load-factor for ZNE homes is expected to be low (<0.3) implying low electric system asset efficiency with mid-day excess net generation and a late-afternoon peak-demand most of the year. Figure 1 illustrates expected load shapes for ZNE homes built to different levels of energy efficiency. Note that the evening ramps, which can substantially impact the grid are steeper and larger for lower levels of energy efficiency, reiterating the role of EE in providing grid capacity benefits.

Figure 1: Modeled impact of level of energy efficiency on load shapes



The project evaluates impacts to distribution system, and their mitigation. Models are developed in GridLab-D and CYME, and combined with EnergyPlus models to represent the distribution system. The added benefits of reduced distribution costs and GHG reductions could enable IOUs to promote smart ZNE communities with load balancing, possibly reducing their cost to buyers through reduced infrastructure (gas and electric) charges. All homes in the study have an Energy Management System (EMS) that serves as an IDSM controller – managing end uses for Energy Efficiency (EE) and Demand Response (DR) in tune with consumer preferences. DR is used for load shaping and to manage future EV-Ready requirements. Customer side energy storage provides additional load balancing. The results can be used by utilities and the building codes to incentivize measures in ZNE communities, such as community scale solar and storage that could enhance electric grid reliability.

ZNE Neighborhood Drivers and Requirements

Developing a ZNE neighborhood requires a more complex planning process than designing single homes. Given the intent to evaluate grid impacts, it was important to design the neighborhood in a manner that develops the appropriate control volume for electrical measurement. Some of the considerations in planning the neighborhood were driven by study objectives and included:

1. Demonstrate economic feasibility of entry level ZNE homes: It was important to establish economic feasibility at scale through entry level homes.
2. Demonstrate customer acceptance for ZNE: It was important to establish that ZNE homes could be sold to a “normal” homebuyer in volume, based on location, pricing and features, just as it will be when every new home is ZNE.
3. Evaluate impact of ZNE definitions: Modeling was used to evaluate the impact of TDV ZNE definitions on PV size and energy use reduction with EE.
4. Evaluate load shape impact of EE and PV sizing: Modeling was used to evaluate how energy efficiency and PV can assist in helping to frame load shape.
5. Measured performance of ZNE homes: These homes are “ZNE by design”. A key objective is to compare operational against modeled performance.
6. Evaluate impact to distribution grid at various levels: It was important to understand grid impacts when ZNE home occupants are not as “energy aware” as early adopters.
7. Evaluate feasibility and impact of electrification: Evaluate both customer acceptance and grid impact of electrification of end use loads
8. Evaluate grid balancing through connected loads: The energy efficiency measures are designed with built-in connectivity, which enables both behavioral EE and DR. The connected loads and storage provide flexible load management through aggregation.
9. Role of energy storage in ZNE: This project is evaluating cost effectiveness and need for energy storage, which is sometimes represented as a “cure-all”.
10. Long term reliability: Products should be market ready, with UL ratings and backed by strong companies, relieving homebuyers and builders of warranty concerns.

Design of Zero Net Energy Homes and Neighborhood

Designing the neighborhood required multiple decisions on location, number of homes, home elevations, EE package development and PV sizing, all the while keeping sight of marketability of the homes. It was a consensus process between all entities involved, with close coordination and leadership from the Southern California operating division of Meritage Homes.

Location Decision

Meritage Homes simultaneously develops 10 – 12 subdivisions in Southern California. Instead of a full community, it was decided to develop a neighborhood and support the full incremental cost of ZNE measures, with all the homes being concentrated on two distribution transformers. The goal was to simulate the 2020 reality, when every home on every transformer would be ZNE. The Sierra Crest community in Fontana, CA was chosen as it was an entry level community, with home price well below the average for the Los Angeles metropolitan area. It was also in the early stage of development, providing significant choice to the project team on site selection. The community had three home collections – the Yosemite, Grand Canyon and Rocky Mountain, and a total of 168 lots. The 9 homes (lots 121 – 129) were from the Yosemite

collection with homes sizes between 1900 and 2300 square feet and the 11 homes (lots 6 – 16) in the Grand Canyon collection between 2600 – 2900 square feet were selected. The entire team worked together to map the electrical grid and pick the lots where the ZNE homes would be built (shown in the figure below) and decided on twenty homes concentrated on two distribution transformers. The nine smaller homes (lots 121 – 129, Yosemite collection) were fed by a 50 kVA transformer, while the eleven larger homes (lots 6 – 16, Grand Canyon collection) were fed by a 75 kVA transformer. This required mapping the lots against the actual SCE electrical layout for the community. The actual selection of homes is shown in the figure below.

