Zero Net Energy Case Study Homes

Volume 1

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Foreword

What's So Great About ZNE?

To some steeped in the culture of energy efficiency or engaged in efforts to roll back climate change, the value of zero net energy (ZNE) homes may be obvious. Yet it's important that *all* the benefits of ZNE homes not escape notice. Indeed, to many individuals these benefits are likely to be of greatest value.

The most essential feature of a ZNE home is a high-quality thermal enclosure, with lower utility costs a benefit few are apt to dispute. Less well-recognized benefits – albeit equally important – are increased comfort, and protection from excessive heat or cold in power outages. In some places, a solar energy system may be optional to achieving ZNE, as 100 percent renewable energy is offered by some California utilities and community choice aggregators in an ever-increasing number of locales – at very low cost. A solar lease is another low- or no-cost option in many areas. In any of these scenarios, an enclosure built to ZNE standards carries valuable non-energy benefits.

Perhaps most importantly, as California reels from a series of devastating fires, resilience looms large as a universal goal. ZNE homes with solar arrays plus battery storage and controls will be able to serve as resilience centers in their communities, maintaining critical functions in power outages. The stringent durability and air quality standards to which ZNE homes are built bolster other aspects of resilience.

ZNE is the Future

This book, although describing just five projects, is an indicator of a nascent movement that is changing the face of American home-building, and doing so at a rapidly increasing clip. Just a dozen years ago, in late 2006, Habitat for Humanity in Metro Denver produced utility data confirming, for the first time, a home that was operating at ZNE. That groundbreaking home, in Wheat Ridge, Colorado, was heralded in the February 2007 edition of *Energy Design Update*.

Today, the number of "ZNE-ish" housing units in the US and Canada tops 15,000. Recent growth has been exponential, with a one-year increase of 70 percent recorded in the most recent inventory.[i] While ZNE homes still represent a tiny fraction of our housing stock, this burgeoning movement is making waves.

The first wave consisted principally of bespoke custom homes and one-off demonstrations. In an interesting turnabout, the second wave has been dominated by affordable multifamily developments. The third wave, just starting to gather steam, is the adoption of ZNE by front-runners in the production home-building industry. These latter two groups evidence the viable business case for building ZNE homes at scale; this key finding – illustrated by two of the case studies in this volume – will be pivotal in transforming the housing industry.

State Influence on Housing

Another fact gleaned from the residential ZNE inventory is California's preeminence as the state with the largest number of ZNE housing units. It is not coincidental that the State of California is also an energy policy leader – where there are advanced energy policies, innovation follows. Perhaps less obvious is the role of industry leaders in creating fertile ground for policy leadership. Were it not for successful models created by pioneers such as those highlighted herein, it would be much more challenging politically to enact ZNE-supportive policies.

A key California policy landmark was Governor Schwarzenegger's 2006 executive order establishing "big, bold" energy goals for California, chief among which was that all new residential construction should be ZNE by 2020. The energy code that will go into effect on January 1, 2020, has been adopted, and while not yet requiring ZNE, it represents a significant increase in energy efficiency for new homes, and also sets a U.S. precedent in requiring installation of photovoltaics.

Along with further progress toward ZNE, forthcoming State policy developments and technology investments will inevitably focus on reductions in emissions, or 'decarbonization' – via electrification, among other measures.[ii] This is reflected in allusions herein to all-electric ZNE homes as "zero carbon." While it's only possible today for a grid-tied home to be carbon-free in the rare instance where the home is all-electric, ZNE, *and* already served by emissions-free electricity from the grid, every all-electric ZNE home has the potential to operate carbon-free, when all electricity supplied by the grid comes from clean energy sources – a very real prospect. During his last months in office this year, Governor Brown signed SB 100 into law, committing California to transition to 100 percent emissions-free electricity by 2045. A number of California municipalities may achieve that transition well ahead of 2045.

The Case Study Projects

Members of the ZNE community outside California – in places that have "real" weather – sometimes scoff at the lack of challenge of accomplishing ZNE here. Admittedly, our populous coastal areas benefit from benign climates, but we also have both very cold climates, such as Redding (similar in heating degree days to Chicago), and very hot ones, such as Palm Springs. Other factors also make this a challenging environment for housing innovation, among them high costs, a highly mobile workforce, and a notoriously litigious culture. Thus creating successful, marketable, ZNE projects is a non-trivial feat.

All the projects represented here have met the pinnacle of ZNE achievement: verified site ZNE. That is, not only was each project designed to be *capable* of achieving ZNE, but utility bills provide objective evidence of occupants' energy use yielding ZNE *in actual operation* over the course of a full year. Further, site ZNE (explained in the introduction) is the most difficult definition to meet.[iii] These projects therefore demonstrate, importantly, that *operational site ZNE* (to which source ZNE is equal, for all-electric projects) is an achievable benchmark. These proofs of viability are absolutely critical to supporting the State's likely push towards residential electrification in years to come. The project developers whose work is showcased here are thus to be both congratulated and thanked for their significant contributions to the future of housing in California, and beyond. Read on, and benefit from their experience.

—Ann Edminster, Principal, Design AVEnues LLC

[i] The Net-Zero Energy Coalition conducts an annual inventory based on self-reporting by ZNE project teams, who record projects in design and construction as well as completed, and with energy performance (modeled or measured) within 10 percent of ZNE. ZNE-ready homes – e.g., those participating in the US Department of Energy's Zero Energy Ready Homes program – are also included. http://netzeroenergycoalition.com/zero-energy-inventory/

[ii] California Energy Commission business meeting, May 9, 2018.

[iii] The reasons for this are explained in *Zero Energy Buildings: A Critical Look at the Definition*, Torcellini, et al., 2006.

Introduction

This book is the fourth in a series on case studies of *zero net energy (ZNE)* buildings developed under the direction of the California Public Utilities Commission to support the adoption of ZNE building practices[1]. It is the first one that profiles residential projects, but shares the same objectives and approach as the preceding volumes. Each case study focuses on the process of decision-making that resulted in the solution as it was built, and offers a detailed analysis of the project's performance, along with the all-important lessons learned.

This volume presents details about the design, construction and performance of five *Zero Net Energy (ZNE)* residential projects in California. Each project is representative of a particular housing type of the residential market in California: single-family home (renovation), single-family home (new), subdivision tract housing, modular (factory-built) housing and low-rise multi-family affordable housing.

Within this simple summary are contained several complex distinctions that are important to understand before beginning to focus on these individual projects. The descriptive term, *zero-net-energy*, for example, has several different meanings, especially in the residential sector among institutions and government agencies that track progress in this area. The regulatory environment has different metrics for ZNE, as broad goals are defined and action plans are developed. The housing industry itself consists of different producers, from small local builders to corporate production companies, giving rise to different criteria for decisions.

This Introduction section will clarify these distinctions and set the common basis for each of the case studies that follow.

Metrics of *Zero Energy* Residential Projects

1. Basic Technical Metrics.

Depending on how the accounting of energy use over the course of a year is done, there are three distinct technical definitions of what is meant by a *zero net energy* or *ZNE* project currently used in practice: Site ZNE, Source ZNE and *TDV* ZNE. ("TDV" or "Time-Dependent Valuation" is the definition used in California's building code.)

As a practical matter, all three definitions have several aspects in common. First, the accepted time frame for ZNE accounting is one calendar year: a project is *ZNE* if the energy consumption equals renewable energy production over a one-year period. Second, the dominant form of renewable energy production selected is solar photovoltaic (PV) energy; there are other sources that would meet the renewables definition, but they are rarely selected as the most cost-effective and practical solution at the building level. Third, "at scale" deployment of ZNE residential projects presumes that the buildings are grid-connected. Though not a definitional requirement, grid-connectivity provides the most practical and cost-effective means of meeting ZNE performance targets.

A *Site ZNE* building has an on-site renewable energy supply, and the amount of energy used by the building over the course of a year is equal to the amount of energy supplied by the on-site system. For grid-connected buildings, the power drawn from the utility grid equals the power exported to the utility grid. This is known as *Site ZNE* since the line of transaction is drawn at the building site boundary. It is the one ZNE metric that can be directly metered and measured.

[1] The three earlier ZNE case study books, *Zero Net Energy Case Study Buildings, Volume 1*, (2014), *Volume 2* (2016), *Volume 3* (2018) can be found at: https://www.amazon.com/s/ref=nb_sb_noss_2?url=search-alias%3Daps&field-keywords=zero+net+energy+buildings

The *Source ZNE* metric recognizes that there are large energy losses attributable to the generation of electric energy at the power plant as well as additional energy losses associated with its transmission and distribution to the building site. Since these losses cannot be avoided for grid-connected buildings, the *Source ZNE* metric accounts for these losses, attributing them to the building's energy use. By this definition, the line of energy transaction is no longer at the building site boundary, but extends to include the grid itself. For individual projects where energy performance is measured and recorded, the absence of the ability to meter the *source energy* at any particular time makes the use of this metric impractical.

Finally, in its building code, California uses a hybrid energy metric known as *Time-Dependent Valuation* or *TDV*, with hourly economic multipliers applied to the site energy consumption (and production) as modeled for that building by energy simulation software. This software is used to document energy code compliance at the time of permitting the project. The "economic multipliers" can be used by code officials to account for time-of-day costs of energy generation. *TDV-ZNE* represents a code path to ZNE in California, the future objective for the state energy code for building projects. However, like the *Source ZNE* metric, TDV-ZNE cannot be determined for a built project because there is no measured "TDV" data—it is only a useful metric before the project is constructed as a code required standard. Even then, TDV-ZNE is not a metric of a particular energy performance; rather, it is a metric of the *value* of a particular energy performance.

Since the emphasis in ZNE performance is on actual measured data over the course of a particular year, *Site Energy* is the only practical metric to use. *Site ZNE* is therefore the criterion used in this book for verifying zero-net-energy performance of residential projects.

2. Broadening the Metrics of "Zero Energy Homes"

While *Site ZNE* is the only practical metric for a residential project to be *verified* as achieving ZNE performance, there are other "labels" that purport to be indicators that a residential project is ZNE. At the national level, the U.S. Department of Energy maintains a *Zero Energy Ready Home (ZERH)* program that offers to certify a residential project as "Zero Energy Ready" if its design meets several specific energy-efficiency standards and if it can accommodate a properly sized solar PV system that would theoretically result in ZNE performance[2]. Through a complex point system that rates all of these design features, a residential building is given a point total on a *HERS Index*[3] scale. When the solar PV system is added at the correct size, the Index drops appropriately to *zero* and the project can be labeled as a *Zero Energy Home*.

An example of the HERS Index for a house with a point total of 65 is shown on the following page. Therefore, to be labeled as a *Zero Energy Home,* the example house would be required to have a solar PV system large enough to register enough points to tabulate a total score of zero.

Presumably, the rating system can require the size of the solar PV system to be adequate to offset the total *source energy* calculated to be used, but in any event, the rating is done pre-construction and the label of *Zero Energy Home* is not based on any kind of measured result. In the absence of any actual performance data, the building cannot be considered a *verified* ZNE project.

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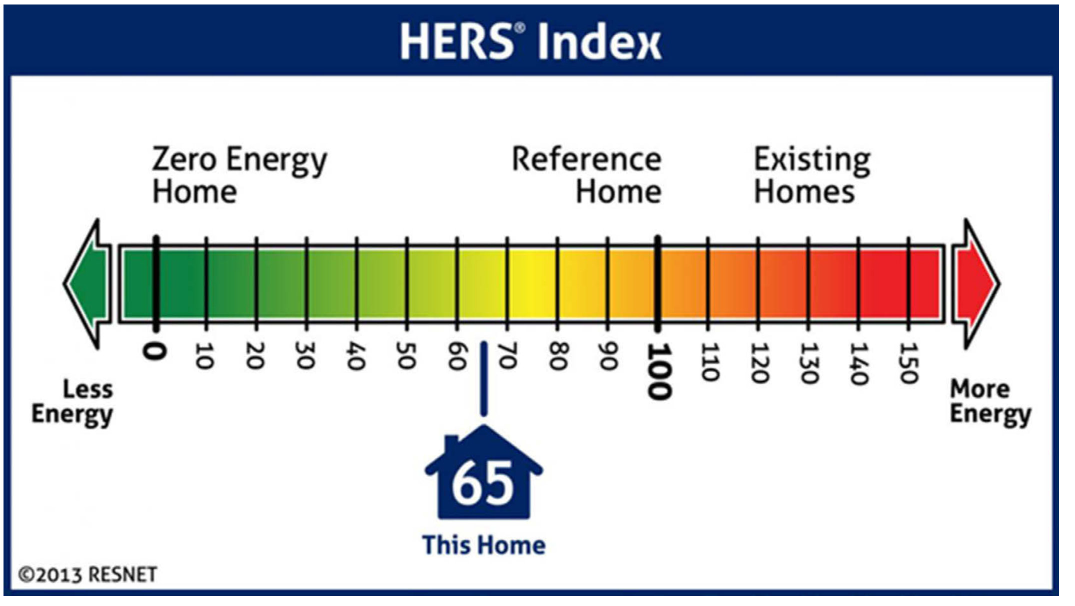
[2] There are additional non-energy requirements also. Full details at https://www.energy.gov/eere/buildings/guidelines-participating-doe-zero-energy-ready-home-program

[3] The *Home Energy Rating System (HERS) Index* is a method of rating the energy efficiency of a house based on design features, created by the Residential Energy Services Network (RESNET). https://www.resnet.us/hers-index

(Right) The HERS Index rating for a candidate *Zero Energy Ready Home (ZERH)* that meets all prescriptive requirements and achieves a point total of 65. If the home can accommodate a right-sized solar PV system to drop the HERS Index rating to zero, then it would be considered *Zero Energy Ready* according to the federal program.



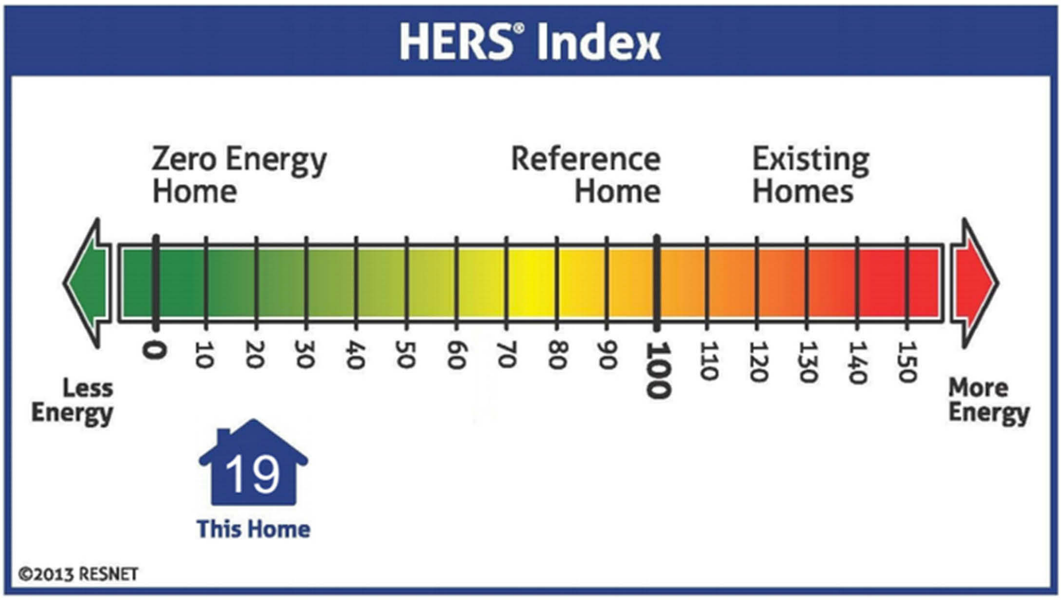
3. California Variant of Metrics for "Zero Energy Homes"

The California Energy Commission (CEC) has established a similar rating system for residential projects, though without all the prescriptive requirements for the design and construction as the federal ZERH program. Rather, the California program uses primarily certified energy modeling on the project design features to calculate an *Energy Design Rating (EDR)*, which is "aligned with" RESNET and the HERS Index scale. This EDR calculation by the energy model includes both energy use and energy production by any solar PV system that is included as part of the design, so it is capable of representing the annual net-energy performance of the residential project. (Some residential projects may also comply via a "prescriptive path", as described in the *2016 Residential Compliance Manual*[4], in which case an efficiency EDR is not calculated.)

Peculiar to the structure of the California energy code, however, the energy model calculation uses the *TDV-ZNE* metric to output a number on the HERS Index scale corresponding to the "energy performance" of the residential project (or rather, as noted above in the section on Technical Metrics, corresponding to the *value* of the energy performance.) On this scale, the "baseline" number of 100 corresponds to the TDV energy performance of a building project meeting the building envelope requirements of the 2006 International Energy Conservation Code (IECC). A score of zero (EDR = 0) means that a residential project can be labelled "Zero-Energy", or rather more precisely, "Zero TDV Energy". Such a project's design would combine a high level of energy efficiency and a solar PV system such that the modeled annual net-energy performance of the project (using the CEC-certified software and the TDV metric) is net-zero or net-positive.

As with the federal rating system for certification of a "Zero Energy Home", the California rating index, EDR=0, is not based on data measurements of the built project for at least one full year and therefore the project cannot be regarded as *verified ZNE*. The EDR system, like the corresponding federal program, is a method of labeling a residential project in a particular location before occupancy.

[4] https://www.energy.ca.gov/2015publications/CEC-400-2015-032/CEC-400-2015-032-CMF.pdf, pp. 1-17.



(Left) The HERS Index as "aligned with" the California *Energy Design Rating (EDR)*, the rating system for residential projects as established by the California Energy Commission and as calculated using certified energy modeling software based on the TDV metric.

4. Practical Categorization of "Zero-Energy" Projects

The Net-Zero Energy Coalition (NZEC), a private, non-profit organization dedicated to the facilitation of knowledge transfer about ZNE buildings, defines a zero-energy project as simply one that produces as much renewable energy as it consumes in a year[5]. NZEC categorizes ZNE residential projects as one of three types: "Net Producer", "Zero Energy" or "Zero-Energy Ready". These types of ZNE projects are defined as follows:

A "Net Producer" project has an on-site renewable energy system that supplies 110% or more of its annual energy use. ("Net Positive" is another term sometimes used to describe the same type of performance.) A "Zero Energy" project has a renewable energy system that supplies 100% to 110% of its annual energy use. Alternatively, the project can be certified as ZNE by the third party organizations, International Living Futures Institute or the Thousand Home Challenge to qualify for the "Zero Energy" label by NZEC.

The third category, "Zero-Energy Ready" [6], is a deliberately broad category to be as inclusive as possible of projects that don't quite meet the standards of the first two categories. These include projects which:

- Have a renewable energy system that supplies 90% or more of its annual energy use;
- Will be able to meet the requirements of the "Zero Energy" category if/when sufficient renewable energy capacity is added;
- Are designed to meet the requirements of the "Zero Energy" category, but no documentation is available (one possible example: because the project has not yet been in operation for a year);

[5] Net Zero Energy Coalition, "To Zero and Beyond", (April, 2018), p. 10.
[6] The NZEC "Zero-Energy Ready" category is not exactly the same as the federal performance category of the same name since more specific energy-efficiency measures are prescribed for the federal label. However, a "Zero-Energy Ready" home in the federal definition would automatically qualify for NZEC category.

- Are certified under one of a number of qualifying ZE asset rating programs (e.g., the federal ZERH program or the California Zero Energy Homes rating system).

To be listed as one of these three types in the NZEC database of the inventory of ZNE buildings, the project must have "documentation" that indicates that the project satisfies the criteria for that type of ZNE project. The "documentation" required is not specifically described on the NZEC website, and is in fact not required to be actual annual energy performance data. "Documentation" can be the results of an energy model for the project. Also, this documentation does not actually have to be submitted (whether energy model or utility data) in order to list the project in the NZEC inventory; the submittal for the project simply has to indicate which category is appropriate based on the project. NZEC is therefore an honor system rather than a system of *ZNE verification*.

5. Metric for Annual Energy Use: "Energy Use Intensity (EUI)"

One other metric deserves brief mention: Energy Use Intensity, or EUI, expressed in kBtu/sf per year. A State-funded technical study[7] in 2012 found that ZNE was technically achievable with EUI values varying (by climate zone) from 11.5 to 17.3 for single-family homes, and from 16.0 to 18.6 for low-rise multifamily homes. The projects in this book have EUIs ranging from 7.4 (Meritage, in Fontana) to 18.6 (Oak Haven, in Ojai), providing further validation of the achievability of ZNE in practice, not just in theory. (Note that because EUI is a per-square-foot metric – not a per-occupant metric – it will tend to be higher for smaller than for larger homes.)

Zero Net Energy Residential Projects As Defined for this Case Studies Book

The broad and inclusive national listing of zero-energy projects in the NZEC database is valuable in showing the relatively rapid transformation of building industry practice in the number and types of ZNE residential projects. This case studies book utilizes a somewhat stricter definition of ZNE, however, in evaluating the overall performance of the project and its inclusion in this book. Specifically, the case study project must have measured energy data for at least one full year and must account for all energy use, both electric and gas, with the gas energy use shown to be offset by the on-site renewable energy system.

We have, however, partially adopted NZEC's concept of "Zero-Energy Ready" by including projects that, according to the measured data collected for one year, are performing less than ZNE as a total housing group in spite of an initial goal of achieving ZNE, but for which individual housing units within the larger group are indeed ZNE performers as *verified* by the energy performance data. That is, these case study projects are either *verified Site-ZNE* in whole or in part according to actual measured and recorded data for one full year. In one case, there is ample roof space to add solar PV panels that, according to the measured data, would bring the residential project to full "Zero-Energy" performance by NZEC categorization.

Selection of the ZNE Case Study Buildings for this Book

Because the California housing industry is so diverse, ranging from the small builders to the corporate developers, as well as in project types from small renovation to dense multi-family housing, projects were selected to obtain representative examples from each category. The planning, approval and financing of each are very different, and these factors very much influence the ZNE design decisions and ultimate performance of the built project. As such, as part of each individual case study, these issues are discussed in the detail necessary to understand these influences.

[7] "The Technical Feasibility of Zero Net Energy Buildings in California", Arup, et al. 2010.

Case Study Projects ▷

CASE STUDY NO. 1

Corona del Mar New Houses

PHOTO: AMELIA CAMERON

Corona Del Mar New Houses

Case Study No. 1

Data Summary

Building Type: Single-Family

Location: Corona del Mar, CA

Gross Floor Area:
703 Heliotrope: 4,211 gsf
609 Marigold: 2,750 gsf

Occupied:
703 Heliotrope: 2013
609 Marigold: 2015

On-Site Renewable Energy System Installed:
703 Heliotrope: 20.3 kW DC
609 Marigold: 10.9 kW DC

Measured On-Site Energy Production:
703 Heliotrope: 30,650 kWh/year (2016-17)
609 Marigold: Not available

Owner/Client:
703 Heliotrope: Wayne and Shannon Inouye
609 Marigold: Wayne and Shannon Inouye

Project Team

Contractor: John Steed Homes, Irvine, CA

Architect: Jeanette Architects, Long Beach, CA

(Two-page spread on previous pages): Completed zero-net-energy house at 703 Heliotrope Avenue, Corona del Mar, CA. (Photo courtesy of John Steed Homes.)

The simplest case of residential construction is the new single-family house built on a semi-urban lot—built with new materials, modern construction methods and conforming to current residential building codes. This first case study is therefore an instructive one to illustrate the design and construction process using the current technotogies applied in a straight-forward, cost-effective and knowledgable way.

Background

703 Heliotrope Avenue and 609 Marigold Avenue are two examples of single family residences that have achieved zero-net-energy (ZNE) performance. The two houses are entirely new construction, built on previously developed lots.

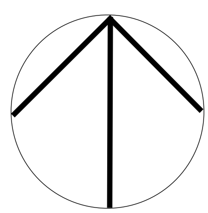
The house at 703 Heliotrope was the result of a desire by the owners to build a "deep green" home for themselves near the ocean. They purchased a "tear-down" structure on a standard-sized lot in Corona del Mar in 2010. The primary goal of the project was to build a comfortable home that would achieve ZNE performance and could obtain a LEED-Platinum certification.

This case study describes the process of design and construction of this house to reach successfully the ZNE goal. When this first project was in fact successfully completed in 2013, the owners and contractor then decided to build another ZNE house in the same neighborhood, this time as a speculative venture, advertising it on the market as a "zero-net-energy house". They found a similar though narrower lot at 609 Marigold, several blocks away, and proceeded to apply the techniques and lessons learned from the first ZNE house at 703 Heliotrope.

As paired projects with the same energy performance goals, both houses are described as part of this case study, with differences noted of intent and budget, and how these affected design decisions.

(Above) Original house on the property at 703 Heliotrope torn down for new construction.

Corona del Mar New Houses - General Vicinity Plan




703 HELIOTROPE AVENUE


609 MARIGOLD AVENUE

(Opposite page) Satellite vies of the two ZNE houses in Corona del Mar. Solar PV systems are evident on each rooftop.

Project Process

Building Program

703 Heliotrope is a 4,211 sq. ft. two-story house. The ground floor consists of one office, two bathrooms, kitchen, dining, living room, two music rooms and a two-car garage. The second floor has three bedrooms, three bathrooms and two outdoor patios. It was designed as the primary residence of the owner, who also developed 609 Marigold for sale on the residential market.

609 Marigold is 2,750 sq. ft. two-story house with one oversized garage. The ground floor is made up of a front patio, living room, dining room, kitchen and bathroom. The second floor also has an outdoor patio, an open seating area next to the staircase, as well as three bedrooms and three bathrooms.

See floor plans and sections for both houses on the next pages.

Site Constraints

Both 609 Marigold and 703 Heliotrope were constructed on developed lots with existing single-family dwellings, which had to be demolished before building the new houses. Some of the materials from the demolished homes were recycled or repurposed. For the LEED certification, a certain percentage of the demolished materials had to be diverted from the landfill.

Both houses were built on relatively small lots typical of beach communities and where zoning rules required only 3-foot side yard setbacks. The proximity of the neighbors' houses and yards meant that not only did some trees interfere with construction, the house had to be carefully designed to access the available natural light facing these side lots.

There is a slight east/west slope to the lot at 703 Heliotrope, although it did not significantly impact the construction of the house.

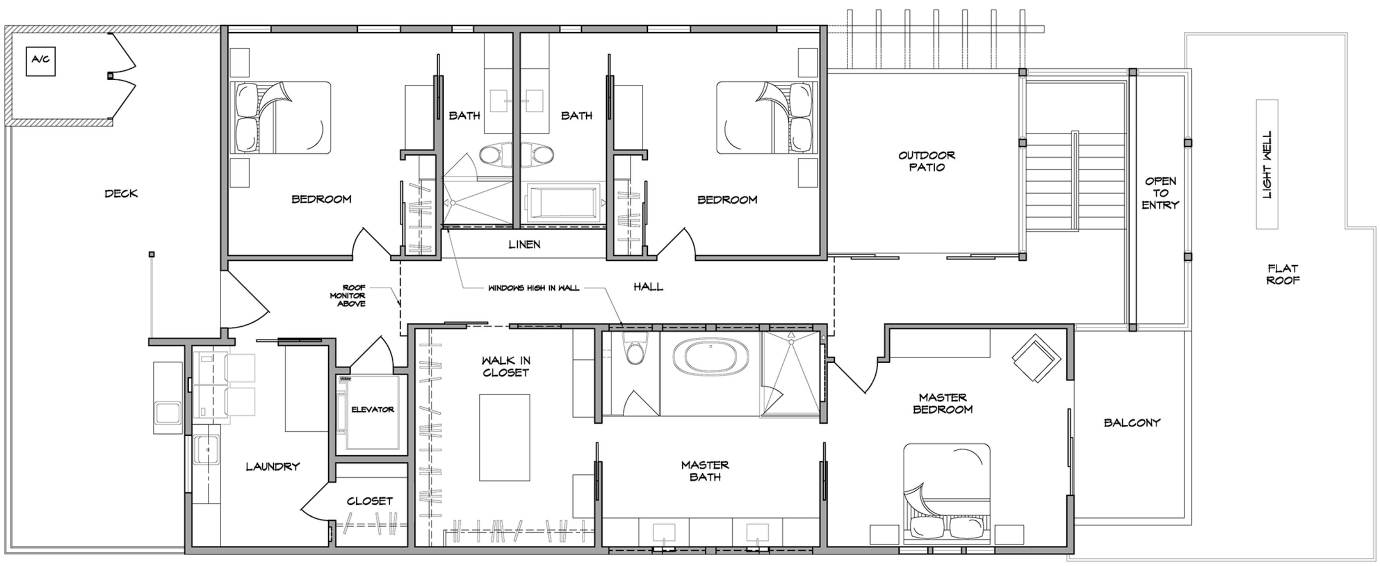
Both lots have good solar exposure for the rooftop PV panels, though limited sunlight access for windows on the long sides of the houses that face southwest. The southeast side of each house, which has good access to morning sun, faces the public street, necessitating a balance of privacy and passive solar features such as large glass areas.

Low Energy Design Strategies

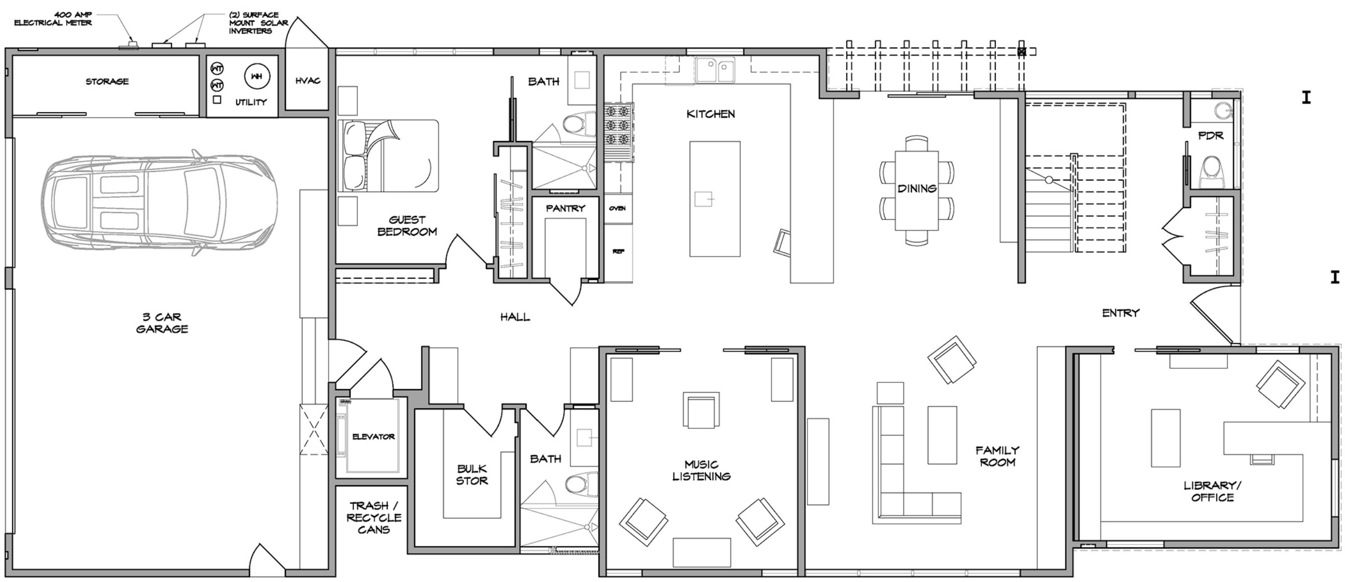
Building Envelope – Insulation and Windows

Standard batt insulation was not used in either house. At 703 Heliotrope, the contractor used closed cell spray polyurethane foam insulation, which has an R-value of 6.9 per inch and also serves as an air barrier. (See below.) Since the framing is done with 2X6 wood studs, 5" of the foam insulation was installed, providing an overall R-value of 35. The roof and clerestory were similarly insulated with 10" of the closed cell foam, yielding an R-value of 70 for that part of the building envelope.

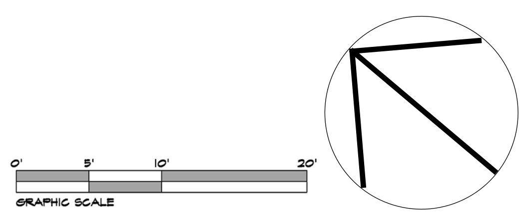
For the house at 609 Marigold, the contractor used *open* cell spray polyurethane foam instead, which was less costly but has much lower insulating value (slightly more than half the R-value of closed cell). The client and contractor recognized that the closed cell spray foam was actually not cost effective in a mild climate such as Corona del Mar and that the performance of the building envelope would be comparable to that of the closed cell alternative.