Figure 2: Community plot showing location of ZNE homes concentrated on two transformers



Designing the ZNE homes

The energy efficiency packages for the homes were designed around Meritage’s standard construction practice. Every one of their homes is built with a high performance envelope. Foam insulation on the underside of the roof creates a conditioned attic space, which places ducts in conditioned space and reduces duct thermal losses. Foam insulation within the 2x6 walls also substantially reduces the cooling and heating loads. The heating systems are electric heat pumps for long term GHG reduction, uncommon for Southern California, but helps with GHG reduction. The reduction in loads assists in transitioning heating systems to heat pumps, as the energy efficiency built into the homes keeps the electric rate in Tiers 1 and 2, and below 15c/kWh. Figure 3 shows the reduction in individual loads, and the offset from PV generation in source energy (Btu/hr).

In addition, heat pumps also provide greater comfort through increased run times. The Heat Pump Water Heaters (HPWH) serve a dual purpose in also providing a flexible load that can ramp up and down to balance net generation and steep load ramps. These measures enabled a substantial reduction in total energy use of these homes, with gas usage reduced by 85% (only for dryers and cooking), and electric usage similar to a baseline home with gas heating (energy efficiency offsets electrification). Figure 3 shows the distribution of the loads in the home and Table 1 shows the annual energy use and PV size for each home in the neighborhood. Within California’s TDV based ZNE definition, the energy efficiency measures help to substantially reduce the size of the PV system required. Reducing PV size gives builders more flexibility on lot orientation provides homebuyers greater choices in floor plan and elevation.