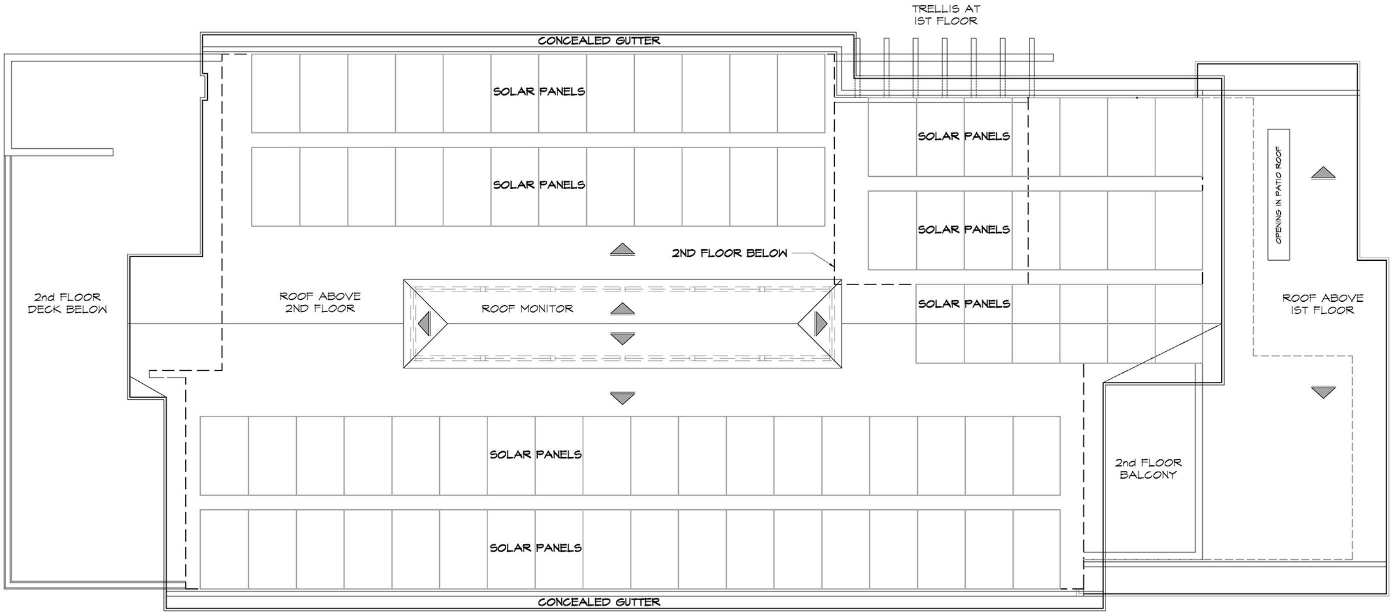
SECOND FLOOR PLAN



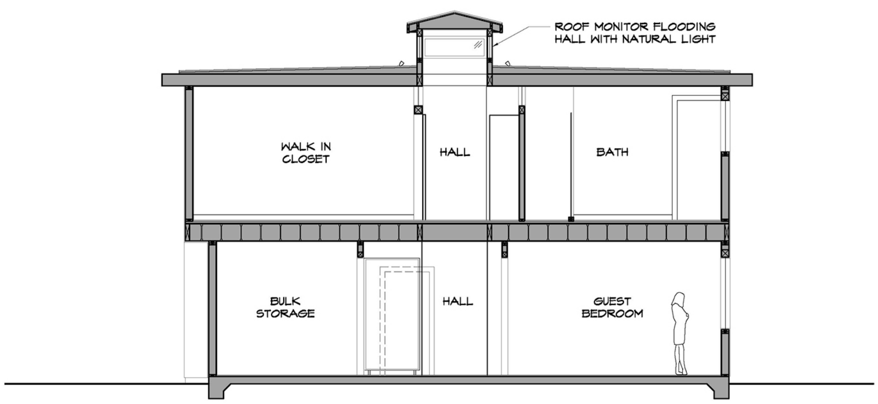
GROUND FLOOR PLAN



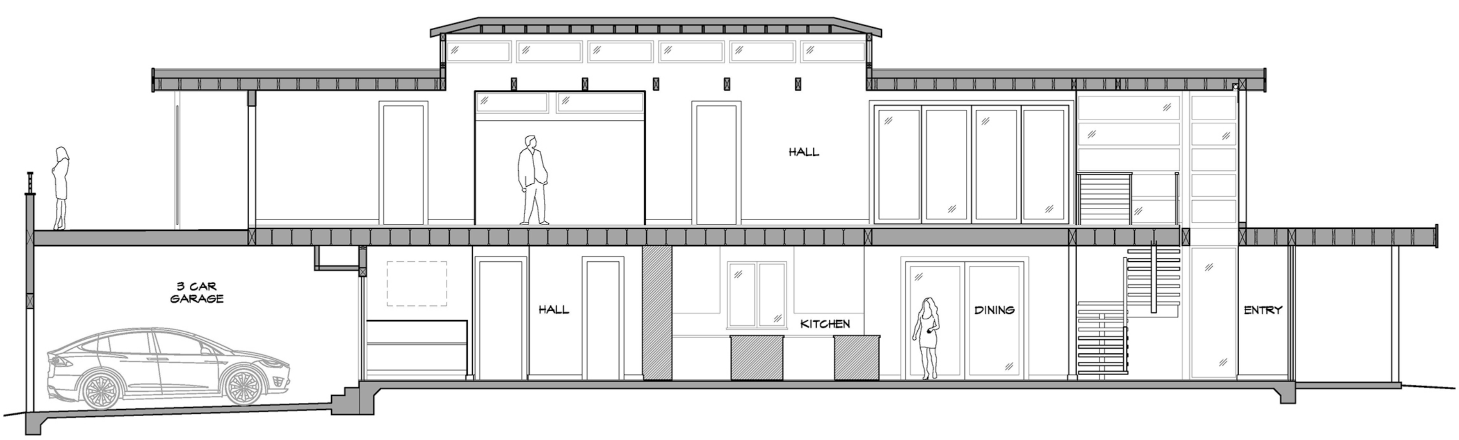
703 HELIOTROPE: FLOOR PLANS AND BUILDING SECTIONS



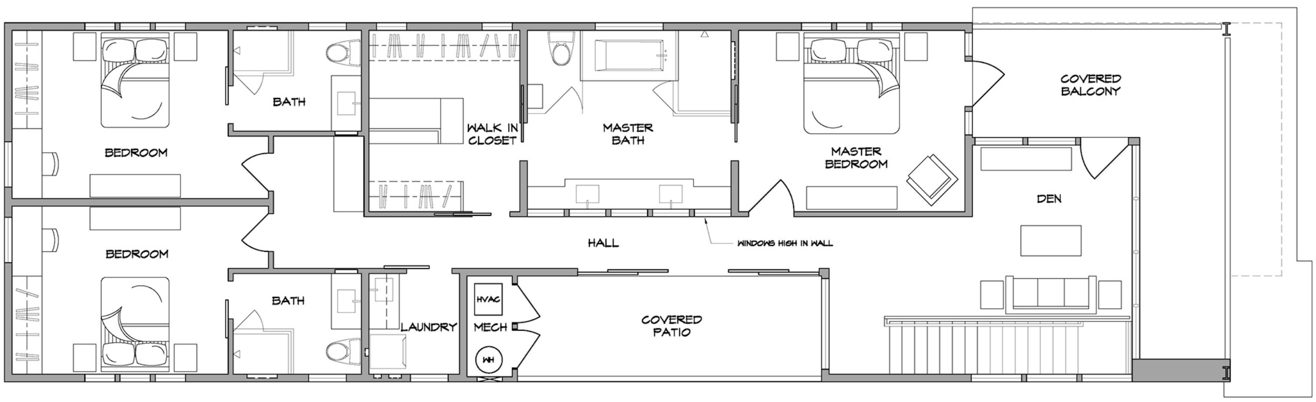
ROOF PLAN



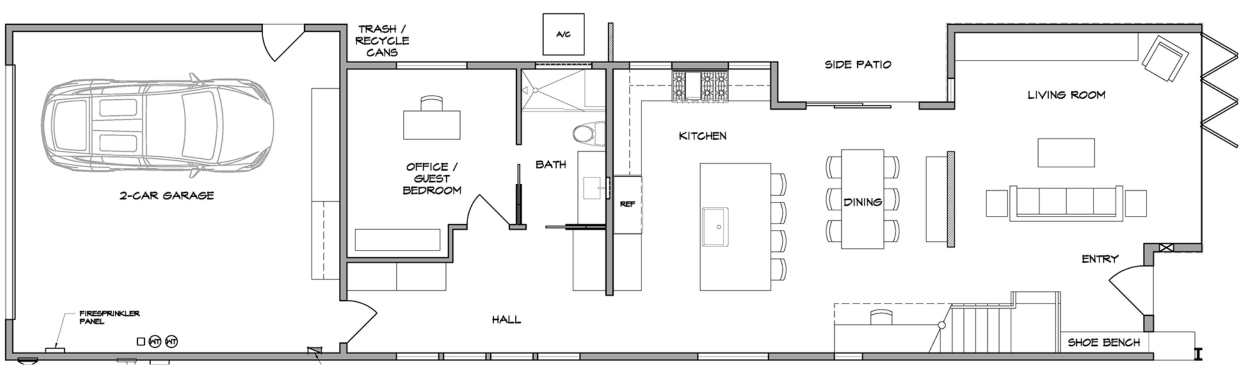
TRANSVERSE (CROSS) SECTION



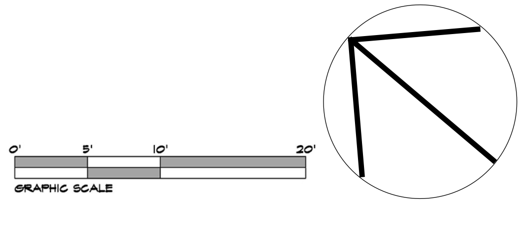
LONGITUDINAL SECTION



SECOND FLOOR PLAN

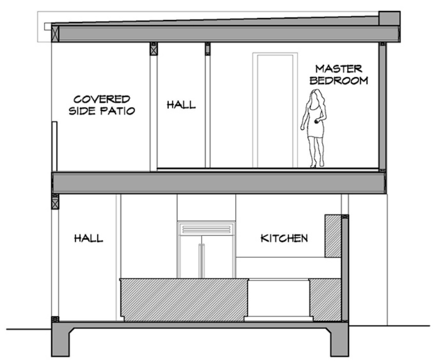


GROUND FLOOR PLAN

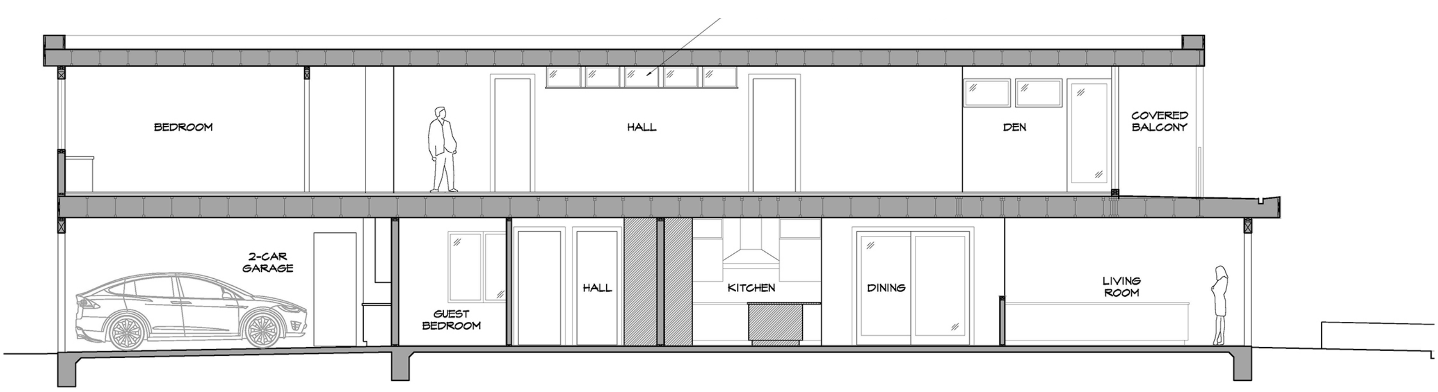


609 MARIGOLD: FLOOR PLANS AND BUILDING SECTIONS

ROOF PLAN

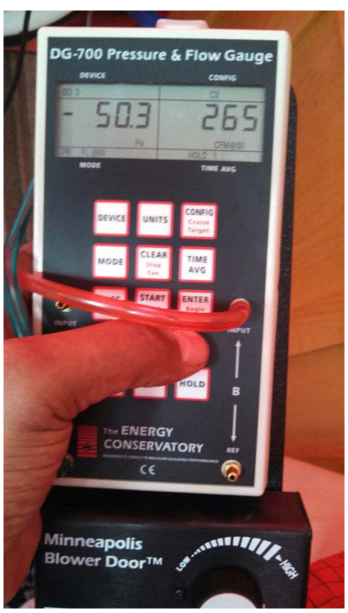


TRANSVERSE (CROSS) SECTION



LONGITUDINAL SECTION

(Above) Airtightness: attaching the gaskets to the bottom of the wall frame. (Photos courtesy of John Steed Homes.)



(Above) Airtightness: measurement device, called a manometer, for testing the number of air changes per hour at a certain air pressure created by the Blower Door. (Photos courtesy of John Steed Homes.)

For insulation value, the windows at 703 Heliotrope are triple-glazed, providing an R-value equal to 5. As noted above, the solar exposure of the southeast-facing street facade suggested passive solar design using large window areas. To admit solar heat during the winter, the middle glazing layer has a special coating that admits sunlight readily but excludes the ultraviolet light to minimize its damaging effects. (Solar heat gain coefficent = 0.47). In the summer, blinds internal to the window units can be operated to provide shading.

At 609 Marigold, double-glazed windows were installed, which was the more cost-effective choice while still providing good thermal performance in this mild climate.

Building Envelope – Airtightness

One of the keys to minimize energy use in residential construction is *airtightness*. Building scientists confirmed this in the 1970s and it led to many construction techniques, products and testing methods that are used today. These are essential in ZNE residential structures, as will be discussed in all the case studies in this book. The houses of Case Study No. 1 utilized all recommended methodologies to control energy-wasteful air leakage and to verify via testing the air-tightness level achieved. As such, they are a good set of projects to begin that discussion.

One of the principal techniques to develop airtightness is to seal the wall and roof planes using air/vapor barrier tapes and sheet material, plus carefully seal the joints at exterior windows and doors. Enhanced air-sealing of these planes can be achieved by using closed cell spray foam insulation between the framing members, as was done with the construction of the house at 703 Heliotrope. Open cell spray foam insulation is permeable and does not have the air-sealing characteristics of the closed cell product. 609 Marigold is therefore not as airtight as 703 Heliotrope, which was borne out by the results of the testing procedure.

Another important technique is to seal the joint between the framing and the foundation system. This is achieved in both houses by using gaskets manufactured by Strandguard between the foundation and the framing to seal that common source of air leakage. (See figure at upper left.) The gaskets were compressed down to 1/16", which created an airtight seal.

Good quality (airtight sealing) windows and doors are essential. In both houses, the contractor sealed the joints around these openings with bituthene flashing.

With "airtight" construction techniques employed to the appropriate degree, the houses were tested using a *Blower Door*[1] and associated testing meters and recording devices.

In general, the result of the test is a number that gauges the airtightness of the house, known as *ACH50*, which is the unit of measurement for the number of air changes per hour at 50 pascals of pressure. The house is pressurized using the blower door and then the pressure difference is measured between inside and outside (after any leak points are located and sealed). As the contractor, John Steed, described in his blog about the projects in 2012, the benchmarks for airtightness of a house can be described as follows:

- >20 ACH50: poor airtightness (i.e., leaky) house
- 5 ACH50: adequate tightness per California Title-24 energy standards
- 2.5 ACH50: "stuffy" house—needs fresh air ventilation system
- 0.6 ACH50: *Passive House*[2] standard

The result of the *Blower Door Test* for the house at 703 Heliotrope was 0.4 ACH50, below even the Passive House standard of 0.6 ACH50.

[1] For a description of the *Blower Door Test*, see https://www.energy.gov/energysaver/blower-door-tests.

[2] http://www.phius.org/what-is-passive-building

PHOTO: MERLE STERN

(Above) The zero-net-energy house at 609 Magnolia, Corona del Mar, CA.

PHOTO: AMELIA CAMERON

PHOTO: MERLE STERN

(Opposite page, top)
703 Heliotrope interior view.

(Opposite page, bottom)
609 Marigold interior view.

Heating, Ventilating and Cooling Systems

Since the houses exceeded even the Passive House standard for airtightness, it was necessary to add a fresh air ventilation system to each house similar to the typical Passive House design. Normally, this can be accomplished using an HRV or ERV[3] system, the preferred ventilation system of Passive House. Fresh air is circulated throughout the house using a very low power fan, with the outside air exhaust near the same location as the air intake so that an energy exchange can occur. Such systems are used to create good indoor air quality in general, which is necessary for airtight houses, while at the same time providing a method of thermal energy recovery from the outgoing air stream..

At the Corona del Mar houses, however, a similar system is used but without the heat exchange component. Continuously operating low-power exhaust fans located in the bathrooms combined with fresh air inlets at another location in the house are programmed to provide the right amount of fresh air to the house. They can provide high speed exhaust when necessary and revert to the continuous operation mode as dictated by the automatic settings.

Both houses utilize electric air source heat pumps, thus providing both heating and cooling capability. The heating /cooling coils are located at the heat pump in the utility area in the garage and an air distribution system much like that used by a conventional furnace ducts heated or chilled air to the various house spaces. The supply air vents were placed in the floors because of the insulation system that was used in walls, with enclosed duct chases to the various locations. Separate thermostats on each of the first and second floors provide two separate zones for heating and cooling, with the resulting potentially better comfort levels on each floor.

An alternative approach, not used in the Corona del Mar houses, would have been to pipe the heated and chilled water to the individual spaces and use a ductless *mini-split unit*[4] to provide good individual temperature control in each space. The room units resemble a floor-monted radiator. (This ductless mini-split system is discussed in subsequent case studies in this book.)

Natural Ventilation

The house at 703 Heliotrope utilizes a “pop-up” roof monitor above the central corridor on the second floor, with operable clerestory windows. The idea was to provide a means of ventilating the house with fresh outside air instead of using the mechanical cooling system. By opening the clerestory windows, the high space would act like a “thermal chimney”, drawing air in at the ends of the house and exhausting it through the clerestory windows at the top.

The owners soon found that using this feature also admitted outside noise and unfiltered air—it was a very quiet house with good indoor air quality because of the airtight design. The result was that they decided not to use that potentially energy-saving feature. It also led them in part to the decision to omit the feature from the house at 609 Marigold, which was also a construction cost reduction measure.

Lighting and Plug Load

The two houses are equipped with LED light fixtures throughout, which significantly reduces the energy used for lighting compared with fluoresent sources. With that reduction, the most signifi-

[3] For a description of these fresh-air systems, see http://www.greenbuildingadvisor.com/blogs/dept/musings/hrv-or-erv
[4] For a description of this ductless mini-split heat pump system, see: https://www.energy.gov/energysaver/heat-pump-systems/ductless-mini-split-heat-pumps.


8/17/2011 9:50


8/23/2011 15:26


9/13/2011 13:04

(Opposite page) Series of photos, top to bottom, of construction sequence at 703 Heliotrope from forming for foundations to framing of second floor. (Photos courtesy of John Steed Homes.)

cant use of energy outside of heating and cooling is that of the equipment, or "plug loads". These include electric appliances, TV and stereo systems, computer and network equipment and anything else that "plugs" into a household outlet. Both homes feature Energy Star appliances and the owners are aware to check the label for the Energy Star certification of any equipment purchased for use in the houses.

The house at 703 Heliotrope has the added energy loads of an indoor elevator, an intermittently used type of equipment, as well as charging equipment for an electric car.

Natural Gas Use

The two houses were designed with a dual-fuel kitchen range, namely an appliance with a gas cooktop and an electric oven. The owners decided that this combination minimized the carbon generation while at the same time satisfying their preference for gas stovetop cooking. In addition, the two houses are equipped with gas clothes dryers in each laundry area.

In each case, the solar PV system is so over-sized that this carbon is easily offset by the renewable energy generated.

In general, the choice of energy source for cooking is often seen as a choice between gas and electric stovetop units, where the reasonable selection is gas because of food-cooking characteristics and capabilities. But there is a third choice, namely *electric induction*[5], which is a magnetic technology that is prevalent in northern Europe and arguably has food-cooking advantages over gas-fueled cooktops. This carbon-free type of appliance will be discussed in more detail in subsequent case studies in this book.

Domestic Hot Water

Domestic hot water is supplied in each house using a 50-gallon heat pump water heater. To conserve water, the sinks at 703 Heliotrope are equipped with an automatic recirculating pump that saves water when the hot water tap is about to be opened, as signaled by a motion detector when someone enters the room. The operation is initiated by the control device at the pump to use the cold water line as a return pipe to the hot water tank until the water in the hot water line reaches high temperature rather than let the water from the hot water tap go down the drain while the water heats up.

703 Heliotrope has a soaking tub in the master bathroom, which is heated by a dedicated tankless ("instant hot") water heater. The instantaneous hot water device is also used in the small powder room in this house.

Construction

During the construction of both houses, the contractor paid particular attention to details that would affect the airtightness of the construction (see above) and continuous insulation characteristics (no thermal breaks or thermal bridging), which might appear inadvertantly during the course of construction. A basic sequence of the milestones of the construction of the house at 703 Heliotrope is shown on the facing page.

[5] See the following article for a technical comparison of cooktop alternatives:
(1) http://ovens.reviewed.com/features/induction-101-better-cooking-through-science;
(2) https://www.consumerreports.org/electric-induction-ranges/pros-and-cons-of-induction-cooktops-and-ranges/.

(Right) Installation of solar PV panels on the roof of 703 Heliotrope. (Photos courtesy of John Steed Homes.)

Renewable On-Site Energy Supply

The on-site solar PV system at 703 Heliotrope consists of 78 panels made by Yingli Solar (260 watts per panel), a Chinese manufacturer, for a total of 20.3 kW (DC). There are two 10kW inverters for the system located in the garage.

Since the owner considered this house to be a "luxury home", the system was not designed to meet their estimated energy production requirements. Rather, the intent was to fill all available roof space and have the capacity to generate as much energy as possible in anticipation of possible future additional needs such as electric vehicles. The owners also felt that they wanted to be net zero carbon in all respects, so that meant having enough clean power to offset the small amount of gas use on site, personal air travel and the embodied energy of the construction materials (including that of the solar panels themselves). The marginal cost of the extra panels was considered to be affordable.

When the panels were initially installed, the owners and their neighbors realized that the row of panels nearest the street were partially visible. Although not legally required to do so, the owners removed two panels and repositioned others so that the visual aspect of the panels was less prominent. There was a 5% reduction in the power output as a result, but there was still ample surplus production.

The owners also arranged for the panels to be cleaned every three months because of the proximity of the house to the ocean, as well as to the busy Pacific Coast Highway and the Orange County airport.

The house at 609 Marigold, on the other hand, is smaller (65% of the floor area) and was built for sale to buyers with an unknown energy use pattern. The intention was to advertise a "zero-net-energy home", so the size of the PV system was determined by assuming average energy use totals. This was calculated to be 42 panels (Yingli Solar) generating 10.9 kW (DC)., about half the size of the system at 703 Heliotrope.

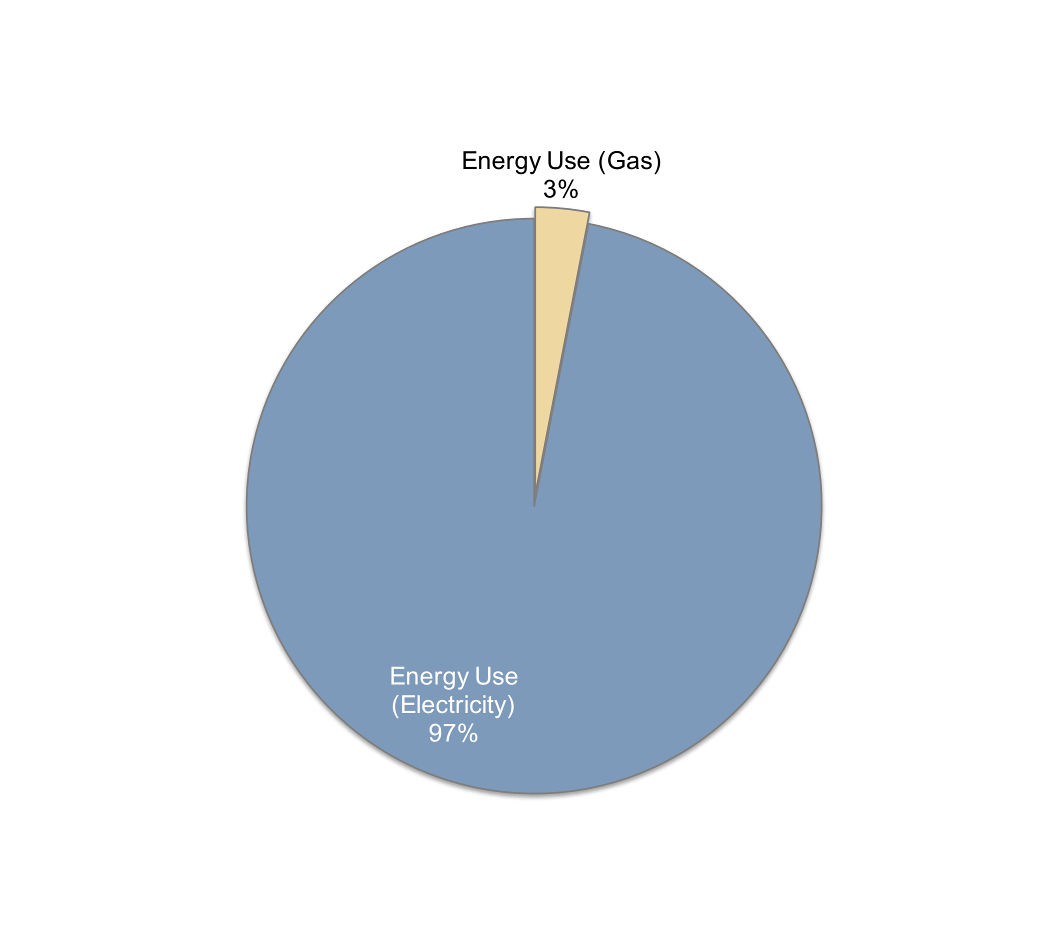
The builders also provided the support structure for additional panels that could easily be added by the new owners at a future date if their energy use were higher and they wanted the house to have on-site ZNE performance. Space was provided for 26 additional panels or at least an increase in 6.7 kW (DC). As it turned out, the buyers' household consisted of only two people and the installed PV system provided enough energy so that the house achieved ZNE.

Energy Performance
Post-Occupancy Measurement

Energy Use—Monitoring and Measurement

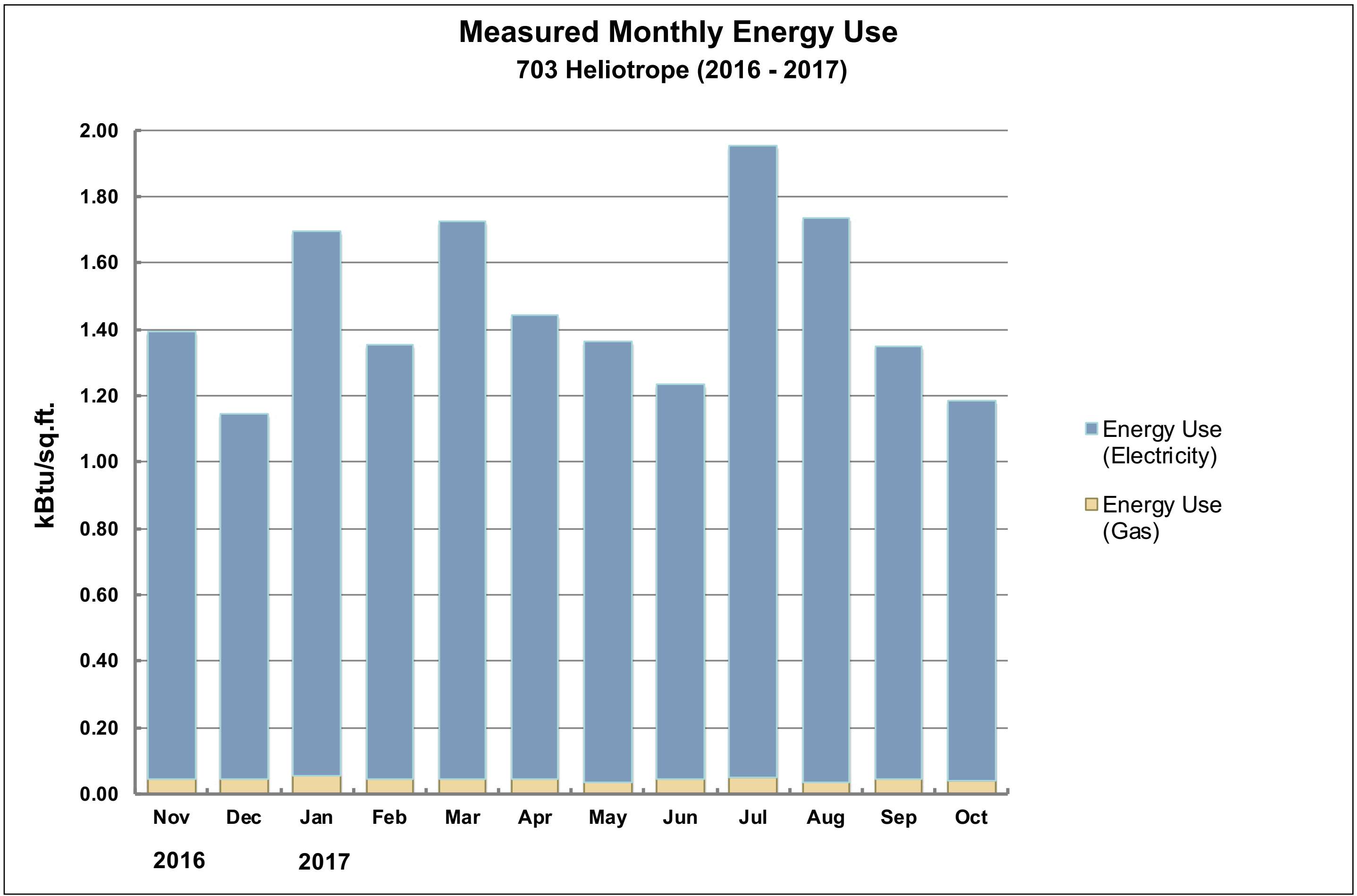
Southern California Edison provides monthly *net meter* reports to the homeowner, that is, the total net energy provided by SCE to the house every month. If the energy production by the solar PV system exceeds the energy use for a reporting period, the total net energy provided by SCE will be negative. (The meter runs backward when production exceeds demand.) If meters are installed on a solar PV system, or the output of the system is otherwise recorded, the monthly energy use can be determined from this solar PV meter data and the SCE net meter report: a simple addition of the two numbers will provide the energy use for that period.

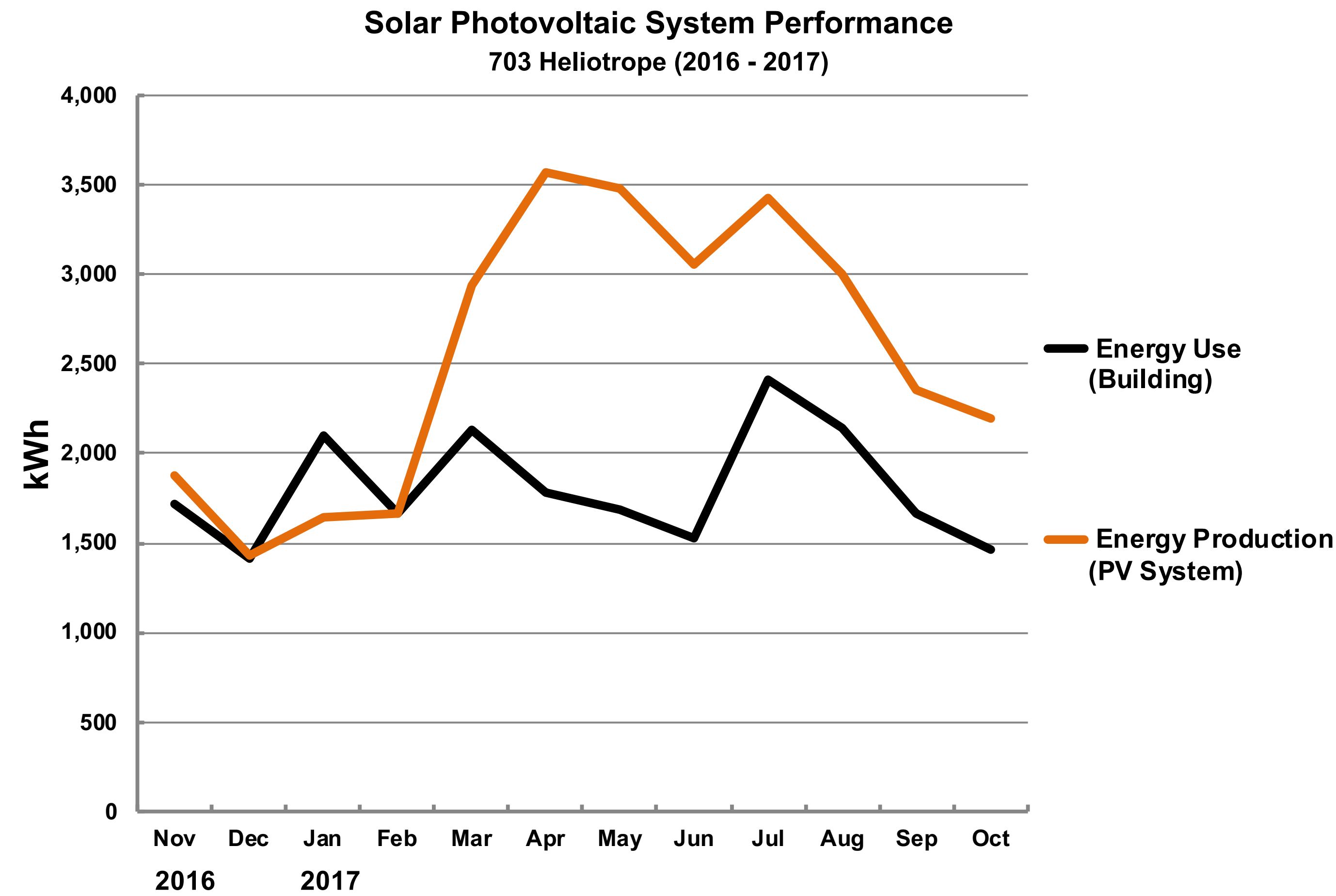
For 703 Heliotrope, the owners installed a monitoring system by Tigo. Using the SCE net meter reports, the energy use for the house during the one-year period from November, 2016, until October, 2017, was calculated and is shown in the charts on the opposite page.