Figure 3: Energy use in ZNE home and savings by load

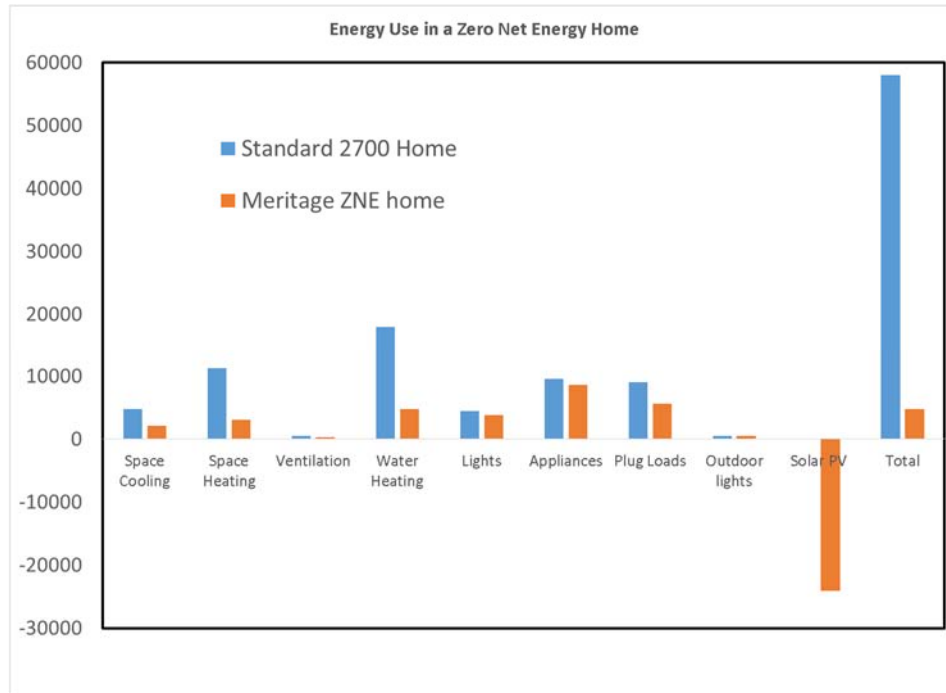


Table 1 Energy use and PV size for each home in ZNE neighborhood

Lot Number	Plan & Elevation	Home Size (ft2)	PV Size (kW)	HERS	kWh, 2013-T24	kWh, ZNE, with PV	Therms, 2013-T24	Therms, ZNE, with PV
6	Y2C	2842	4.5	-7	6,841	471	273	57
7	Y3B	2915	4.5	2	7,603	1,292	281	66
8	Y1A	2673	4.0	-6	6,729	254	278	57
9	Y3C	2915	4.5	2	7,603	1,292	281	66
10	Y1B	2673	4.0	0	6,717	1,074	275	57
11	Y2A	2842	4.0	-4	6,632	377	276	57
12	Y3B	2915	4.0	2	7,397	297	300	66
13	Y2C	2842	4.0	-3	6,861	600	289	57
14	Y3A	2915	4.0	2	7,579	1,096	285	66
15	Y2B	2842	4.0	-4	6,817	556	282	57
16	Y2A	2842	4.0	-7	6,703	456	280	57
121	G3A	2319	4.0	-12	6,334	(297)	229	57
122	G2B	2182	3.5	5	6,202	1,419	248	57
123	G1C	1936	3.75	-2	6,093	698	233	57
124	G2A	2182	4.0	-5	6,213	649	242	57
125	G2B	2182	3.5	0	6,290	928	254	57
126	G2C	2182	3.75	-5	6,190	489	253	57
127	G1A	1936	4.00	-9	5,961	208	242	57
128	G2A	2182	3.75	-1	6,096	1,003	256	57
129	G2A	2182	3.75	-1	6,096	1,334	256	57

Connected Homes and Data Monitoring

Each home was upgraded for connectivity of end use appliances to promote both energy efficiency and grid integration, as well as promote customer convenience and acceptance. The connected features included:

- Nexia (Trane) ZL824 wifi thermostat with Z-Wave hub to connect plug load controls.
- A.O.Smith Heat Pump water heater was a wifi module and available app.
- Plug load controllers that monitor and control energy use from plugs of user choice.
- SiteSage circuit level metering system with wifi connection.
- PV Inverters connected through the RS 485 port
- A Rainforest Eagle gateway to read real time AMI data for controls
- LG Chem/EGuana 5 kW/6.5 kWh energy storage systems for nine smaller homes

Figure 4 illustrates the various devices and systems in these homes. All these various energy related systems were connected together using an aggregation platform described in the next section.