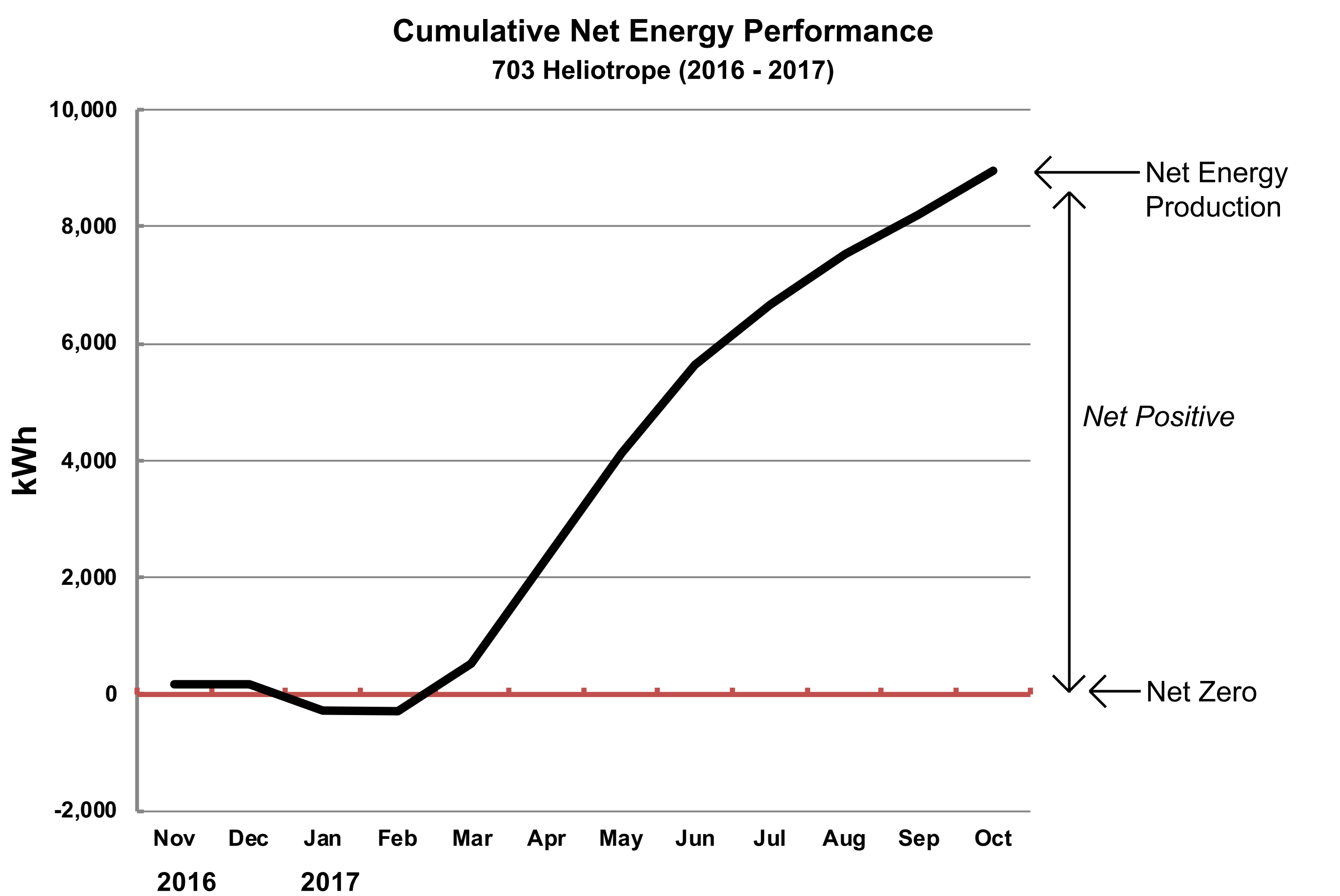


Measured Energy Use
703 Heliotrope
(2016 - 2017)

21,694 kWh/year
Measured EUI = 17.6




Solar Photovoltaic System Performance
703 Heliotrope (2016 - 2017)
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
kWh
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
2016
2017
Energy Use (Building)
Energy Production (PV System)


Cumulative Net Energy Performance
703 Heliotrope (2016 - 2017)
10,000
8,000
6,000
4,000
2,000
0
-2,000
kWh
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
2016
2017
Net Energy Production
Net Positive
Net Zero

609 Marigold, as a speculative house built for sale, was not equipped with a monitoring system for solar PV system. As a result, the data on household energy use for that house is not available.

Energy Production versus Energy Use: Zero Net Energy Performance

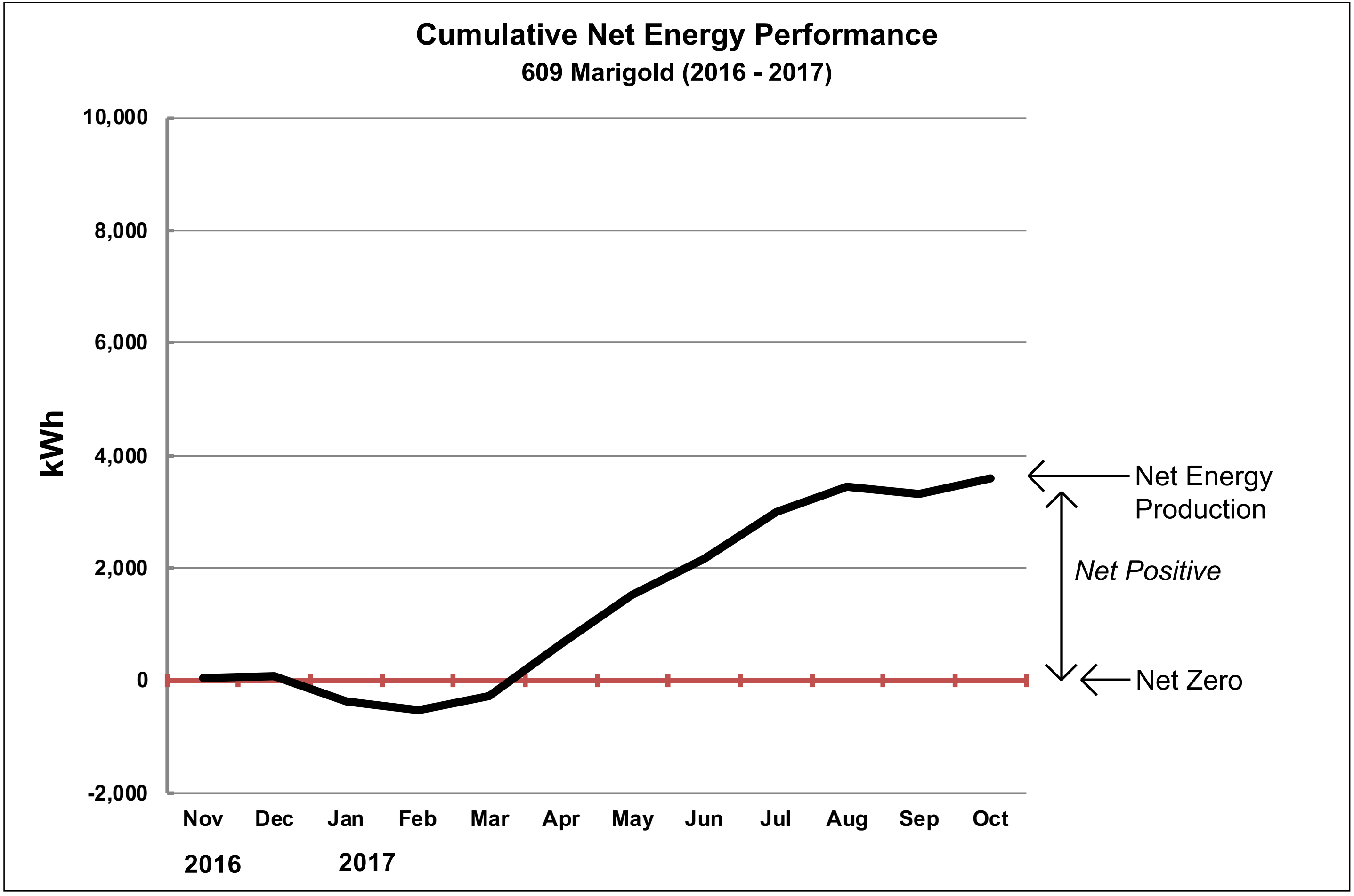
The charts on the opposite page and below show the relative PV system performance over the course of the one year (11/2016-10/2017). The chart of solar production compared to energy use (top) for 703 Heliotrope clearly indicates the excess production as the result of the over-sizing of the system.

The cumulative *net* energy production charts essentially show the progression of the energy performance toward ZNE by adding each month's net energy performance to the previous month's total—if, at the end of the year, the curve remains on the positive side of the zero axis, then the building is indeed performing at ZNE. 703 Heliotrope, as can be seen, performed much better than ZNE because of its extra system capacity. 609 Marigold, even with the smaller system, is also *net positive* by a comfortable margin. (These charts can be made from the SCE monthly net meter reports.)

Post Occupancy: Observations and Conclusions

As the performance data shows, the triple-glazed windows and closed cell spray foam insulation were likely unnecessary to achieve ZNE performance in the warm marine climate of Corona del Mar. The house at 609 Marigold, with double-glazed windows and less airtightness provided by the open cell spray foam insulation was still *net positive*, while the house at 703 Heliotrope was dramatically over-producing, even considering the added demand of the electric vehicle.

At 703 Heliotrope, the owners realized that it was more efficient to have the recirculating pumps that were located at the sinks placed immediately next to the DHW heater, and controlled by a push button at the sink rather than motion detectors. The pumps were frequently activated when they were not needed, therefore using power unnecessarily. The pumps were moved closer to the water heater because shortening the circulation loop meant less power used and less heat lost.



CASE STUDY NO. 2

Fortunato House Renovation

PHOTO: LAWRENCE ANDERSON

Fortunato House Renovation

Case Study No. 2

Data Summary

Building Type: Single Family

Location: Hermosa Beach, CA

Gross Floor Area: 2,150 gsf

Occupied: 2012 (renovation completed)

On-Site Renewable Energy System Installed: 6.5 kW DC

Measured On-Site Energy Production: 10,466 kWh/year (2016-17)

Measured EUI (Site): 16.5 kBtu/sf-year (2016-17), includes two EVs.

Owner/Client

Robert and Monica Fortunato

Project Team

Designer: Robert and Monica Fortunato

Mechanical & Plumbing Engineer: P2S Engineering, Long Beach, CA

Structural Engineer: Envision Engineering, La Jolla, CA

Hot Water Systems: Gary Klein and Associates

Lighting Design: Lighting Design Studio, Hermosa Beach, CA

Green Point Rater and Materials Selection: Healing Spaces by Design, Pasadena, CA

General Contractor: Robert Fortunato

Subcontractor (Building Envelope): Harding Construction

Perhaps more challenging in some ways than a *new* single-family house, a renovation project must deal with existing construction, less-than-optimal features with regard to energy efficiency and often labor-intensive correction of code deficiencies. The cost of an extensive renovation can be close to that of a new house on the same site. However, aside from the slight cost savings and issues such as historical significance and neighborhood location that may affect a decision to renovate rather than build new, *sustainability* considerations of reusing the existing structure are becoming a factor for many people.

It is useful to consider the set of constraints and opportunities affecting the decision process as they differ from those of new houses. This case study illustrates a process of design and construction that is instructive in the adaptation of state-of-the-art energy-efficient techniques and systems to a relatively old structure and, as a result, the renovated house achieves a high degree of *sustainability* and zero-net-energy performance.

Background

This particular case study is an unusual example of a renovation project in its origin and execution, nevertheless the ideas are generally applicable and based on sound principles.

The original house was built in 1959 in a beachside community of Los Angeles. It consisted of 1,320 sq. ft. on two levels on a sloping lot, where the lower level included a garage opening to the street, with the living spaces on the upper level, and which opened on the uphill rear yard. The owners acquired the house in 1995 and did not start planning the renovation and expansion until 2008, when the need for additional space became apparent.

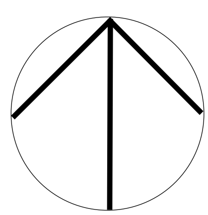
A personal commitment to a high degree of sustainability, including a minimal carbon footprint, water recycling and a healthy indoor air environment, set the approach to the project from the beginning. When they initially researched similar residential projects, the owners found a lack of definitive data about the net energy use of these “solar” houses and decided to embrace the additional challenge of achieving a data-verified zero-net-energy performance.

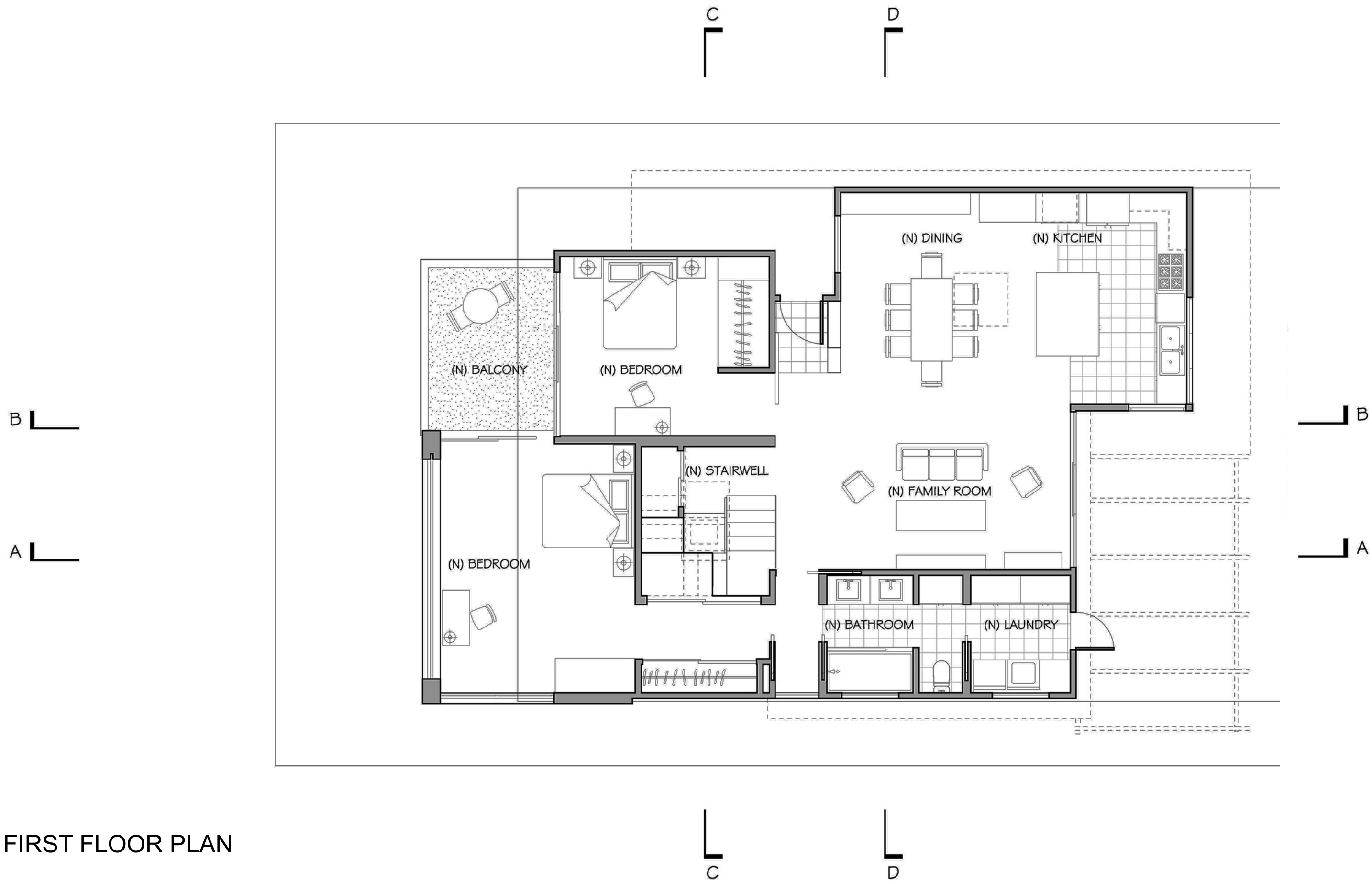
This combination of *deep green* goals for the project gave rise to a brand name for the house, the “Green Ideas House”, which the owners decided to publicize via a project website[1]. A detailed project journal documenting the entire process of design, construction and occupancy is featured on this website.

(Left) The original house, built in 1959.

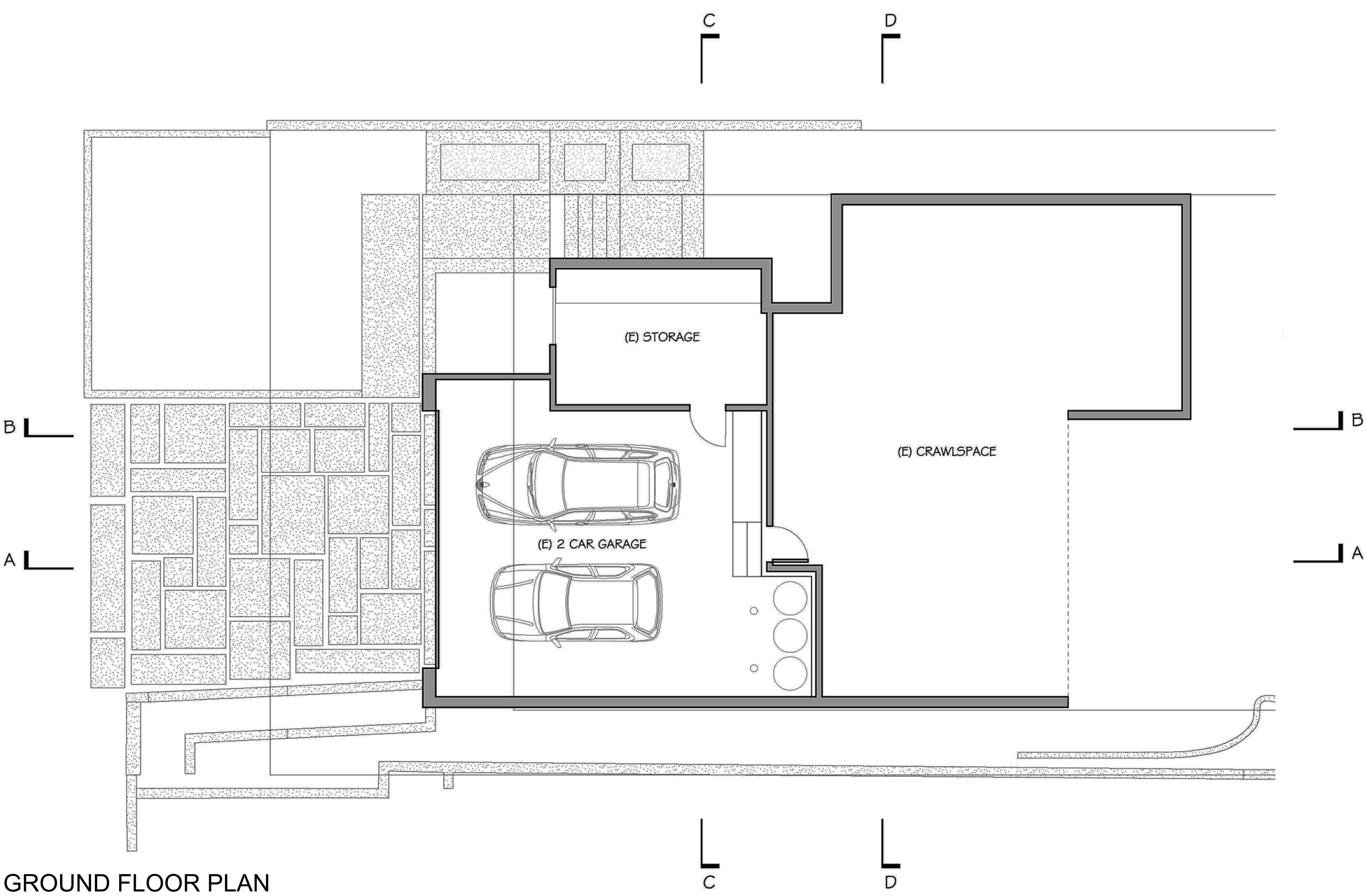
[1] Green Idea House website: http://www.greenideahouse.com/. The website includes a “Project Journal”.

Fortunato House - General Vicinity Plan

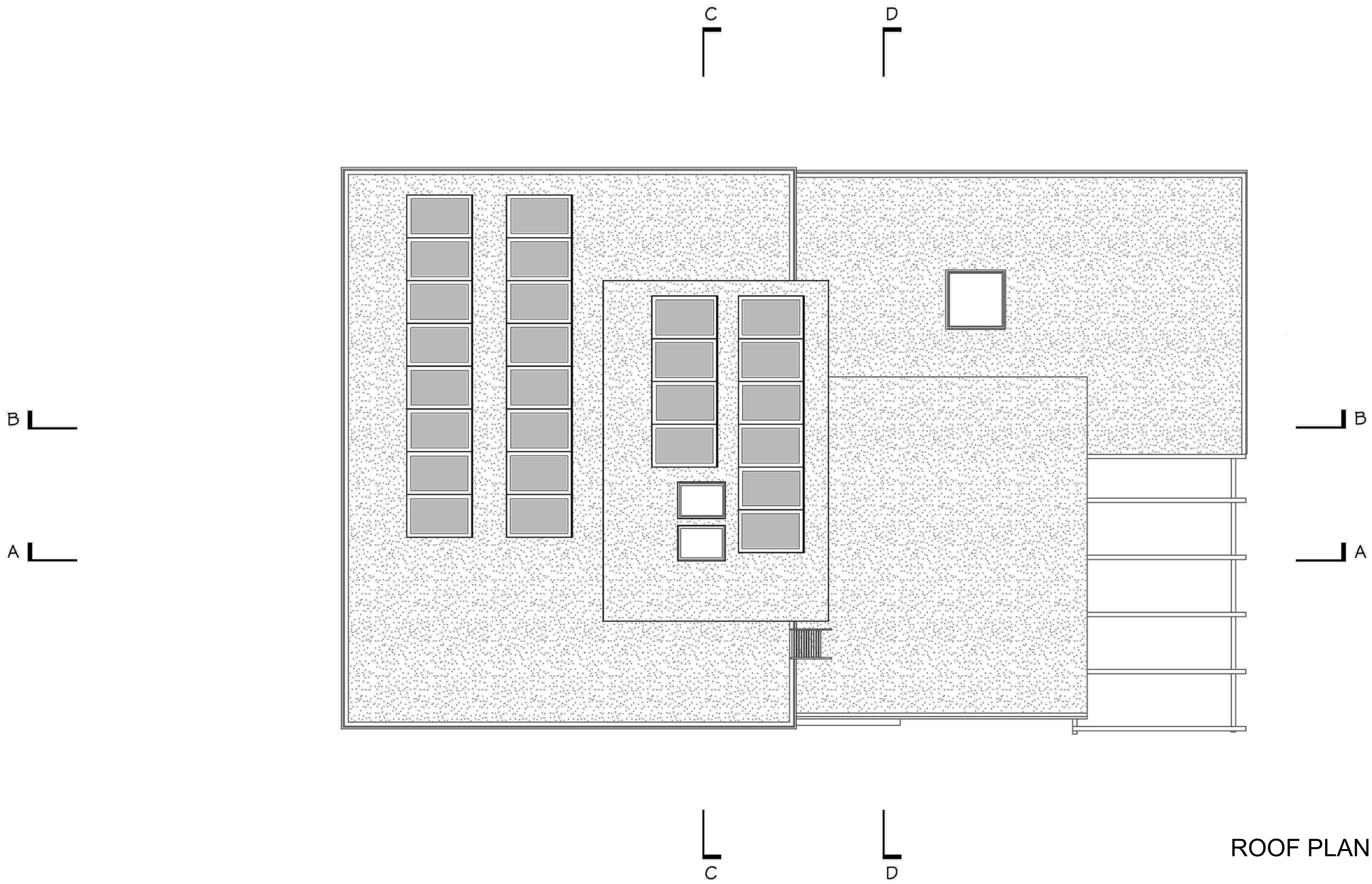




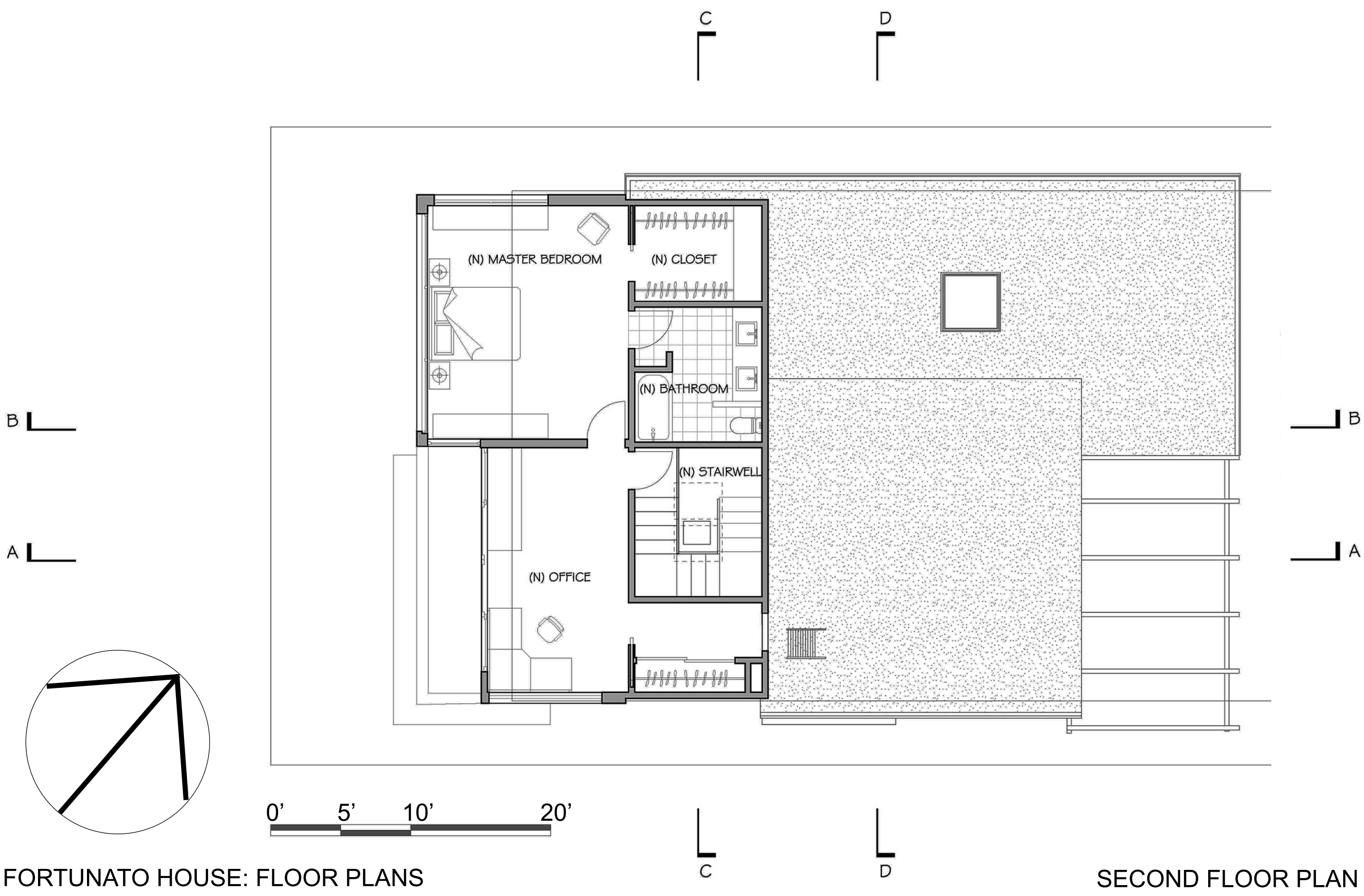
FIRST FLOOR PLAN



GROUND FLOOR PLAN



ROOF PLAN



FORTUNATO HOUSE: FLOOR PLANS

SECOND FLOOR PLAN

In addition, the owners decided to set a general goal for the cost of this "deep green" house, namely that by using available "off-the-shelf" techniques and building technologies, the desired project outcomes could be realized at the same or less cost than a "standard house". This cost would be measured in all aspects of specific *sustainability* features employed to construct the new 2,150 sq. ft. renovation/addition, including the re-use of a portion of the 1,320 sq. ft. existing structure.[2]

Finally, this project is somewhat unusual since the owners decided to act as both project designers and general contractor for the execution of the design ideas. This permitted full engagement with these ideas and resolution of their application in the physical construction of the house. While the design and execution were directed essentially by the owners, engineers and construction professionals were consulted on various aspects of the project.

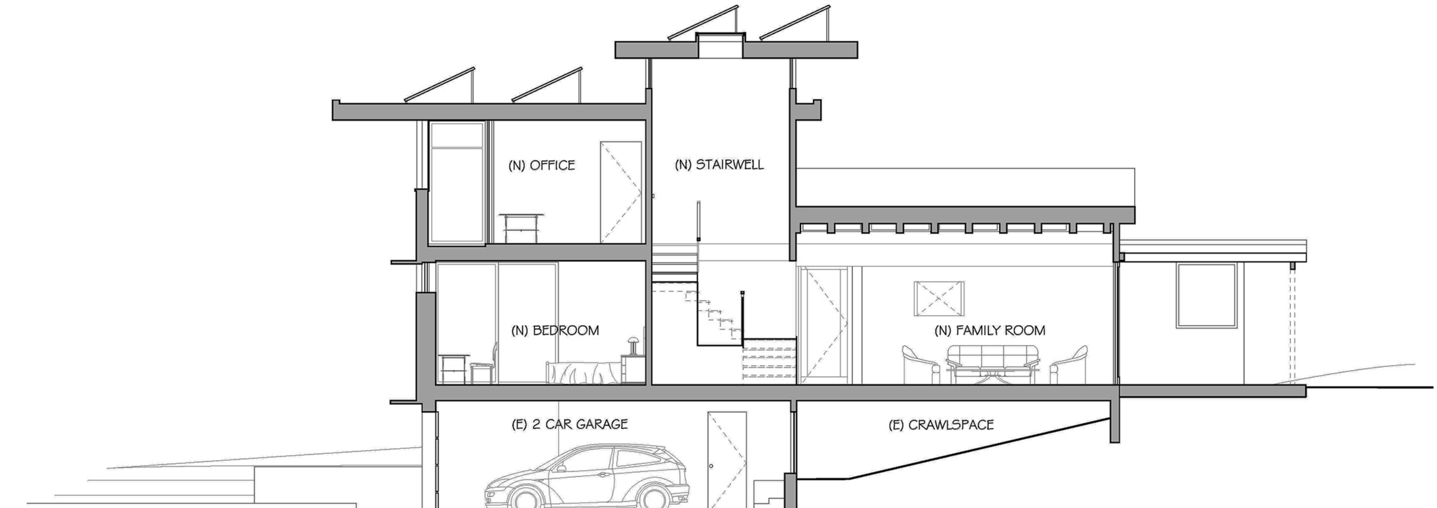
Project Process

Building Program

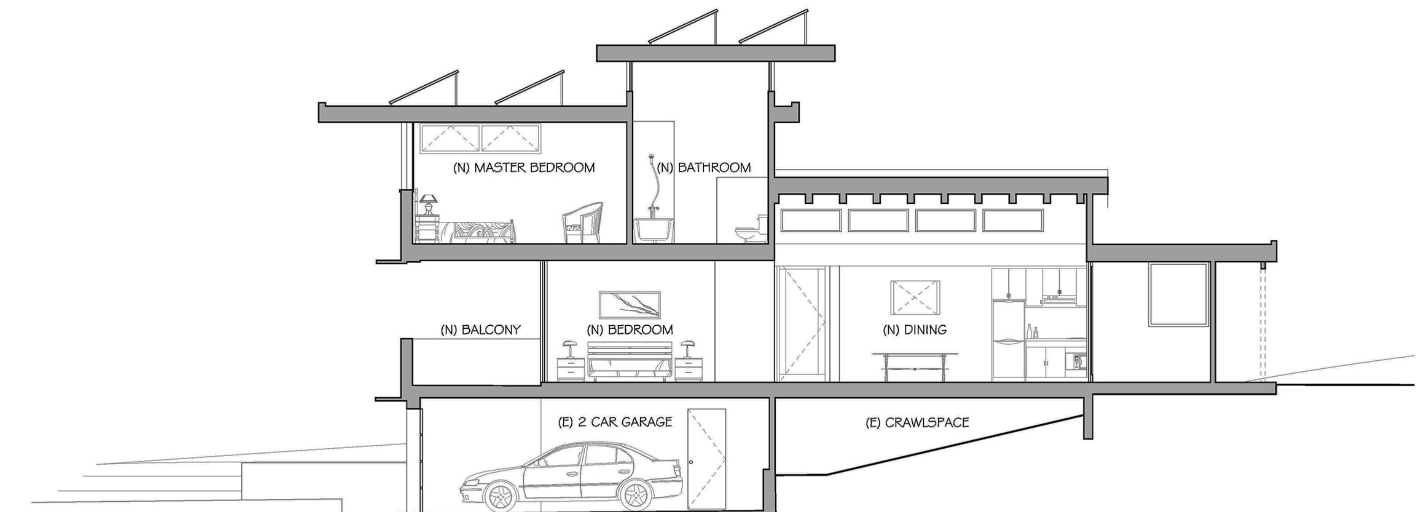
The renovation basically consisted of the addition of a new 830 sq. ft. floor level to the two-story existing house and extensive work on this existing structure. This added a new master bedroom suite and an office at this upper level, while the main level was reorganized into two bedrooms with a shared deck, a bathroom/laundry and a main living space adjacent to the rear garden area. (See the floor plans and building sections.)

[2] As it turned out, only the rough framing and foundation of the existing house were reused in the new structure. Nevertheless, this cost saving plus the downsizing of the energy systems through design resulted in an approximate cost for the renovation of $200/sq. ft. Some rebates and tax deductions are also included in this cost reduction, although these did not contribute significantly to the overall savings. This net cost of construction compared well with the cost of construction at the time for "standard" new houses in the same area of $250/sq. ft. and higher.