Figure 4: Energy Efficiency and Connected elements in ZNE home



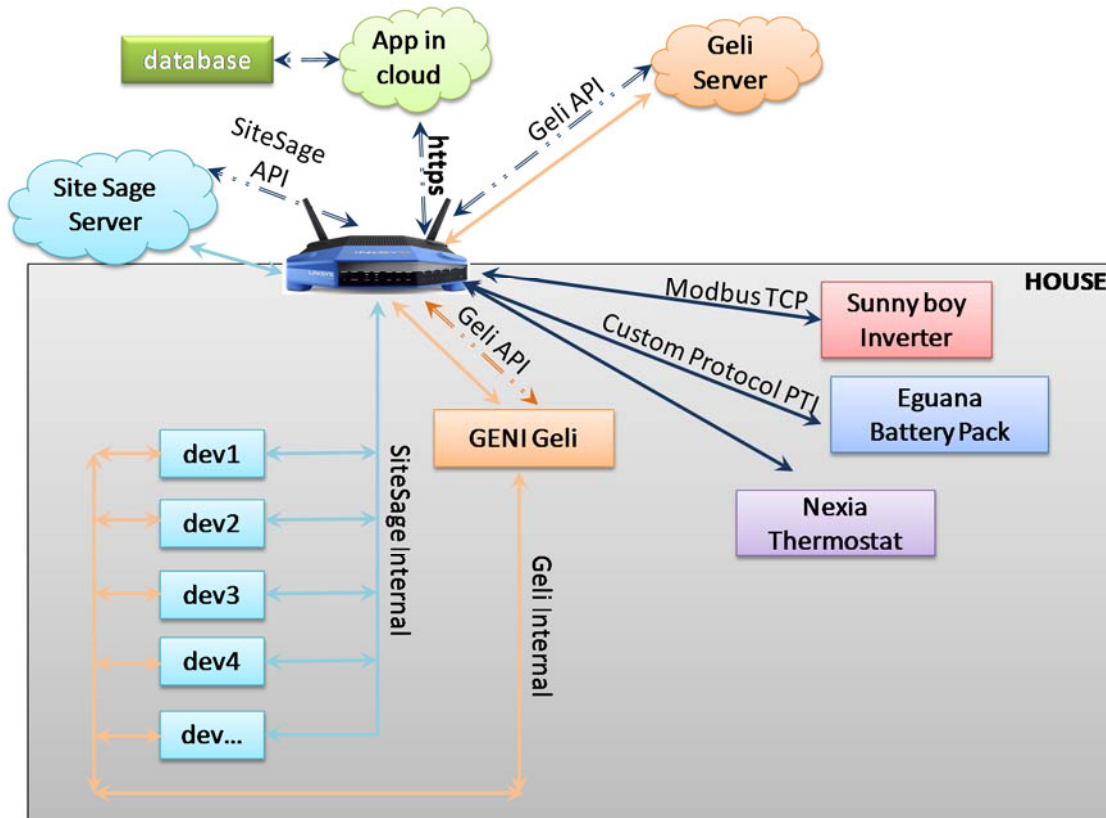
Controls and Grid Integration Platform

System Architecture. A schematic of the system architecture in Figure 5. The control system exists as two parts - (1) each individual house and (2) cloud infrastructure mainly through Application Program Interfaces (APIs). Applications could reside in the house or in the cloud as well. The router is the main interface between the house modules and the cloud infrastructure

where some of the device vendors have setup their servers. The communicating devices connect to the central router in the home primarily through wired Ethernet, but some such as the water heater communicate through wifi. To ensure reliability of communications, a dedicated network with its own router, and 4G modem to both manage the data, as well as provide customer user interfaces was installed. Some of the devices communicating in the house include:

- Power consumed read using Site Sage API connected to the SiteSage central server.
- E-Gear system that provides state of charge, charge rate and PV production.
- The Solar panel output is connected to a Sunny Boy inverter with a web box interface. This box supports the Modbus-TCP protocol. An application on the local network will query the current outputs of the system. In this case, data needs to be read from the system.
- Thermostat: Nexia through private API provided by Ingersoll Rand

Figure 5: System Architecture Diagram

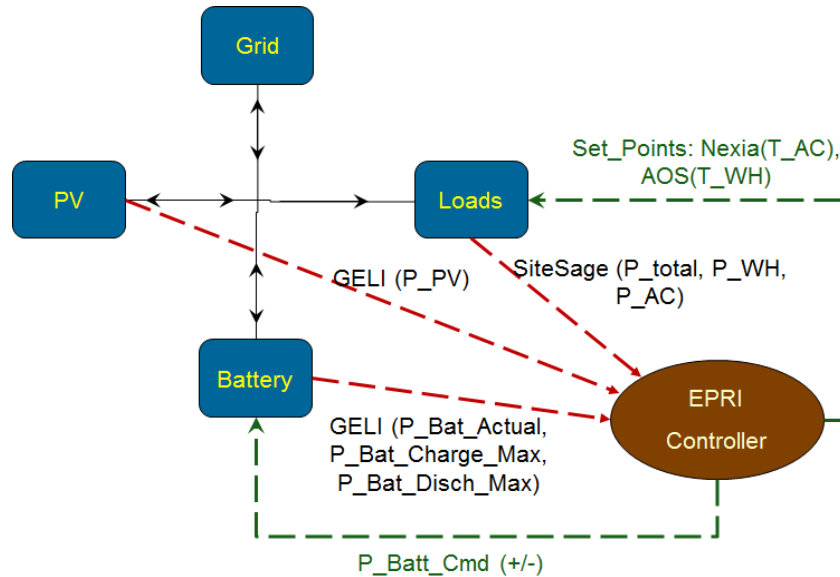


Control Logic for grid integration. The control logic for the DER integration is to:

1. Query the power consumed by all devices (through circuit level measurement), query the power generated (Inverter modbus TCP interface) , query the battery SOC and other battery parameters (TCP wrapper on a RS 485 modbus interface) and post the data to the cloud so that the data can be stored in a database.
2. Calculate the total value of power consumed
3. Compute the value of power generated

4. If power generated > consumption
 - i. If SOC of battery is < 100 % then instruct the battery to charge
 - ii. Else instruct the inverter to send power to the grid.
5. If power generated < consumption
 - i. If SOC of battery is > 10% (threshold) , then instruct battery to discharge.
6. Repeat steps 1 to 5 every second. If that timing is not possible, try to set values that would work.

Figure 6: Control Logic and strategy for Grid Control



Since consumption and PV generation could change in short time scales, the control loop must run quickly, suggested timing for controls cycles are in the range of 1 to 25 seconds. The other consideration is that the battery cannot be switched between charge/discharge cycles every second. Hence, any changes to the battery pack must be implemented every few minutes, but the amount of power being used for charging / discharging can be changed more often. To run the control strategy loop on a short timescale, it is preferable to run the control strategy application in the local router as it reduces the latency of controls, except for high latency systems like the thermostat and water heater. Also generally most cloud based applications use a RESTful API methodology rather than a permanent connection to the devices in the system. Considering that processing all the homes in the cloud app would require larger computational resources (and greater cost), the controls are set up to operate in the local router.

Data Collection and Management. Data is being collected from multiple gateways and collated in a large database. The APIs used for collecting data include the SiteSage API, e-Gear API, A.O.Smith API and Nexia APIs. The APIs allow us to collect between 35 – 50 data points per home including power consumption, indoor temperatures, operating schedules, etc. This data can be collected at very low incremental cost, compared to traditional data monitoring which would cost tens of thousands of dollars per home to collect similar data.

The large data sets require cloud based storage and controls. Because of the large number of services, the AWS platform has the maximum flexibility and also has a slightly higher cost.

For this type of non-mutable data, we would prefer to store them as flat files in an affordable cloud storage solution. The AWS service easily scales upto 5000 TB/ month at \$0.0275 per GB and can be used with any cloud provider as Amazon provides SDKs for most of the commonly used web platform languages. Regular users will be able to access their data and admin users will be able to access all data. An example data set with 1 minute data from multiple loads is illustrated in Table 2.

Table 2: Example data stream for load measurement

Date/Time	CH2-Mains	CH4-GFI Bat	CH5-Kitcher	CH6-Dining	CH7-Furnao	CH8-Loft	CH9-Furnao	CH10-Air Co	CH11-Air Co	CH12-220V	CH14-Micro	CH15-Bedro	18275/Volts	Outdoor Tem
2/18/2016 20:29	90	0	97	0	16	0	4	8	4	0	3	0	123.1	
2/18/2016 20:30	90	0	97	0	15	0	4	8	4	0	3	0	122.5	
2/18/2016 20:31	89	0	97	0	15	0	4	8	4	0	3	0	122.8	
2/18/2016 20:32	90	0	97	0	16	0	4	8	4	0	3	0	122.7	51
2/18/2016 20:33	101	0	97	0	15	0	4	8	4	0	3	0	122.4	
2/18/2016 20:34	130	0	37	0	16	0	4	8	4	0	3	0	122.7	
2/18/2016 20:35	113	0	0	0	16	0	4	8	4	0	3	0	122.5	
2/18/2016 20:36	125	0	0	0	16	1	4	22	6	0	3	0	123.5	
2/18/2016 20:37	422	0	0	0	115	0	92	429	146	0	3	0	122.1	
2/18/2016 20:38	483	0	0	0	274	0	251	454	155	0	3	0	122.6	
2/18/2016 20:39	478	0	0	0	274	0	251	445	155	0	3	0	122.1	
2/18/2016 20:40	482	0	0	0	252	1	231	471	163	0	3	0	122.8	
2/18/2016 20:41	488	0	0	0	247	0	227	484	176	0	3	0	122.3	
2/18/2016 20:42	500	0	0	0	248	0	228	496	179	0	3	0	122.7	
2/18/2016 20:43	528	0	0	0	248	0	228	507	184	0	3	0	122.8	