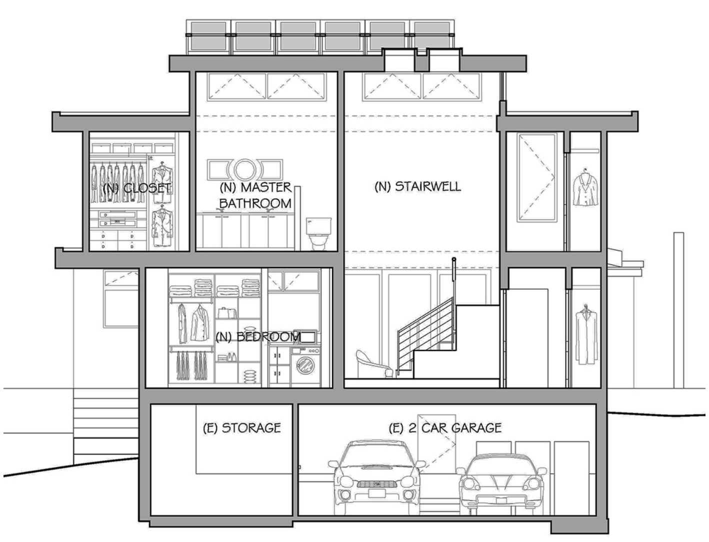
(Right) View of final "deconstructed" original house, with some rough framing and foundations from the rear half of the 1959 house salvaged for the new structure. The west half of the new house would be mostly new construction.

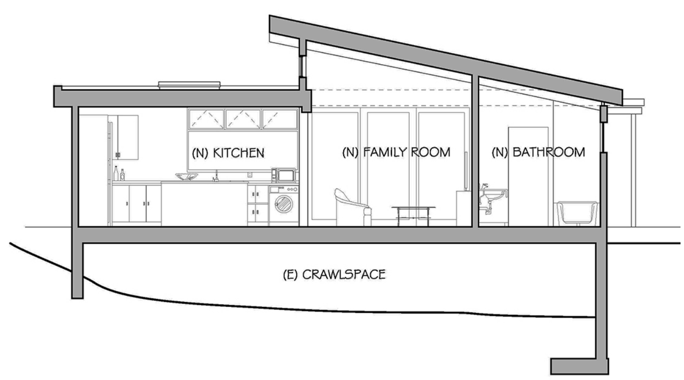


SECTION A



SECTION B





SECTION C

SECTION D

(Opposite Page) Rear view of the newly renovated house, facing east.

Site Constraints

The site slopes from the rear of the lot toward the street level at the front, dropping a full story in height across the length of the property. The orientation of this sloping site is toward the southwest, which is the general direction of views to the ocean. This led to the planning decision to cluster the spaces of the new addition at that end of the house, which faces the street and coincidentally is exposed to the afternoon sun. The spaces naturally were given large window areas on that façade to maximize the view opportunity. The lower angle sun in the afternoon then became an important design consideration with regard to solar heat gain and glare in the afternoon.

The solar PV system had similar constraints because of site orientation. The southwest-facing panels were less productive in the winter months but had an advantage in summer months when the weather pattern in this marine location provides more available solar exposure in the afternoon.

Two palm trees located along the southeast property line abutting the neighboring lot were not a significant shading issue because the shadows were cast on the rear of the site and building by midday. The location of the new spaces with its high flat roof where the solar PV panels would be installed thus also minimized the potential effect of these trees.

Low Energy Design Strategies

General Design Considerations

Site constraints and the building program (how much additional space was needed) dictated some of the basic design considerations, as discussed above. Additional ideas resulted from the owners' initial research and discussions with several professionals, as well as from various site visits to local *green* homes. They also adopted some design guidelines that would inform their choices as they proceeded: (1) select solutions that involved materials and "off-the-shelf" technologies to demonstrate that ZNE homes were affordable and realistic for middle-class families; (2) choose no system that utilizes natural gas in order to guarantee a "net zero carbon" house without any "carbon offsets".

Building Envelope – Insulation and Windows

The existing structure, which was to be reused, was built using standard 2X4 framing spaced at 16" on-center. For cost reasons, this framing system was used for the additional floor level also, with a modification of the wood stud spacing to a wider dimension of 24". This was structurally equivalent (and allowed by the state building code exception for *Advanced Framing*). In addition, two layers of half-inch thick "insulated sheathing"[3] board was installed over the exterior side of the wood studs. This wider spacing allowed for a higher overall insulation value and air-tightness for the wall assembly.

The "insulated sheathing" board also mitigated heat loss via thermal bridging through the wood studs by providing a continuous layer of material with an R-value equal to 2.6. (There are additional environmental advantages of the product, including absence of formaldehyde found in plywood glues and reduction of noise transmission through the exterior building walls.) The net result was an economical system of structural framing that also had good environmental performance characteristics.

[3] There are several types of insulated sheathing products with different material properties. See *Guide to Insulated Sheathing*, Building Science Corporation (January, 2007), www.building-science.com.

PHOTO: ETHAN PINES

PHOTO: ETHAN PINES

(Opposite page) The central space containing the connecting stair acts as a “thermal chimney”, providing passive ventilation and free cooling of the house at all times.

The building’s new flat roof joist space is filled completely with fiberglass insulation and the slight roof slope for rainwater drainage is created by a tapered polystyrene insulation layer. The result is a total average R-value equal to 32 for the roof assembly. The owners also selected a reflective single-ply membrane roof material that is recyclable at the end of its natural life.

The floor structure of the main level is also well-insulated since it is above the garage space and a large sloping crawl space. The owners decided that they could reduce heat loss through that floor further by controlling outside air leakage in these lower-level unconditioned spaces, so they sealed them and installed a low power fan to ventilate the crawl space minimally to prevent moisture development there. The result was a type of “thermal buffer zone” there.

High performance double-glazed window units were installed per code. The primary orientation of the largest area of glazing is toward the views to the southwest and west, requiring close attention to the design of sun control on that façade. Deep overhangs were created above those windows, which provided shading of the glass during the hottest part of the day in the summer.

Building Envelope – Air Tightness

As in the previous case study, the owners recognized the importance of air-tightness to the low-energy performance of the house. When the house had been structurally framed, with the insulated sheathing and windows installed and sealed, but before the insulation and interior finishes were applied, the house was subjected to a *Blower Test*[4]. Air leakage points in the building envelope were identified and sealed.

When the final test was performed after the corrections were made, the house measured 1.12 ACH50, an exceptional level of air-tightness. This compares with the Passive House[5] standard of 0.6 ACH50 and the California energy standard of 5.0 ACH50. (See the table for benchmarks of air tightness on p.12 of Case Study No. 1, “Corona del Mar New Houses”.)

(Above) Meter reading of final *Blower Door* test showing 376 cu. ft. per minute at the blower door fan with 50 pascals of pressure in the house, converting to 1.12 air changes per hour (1.12 ACH50).

Natural Ventilation

Natural ventilation is induced on warm and pleasant days by the central stairwell that had to be added for access to the new upper level of living spaces. Extra height was added to this central space, which takes advantage of the natural buoyancy of air to induce air flow from window openings on both living levels to the openable clerestory windows at the top of tall space. Like the case study house at 703 Heliotrope (see Case Study No. 1), this “thermal chimney” design feature provides a natural cooling option with no use of electric energy.

Because the building envelope is well-sealed and constructed with the insulated sheathing board, which also acts as a sound barrier, the natural ventilation “mode of operation” (with open windows) is noticeable because of the difference in the interior acoustic environment. The owners find it acceptable for them at this site location, unlike with the case study house at 703 Heliotrope (see Case Study No. 1).

Because of the air-tightness of the construction, indoor air quality (IAQ) is an important factor to consider. There can be a build-up of toxins and chemicals in the air if there is not adequate outdoor air flow that effectively removes them. One option, standard in a Passive House, is to include a separate system for fresh air supply such as an HRV (heat-recovery ventilator) or ERV

[4] See this volume, “Case Study No. 1-Corona del Mar New Houses”, p. 12, for a description and benchmarks of air-tightness in houses. See also https://www.energy.gov/energysaver/blower-door-tests.
[5] http://www.phius.org/what-is-passive-building

(Opposite page, top) Interior view, Second Floor at Office, showing deep overhang shading large glass areas for view and daylight.
(Opposite page, bottom) Interior view, First Floor at Family Room.

(energy-recovery ventilator)[6]. Although ideal in terms on automatic control of minimal required flow of fresh outdoor air, this system requires some ductwork for the air distribution.

Instead, for this case study house, the owners first made an effort to determine potential sources of such unhealthy chemicals, both in the construction materials and household products, and to eliminate them. The thermal chimney, as well as kitchen and bathroom ventilation fans, remove any remaining unhealthy air contaminants, moisture and cooking odors. Continuous air movement through the rooms of the house is accomplished by having the operable windows at the top of the thermal chimney (central stairwell) slightly open at all times of the year. As a result, there is minimal but steady air flow induced in all the rooms via this natural ventilation mechanism. Given the care in eliminating the sources of air contaminants, the owners did not feel that it was necessary to incur the cost of the more elaborate HRV system. No sensoring system is installed, however.

Heating, Ventilating and Cooling Systems

An air-source electric heat pump integrated with an 80 gallon water storage tank was selected as the basis of the design for heating because of its inherent efficiency, a choice that works well in some renovation projects. The heat transfer medium is heated water, which can be easier to integrate with an existing structure than air ducts and is a more energy efficient medium because it does not involve energy-consuming fans or duct losses. The hot water is piped through manifolds that are controlled by thermostats in each room; it is then delivered to the room's hydronic baseboard units.

The heat pump's normal cooling capability is not used because of the house's efficient design and the relatively benign marine climate.

Domestic Hot Water

The domestic hot water (DHW) is provided by a separate 50-gallon electric heat pump water heater. In addition, a *drain water heat recovery unit* is installed at each of the shower drain lines, which captures some of the heat energy from the draining water as it is piped to the exiting greywater line. Each cold line from the water main to the showers is first run to the *drain water heat recovery unit* before going to the shower mixing valve. This essentially provides preheating of the input water and reduces the amount of hot water needed.

The system design also uses a recirculating pump at the sinks in the kitchen and upstairs bathroom, which are the longest runs for the hot water piping. (Originally, this was occupancy-sensor-driven—see Post-Occupancy section.) These pumps save water and energy by using the cold water line as a return pipe to the hot water tank until the water in the hot water line reaches high temperature. (This can be a considerable amount of time because of the distance from the hot water tank.) This is in contrast to the normal situation where the water from the hot water tap goes down the drain while the water at the sink gets hot enough to use.

Lighting

The owners have replaced many of the original compact fluorescent lamps with LED sources in the past few years, which has had a beneficial effect in lowering energy used for lighting. In addition, glare-free daylight from well-shaded, large window areas, as well as daylight penetration in the middle of the house provided by the central stair space, create a sense of balanced daylight and openness throughout the house. As a result, use of the electric light sources is largely unnecessary on most days.

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[6] See M. Holladay, "HRV or ERV?", Green Building Advisor (January 2010), www.greenbuildingadvisor.com. The HRV provides reassurance of consistent high quality IAQ without undue air leakage. The tradeoff is the introduction of a low-wattage fan that operates continuously.


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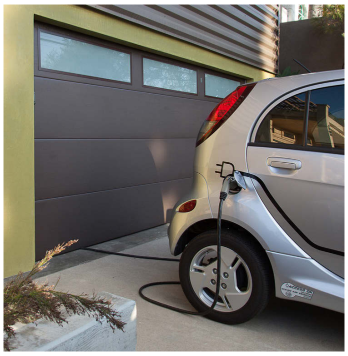

(Above) Electric vehicle charging.

Plug Load and Equipment

Most of the home appliances are *Energy Star*[7]—refrigerator, dishwasher and washer-dryer. Cooking is done in either the speed cook oven or on the induction cooktop[8].

There are two electric vehicles that must have access to electric charging capability in this garage for overnight charging, a significant electric equipment load that is added to the overall energy use of the house. Even with this added regular load, the meters recorded an annual performance of zero net energy for the house plus the two cars, indicating a remarkable "right-sizing" of the solar PV system.

Control Systems

The owners opted to have all controls and systems operated manually, aside from thermostats associated with the baseboard heating units and *vacancy switches* in the bathrooms. (The vacancy switches turn off lights or fans if no motion is detected in those rooms.) This is worth noting because of the many "smart" systems now available, including remote controls using mobile phone apps.

Overall Evaluation of Design Strategies

There are a number of non-profit building industry organizations that promote *green building* practices through their programs of education, benchmarking and recognition of successful sustainable building designs. The common method of recognizing best practices is a point-based rating system for sustainable design strategies and features that are employed. This is typically a point-system, where points are awarded per feature or degree of performance. A total point score determines a "Rating" for the building, allowing comparisons and standards to be applied.

For residential buildings, *Build It Green*™ offers and maintains such a rating system for the building industry and governments within California, known as *GreenPoint Rated*. Point categories include energy efficiency, water conservation, indoor air quality, resource conservation and community. Points are determined by an independent third party GreenPoint Rater. For new houses, the complete range of point totals is typically 50 to 140.

The Fortunato House was evaluated by a GreenPoint Rater and was scored at 162 points, well above the usual maximum. Were it considered a new house, it would merit a "Platinum" rating on the New Home scale. It is also certified as ZNE by the International Living Futures Institute.

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[7] See *About ENERGY STAR*, https://www.energystar.gov/about

[8] Induction cooking is a magnetically induced heating method for cooking as opposed to direct electric coils or gas burners. Of the three types, the electric coil is generally regarded as the least energy efficient, the poorest method for cooking because of its relatively slow response to controls and the least safe from casual burns. Gas burners have quick response to controls—their advantage over electric coils—but are a source of toxic chemical by-products and still have a serious burn risk. Induction cooking has all of the advantages of gas cooking, including the degree of control for cooking, is toxin- and carbon-free and the "burner" never feels hot to the touch. (Cookware must have ferrous content—stainless steel or cast iron, but not pure aluminum.)

Use of induction cooking, like the microwave oven when it first appeared, is a technological invention that must achieve a familiarity and an acceptance level among homeowners (and chefs). But it is the recommended choice for ZNE and ZNC homes. See the following article for a technical comparison of cooktop alternatives:
(1) http://ovens.reviewed.com/features/induction-101-better-cooking-through-science;
(2) https://www.consumerreports.org/electric-induction-ranges/pros-and-cons-of-induction-cooktops-and-ranges/

Renewable On-Site Energy Supply

The on-site solar PV system consists of twenty-six 250-watt panels made by SolarWorld, a U.S.-based company, for a total power production rating of 6.5kW (DC).

Even for a modestly-sized house, this is a not a large system for a house that is performing at ZNE, especially with two electric cars adding to the overall electric load. In fact, before the acquisition of the electric vehicles, the house was significantly net positive in its performance. It is a testament to the high energy efficiency of the design and operation of the house that the PV system can be so small and the performance is still ZNE.

(Below) Rooftop solar PV arrays, with clerestory windows beyond that are at the top of central stairwell space.

Energy Performance

Post-Occupancy Measurement

Energy Use—Monitoring and Measurement

In 2016, the owners arranged for meters to be installed to record separately the energy use and the energy production by the solar PV system. A full year of data was recorded for the period 4/2016-3/2017. The house plus two electric vehicles (EVs) used 10,466 kWh in that period, which was confirmed by SCE's net meter total. A reasonable estimate of the annual electric energy used to charge the EVs was done based on recorded miles driven for this period and a "mileage" rate of 3 miles per kWh. This estimate was 3,118 kWh, which gives a (non-metered) total energy use for the house alone of 7,350 kWh. This translates to an EUI of 11.7 kBtu/sq.ft.

The total energy use by month (house plus cars) is given in the performance chart below. The data includes monthly energy use to charge two electric vehicles since this category of energy use was not separately metered or estimated.

Energy Production versus Energy Use: Zero Net Energy Performance

The charts on the opposite page show the relative solar PV system performance over the course of that one year, (4/2016-3/2017). The chart of solar production compared to metered energy use of house plus cars shows the balance between the excess energy use in the winter months with the excess energy production in the summer.

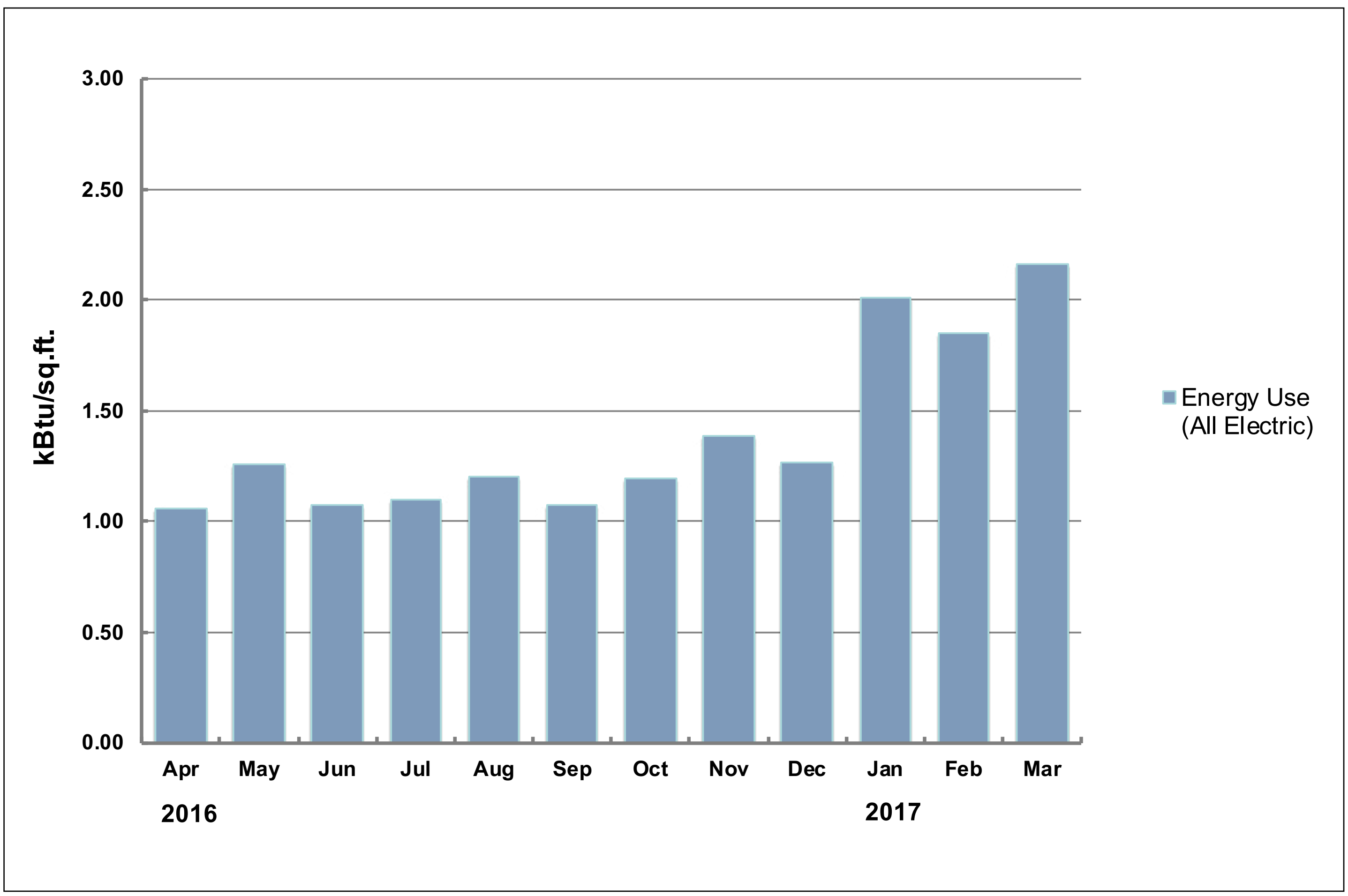
The precise balance is indicated in the chart giving the *cumulative net energy production*. This chart shows the progression of the energy performance toward ZNE by adding each month's net energy performance to the previous month's total. If, at the end of the year, the curve remains on the positive side of the zero axis, then the building is indeed performing at ZNE. For this case study house plus the two EVs, the curve essentially reaches precisely the "net zero" mark at the end of one year, a near perfect outcome showing a match of design, operation and weather.

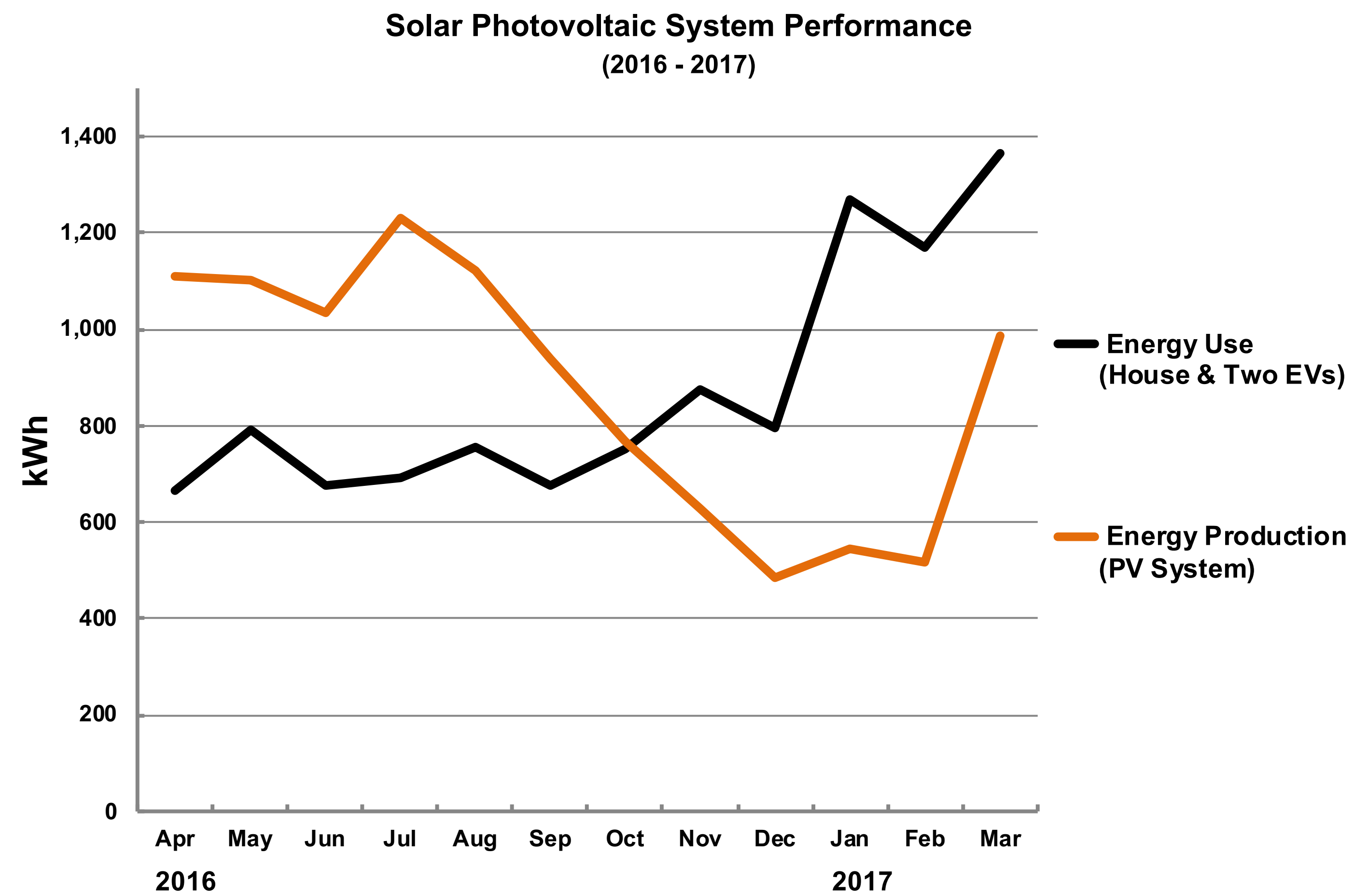
Measured Energy Use

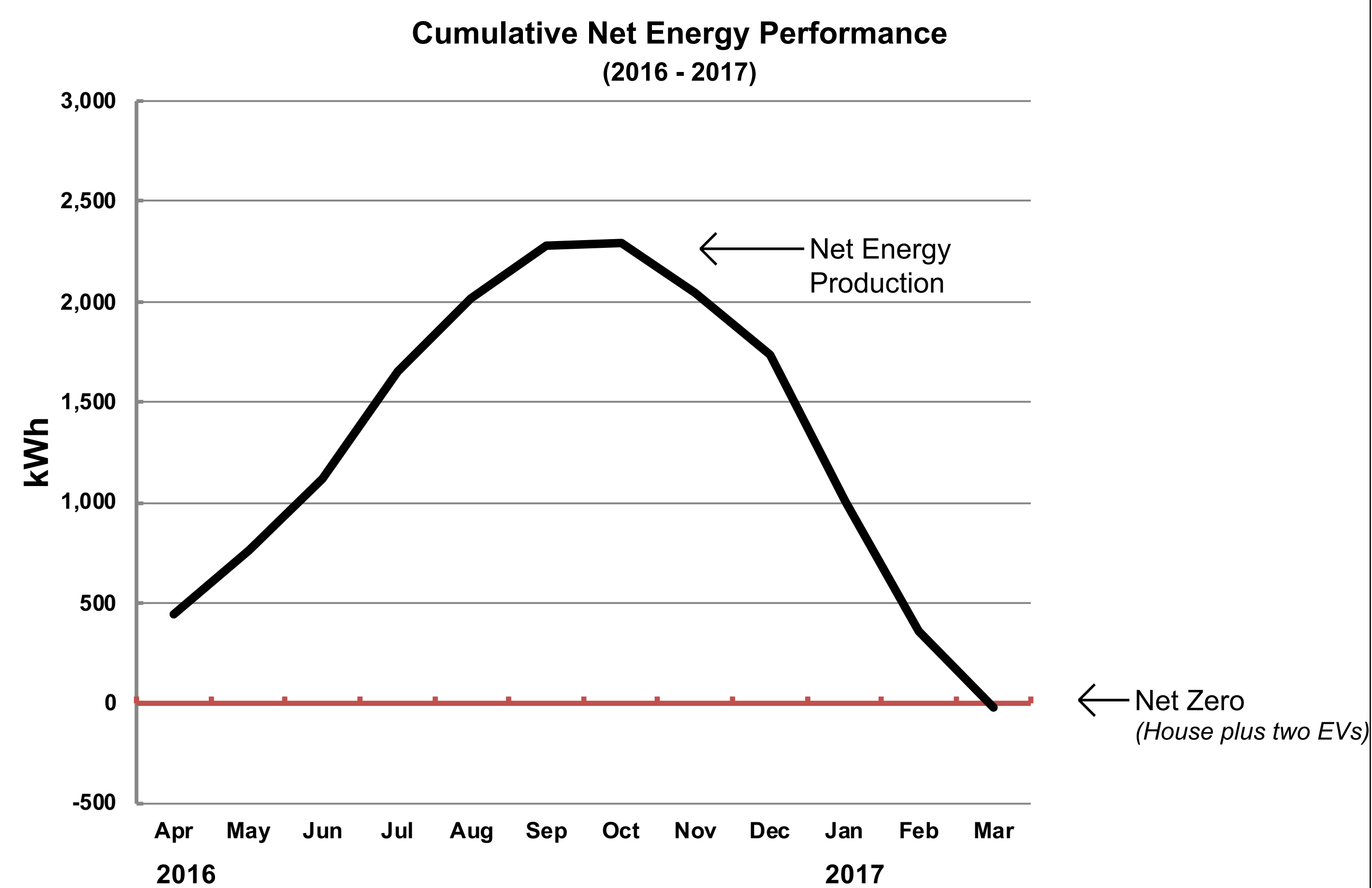
(2016 - 2017)

7,350 kWh/year
Measured EUI* = 11.7

*house only—deducts estimated annual energy use for charging EVs from metered total.




Solar Photovoltaic System Performance
(2016 - 2017)
kWh
1,400
1,200
1,000
800
600
400
200
0
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
2016
2017
Energy Use
(House & Two EVs)
Energy Production
(PV System)


Cumulative Net Energy Performance
(2016 - 2017)
kWh
3,000
2,500
2,000
1,500
1,000
500
0
-500
Net Energy
Production
Net Zero
(House plus two EVs)
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
2016
2017

Post Occupancy: Observations and Conclusions

This case study house is unusual because of the degree of involvement by the owners in all aspect of the design and construction. It is a process that is not easily transferable to other similar projects, but the ideas are sound and the outcome achieved their goal of a ZNE home that actually cost them less than a comparable "standard" structure.

Post Occupancy: Construction and Air-tightness Issues

The methods used by the owners to achieve a high degree of air-tightness in the building are described above. During construction, the owners evaluated products for low or no *volatile organic compounds* (VOCs)[9]. An adhesive recommended by the framer had apparently sufficiently low VOC levels, but the actual smell when applied suggested a closer examination of other chemical content disclosed as required on the label. The solvents used were in fact potentially hazardous, according to the label. As a result, an alternative was found with a lower level of VOC content and without the harmful solvents. The result of this experience was a determination to examine all product labels closely for all chemicals of concern.

While this scrutiny is important, there is some experience that product manufacturers sometimes do not receive accurate chemical component information from third-party suppliers, so it is possible for label information to be incomplete or inaccurate. It is recommended that every type of product where there may be a question concerning chemical components be specified as requiring an *HPD* (Health Product Declaration)[10]. To prepare an HPD, the certifier needs to obtain information from the product manufacturer's supply chain. Thus, the HPD effectively guarantees that the all the product information is correctly listed.

A backup solution, especially for houses that are of air-tight construction as measured by a Blower Test at 5.0 ACH50 or less, is to employ a very low power exhaust fan or an HRV/ERV system to provide constant minimal air changes of outside air. Such a system will reduce the risk that the resulting indoor air is sufficiently diluted of potentially harmful levels of chemical and toxin content. There are now also affordable indoor air quality sensing and reporting devices now available for home use that assist in monitoring indoor air quality levels.

Post Occupancy: Building Envelope

The skylights at the top of the central stairwell are not equipped with automatic integral shades, available on many manufactured units. The amount of solar heat gain through the skylights is significant in summer, and the owners report an overheating of the space even when the clerestory windows are open.

Some skylight models with integral shades utilize built-in sunlight sensors that automatically draw the shade, which still admits a certain amount of daylight while protecting against solar heat gain. These models provide better control and work well in California climates.

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[9] VOCs are gaseous chemicals, some of which have been shown to have adverse health effects. See https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality. See also California Department of Public Health: https://www.cdph.ca.gov/Programs/CCDPHP/DEODC/EHLB/IAQ/Pages/VOC.aspx

[10] See *Health Product Declaration Collaborative*: https://www.hpd-collaborative.org/.

PHOTO: ETHAN PINES

CASE STUDY NO. 3

Oak Haven Modular House


PHOTO: LAWRENCE ANDERSON

Oak Haven Modular House

Case Study No. 3

Data Summary

Building Type: Single-family
Location: Ojai, CA
Occupied: 2012

Project Name: Oak Haven

Number of Houses/Units: 22

Representative ZNE House:

Lot 18 - 1885 Maricopa Hwy

Gross Floor Area: 1,152 gsf

On-Site Renewable Energy System Installed: 2.0 kW DC

Measured On-Site Energy Production: 2,939 kWh/year (2016-17)

Measured EUI (Site): 18.6 kBtu/sf-year (2016-17)

Developer

Modular Lifestyles, Irvine, CA

Project Team

Designer: Steve Lefler, Modular Lifestyles

Modular Home Builder (Factory): Cavco Industries, Phoenix, AZ

On-Site Contractor: Cirus Development, Irvine, CA

Property Management: Newport Pacific Capital, Irvine, CA

Another generic type of residential construction is *factory-built housing*. What distinguishes this category of housing is that most of the components of the house are assembled in a factory rather than on the parcel of land where it will reside. There are some important distinctions in relation to building codes, energy standards, permits and regulations, which are discussed below, but there are also low-energy design strategies and opportunities that differ from conventional methods of housing construction.

This case study is intended to illustrate these differences while at the same time showing the special capabilities of this type of product for ZNE performance compared with standard site-built housing.

General Background: Factory-Built Housing

The ZNE Potential of Factory-Built Housing

It seems logical that houses, at least from the foundation upward, should benefit from being built in the controlled environments of factories just like cars, airplanes and furniture. To a large extent, this has been true in industrialized parts of the world since the early 20th century: Sweden, Germany and other northern European countries have developed a strong industry of factory-built houses that parallels their automobile industries in relative product quality and design.

In Sweden, for example, 85% of the housing is factory-built, which has been the same consistently high share of the market for decades. One of the reasons for this high percentage is the climate, where rapid construction time is valuable and favors the remarkably quick erection time of factory-built components. The result of this cold climate has also been the development of highly energy-efficient houses as a standard. Thirty years ago, Swedish factory-built houses were approaching current Passive House standards—super-insulation, airtight construction and even heat recovery ventilators (HRVs) to maintain indoor air quality in these high-precision products.