Hardware and Security. To keep the costs low and still achieve some flexibility, modifiable off the shelf units were leveraged for the router and connectivity hardware. An off the shelf Linksys AC1200 RT was selected as it was a newer product with OpenWRT supported components in the unit. The tools for applications development using the OpenWRT kernel was also provided, and were used to develop and install applications on the router to perform the different control strategy loops and data collections methodologies. Security is a very important factor for user data. Security needs to be considered in three domains; within each house in the community, between the house and the cloud infrastructure, and storage and retrieval of data from the cloud infrastructure. We used standard methodology of security used in web transactions, such as HTTPS, for data uploading. When the user/admin wants to view historical data the encrypted data is obtained from cloud storage. Then the data is decrypted and unzipped, and then the data is provided to the client browser interface using https only.

Distribution Impacts Modeling

The true impact of Zero-Net-Energy (ZNE) residential communities has not been observed yet because large communities of ZNE have not permeated the electric grid yet. Before this can occur there are important questions to answer in preparation for a fundamental shift in residential electricity usage. The questions are ultimately driven by two groups of stakeholders: Policymakers and Electric Utilities. The policy makers will need to address questions such as the financial impact of ZNE on the ratepayers, and at what concentrations do ZNE homes become an issue on traditionally designed infrastructure?

On the utility side, SCE’s distribution planning department has historically used air conditioning loads as the primary driver for calculating expected peaks. If peak ZNE end-use loads differ enough from traditional A/C driven peaks then the long sustained practice will need to change to accurately capture ZNE impacts. Potentially a grid-friendly and ZNE-enabling technology, energy storage, is always viewed as a load by current distribution planning

processes. Energy Storage can be a support to the grid if deployed at times when the grid is stressed, however customer sited storage might be controlled based on rates, and could exacerbate the impact of ZNE homes on the grid. Questions of interest to SCE include:

1. What are the technical impacts of ZNE on the electric grid?
 - a. Impact on the transformer?
 - b. Impact on the feeder and other circuit-level equipment (switches, laterals, relays, etc.)?
2. How can we better plan for a ZNE community?
 - a. What distribution standards need to be added/modified for ZNE communities?
3. What end-use loads drive the aggregated load curve at the transformer and feeder level?
 - a. Are there any new demand response (DR) opportunities that exist?

Electric utilities have different practices for grid planning, but in California the electric utilities follow the same general principles when designing their grids. Planning's objective is to ensure reliability during the peak season because if there are no thermal overloads during the peak season then there should be minimal issues for the rest of the year. SCE's Peak season is summer and peak is driven by A/C loads. SCE's distribution planning analyzes expected A/C load based on square footage of connected homes and climate zone to return an expected peak demand and choose the transformer based on expected peak load.