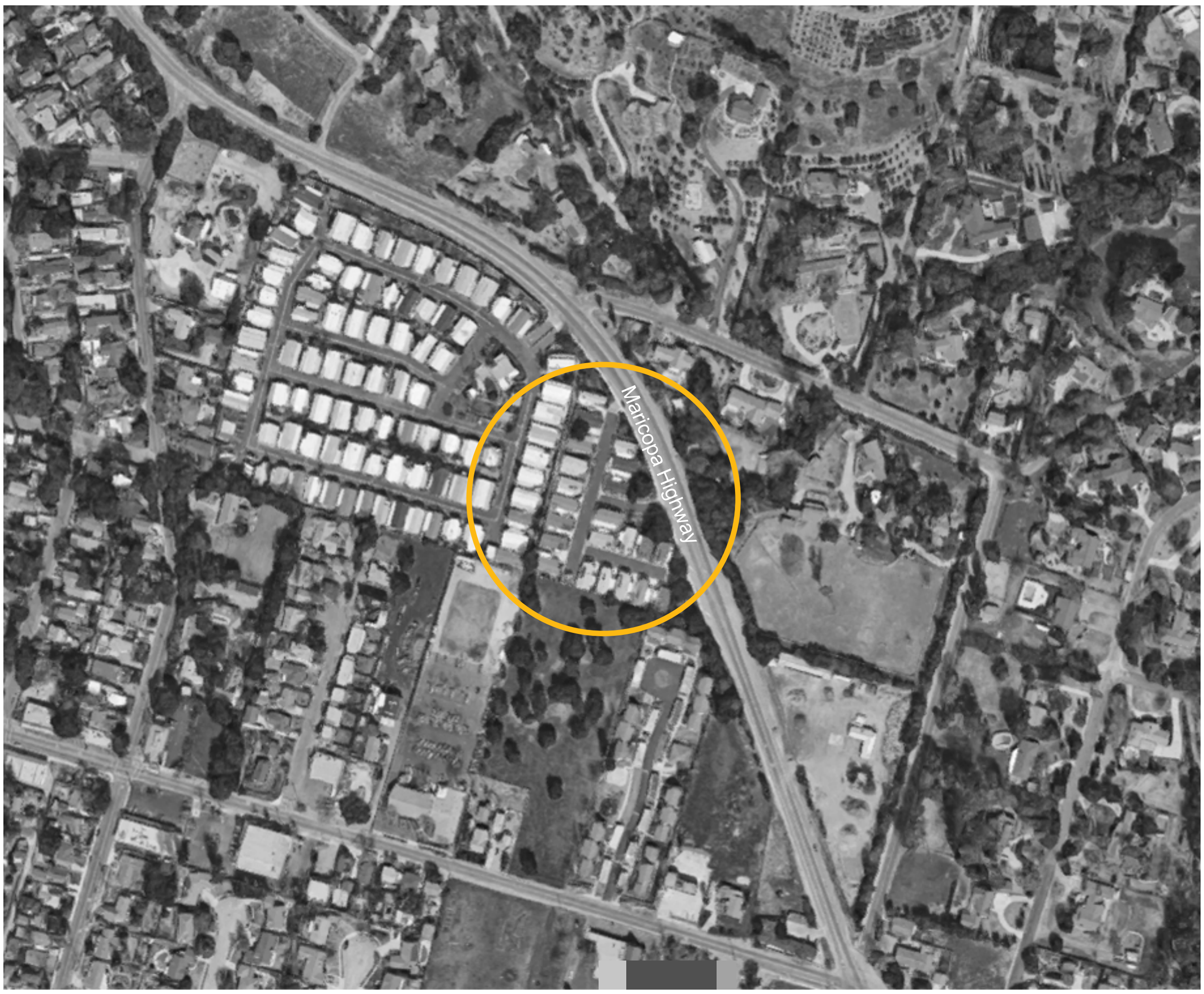
There has always been the potential—realized in these other countries—for producing all these energy-efficient characteristics at lower cost, less intensive labor methods and much less on-site construction time by utilizing a factory-built approach. Adding solar PV systems to such houses is another potential path to the development and growth of one type of robust ZNE housing sector—one that is affordable and of consistent high quality construction.

Factory-Built Housing in the United States—A Historical Anomaly

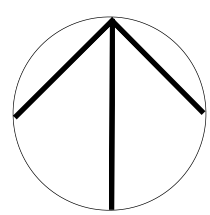
By contrast with the Swedish factory-built housing industry, United States factory-built housing is only 2%-3% of all new housing built in this country in recent years[1]. This small share has also remained consistent throughout the last few decades. Given the great potential across all categories (consistent product quality, cost, time), including ZNE performance, what has historically held back the widespread adoption of factory-built housing in the United States and what are the prospects for change?

The history of factory-built housing In the United States in the first half of the 20th century matched that of the rest of the industrialized world and has been well documented[2,3]. At mid-century and partly as the result of World War II, the need for housing spiked everywhere and the interest in factory-produced housing grew in the industrialized countries. While Sweden developed its

[1] https://www.census.gov/construction/chars/pdf/conmethod.pdf
[2] Burnham Kelly, *The Prefabrication of Houses*, The Technology Press of MIT and John Wiley and Sons, Inc., New York (1951).
[3] http://www.searsarchives.com/homes/



Oak Haven: General Vicinity Plan



factory-built housing industry as the result of the central government's ambitious *Million Homes Programme*, private ventures were undertaken in the United States in a more limited way.

The home-building industry in this country has always been greatly decentralized, characterized primarily by small independent developers and contractors, strong labor unions in the various building trades and large numbers of independent local government agencies with jurisdiction over construction. Combined with temperate climates and a relatively long building season, strong reasons to turn to factory-built housing were not apparent. Contributing to these negative factors was the early experience of post-war factory-built homes as primarily trailers and mobile homes, which created a negative impression about design and general construction quality. This poor-quality stigma still persists in this country, especially in the market of mass-produced houses in the suburban setting.

The result since the mid-20th century has been resistance to the use of factory-built housing in the place of the overwhelmingly-favored site-built ("stick-built") approach.

Recently, however, there has been resurgent interest in the advantages offered by factory-built housing, driven primarily by cost escalation and disappearing affordability of housing (especially in California) and the interest in low-energy (and ZNE) performance. This case study is a description of one such approach that produced a housing product that succeeded in delivering both affordability and ZNE performance.

General Background: Definitions

Before describing this project, however, it is important to address nomenclature that evolved in this post-war period and which affects both the perception of factory-built housing and the regulation process that has such an important effect on it.

Site-Built Housing

On-site construction, primarily the type commonly called "stick-built", is the standard method of construction in the United States, used in almost all housing. Each house is assembled on-site, piece-by-piece, using multiple trade sub-contractors. The local city or county government agency issues a building permit based on a unique set of construction documents and sends building inspectors to the site on a periodic basis for review and sign-off.

"Manufactured Home"

Until 1976, this type of housing was known as a *Mobile Home*. The mobile home was built on a non-removable steel frame, known as a chassis, which was used for transporting the home and was an integral part of the structure. These types of *manufactured homes* were typically limited in width to the size of a traffic lane since they were transported via highway. They were often placed on foundations and formed the structures seen in a typical trailer park. Historically, they came to represent the public perception of factory-built housing in the U.S.: generally inferior design quality and impermanent.

In 1976, the federal government adopted regulations of these *manufactured homes* due to concerns about safety, which became embodied in a building code under the U. S. Department of Housing and Urban Development—usually called "the HUD Code". The manufactured home is not subject to local building codes, but only to the national HUD Code. A structural foundation is now required by the HUD code (thus the home is no longer called "mobile").

"Modular Home"

A *modular home*[4] Is the general name for a factory-built house, which can be pre-assembled at a factory either as a panelized system (walls, floor panels, roof panels, trusses, etc.) or as whole modules. Both types of modular house systems can be transported by truck to the site where a foundation has been prepared and then joined together to create the whole house. (Swedish factories produce panelized houses based on a customer-selected design from a catalogue.) The modular home is the type of factory-built housing that has such great potential for ZNE performance.

The modular home is typically of much higher quality than a manufactured home and, because the factory-built components are assembled on site, there is no size limitation. In fact, it is usually the case that the appearance of a modular home is indistinguishable from that of a "stick-built" home when finished.

Modular homes are different than site-built homes, however, in terms of the approach to regulation. Because the components are built into the panels or modules in the factory, the usual procedure of having the local building department carry out plan review and approval, as well as inspection of the in-process assembly, cannot be carried out. Therefore, the California Department of Housing and Community Development (HCD) assumes responsibility for the approval process at the state level. The local agencies are still responsible for planning/zoning review and the foundation construction.

HCD reviews the design and construction of the specific modular home design at the factory for state building code compliance and, in particular, California Title-24 energy standards. When completed, an HCD-approved label for that model of modular home can be attached to every identical house that is shipped from the factory. There is an advantage with the state agency having jurisdiction since the design and construction of a modular home then is uniform throughout the state and not subject to the possible variable requirements of local building departments.

Specific Background: The Case Study of a Factory-Built Housing Project

There is currently housing construction activity in this sector of the housing production industry in California, namely *modular housing*, primarily by developers who partner with modular housing factories. A subset of these developers has been specializing in very-low-energy and *ZNE-Ready*[5] houses. This case study is a description of one of these housing developments and of a representative house within this development, with a performance analysis of this individual structure.

A New Idea—The Zero-Net-Energy Factory-Built House

The idea of using the model of the energy-efficient Scandinavian factory-built house and adapting the techniques to the United States modular housing industry has been tried intermittently over the past several decades. With the advent of the *zero-energy* house and the marketing

[4] *Prefabricated house*, or "Prefab Home", is often used interchangeably with *modular home* or to refer to only *panelized modular homes*, but to avoid confusion we will use only the term, "modular home" to signify this type of factory-built housing.
[5] https://www.energy.gov/eere/buildings/zero-energy-ready-home.
In addition, see http://www.energysoft.com. for California-certified energy compliance software (EnergyPro) that allows demonstration that a residential building meets the ZNE definition that the California Energy Commission describes in the CF1R document.


Maricopa Highway
Lot 18
OAK HAVEN RESIDENTIAL DEVELOPMENT


Lot 18

(Opposite page, top) Overhead view of the Oak Haven Residential Development in Ojai, with the ZNE house on Lot 18 indicated. *(Opposite page, bottom)* Oblique aerial view of the same, under construction. (Photo courtesy of Modular Lifestyles.)

cachet associated with that term, more developers have brought such projects to market working with the available U.S. production framework of modular house factories.

The approach is to apply the proven ZNE design and engineering strategies for residential structures to the factory-built houses and to take advantage of the factory environment to provide quality control, tight tolerances, testing and inspection and consistency of production, thus assuring the ultimate ZNE performance.

Project Process

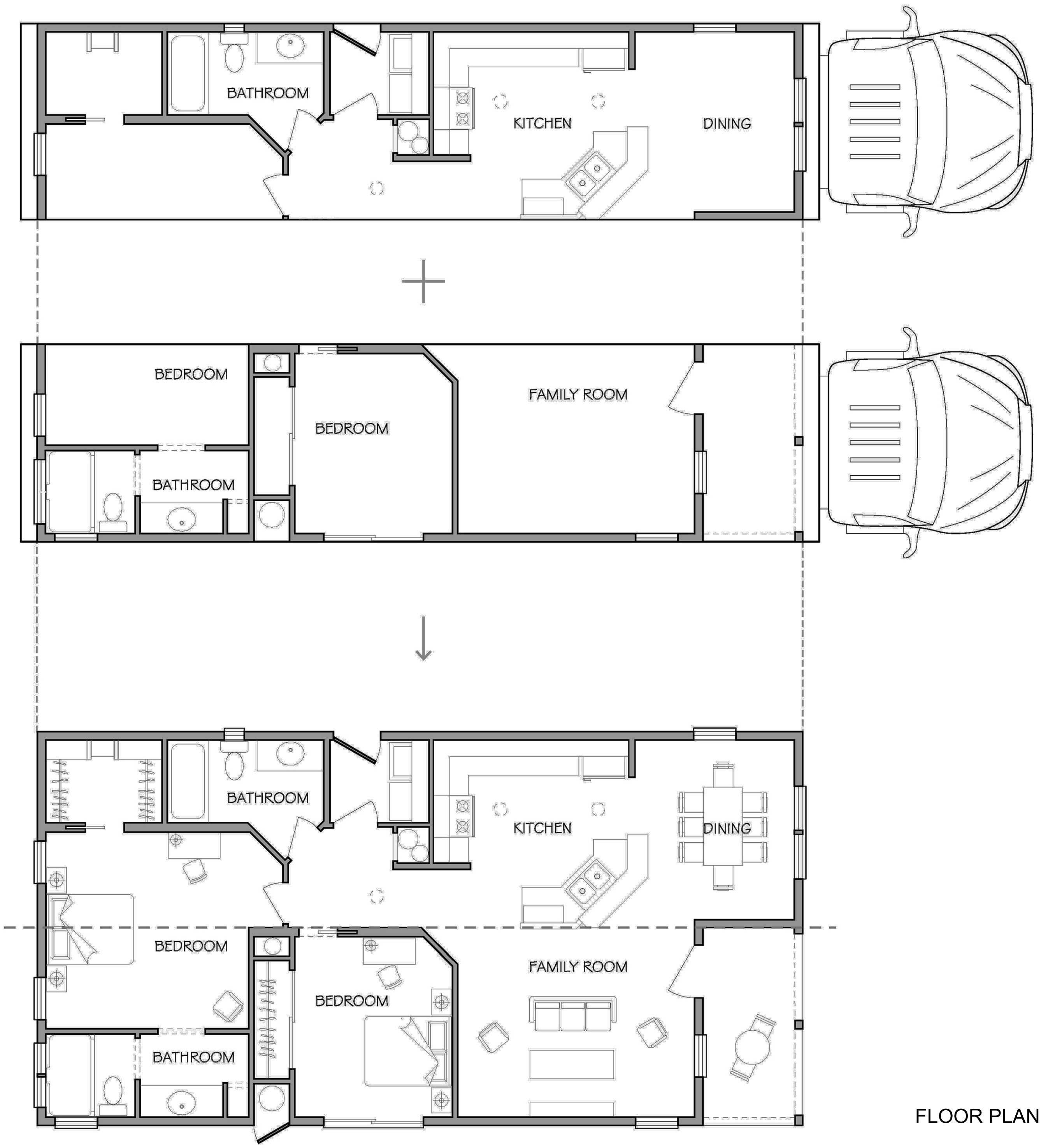
The developer for this case study project contracted with a factory located in Phoenix, Arizona, to produce modular house designs to the developer's ZNE-features specification and a construction company in California to build the foundation, assemble the house components on site and connect the utilities. In this case, the modular houses were assembled from whole modules rather than flat panels.

The 22-lot housing development in Ojai known as Oak Haven offered "Modular Net Zero Green Homes" to potential buyers in 2009. Each house was customized with additional features, such as a deck or porch, as well as a particular "style" as defined by exterior finish, decorative elements and roof shape. A potential buyer ordered the preferred design using images provided by the developer or based on the model home initially constructed on the larger site. In this approach, the project was not unlike a conventional single-family housing development in its final appearance, but the intrinsic differences were that this project used factory-built modules of high construction quality and it incorporated advanced design techniques that could provide a ZNE performance.

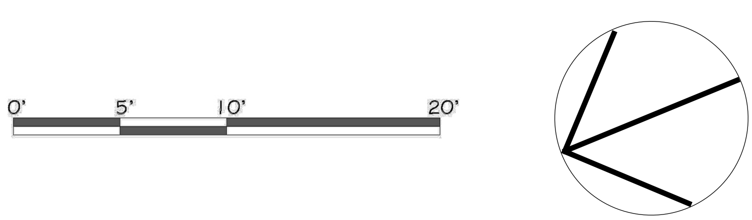
The representative house in Oak Haven is the house on Lot 18, 1885 Maricopa Highway, which was purchased by a retiree attracted by the development's *green* house construction with ZNE performance capability. After the buyer selected the preferred floor plan and a "Santa Fe" style, the developer ordered the house from the Arizona factory, specifying the ZNE features (described below). The foundations were built on Lot 18 and the two house modules were delivered to the site in a matter of weeks, where they were lifted into place by a crane and tied together in the same day. Finish features and the solar PV system were then added to complete the construction of the house.

(Below) Ground level view of part of the Oak Haven Residential Development with initial installations of solar PV systems.

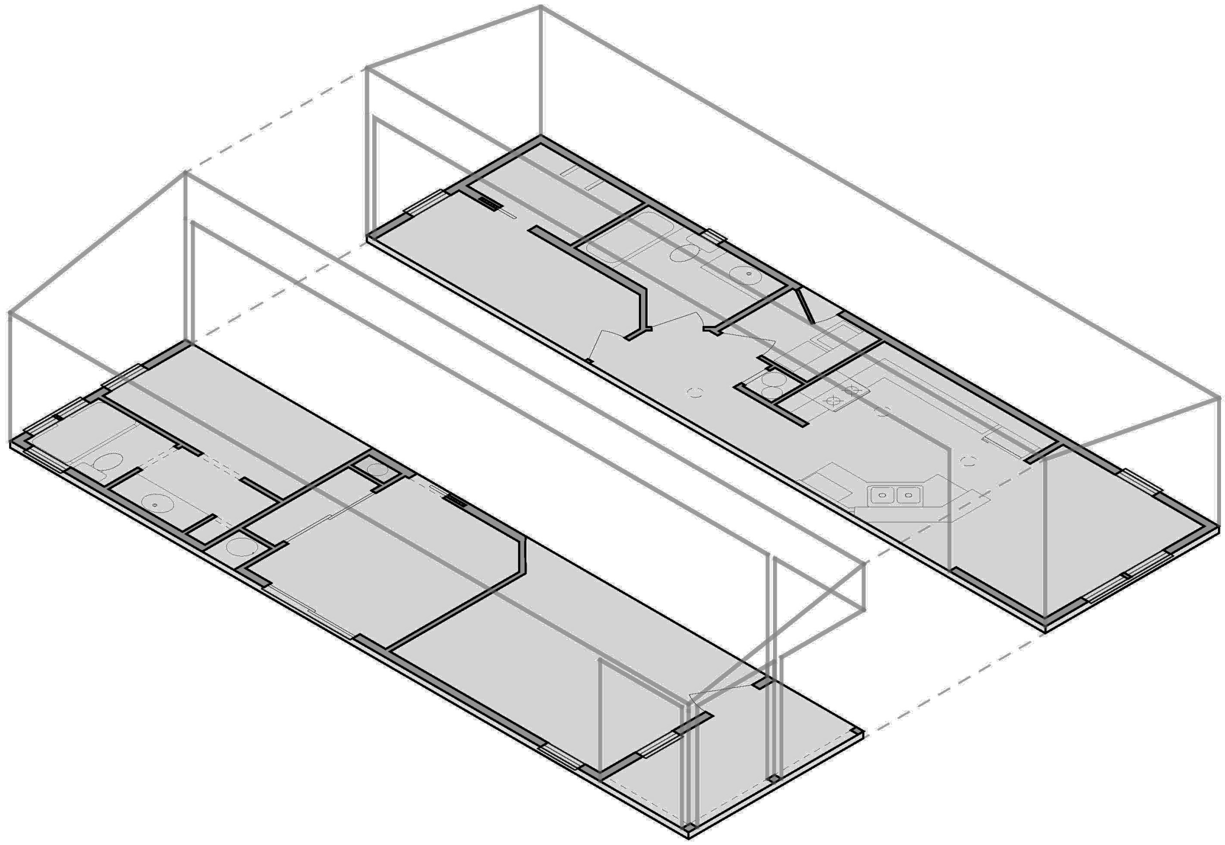
PHOTO: LAWRENCE ANDERSON



FLOOR PLAN



OAK HAVEN MODULAR HOUSE - LOT 18: FLOOR PLAN AND ASSEMBLY DIAGRAM



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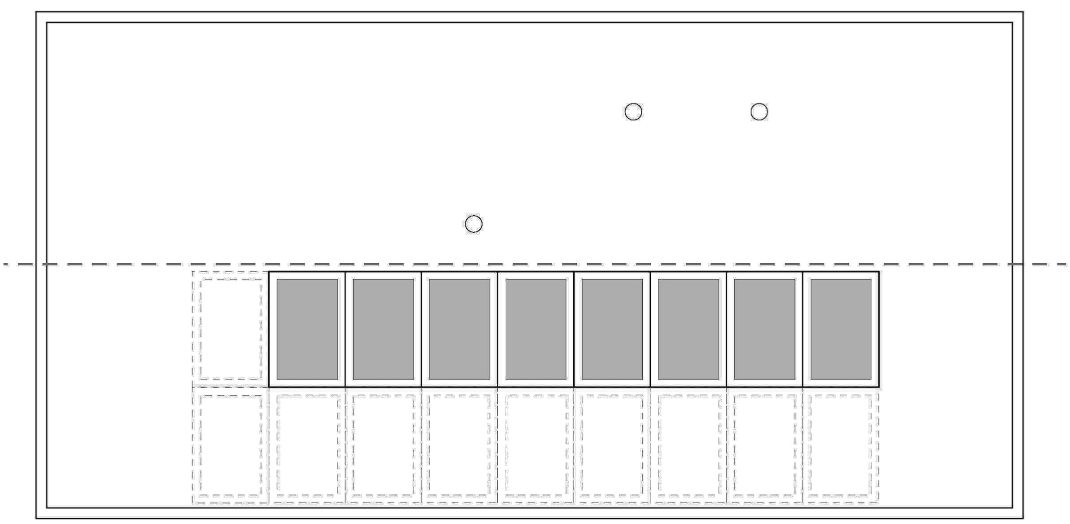


ROOF PLAN

(Left) Completed modular house components in the factory lot and in transit to the project site.

Building Program

The plan selected by the buyer contained a master bedroom suite with a master bathroom, a second bedroom, a separate bathroom, laundry room, an exterior porch and living spaces consisting of kitchen, dining and social areas, for a total of 1,152 sq. ft. This program fit neatly into two modules that were 11'-8" X 46'-0" each, easily transported by two trucks.

Site Constraints

The lots and streets of the Oak Haven neighborhood of *green homes* are not configured to favor a southern orientation for the rooftop PV panels, nor as a result are the houses themselves because of the small lot size. But since the roofs have a shallow slope, the reduction in energy production of the PV systems located on the west-facing roofs, which includes the house on Lot 18, is only roughly 10%-15% compared to the optimal orientation of the panels.

Low Energy Design Strategies

General Design Considerations

The developer, Modular Lifestyles, worked with the factory to develop a series of options typical of modular house design to present to the buyers. For the houses at Oak Haven, the company also specified construction that would exceed California Title-24 requirements by approximately 20% and have a number of additional low-energy features common to ZNE-performing houses.

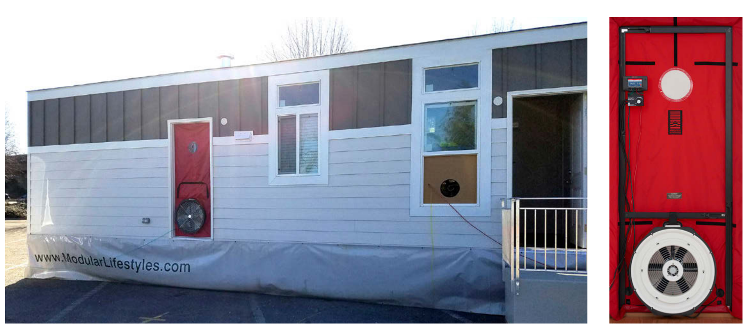
Building Envelope – Insulation and Windows

The factory was given direction to construct the walls of the modules thicker than the standard and filled with insulation, achieving R-28. The roof space between the shallow trusses was filled with 12" of blown cellulose insulation to create a high R-42 value. The plywood roof sheathing is a *radiant barrier*, with low-emissivity foil facing the interstitial space and suppressing heat gain in that small volume.

Windows are double-glazed, as required by Title-24, but they have the additional feature of argon gas within the glass unit, increasing the overall R-value of the window by an additional 33%. There is also a low-e coating on the glazing, which reduces the thermal transmission via radiation, further improving performance.

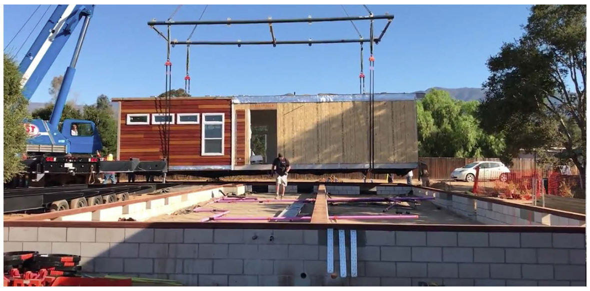
Building Envelope – Air-Tightness

The factory was also directed to seal the envelope at the window joints and penetrations, which was straightforward to execute at the factory. The developer took the additional step of testing the completed module for air-tightness after it left the factory and before it was delivered to the



(Right) A Blower Door test was done after the house left the factory and before it was delivered to the site.

(Right) At the project site, the modular house component is lifted by crane from the trailer truck and is lowered on to the prepared foundation.



site using the *Blower Door Test*[6]. The house at Lot 18 tested at 4.5 ACH50, which is a good value per California Title-24 energy standards. (The developer continues to improve on this one energy-efficient design feature in new modular houses, currently reaching 4.0 ACH50 in a recent test.)

Daylighting and Electric Lighting

General lighting throughout is provided by 10"-diameter *solar tubes*[7]. Daylight admittance, which can produce bright lighting on sunny days, is controlled at the ceiling to create an unusually well-illuminated, glare-free interior in addition to reducing energy use. Where appropriate, electric light fixtures are used. These employ LED or CFL lamps for energy efficiency.

Heating, Ventilating and Cooling Systems

Heating and cooling is provided using an Energy Star air source heat pump with a SEER[8] rating of 13. This is more energy efficient than a combination of a gas heater and traditional air conditioner—it is also carbon-free. Energy Star now requires a minimum SEER rating of 14.5, but at the time of construction of the house of Lot 18, 13-SEER was the minimum to qualify for Energy Star.

Conditioned air is delivered to the various rooms via air ducts in the shallow attic space. In addition, a 90-cfm whole house fan can be utilized to pre-cool the house at night when the temperatures are low enough to be effective. This reduces the cooling load during the following day.

Domestic Hot Water

To keep cost as low as possible, the domestic hot water is supplied via a gas-fired water heater rather than a more expensive add-on feature to the heat pump system. However, the houses were pre-plumbed to add a solar-thermal water heater at a later date.

Plug Load and Equipment

All electric appliances meet the Energy Star standard, providing energy-efficiency guarantees for internal equipment loads. A gas stove is utilized for cooking.

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[6] See the discussion in Case Study No. 1, p. 12 of this Volume 3.
[7] *Solar tube* is the generic name for a tubular skylights, which basically consist of a clear acrylic dome at the roof, roof flashing, flexible or rigid tubing with a highly reflective interior surface, and a diffusing lens at the ceiling. They are compact and effective daylighting devices for interior spaces during the day; they are usually equipped internally with high-efficiency electric lamps to provide light when daylight is unavailable.
[8] The *SEER (Seasonal Energy Efficiency Ratio) rating* of any cooling device is defined as the cooling output during a typical cooling season divided by the total electric energy input during the same period. The higher the unit's SEER rating, the more energy efficient it is.


PHOTO: LAWRENCE ANDERSON


PHOTO: LAWRENCE ANDERSON

(Opposite page) Interior views of the house on Lot 18.

Renewable On-Site Energy Supply

The on-site solar PV system consists of eight 250-watt LG Solar panels for a total power rating of 2.0 kW (DC).

The house of Lot 18 is one of eight houses whose lot configuration requires the low-slope gable roofs to face east and west. As noted above, the slope is shallow enough so that the effect on production efficiency of the PV arrays is only slightly reduced from optimal.

For price competitiveness in the particular market for these types of houses, the installed size of the solar PV system was set at 2 kW. Though advertised as *Modular Net Zero Homes*, these houses were not likely to produce a ZNE performance for an average owner. The idea was to provide roof space and connections for future additional PV panels once the energy use characteristics of the occupants could be evaluated and the required number of additional panels for actual ZNE performance thereby determined.

The houses were therefore initially more than *ZNE-Ready* and would actually achieve full ZNE if desired by the owners by adding the appropriate number of PV panels after a period of time.

(Left) Initial installations of the solar PV systems on the roofs of the Oak Haven houses.

Energy Performance
Post-Occupancy Measurement

Energy Use—Monitoring and Measurement

California Solar Electric Systems Inc. in Ojai was hired to install and monitor the solar PV system performance for all the houses at Oak Haven using the Enphase Enlighten monitoring system. The PV system energy production for the house on Lot 18 was recorded for a full year beginning in October 2016. Electric energy use of that house was not separately monitored, but Southern California Edison provided net meter data for that period so the monthly and annual energy use totals could be calculated using the Enlighten data with the net meter data. Natural gas use for that period was taken from the owner's gas bill. (The energy use of the house on Lot 18 is charted on the opposite page for the monthly and annual totals.)

The total annual energy use for that house for the period 10/2016 through 9/2017 was 6,285 kWh, or 21,450 kBtu. For the 1,152 sq. ft. house, this gives an EUI of 18.6 (kBtu/sq. ft.), an exceptional performance number.

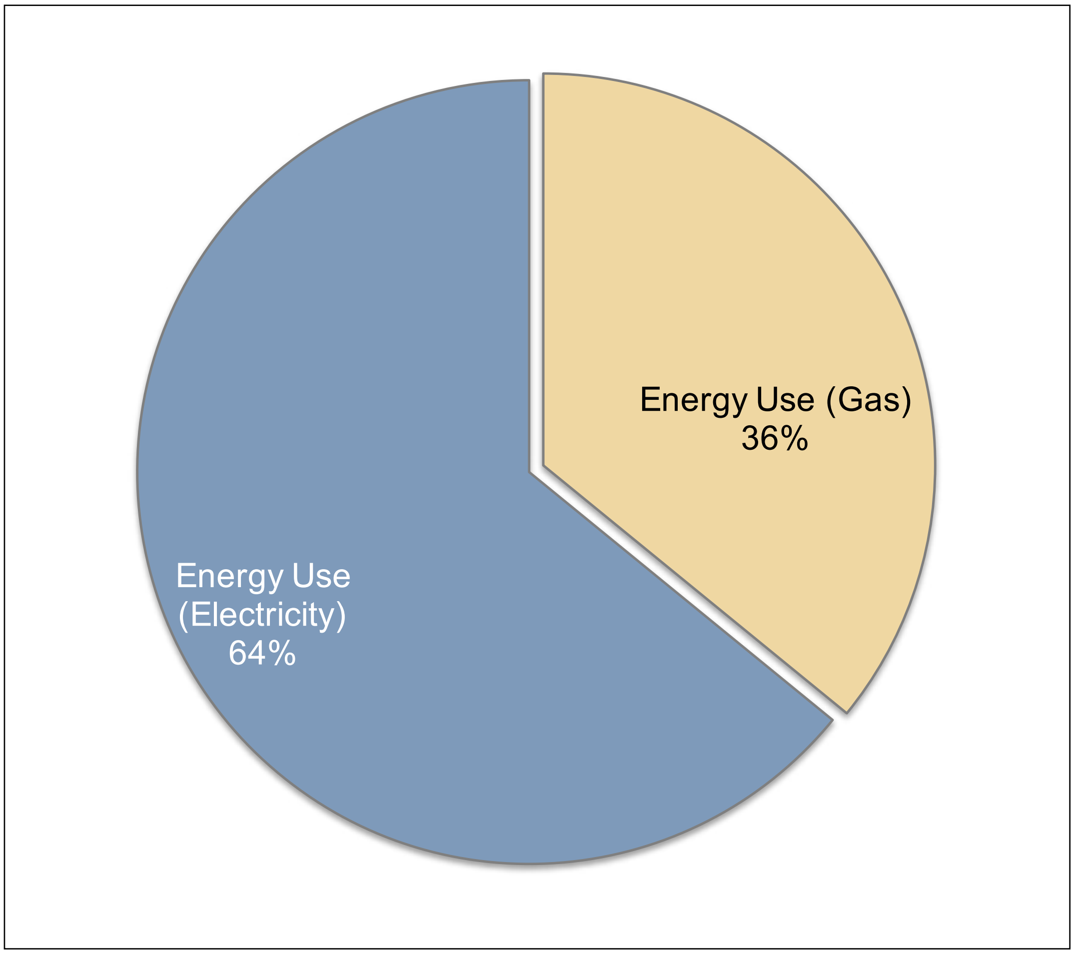
Energy Production versus Energy Use: Zero Net Energy Performance

The solar energy production data of the PV system installed on the house on Lot 18 was recorded for that same period and totaled 2,940 kWh, just less than half of the annual energy use from all sources and about ¾ of the annual electric energy consumption.

As expected, the initial installation of the solar PV system was not large enough to produce ZNE performance. But this data permits a calculation based on actual energy use patterns, which indicates that an addition of 2.5 kW capacity would theoretically produce about 6,600 kWh annually and result in a *Net Positive* performance. This translates to ten solar panels of the same performance rating as the original system, placed on the roof in the space planned for them. (These ten panels are shown dashed in the Roof Plan on p. 51) Energy production efficiency of solar panels has improved in the interim, so that only six or seven panels of the currently available models would deliver the same amount of power.

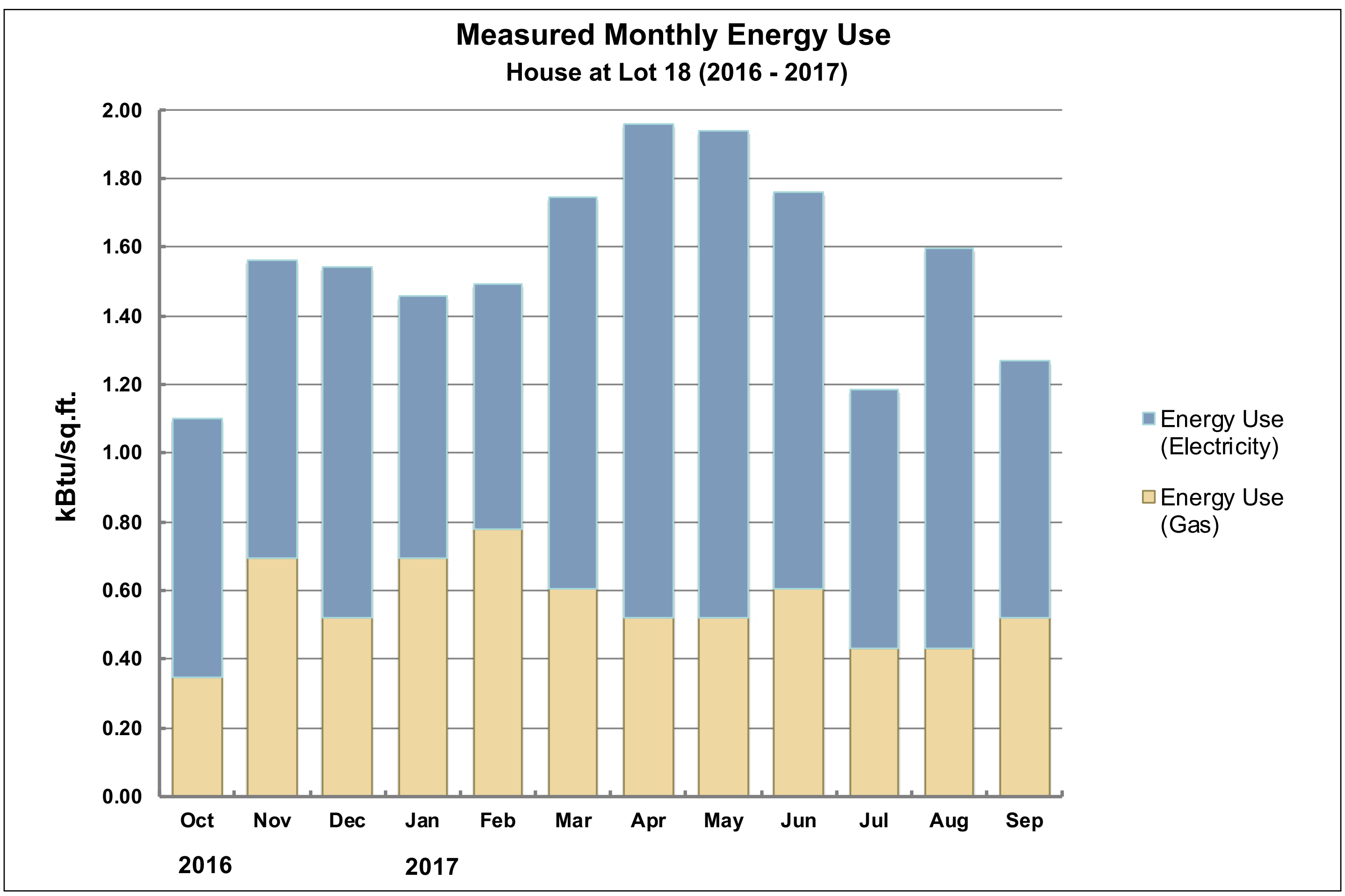
The chart on the next page (top) show the energy use of the house on Lot 18 over the course of the year (10/2016-9/2017) and the corresponding energy production of the initially installed solar PV system (2.0 kW). The dashed curve represents the energy production of a full-size PV system (4.5 kW) that would result in ZNE performance.