Analysis Method & Preliminary Results

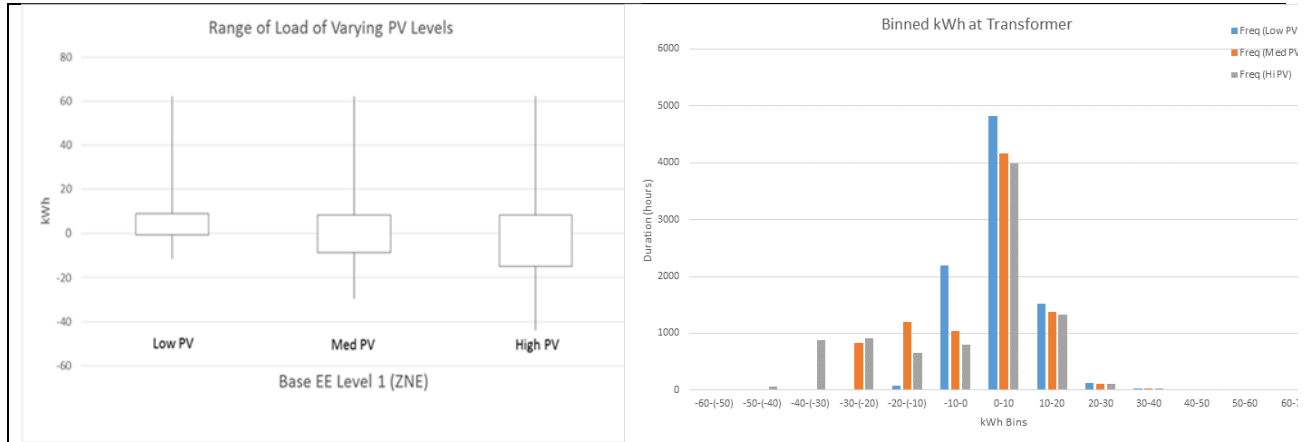
Three levels of analysis can be conducted to evaluate Transformer impact, End-use loads, and Feeder level impact. The transformer analysis consists of aggregating various combinations of individual homes metered at the end-use level to understand the difference in impact at the transformer. The variables include energy storage, solar PV sizes, and energy efficiency. By analyzing net impact at the transformer with these various combinations it becomes easy to understand the optimal configuration for the grid and which end-use loads mitigate negative impacts. Different scenarios were run with various PV sizes, depth of energy efficiency and with energy storage. Three PV sizes were chosen – 2 kW for a solar standard community, 4.5 kW for a ZNE community with high energy efficiency, 6.5 kW where ZNE is attained through additional solar instead of energy efficiency measures.

Figure 6 shows the range and median of kW at the transformer throughout the year. As expected, the Low PV case backfeeds (reverse flow) less often than Medium or High PV. The peak load in all three cases is ~62 kW. However, the peak loads are non-coincident with PV production as the summer peaks are around 6 PM and the winter peaks are around 6 AM, both time periods with limited or no generation from PV. One type of these analyses is variance analysis, which would help quantify how spread out the transformer load is throughout the year. For utilities, the lower the variance, the better the resource. Utility rates incentives reduction of variance, as is evidenced in time-of-use retail rates or resource adequacy charges. Binning of the transformer power draw allows us to look at the variance. Figure 6 shows the binned kWh and shows that the maximum kW draw at the transformer is 62.15 kW regardless of PV size, but the minimum is -43.78 kW, -29.44 kW and -11.5 kW for the large, medium, and smaller PV array sizes.

The high PV case shows greater variability, which increases uncertainty in distribution planning. That takeaway is that for ZNE community, driving greater energy efficiency, which

decreases PV size, will probably result in better distribution asset utilization, and possibly avoid added utility infrastructure cost. The binned kWh also shows that transformer exceeds its capacity (capacity is 50kVA) for a couple of hours a year when the heating loads are electrified.