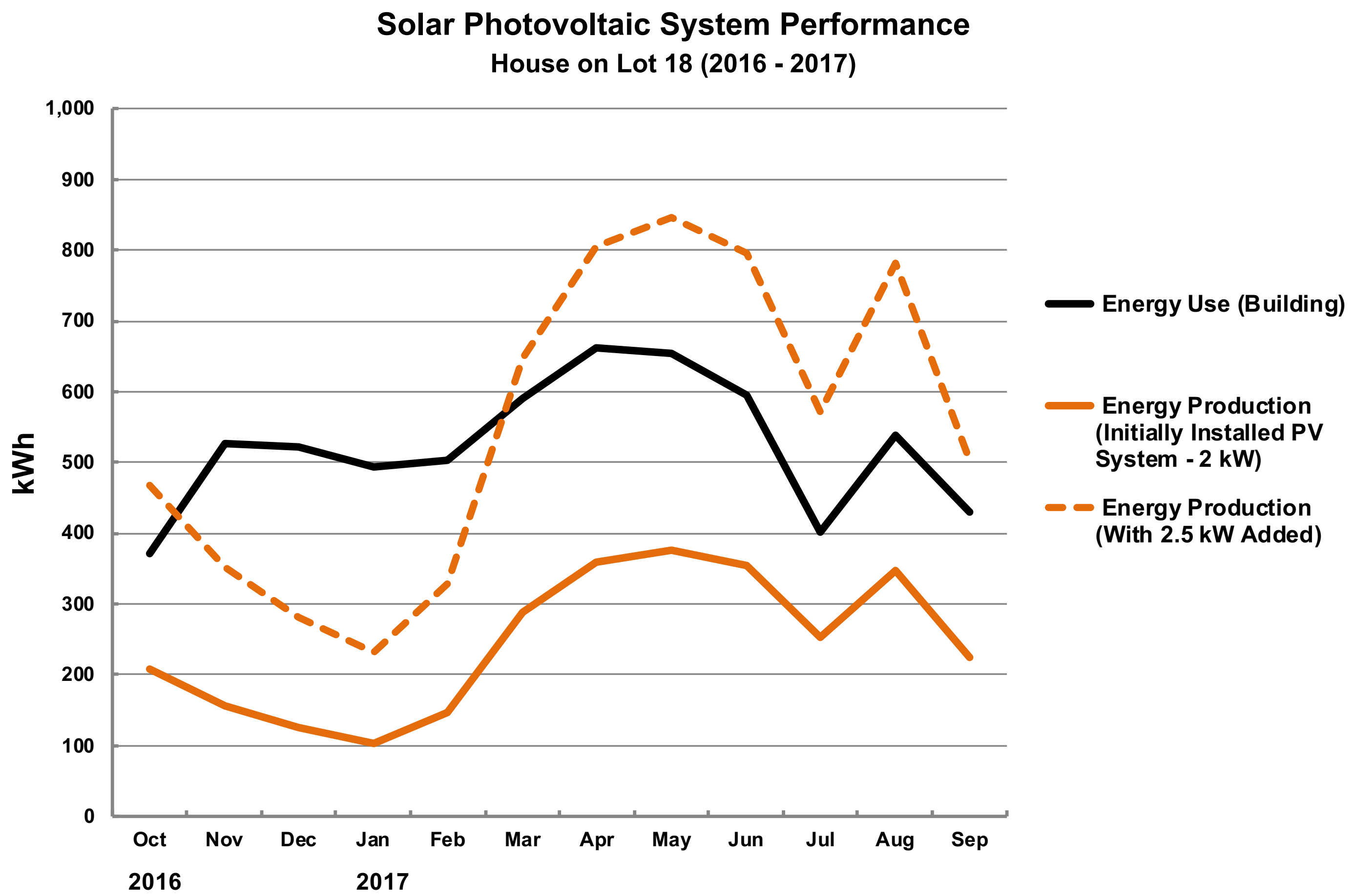
The second chart on the next page (bottom) shows the *cumulative net energy production* for the house with this measured energy use over this same period and the energy production of the full-size PV system. (Again, this chart shows the progression of the energy performance toward ZNE by adding each month's net energy performance to the previous month's total. If, at the end of the year, the curve remains on the positive side of the zero axis, then the house is indeed performing at ZNE.) The chart confirms that the full-size system of 4.5 kW would result in the house performing slightly better the *Net Zero*.

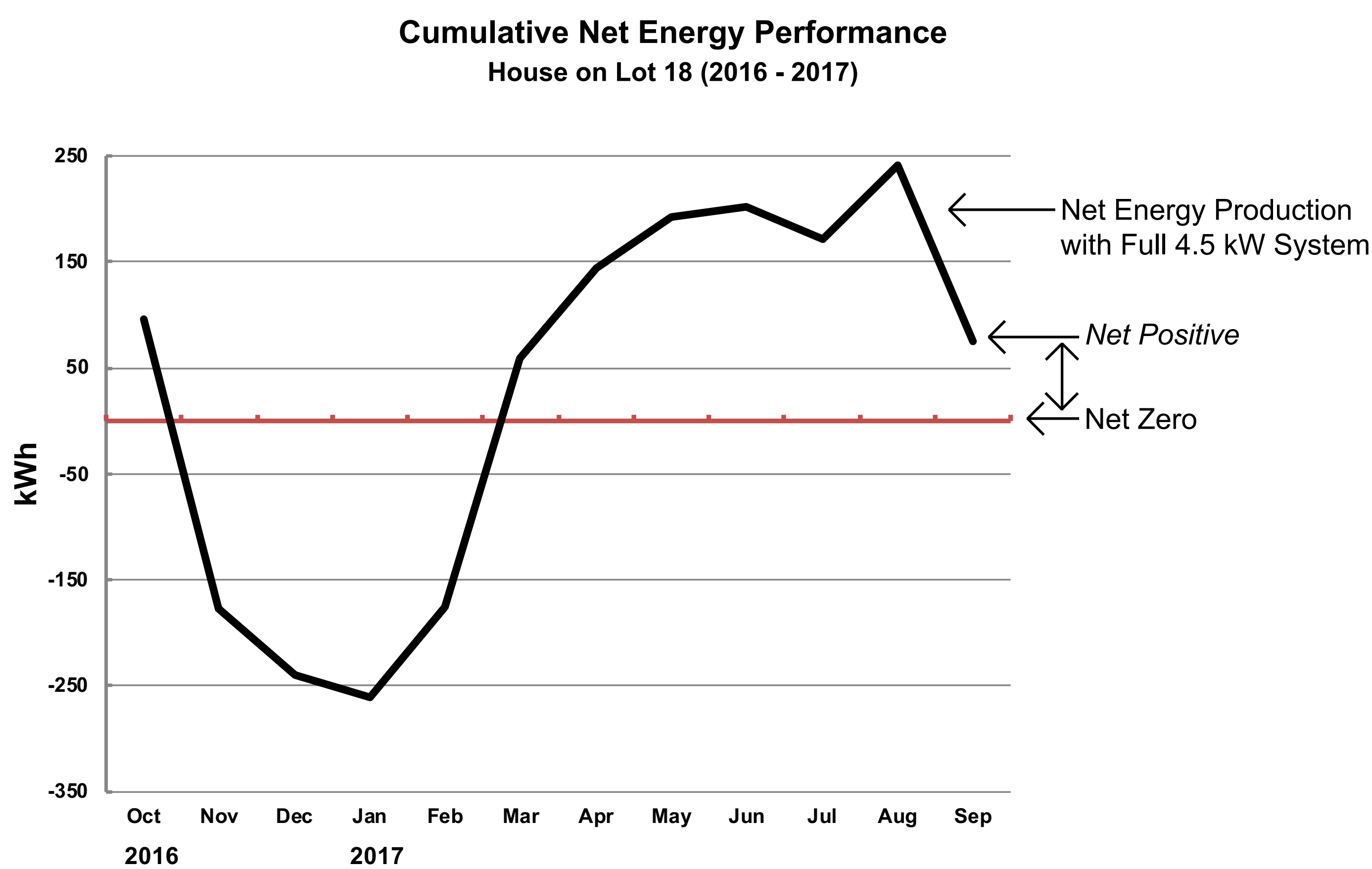


Measured Energy Use
House at Lot 18
(2016 - 2017)

6,285 kWh/year
Measured EUI = 18.6




Solar Photovoltaic System Performance
House on Lot 18 (2016 - 2017)
kWh
1,000
900
800
700
600
500
400
300
200
100
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
2016
2017
Energy Use (Building)
Energy Production (Initially Installed PV System - 2 kW)
Energy Production (With 2.5 kW Added)


Cumulative Net Energy Performance
House on Lot 18 (2016 - 2017)
kWh
250
150
50
-50
-150
-250
-350
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
2016
2017
Net Energy Production with Full 4.5 kW System
Net Positive
Net Zero

Post Occupancy: Observations and Conclusions

The primary observation is that the Oak Haven project demonstrates that modular housing can be built for ZNE performance at market prices.

One can apply ZNE design strategies in the same way as in “stick-built” houses—insulation, high-efficiency heating and cooling systems, Energy Star equipment, solar PV systems—and the Oak Haven houses show that this is possible within the normal profitability goals of a developer. This may be due in part to the appeal of a project like Oak Haven to a sector of the market that values this kind of quality construction while at the same time the modular product reduces cost due to the type and speed of construction.

Post Occupancy: Building Envelope

Of particular interest is how ZNE modular house construction fits within the general discussion of the technical advantages of factory-built housing and the consistent quality of the product that is possible. The principal aspect where this seems to occur is with the building envelope, particularly its thermal integrity (continuous, tight-fitting insulation) and the air-tightness components. Given the importance of these features for low energy use, the high degree of good quality control possible in a factory setting undoubtedly results in a consistently superior energy performance compared to the range of quality with “stick-built” structures.

In particular, air-tightness seems to be well-suited to factory construction and testing. The controlled environment of the factory plus the routine methods of quality assurance in the factory setting would seem to make air-tightness a noteworthy advantage of the factory-built house. Again, the potential consistency of this feature in the product provides the advantage of the modular house over the “stick-built” house.

The developer of the Oak Haven project carried out the air-tightness testing separately from the factory, thus not taking advantage of the complete set of possible quality control procedures. Ideally, as ZNE techniques and features are adopted in the factory environment, it would be routine for construction methods of air-tightness to be employed and tested to ensure consistently good results.

CASE STUDY NO. 4

Meritage Production Houses

PHOTO: LAWRENCE ANDERSON

Meritage Production Houses

Case Study No. 4

Data Summary

Building Type: Single-family
Location: Fontana, CA
Occupied: 2015

Project Name: Sierra Crest

Number of Houses/Units: 187 Houses Total, 31 in the ZNE Study Group

Representative ZNE Houses:
House #7 -

Gross Floor Area: 1,936 gsf

On-Site Renewable Energy System Installed: 4.0 kW(DC)

Battery Storage: 6.4 kWh

Measured On-Site Energy Production: 6,842 kWh/year (2016-17)

Measured EUI (Site): 11.6 kBtu/sf-year (2016-17)

House #12 -

Gross Floor Area: 2,673 gsf

On-Site Renewable Energy System Installed: 4.0 kW(DC)

Battery Storage: None

Measured On-Site Energy Production: 6,720 kWh/year (2016-17)

Measured EUI (Site): 7.4 kBtu/sf-year (2016-17)

Developer/Builder

Meritage Homes, Corona, CA

Project Team Consultants

Architect: BSB Design, Sacramento, CA

Energy Consultant/Modeling: BIRAenergy, Stockton, CA

This case study focuses on a sector of the housing industry in the U.S. that developed significantly after the mid-twentieth century, to a large degree to provide housing at a reasonable cost in the rapidly expanding post-war suburbs of American cities. Known as “production housing” or “tract housing”, this type of housing is built on a single tract of land initially owned by the developer, which is then subdivided into individual small lots for each house. These suburban housing developments are therefore sometimes called “subdivisions”.

Production housing developments are usually built by large corporations consisting of real estate professionals, marketing and finance departments, and occasionally design groups and construction crews. The houses typically are the same construction and have basically the same features for a specific “model”, varying within that model-type only by compass orientation and a limited number of optional design features. The number of model-types is limited, allowing the corporate builder/developer to take advantage of economies of scale and speed of construction.

The reasonable cost of this type of housing for middle-class Americans has led to the large growth of this type of residential development as a percentage of the new housing market. The question, therefore, of the adoption of ZNE design and construction strategies for production housing is interesting not only from the perspective of the technical issues, but also that of the constructability, marketing and cost issues associated with these types of houses.

Because of the large number of new single-family houses built by this part of the industry and the formulas developed for profitability by the companies that build them, an examination of how ZNE performance can be realized within those financial constraints would have a large impact, perhaps even effecting beneficial change within that industry.

This Case Study No. 4, the *Meritage Production Houses*, considers these issues in conjunction with the results of a particular research study into the possible wide-scale adoption of ZNE in this part of the new housing market.

Background: Origin of the ZNE Production House Project

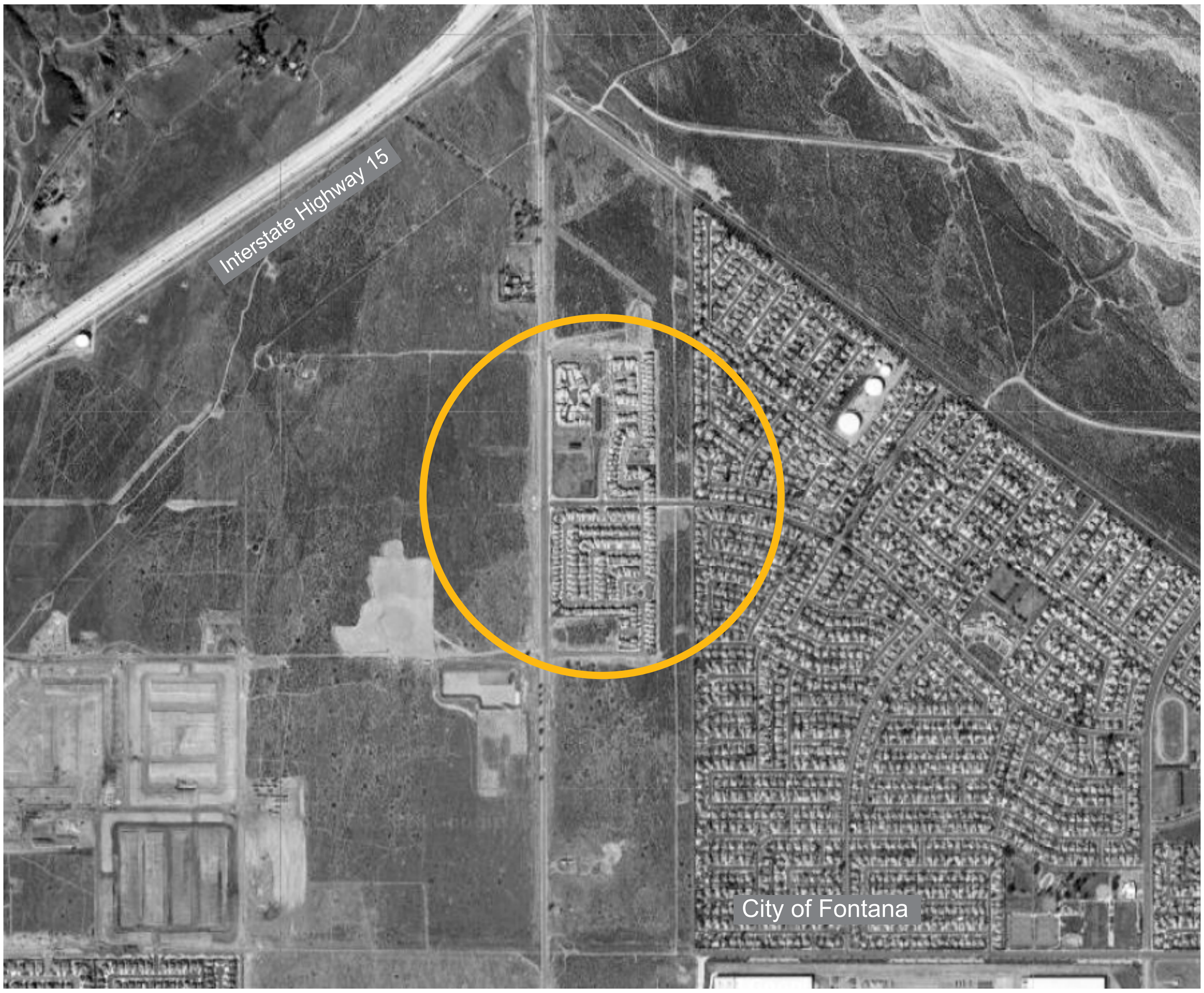
In 2013, the production house builder, Meritage Homes, initiated the design of the *Sierra Crest Homes* project for a tract of land on the outskirts of Fontana, a city in San Bernadino County. Consisting of 187 houses, the development was planned like a typical suburban subdivision.

An Important Parallel Research Study

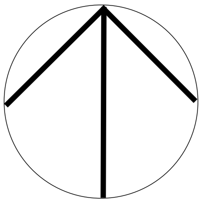
At the same time, a partnership consisting of Meritage Homes, the Electric Power Research Institute (EPRI), BIRAenergy and Southern California Edison (SCE) formed a research team under the auspices of the California Public Utilities Commission (CPUC) via the California Solar Initiative (CSI). The team studied the likely effects of “ZNE-designed communities” on the California power grid by focussing on a subset of the Sierra Crest Homes that would be designed to *near-ZNE* performance capability.

The idea was to take a number of production houses in the subdivision and incorporate various energy-efficiency construction techniques and features, accompanied by a sufficiently large solar PV array at each house, so that the overall annual energy performance of the houses would be nearly ZNE in most cases and equal to ZNE in some. (It was assumed that the solar PV system had to be sized in a cost effective manner, that is, a system size that would not be producing more energy than likely would be used for the houses in the group.)

This group of near-ZNE and full-ZNE houses would then be comprehensively metered after sale and occupancy to assess the patterns of net energy use and peak demand. The results would



Fontana Subdivision Houses: General Vicinity Plan



then be extrapolated to gather insights into the effect of the large-scale adoption of ZNE in this housing market sector.

Of particular concern to the CPUC and independently-owned utilities (IOUs) like SCE was whether the widespread adoption of ZNE in the new housing market, already well underway and also until recently a mandated goal for the State of California by 2020, would present technical stability issues to the existing power grid as described by the famous *Duck Curve* [1]. The research study undertaken at the Sierra Crest subdivision was intended to examine not only the potential problem areas but also possible mitigation measures. The introduction of energy storage using batteries integrated with the solar PV system was identified as such a mitigating measure and was included as an essential part of the study.

A total of 20 houses out of 187 houses in the Sierra Crest subdivision development were selected to be the subject of this research study, which were designated the *ZNE Study Group*. Roughly half of the group was equipped with battery storage and the remaining houses in the group had no energy storage equipment. (A third equally-sized group was selected from the non-ZNE houses as a *control group*, which were monitored and used to compare and check the data from the sample of ZNE houses.)

Detailed data was collected for more than a year as part of the research study. (Data collection is still ongoing.) The results are contained in a 2017 technical report to the CPUC by EPRI[2], which draws conclusions about the advantage of requiring battery energy storage with solar PV systems, controlled in coordination with a time-of-day utility rate schedule.

This general issue is still being studied and the ultimate resolution will have a major impact on the future of California IOUs and housing construction. But it is not a subject of this case study. This case study examines the design, construction and occupancy of the production houses in this research study that achieved ZNE performance according to the detailed recorded data, and the conclusions that can be drawn about them and this housing type.

Project Process

The production housing builder, Meritage Homes, participated in the research study by designating 20 houses in the Sierra Crest Homes subdivision to be built to a ZNE house specification, incorporating construction features, a solar PV system and, for nine of the houses, a battery energy storage component.

The research study partners (Meritage, SCE and EPRI) collaborated on the construction features and technologies that are employed in these ZNE houses, assisted by a consulting firm specializing in ZNE systems and energy modeling in residential construction (BIRAenergy). These ZNE features are described in the sections following below.

A "ZNE Model Home" was designated to illustrate these ZNE features for prospective buyers as part of a marketing effort to alert the buyers to the opportunity to purchase a ZNE home.

[1] See the Introduction to this volume of *Residential Zero Net Energy Case Studies* for a discussion of the *Duck Curve* and the effect on the state power grid.
[2] R. Narayanamurthy, B. Clarin, R. Handa, (EPRI), "Grid Integration of Zero Net Energy Communities", California Solar Initiative RD&D, January 2017, http://www.calsolarresearch.ca.gov/Funded-Projects/.

(Left) Site sign advertising the ZNE homes for sale in the Sierra Crest subdivision.

Building Program

Certain models were designated for the *ZNE Study Group*, with limited optional features for the plan and architectural style as is typical for production houses. Only the presence of an initial-installed solar PV system was an indication of anything special about these houses compared to other houses in the subdivision. A typical brochure description of a particular model home ("The Bridalveil") with possible variations is shown below.

Yosemite Collection at Sierra Crest

Elevation A

Elevation B

Elevation C

The Bridalveil

2,673 Square Feet

3 Bed • 2.5 Bath • 2 Car Garage • Game Room

(Left) A typical brochure description of a particular model home ("The Bridalveil") with possible variations shown.

The relevant "program" for the houses of the *ZNE Study Group* is given in the table below, which lists the house floor areas, the designated model type, a description of the solar PV array and the if battery energy storage is included.

Site Constraints

The single-family houses are planned according to a typical approach to site planning for production house subdivisions—good vehicular access and maximizing the number of units among the most important. The houses in the ZNE Study Group are indistinguishable from the rest of the subdivision, embedded within the larger collection of similar houses and relying on materials and technology to achieve ZNE performance.

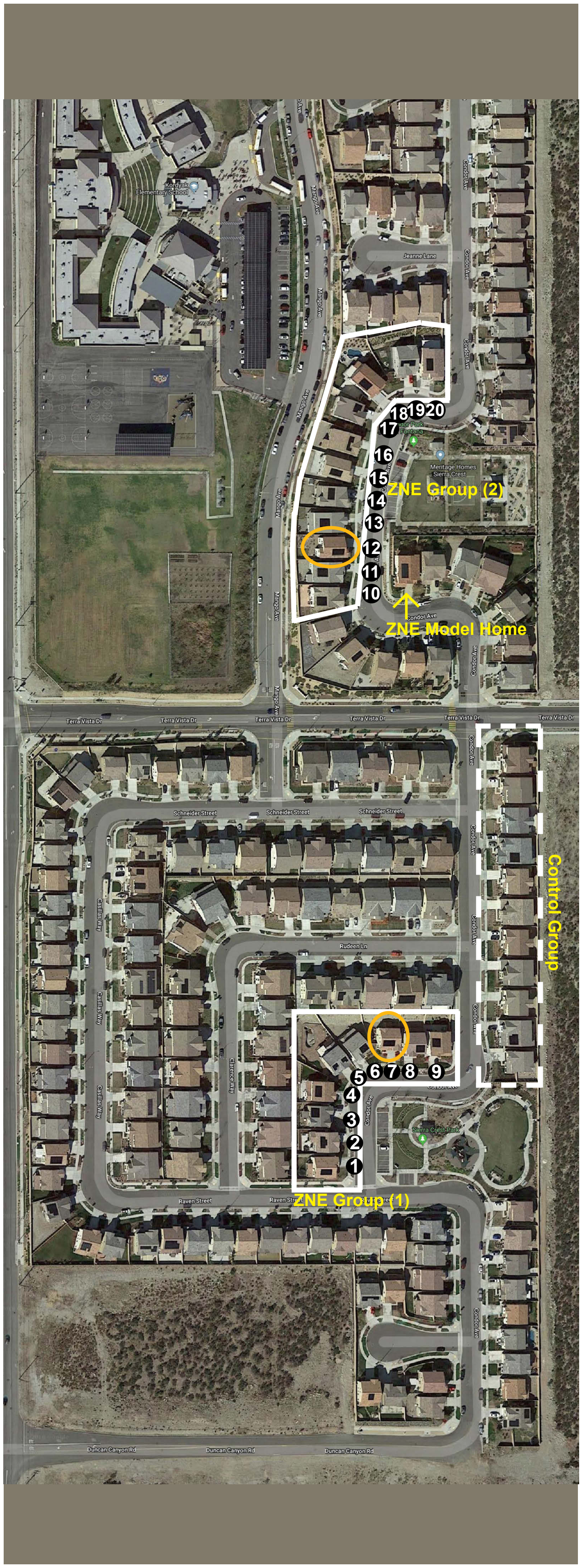
The metered data for these houses for the period August 2016 through July 2017 showed that only two houses achieved a ZNE performance: House #7 and House #12. These are indicated in the aerial image on the opposite page of the portion of the site occupied by the *ZNE Study Group* and the control group for data analysis in the EPRI study.

The remaining 18 houses of the *ZNE Study Group* can be characterized as *near-ZNE*, ranging from 24% ZNE to 77% ZNE, with most houses clustered at the upper end of that range, according to the EPRI data.

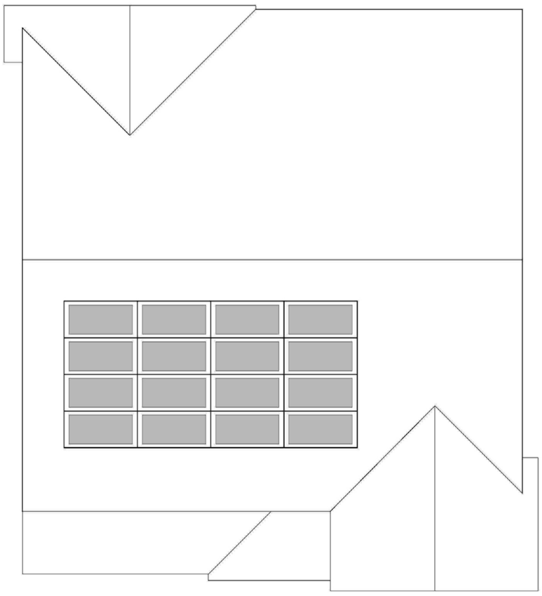
This case study now focuses on the ZNE-performers, House #7 and House #12.

(Below) Table of basic properties of houses in the ZNE Study Group.

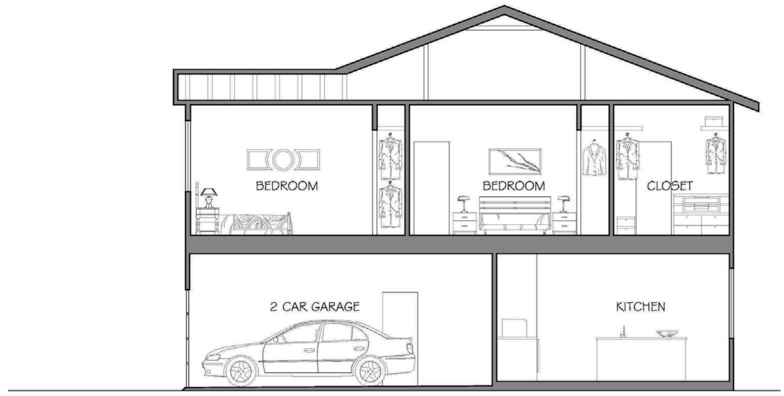
ZNE Study Group - House No.	Model Name	Gross Floor Area (sq. ft.)	Energy Storage (Battery)	Installed Solar (kW-DC)	Roof/Panel Orientation	Zero Net Energy Performance (2016-2017)
1	Walhalla	2,319	√	4.0	South	
2	Mojave	2,182	√	3.5	South	
3	Grandview	1,936	√	3.8	West	
4	Mojave	2,182	√	4.0	West	
5	Mojave	2,182	√	3.5	Southwest	
6	Mojave	2,182	√	3.8	Southwest	
7	Grandview	1,936	√	4.0	West	√
8	Mojave	2,182	√	3.8	West	
9	Mojave	2,182	√	3.8	West	
10	Capitan	2,842		4.5	West	
11	Toulumne	2,915		4.5	West	
12	Bridalveil	2,673		4.0	South	√
13	Toulumne	2,915		4.5	West	
14	Brideveil	2,673		4.0	West	
15	Capitan	2,842		4.0	South	
16	Toulumne	2,915		4.0	Southwest	
17	Capitan	2,842		4.0	Southwest	
18	Toulumne	2,915		4.0	Southwest	
19	El Capitan	2,842		4.0	Southwest	
20	Capitan	2,842		4.0	West	



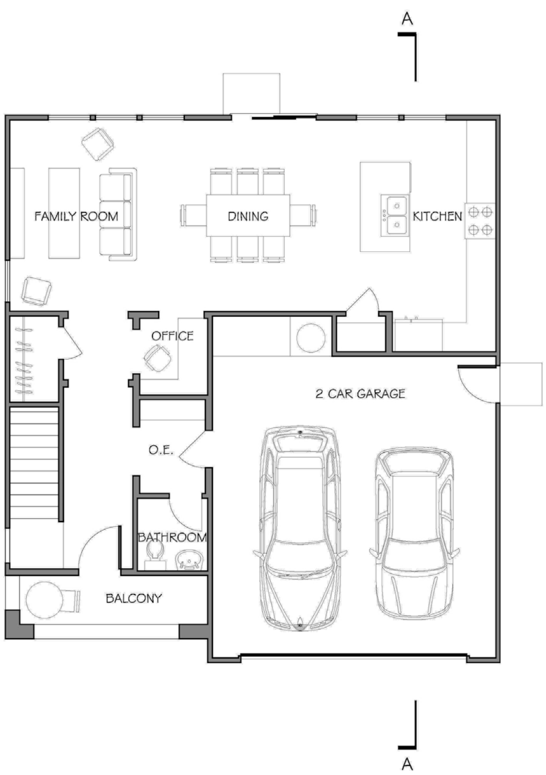
(Left) Aerial view of a portion of the Sierra Crest Homes subdivision, delineating the *ZNE Study Group* of 20 homes, the data control group of 11 homes and the location of the *ZNE Model Home*. House #7 and House #12 (circled) achieved ZNE for 2016-2017.



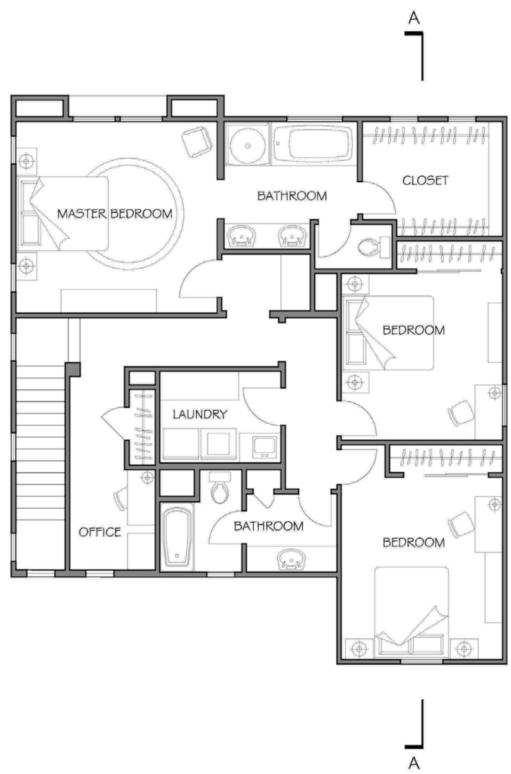
ROOF PLAN



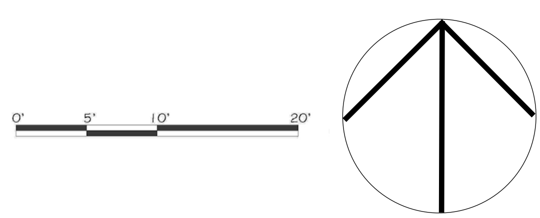
SECTION



GROUND FLOOR PLAN

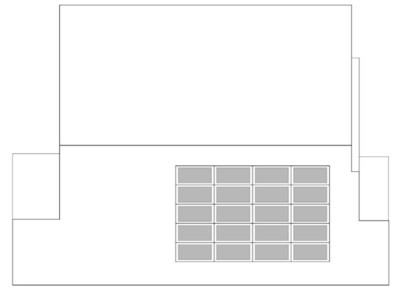


SECOND FLOOR PLAN



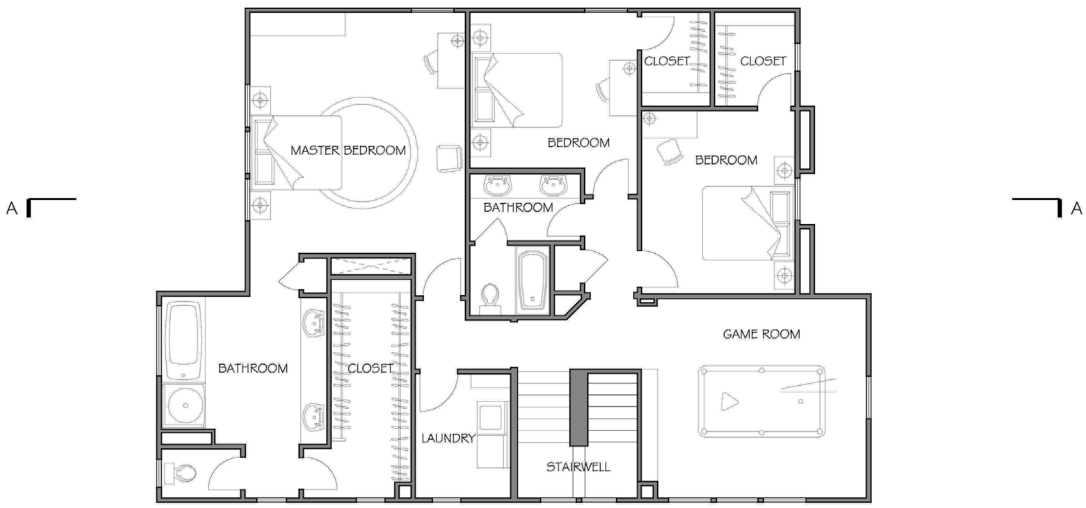
HOUSE #7: FLOOR PLANS AND BUILDING SECTION


4792
PHOTO: LAWRENCE ANDERSON

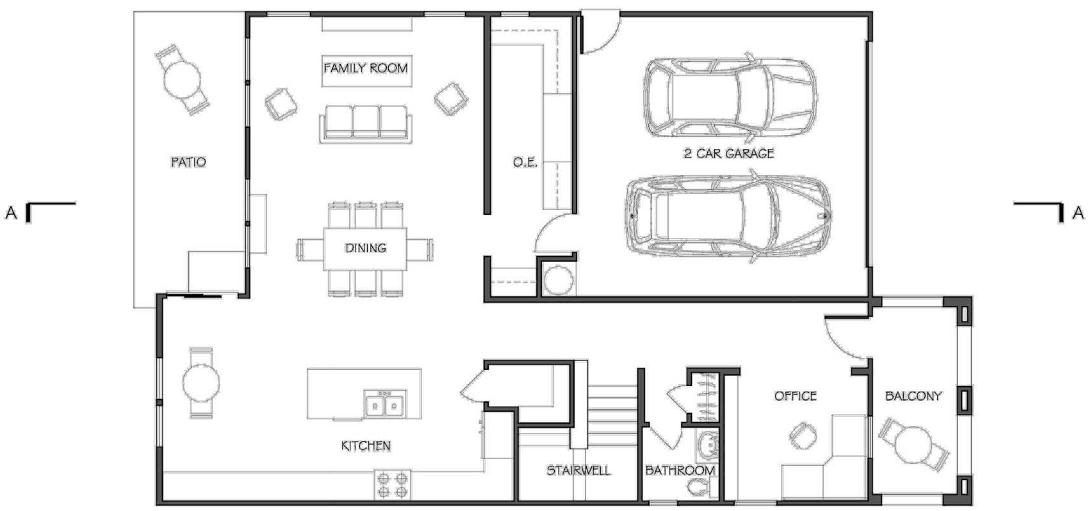


ROOF PLAN (HALF-SIZE)

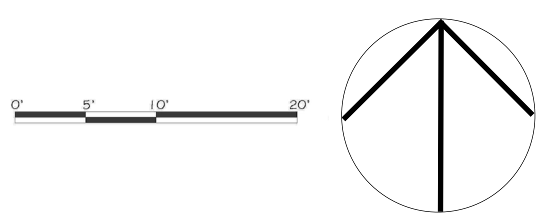
SECTION



SECOND FLOOR PLAN



GROUND FLOOR PLAN



HOUSE #12: FLOOR PLANS AND BUILDING SECTION


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PHOTO: LAWRENCE ANDERSON

Low Energy Design Strategies

General Design Considerations

The working principle for the design of the ZNE houses at Sierra Crest was that they should look and function no differently than any other house. The differences would be in the construction techniques and the energy technologies used in the houses, which would be basically invisible to the owners and their neighbors. Therefore, the basic design strategies would have to be higher insulation levels and air-tightness of the envelope, EnergyStar appliances, high-efficiency LED light fixtures, electric heat pumps for heating and cooling, heat pump water heaters and, of course, a baseline solar PV system.

Building Envelope – Insulation and Windows

The houses were built with *advanced framing*[3], a materials-efficient method of standard platform framing that minimizes the thermal bridging effect. The method of insulation selected was an open-cell spray polyurethane foam (SPF) insulation applied between the exterior framing members, combined with a 1" layer of interlocked expanded polystyrene (EPS) boards over the outside of the framed exterior surfaces. The water-blown spray foam provides a high insulating R-value (R = 4 per inch) and increases the air tightness of the exterior envelope by filling in gaps and holes in the construction[4].

The specific type of SPF product chosen, manufactured by Icynene®, is chemically different from other SPF products on the market that are made with some chemicals of concern[5]. The SPF used in the Meritage Homes was carefully evaluated and selected because of its environmental neutral properties and absence of hazardous chemicals after installation[6]. The higher R-values possible with the use of this SPF and the large reduction in sources of air leakage were considered a good value in return for the added complexity of installing the material.

Although the advanced framing is less susceptible to thermal bridging at the wood framing elements at the exterior surfaces, there remains a significant area where this extra heat transfer can occur. The 1" layer of EPS sheathing, with an R-value of R=4, successfully eliminates all such thermal bridging at the exposed framing members.

(Below) A worker installs open-call SPF insulation on a residential construction site.

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[3] See "Advanced House Framing", United States Department of Energy, https://www.energy.gov/energysaver/energy-efficient-home-design/advanced-house-framing

[4] As noted in Case Study No. 1, *Corona del Mar New Houses*, the open-cell spray foam is permeable and does not have the full air-sealing characteristics of the closed-cell product. Also, the R-value of the open-cell insulation if only about half of that of the closed-cell product. However, for the mild California climate, the open cell product is decidedly more cost effective in terms of energy-efficiency.

[5] "Health Concerns about Spray Polyurethane Foam", United States Environmental Protection Agency, https://www.epa.gov/saferchoice/health-concerns-about-spray-polyurethane-foam

[6] It contains no PBDE (flame retardant) and uses carbon dioxide to expand the foam, therefore having the Global Warming Potential (GWP) of 1 (the lowest number on the index scale). While there is a level of toxicity during installation, after the SPF has cured for 24-72 hours, no measurable outgassing occurs and no toxic chemicals are released if the material burns. The installation of the SPF requires special protection for the workers and the job site must be vacated during the curing period. The workers must be protected by a Tyvek® suit and wear full respiratory masks to protect against inhaling any toxic chemicals or airborne foam particles during expansion.

(Above) First floor framing of a Sierra Crest house in progress using Advance Framing method.

The attic spaces were built as conditioned spaces, with the SPF applied to the underside of the sloped roof structure. The attic space was then used for the mechanical heating, ventilating and cooling equipment in a volume that was maintained at an approximate temperature of 80 degrees all year. In the warm climate of the location, this maintained a "cool roof" condition at the same time as reduced duct losses, air infiltration and the usual attic "greenhouse effect".

The resulting overall R-values for the typical wall assembly comes to R-21 and for the roof assembly the total is R-28 (derated for framing factors that cause thermal bridging).

Windows and doors were specified to have thermal breaks, eliminating another potential source of heat gain/loss through the building envelope.

Building Envelope – Air-Tightness

The use of SPF contributes to the overall air-tightness of the house. In addition, gaskets were used at the top and bottom plates of the framing to control air leaks that normally occur at those locations. A Blower Door test was done at two of the houses as a quality control measure; it was found that the two houses averaged 3.0 ACH50, which is considered below the California Title-24 recommended standard of 5.0 ACH50 but greater than the Passive House standard of 0.5 ACH50.

It also indicates a sufficiently air-tight house to suggest that a ventilation system be installed with good air distribution to each space and a control system to manage the intake of fresh air. (See the following section.)

Heating, Ventilating and Cooling Systems

The houses are equipped with a high-efficiency air-source heat pump split system for heating and cooling (SEER 15, HSPF 9). The air distribution is via ductwork from the equipment located in the conditioned attic space and utilizing an advanced control system to manage fresh-air intake, air-temperature and humidity.

(Opposite page, top) Interior view of Great Room in the ZNE Model Home.

(Opposite page, bottom) Interior view of Kitchen/Dining spaces.

The heating and cooling loads were modeled in advance to right-size the equipment, which determined that only a 3-ton system would be required in general for these ZNE houses.

Domestic Hot Water

The ZNE houses use a 50-gallon, highly energy-efficient electric water heater that is designed based on heat pump technology rather than normal electric heating elements. It uses approximately 50% less energy than a standard water heater of the same size. The houses also utilize water-efficient features such as high pressure/low flow shower heads and faucets to reduce overall consumption of hot water.

Daylighting and Electric Lighting

All of the homes were originally specified with LED light fixtures that provide energy-efficiency, longevity and dimmability. Buyers were allowed to substitute or add specialty light fixtures. Plug-in lamps were also not controlled as part of the research study.

Plug Load and Equipment

All appliances are EnergyStar®, including refrigerator, dishwasher, microwave, washer, dryer, range hood and electric oven. However, due to consumer preference, buyers could opt for a gas range, which was selected in most cases.

Control Systems

The control system monitoring and operating the heating, ventilating and cooling system was Nexia XL824®. In addition, because the research study included detailed energy monitoring of the house energy consumption and PV system production, the data collected was made visible to the owners at the house. Although the system involved only passive monitoring, the owners were able to see real-time data and possibly adjust behavior or system operation in response.

A separate *Energy Management System (EMS)* is used to obtain the lowest utility rates by optimizing the use of the battery storage. To avoid peak power charges, for example, the system may be programmed to charge the batteries in the early morning hours to make sure that there will be enough battery power available during early evening hours when there is no output from the solar PV system and utility rates are high. This is discussed in more detail in the section on Battery Energy Storage below.

PHOTO: C R HERRO

Renewable On-Site Energy Supply

Energy modeling was carried out for each of the houses in the ZNE Study Group in order to size the solar PV system, assuming the same basic information about energy demand. All twenty houses in the ZNE Group have the same system, only varying from 3.5 to 4.5 kW depending on the energy load calculated for the size of the house and the orientation of the roof where the solar array is installed. Both House #7 and House #12 have a 4.0 kW system.

The systems are 335-watt panels installed by SunPower® and are owned and maintained by the individual buyer as part of the house. The number of panels installed was not necessarily determined by the energy modeling calculations, but also depended on the space available on the roof.

For the period August, 2016, through July, 2017, the system on House #7 collected 6,760 kWh over the course of that year, while the same-size system on House #12 collected the nearly identical 6,721 kWh. This occurred despite the fact that the panels on House #7 face west and the panels on House #12 face south.

Energy Performance
Post-Occupancy Measurement

Energy Use—Modeling and Measurement

The houses of this *ZNE Study Group* were initially modeled using *BEopt*, the residential building modeling software supported by the National Renewable Energy Laboratory (NREL). For each of the houses, an annual energy demand and energy production by the solar PV system were calculated. From these calculations, a summary of which is shown in the table on the opposite page (top), the intention was to make these houses Initially *near-ZNE* for the buyer, with the ability to achieve ZNE performance or better by adding a couple of solar panels or reducing the energy use by roughly 10%, easily done well within the conservative assumptions of the model.

On the measurement side, as part of the overall research study, EPRI collected detailed data for both the energy use of the all the houses of the *ZNE Study Group* and the energy production for each solar PV system. The overall results of that data collection showing the performance of the individual houses for the one-year period from August 2016, through July 2017, are shown in the table on the opposite page (middle). The comparative data for the performance of the two ZNE houses (#7 and #12) is apparent in this table.

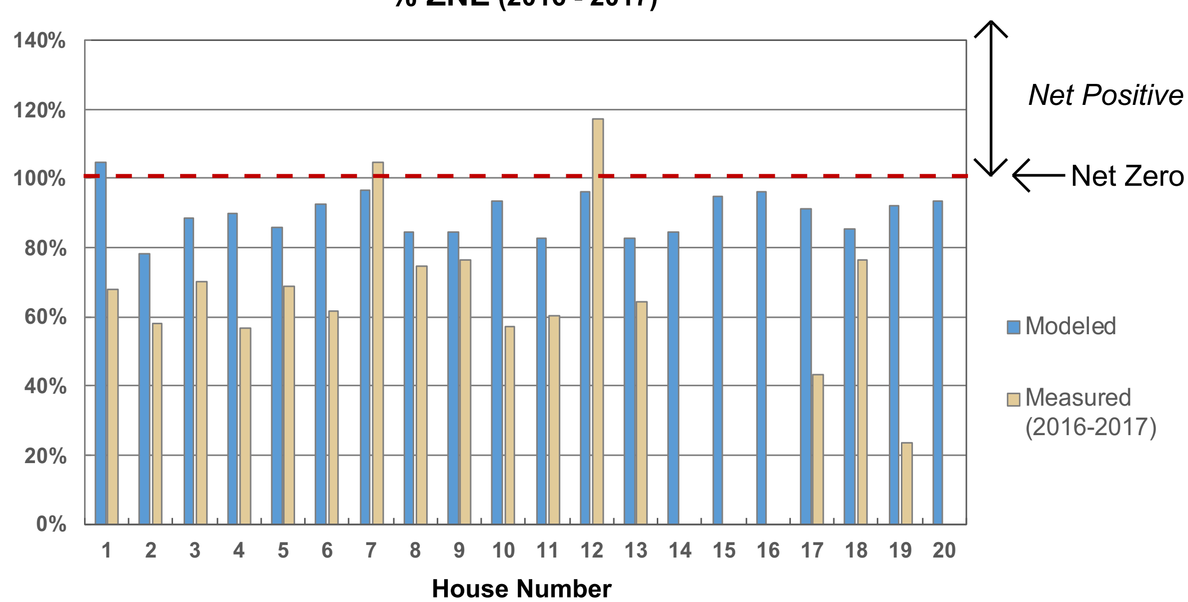
A simple comparison of both the modeled and measured ZNE performance of each of the houses in the ZNE Study Group is shown in the chart immediately below these summary tables. While the solar energy produced by each system was close to the values of the energy modeled, the measured energy use deviates from the patterns assumed in the model. (Some discussion of this occurs in the Post-Occupancy section following.)

Looking closely at the energy performance of the two houses that actually achieved ZNE in the 2016-2017 period, the detailed breakdown by category of energy use for House #7 is given by the performance charts on page 78. The same breakdown for House #12 is given by the charts on pages 80-81. The disparity of energy use patterns for these two ZNE houses shows the limitation of energy modeling to make predictions of occupant behaviors other than on an average basis.

ZNE Study Group - House No.	Model Name	Energy Storage (Battery)	**MODELED** Total Energy Use - Annual - kWh	EUI kBtu/sf-year (Modeled)	Total Energy Production - Annual - kWh	Annual Net Energy Use (Modeled) kWh	% ZNE (Modeled)
1	Walhalla	√	6,331	9.4	6,628	-297	ZNE
2	Mojave	√	6,501	10.2	5,082	1,419	78%
3	Grandview	√	6,143	10.9	5,445	698	89%
4	Mojave	√	6,457	10.4	5,808	649	90%
5	Mojave	√	6,542	10.5	5,614	928	86%
6	Mojave	√	6,504	10.2	6,015	489	92%
7	Grandview	√	6,035	10.7	5,827	208	97%
8	Mojave	√	6,448	10.1	5,445	1,003	84%
9	Mojave	√	6,448	9.5	5,445	1,003	84%
10	Capitan		7,005	8.5	6,534	471	93%
11	Toulumne		7,485	8.9	6,193	1,292	83%
12	Bridalveil		6,882	8.8	6,628	254	96%
13	Toulumne		7,485	8.9	6,193	1,292	83%
14	Brideveil		6,882	8.8	5,808	1,074	84%
15	Capitan		7,005	8.5	6,628	377	95%
16	Toulumne		7,518	8.9	7,221	297	96%
17	Capitan		7,016	8.5	6,416	600	91%
18	Toulumne		7,512	8.9	6,416	1,096	85%
19	El Capitan		6,972	8.4	6,416	556	92%
20	Capitan		6,873	8.3	6,416	457	93%

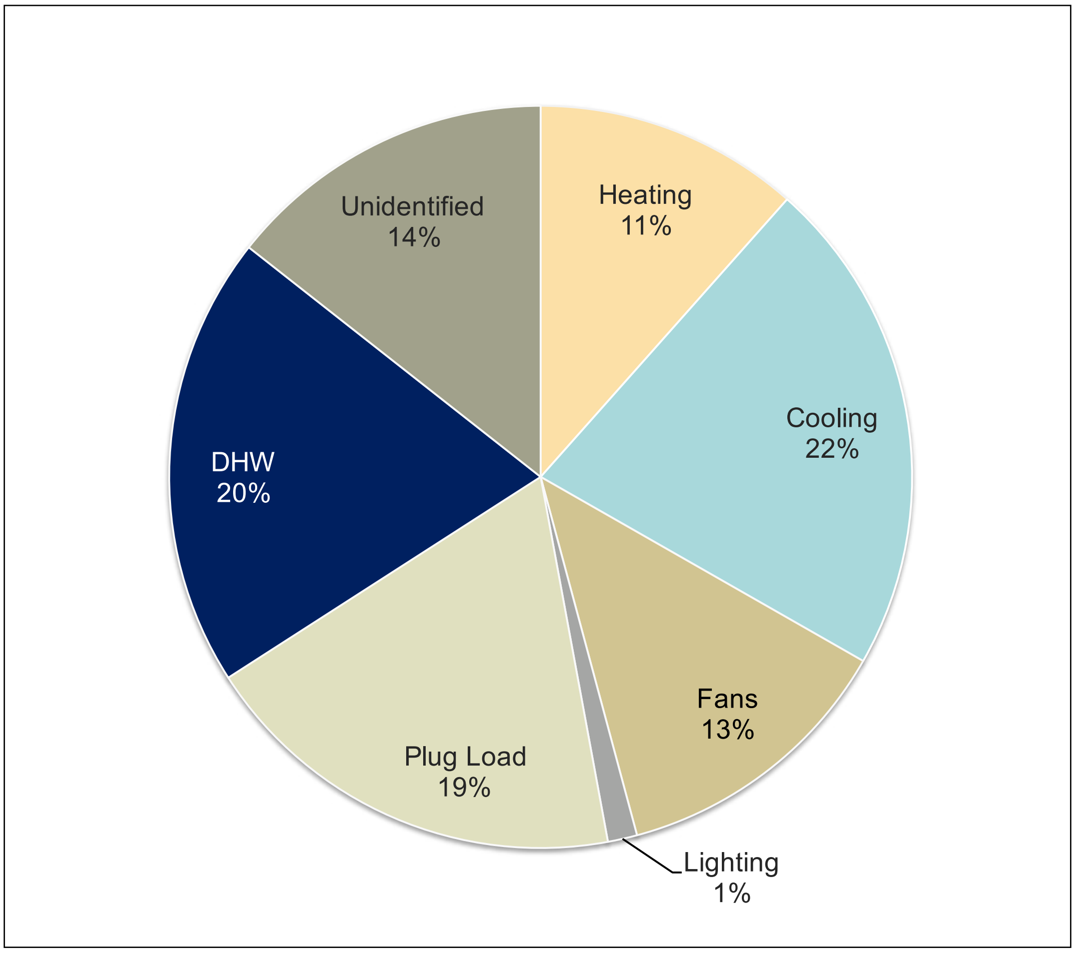
ZNE Study Group - House No.	Model Name	Energy Storage (Battery)	**MEASURED** Total Energy Use (2016-2017) kWh	EUI kBtu/sf-year	Total Energy Production (2016-2017) kWh	Annual Net Energy Use (2016-2017) kWh	% ZNE (2016-2017)
1	Walhalla	√	10,370	15.3	7,045	3,325	68%
2	Mojave	√	9,103	14.3	5,270	3,833	58%
3	Grandview	√	8,027	14.2	5,635	2,392	70%
4	Mojave	√	10,364	16.7	5,882	4,482	57%
5	Mojave	√	8,471	13.7	5,825	2,646	69%
6	Mojave	√	10,083	15.9	6,233	3,850	62%
7	Grandview	√	6,524	11.6	6,843	-319	ZNE
8	Mojave	√	8,727	13.7	6,527	2,200	75%
9	Mojave	√	7,299	10.8	5,591	1,708	77%
10	Capitan		11,296	13.6	6,466	4,830	57%
11	Toulumne		10,743	12.8	6,461	4,282	60%
12	Bridalveil		5,743	7.4	6,721	-978	ZNE
13	Toulumne		10,693	12.7	6,866	3,827	64%
14	Bridalveil		5,988	7.7	-	-	-
15	Capitan		4,153	5.0	-	-	-
16	Toulumne		-	-	-	-	-
17	Capitan		12,229	14.8	5,279	6,950	43%
18	Toulumne		9,416	11.2	7,188	2,228	76%
19	El Capitan		21,496	26.0	5,095	16,401	24%
20	Capitan		-	-	-	-	-

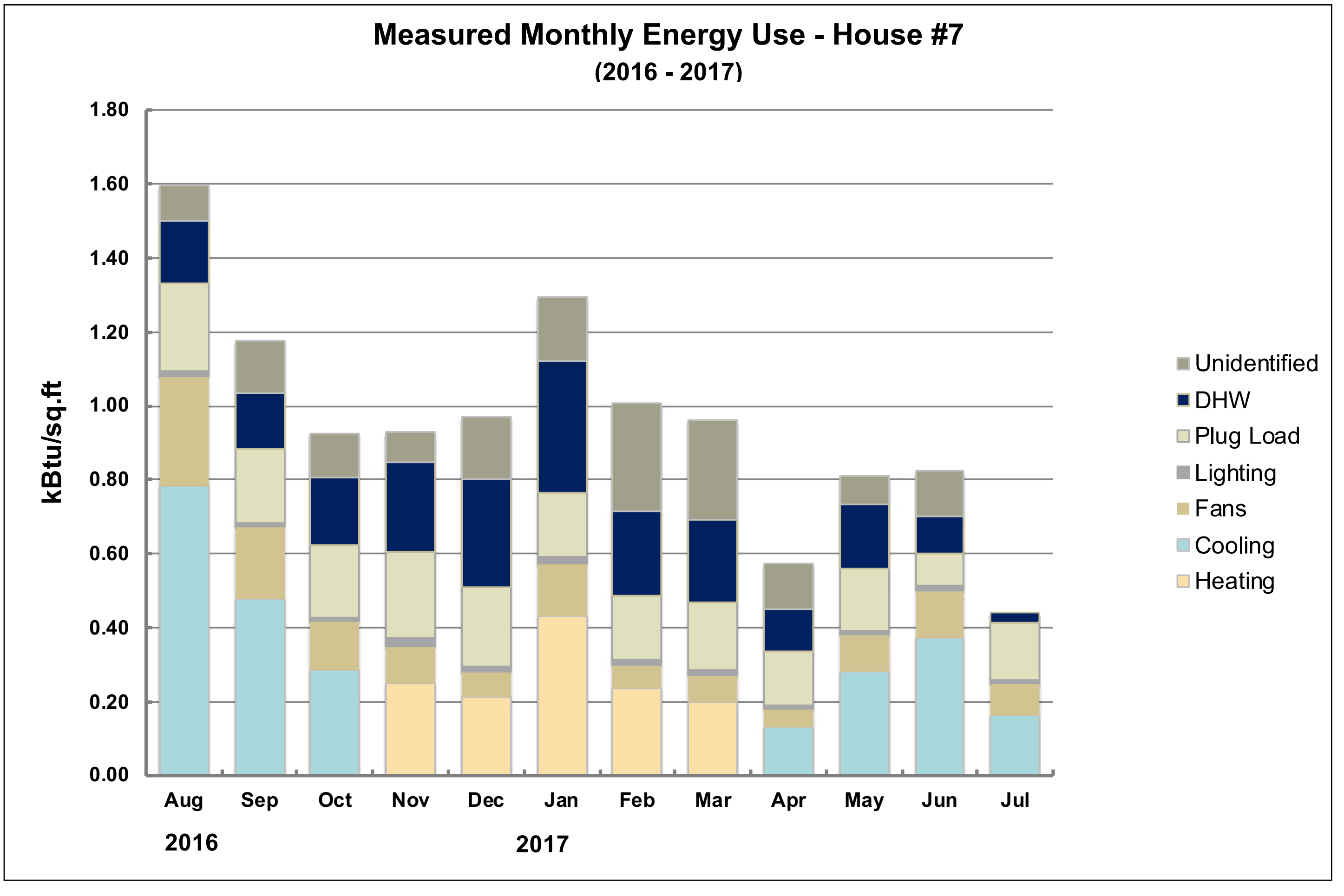
% ZNE (2016 - 2017)

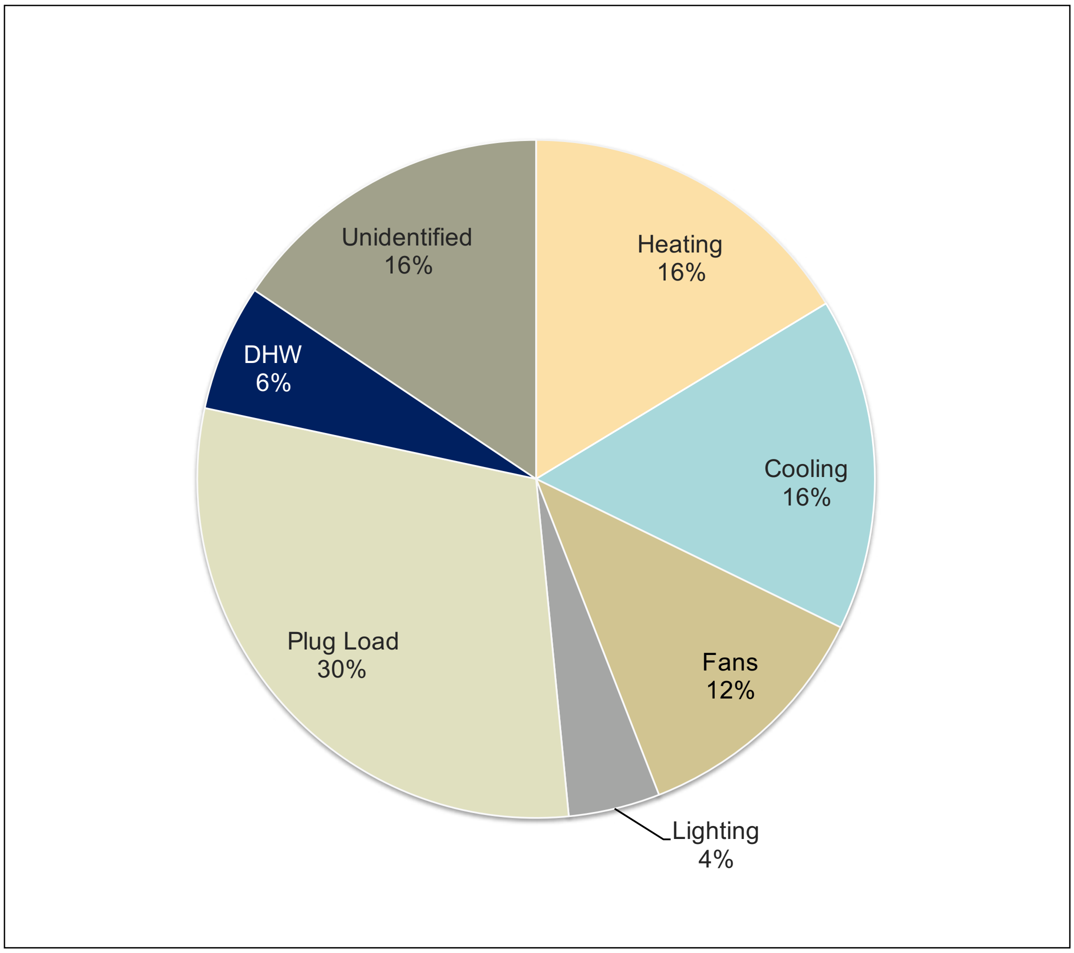


Measured Energy Use
House #7
(2016 - 2017)

6,524 kWh/year
Measured EUI = 11.5

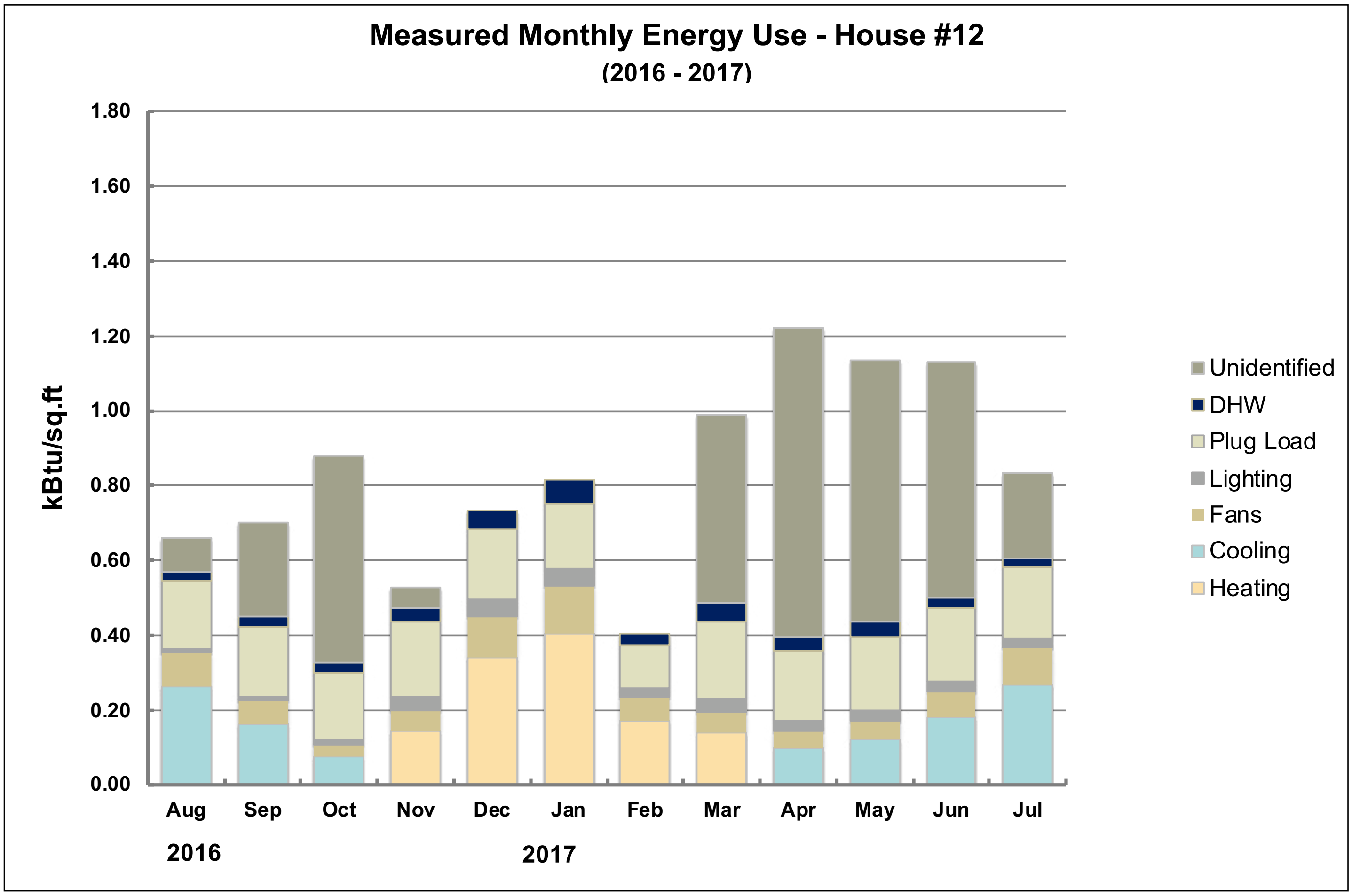






Measured Energy Use
House #12
(2016 - 2017)

5,743 kWh/year
Measured EUI = 7.34



Energy Production versus Energy Use: Zero Net Energy Performance

The energy production and percent-ZNE performance for each house in the ZNE Study Group are shown in the summary table and chart on page 77. The charts of *Energy Production versus Energy Use* for House #7 and #12 on the pages following give the monthly comparison over the one-year period of data collection.