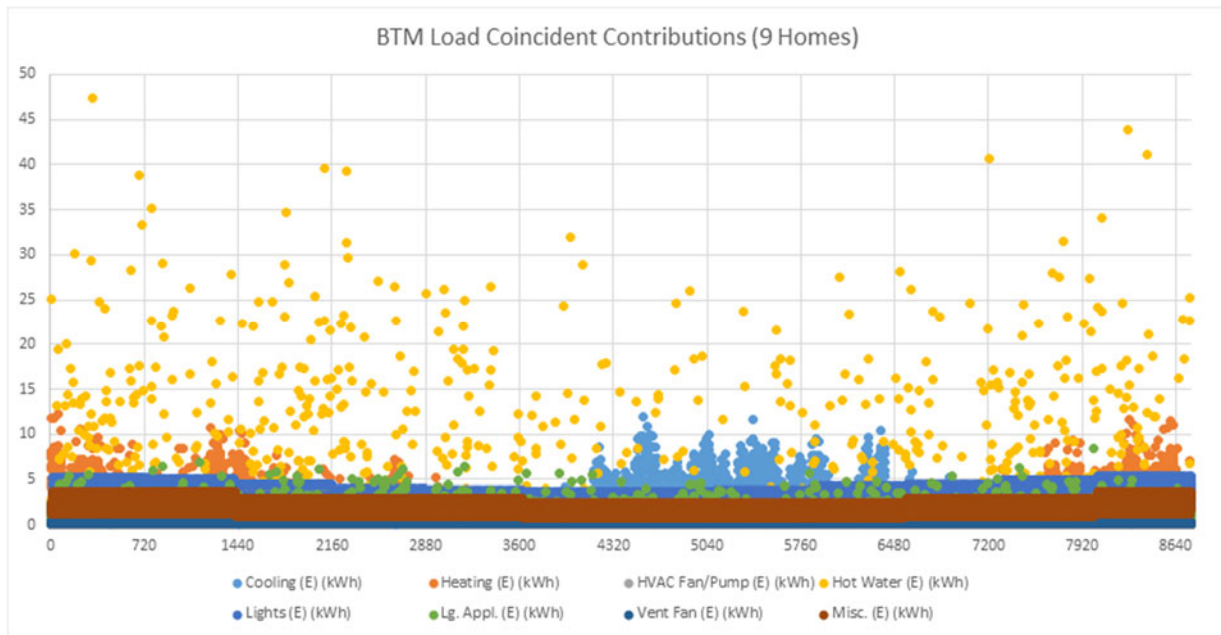
Figure 7: Annual variation of transformer load as a function of PV size



End-use loads

The irony of end-use loads is that they ultimately contribute to grid impacts, but historically the visibility behind the meter has been poor. To understand which of the many end-use loads we should be analyzing, we first must aggregate them to the transformer level to determine the largest coincidental impact. Figure 7 shows **water heating as being the primary driver for peak load seen at the transformer.**

Figure 8: Behind-the-meter Load Coincident Contributions



This is a new paradigm for utilities to understand in California (and other locations with gas water heating) because hot water heaters are normally fed by gas and not electric. This opens up a large opportunity for Demand Response for ZNE homes that did not previously exist. Deeper analysis into this topic will yield results that will help design DR tariffs that can benefit the grid while utilizing a new technology.

Feeder level impact

This analysis will include using results found at the transformer level and aggregating it to laterals (375 kVA), load blocks (1,500 kVA), and feeders (10,000kVA). This analysis will include circuit level simulations to understand current and voltage impacts to the utility grid. It will project potential operational issues and forecast upgrade paths. This analysis has not been completed yet.

Summary of Findings and Next Steps

ZNE communities have a highly skewed load profile similar to the “duck curve” which represents high overgeneration in the morning hours and a steep load ramp in the evening hours. This happens due to reverse power flows from PV generation, and increase in “connected” loads. Both of these conditions could increase the size of wiring and transformers, and increase the cost of energy through additional asset investments. Some of the key learnings are:

1. Building in greater energy efficiency reduces PV sizing which helps the builder and the homebuyer with greater choice of homes and elevations and the grid by providing better capacity.
2. PV generation is non-coincident with load peaks and might not improve the electric system in ZNE communities. Larger PV sizes for ZNE homes can drive increases in required distribution sizing due to higher net load variation.
3. Peak loads are tied to coincident water and space heating in the winter, when end use loads are electrified, and shifted away from cooling.
4. Both batteries and loads can be used to balance variability in ZNE communities
5. Load management and flexible demand response can be a much more cost effective measure than battery storage, especially when addressing just a few hours a year.
6. Aggregation and control of PV, loads and storage can provide certain level of grid balancing in operations, but long term reliability of controls needs to be evaluated before active control strategies can be incorporated into grid planning
7. The load drivers for grid planning shift to heating from cooling in electric ZNE (and non-ZNE) communities, and requires additional research and education of grid planners and operators.

This study is expected to continue into 2017, mainly in a data gathering phase. A follow up initiative is kicking off in 2016 to scale this demonstration through three full communities in Northern and Southern California. The results of these initiatives will be fed into the development of the 2019 Title 24 building code in California and the larger IECC code initiative for incorporation into development of Zero Net Energy communities.