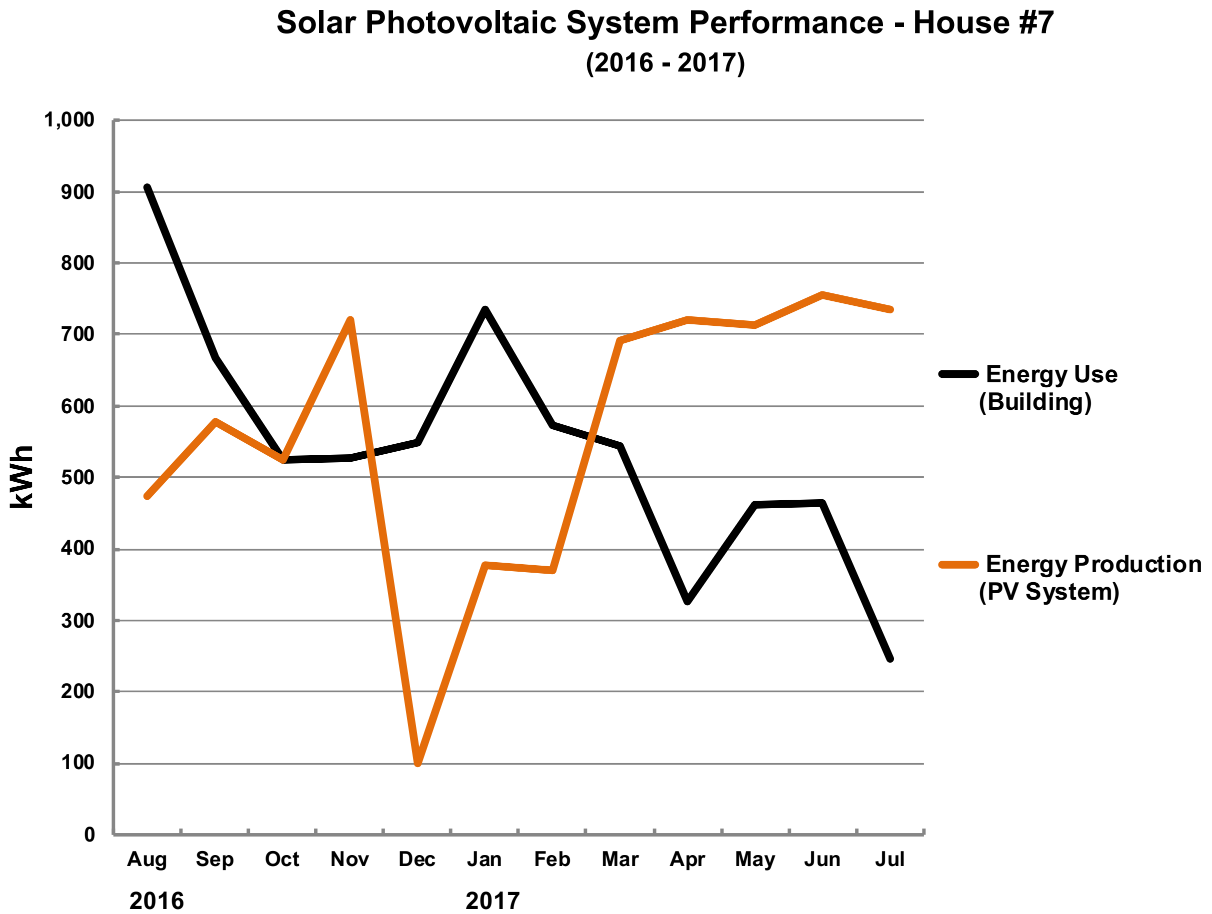
The *Cumulative New Energy Production* charts shows the progression of the energy performance toward ZNE by adding each month's net energy performance to the previous month's total—if, at the end of the one-year period of data collection, the curve remains on the positive side of the zero axis, then the building is confirmed as ZNE. Both House #7 and House #12 can be seen to be *Net-Positive*.

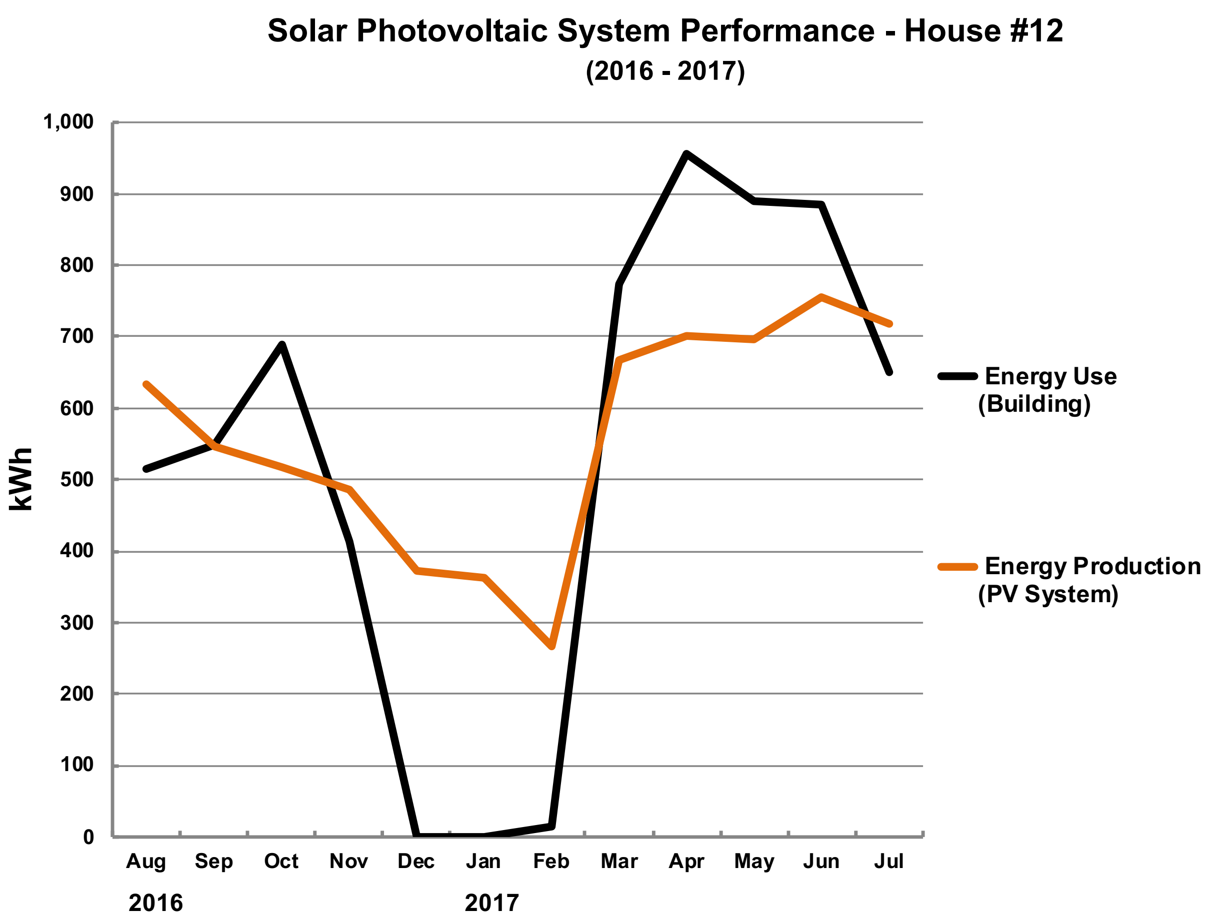
Battery Energy Storage—Impact on Peak Demand and Load Shifting

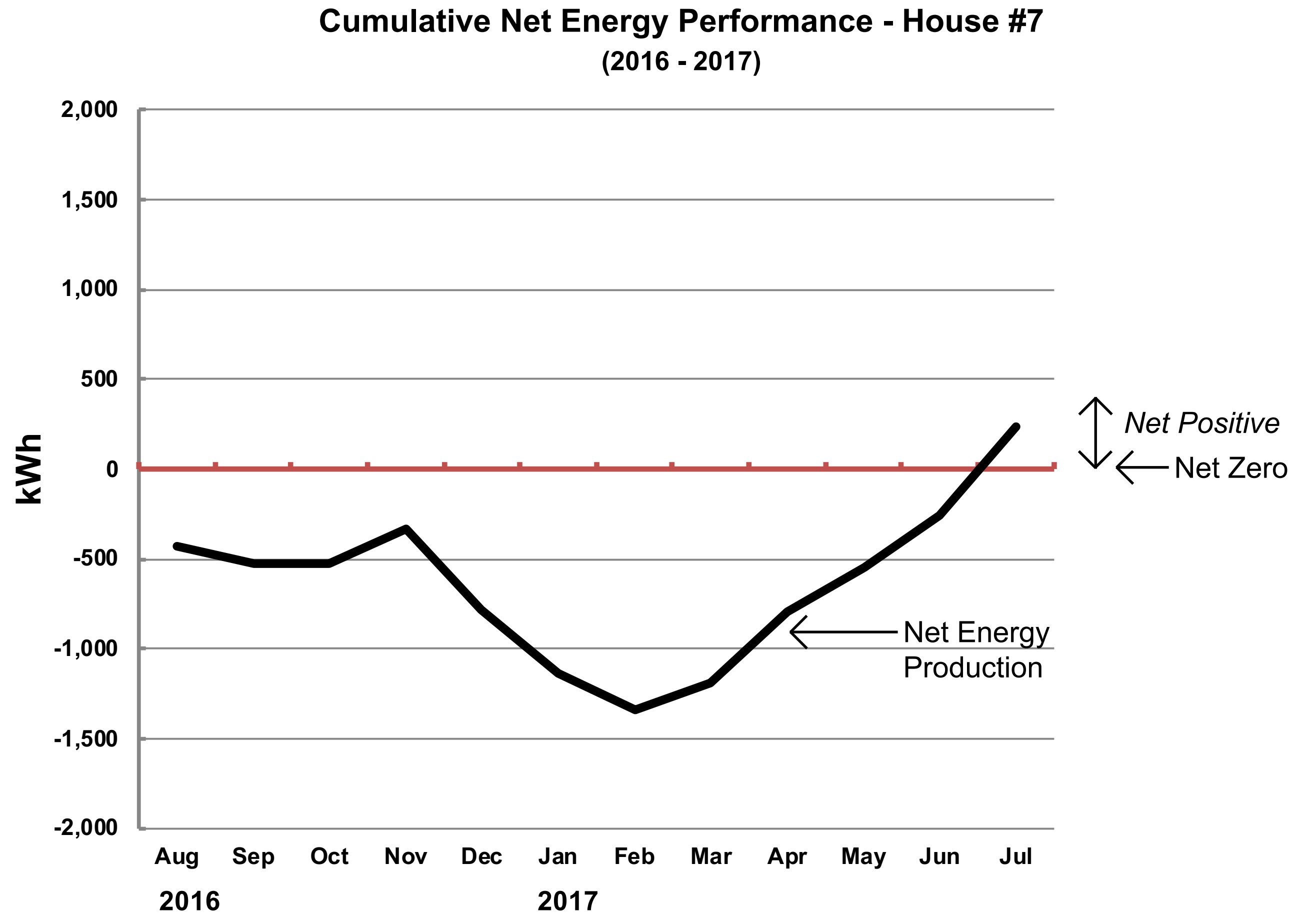
The unique aspect of this particular case study is the main objective of the research study carried out with this project, namely, the inclusion of *battery energy storage* in nine of the houses in the *ZNE Study Group*. (The remaining houses had no battery storage equipment.) Each of these houses were equipped with lithium batteries with a 6.5 kWh storage capacity.

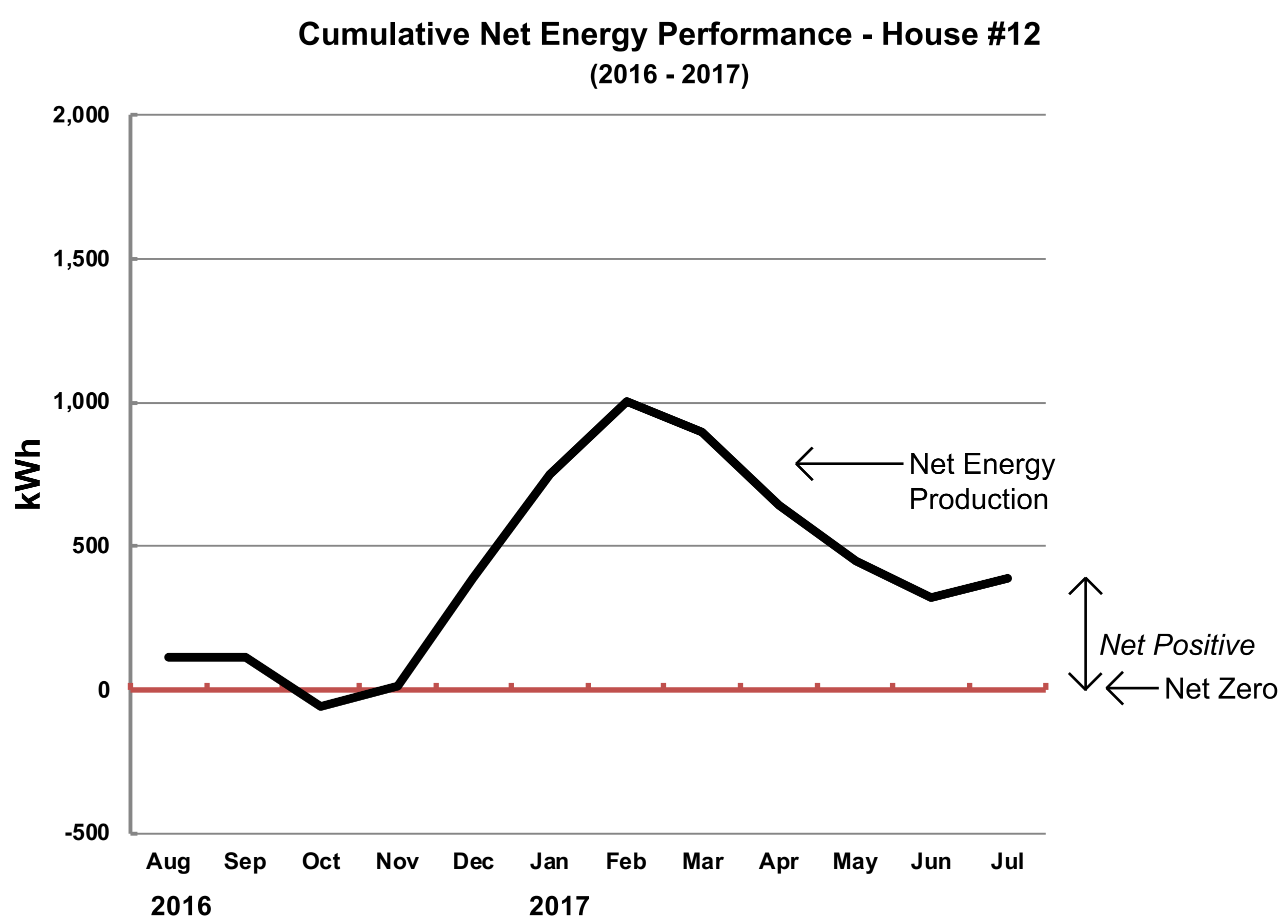
With the ability to control the use of this battery storage to modulate the energy demand placed on the utility grid and to shift the periods of peak demand, the researchers could evaluate the benefits to consumer and utility of better "harmony" with the utility-supplied power.

The EMS for the energy supply of the house could be programmed by the owner to operate in one of two ways: (1) simple prioritization to draw first directly from the energy produced by the solar PV panels, then (if the solar panels were in non-producing mode) to draw from the battery and finally (if there is no energy left in the battery) from the electric utility grid; (2) more sophisticated program that optimizes "time-of-use" rates to charge the battery thus minimizing utility charges. In practical terms, the latter might involve some overnight battery charging, when rates are low, in anticipation of low solar PV production early on the following day.


Solar Photovoltaic System Performance - House #7
(2016 - 2017)
kWh
1,000
900
800
700
600
500
400
300
200
100
0
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
2016
2017
Energy Use (Building)
Energy Production (PV System)


Solar Photovoltaic System Performance - House #12
(2016 - 2017)
kWh
1,000
900
800
700
600
500
400
300
200
100
0
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
2016
2017
Energy Use (Building)
Energy Production (PV System)


Cumulative Net Energy Performance - House #7
(2016 - 2017)
kWh
2,000
1,500
1,000
500
0
-500
-1,000
-1,500
-2,000
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
2016
2017
Net Positive
Net Zero
Net Energy Production


Cumulative Net Energy Performance - House #12
(2016 - 2017)
kWh
2,000
1,500
1,000
500
0
-500
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
2016
2017
Net Energy Production
Net Positive
Net Zero

Post Occupancy: Observations and Conclusions

Data collection as part of the research study is ongoing and in general, all of the objectives of the project have been achieved by both the builder, Meritage Homes, and the other partners in the projects. The performance data has been collected and recorded without problems.

Two of the twenty houses in the *ZNE Study Group* actually performed at ZNE. Given that one of the objectives of this project was to explore ZNE house production within the financial and marketing constraints utilized by the competitive production house industry, this outcome may be both expected and positive. The houses of the *ZNE Group*, judging from the data, for example, can achieve ZNE with the addition of just a few PV panels. All of the houses “fit” in the larger development and cannot be differentiated based on their overall design. In addition, the builder developed firsthand experience in the construction of these high-performance houses, which is replicable and marketable.

Post Occupancy: Energy Use / Occupant Behavior

It is interesting to compare House #12 with the ZNE houses of Case Study No. 1, the spec house at 609 Marigold, and Case Study No. 2, the Fortunato House. They are approximately the same floor area (the Fortunato House is 80% the size of the other two), but House #12 achieved ZNE performance with a 4.0 kW system, while the house at 609 Marigold in Corona del Mar used an installed 10.9 kW system and the Fortunato House has an installed system of 6.5 kW.

Although there are some differences in the ZNE design features of the houses and the climates of the locations (inland versus marine), the primary difference is likely to be the result of user behavior. Given that the other houses in the *ZNE Group* of comparable size did not achieve ZNE performance supports this conjecture.

Another general observation by on-site observers of the research partnership, applicable to some of the houses that did not perform very close to ZNE, is that some of the buyers did not concern themselves with careful and frugal energy use since they considered that the solar energy supplied was “free energy”.

Post Occupancy: Battery Energy Storage / Occupant Behavior

The buyers of the houses in the *ZNE Study Group* welcomed the battery energy storage features, but not for the technical reasons of assisting the electrical grid with the peak load shift.The reported desirability of energy storage was the maintenance of power to the house in a power outage, especially in the event of an emergency such as an earthquake. The buyers thought of it primarily as a resiliency feature.

CASE STUDY NO. 5

Colonial House Multifamily Housing

PHOTO: GLEN MCDOWELL

Colonial House Multifamily Housing

Case Study No. 5

Data Summary

Building Type: Multifamily
Location: Oxnard, CA
Gross Floor Area: 46,552 gsf (total housing area)
Occupied: 2014

On-Site Renewable Energy System Installed: 99.8 kW

Measured On-Site Energy Production:
268,000 kWh/year (2015)

Measured EUI (Site):
All Housing Units Combined - 17.0 kBtu/sf-year (2015)

Owner/Client

Oxnard Pacific Associates, LLP, Eagle, ID

Developer

Pacific West Communities, Inc., a division of The Pacific Companies, Eagle, ID

Project Team

Architect: Coastal Architects, Oxnard, CA

Zero Net Energy Consultant: Redwood Energy, Arcata, CA

Mechanical, Electrical & Plumbing Engineer: Budlong & Associates, Camarillo, CA

Structural Engineer: RGSE Structural Engineers, Simi Valley, CA

Civil Engineer: Huitt-Zollars, Thousand Oaks, CA

General Contractor

Pacific West Builders, Inc., a division of The Pacific Companies, Eagle, ID

The general category of residential building also includes construction types other than wood frame, especially in the case of high-density housing. In this book of residential ZNE case studies, one type of this high-density, multifamily housing is examined in some detail: a low-rise mixed-use project that focuses on *affordable housing*. The process of achieving the ZNE performance goal within the institutional structures of financing, approvals, design and construction for such a project is as informative as the technical features. Both are discussed in this case study.

Background

The project as finally realized bears little resemblance to the project as initially envisioned for this site. It follows a familiar storyline of a California urban housing development and the dealings between private developers and city agencies.

The project gets its name from the restaurant/hotel that was built on the site just before the second World War. The Colonial House restaurant in particular was popular with Hollywood celebrities and it became a popular destination for residents of Oxnard. By the late 1980's it had fallen into disrepair and was sold to the City of Oxnard after years of false starts on developing the two-acre parcel.

Meanwhile, at another location in the City of Oxnard, the Aldersgate Development Company, based in Oxnard, was unsuccessful in getting its 50-acre parcel re-zoned by the City to allow a housing project to be developed there. However, the City saw an opportunity to obtain a good site for a municipal sports facility and proposed trading the large property for the city-owned Colonial House site, with the developer being granted permission to build a high-density mixed-use project there. The deal was struck and, in 2008, the developer proposed a large-scale luxury condominium project, which was approved by the City of Oxnard planning department.

With the *Great Recession* of 2009, financing for housing projects dried up and Aldersgate Development sold the project to *The Pacific Companies*, a developer that specializes in *affordable multifamily housing*[1]. The new developer sought creative ways to finance the project. One of the government programs created at the time was federal funding for low-income farmworker housing through the U. S. Department of Agriculture (USDA).

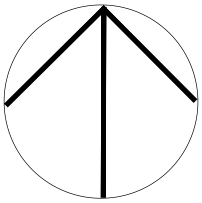
The Pacific Companies decided to seek funding from the USDA program and put together a proposal to compete for an award. The criteria for award of funding, in addition to an effective design for *affordable housing units*, was a number of stated goals for the sustainable design of the project, including a LEED Platinum certification. A special consultant, Redwood Energy, was brought in by The Pacific Companies to go one step further and lead the design team in an aggressive approach to zero-net-energy performance for the entire project. This innovative proposal succeeded in winning the USDA funding award for The Pacific Companies project team and they proceeded to develop plans for the long-vacant Colonial House site.

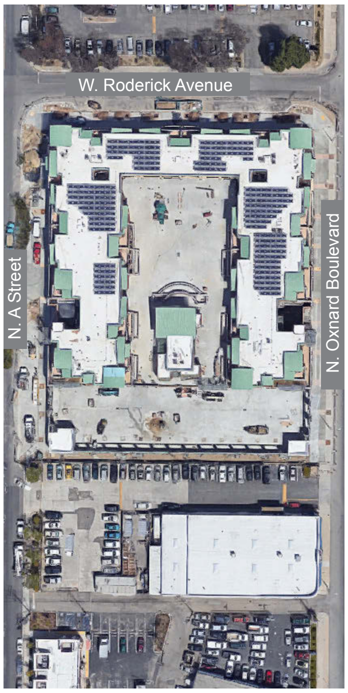
Project Process

As result of obtaining the financing for the project through this program, the "brief" for the programming and design was to utilize the Colonial House site for the maximum number of *affordable housing units* that could be fit on the site and to meet the sustainable design goals—both those required by the grant and those added as part of the successful proposal. Of particular interest for this case study, the latter included ZNE performance for the project as a whole.

[1] In the United States a commonly accepted guideline for *affordable housing* is a total housing cost that does not exceed 30% of the total gross income of a household. In the case of this farmworker housing, where the units were all rental, this concept basically set the maximum amount of the rent that could be charged.

Colonial House Multi-Family Housing: General Vicinity Plan





Building Program

There are four unit sizes in the project, specified by the number of bedrooms (1BR, 2BR, 3BR, 4BR). The eight one-bedroom units average 730 sq. ft. and the eight largest, the four-bedroom units, average 1,445 sq. ft. There are sixteen two-bedroom units, the most popular size, averaging 919 sq. ft., and twelve three-bedroom units averaging 1,204 sq. ft. There is one bathroom in the one- and two-bedroom units, with two bathrooms in both the three- and four-bedroom units. These rental units are planned on two levels above one level of parking and commercial spaces that are located at the periphery of the site at the street frontage.

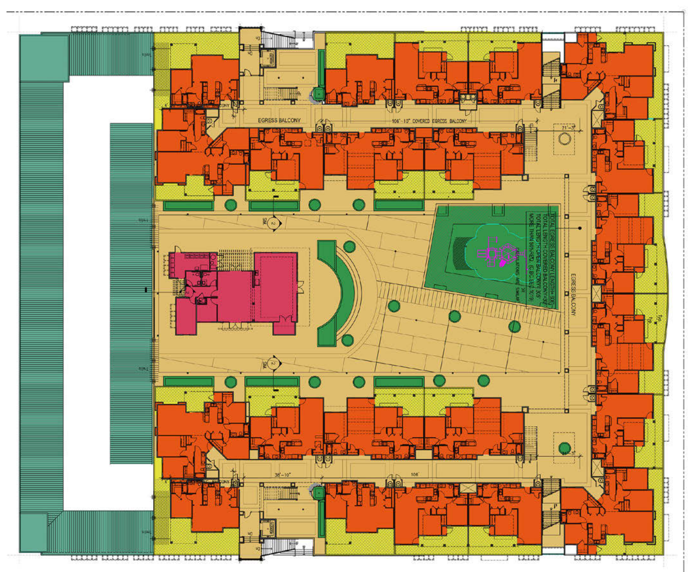
There are community laundry facilities, so no individual unit has a washer or dryer. (The accounting of energy use for the individual unit therefore does not include these usual “plug load” items.)

Each one-bedroom unit is allotted one parking space in the ground-level parking area below the housing podium. All other units receive two spaces each. The commercial spaces located at the ground level are managed separately from the housing units above and are not connected to the LEED or ZNE goals for the building. Their energy use as well as electric loads associated with the parking are not counted in the energy use total for the multifamily housing project.

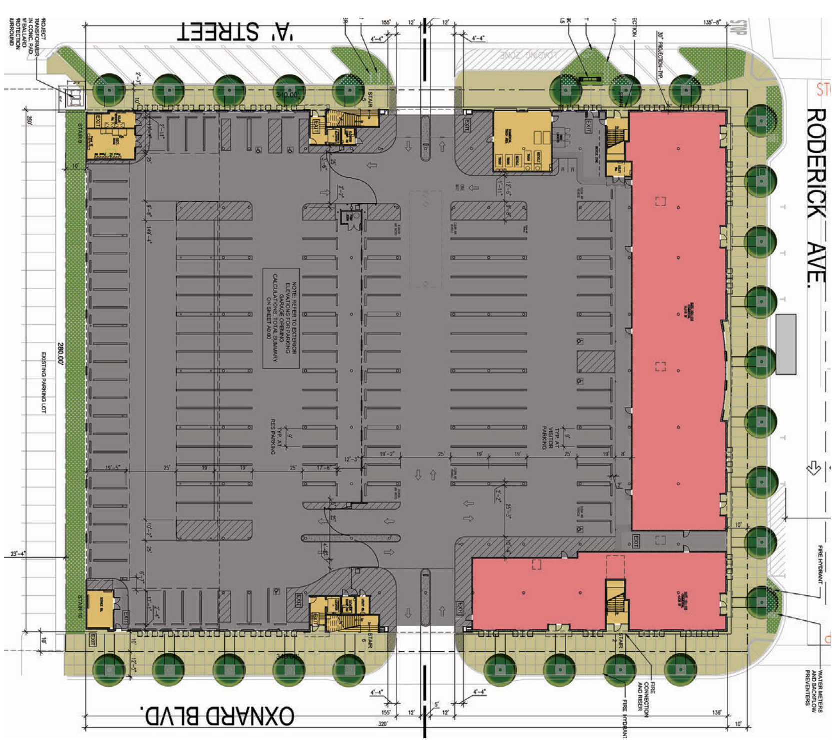
The solar PV system on the roof is dedicated solely to the housing units and community spaces and their ZNE goal. This case study is therefore concerned with the second and third levels of this whole Colonial House project and is limited to the 44 units of affordable rental housing for farmworkers and the associated community spaces.

Colonial House Level Plans

Third Level Plan



Second Level Plan



Ground Level Plan

(Below) View of Colonial House project, two levels of multi-family residential above ground level commercial and parking.

PHOTO: GLEN MCDOWELL

Site Constraints

The site was essentially cleared of all structures at the time of approval and the type of project was limited by zoning to the three levels proposed: ground level commercial and parking and two levels of apartment units. There were no other significant site constraints on the design of the project.

Financing Constraints

Because the project was financed largely through the USDA *Farm Labor Housing Direct Loans and Grants Program* as a result of the Pacific Company's commitment to LEED Platinum certification and ZNE performance of the housing structure as a part of their funding application, this funding came with its associated constraints and requirements.

There were, for example, stipulations about rent and utility allowances. Rents at Colonial House are a fixed 30% of the tenant's annual household income. A monthly "utility allowance" (in dollars) for each type of unit (1BR, 2BR, 3BR or 4BR) is determined by the combination of the output of the solar array and the average consumption of the building during that period, according to a formula given by the California Public Utilities Commission (CPUC). Tenants who consume less energy than the utility allowance receive a credit from the electric utility. Those that exceed the allowance are charged for their additional usage.

Low Energy Design Strategies

The LEED Platinum and ZNE energy performance goals required energy-efficient design strategies and construction features that are discussed in detail below. The low-energy/high-efficiency planning of the affordable housing part of the project was modeled during the design phases to assist in cost-effective decision-making. This energy modeling process is discussed in detail below in the section, *Energy Design Analysis and Energy Performance.*

General Design Considerations

Generally, the number of units was maximized to fit on the two levels, with a large solar PV array installed on the roof to serve the new community as a whole. To minimize the carbon footprint of the project, no natural gas was installed on the site and only electric equipment and appliances are specified. Thus, all heating/cooling, hot water and cooking are electrical only.

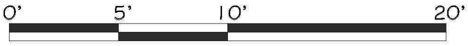
Building Envelope – Insulation and Windows

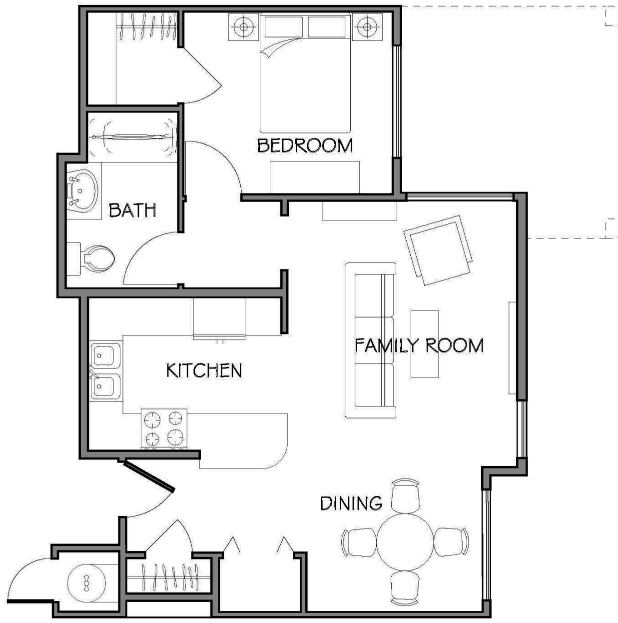
The building is standard wood frame construction with maximum fiberglass insulation used between both the wall studs and the roof joists. No mitigation of thermal bridging through the wall studs is used, such as a layer of rigid insulation over the wood stud wall. The roof joists, however, utilize a layer of sloped rigid foam to slope the roof surface for drainage, which also serves to prevent thermal bridging across the large area of flat roof. The wall R-values range from R-15 to R-21 and the roofs average R-49. The concrete podium, which serves as the floor of the second-floor units, is insulated with panels that have an R-value of R=20.

The glazing properties average U=0.30 and solar heat gain factor (SHGF) equal to 0.37, which are values of good quality *low-e glass*[2]. So the windows have very good thermal property values.

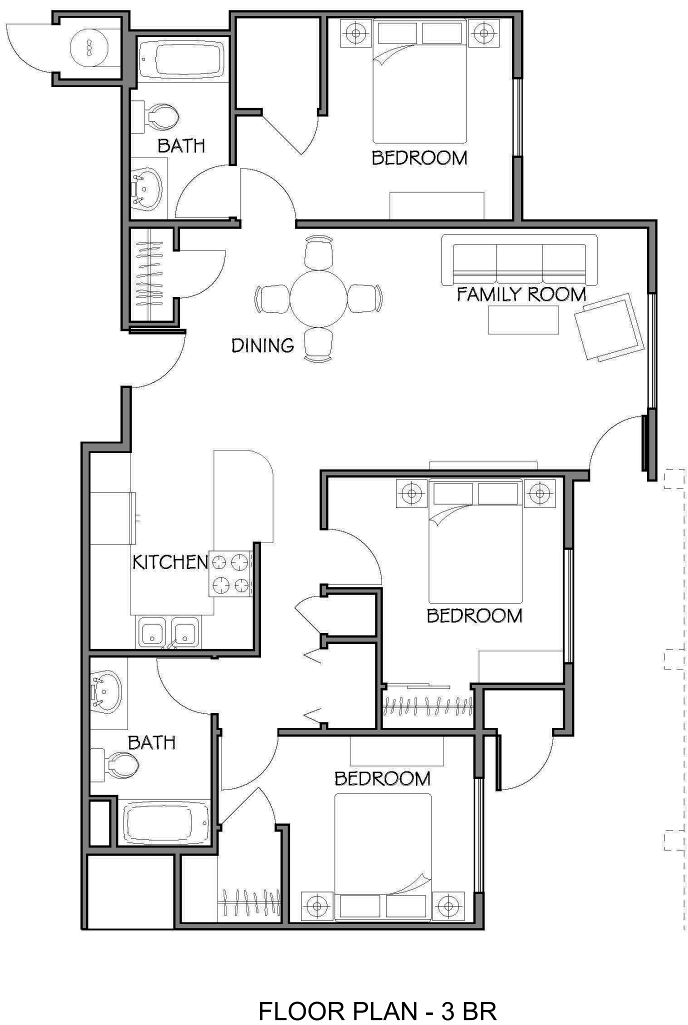
[2] *Low-E*, or low-emissivity, glass minimizes the amount of infrared and ultraviolet light that comes through glass, without minimizing the amount of light that enters the room. *Low-E* glass windows have a microscopically thin coating that is transparent and reflects heat.

Colonial House Unit Plans

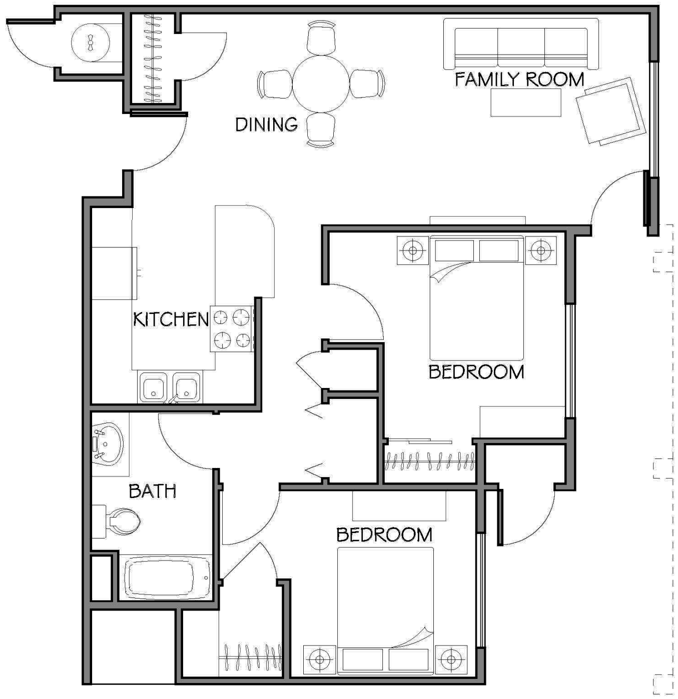




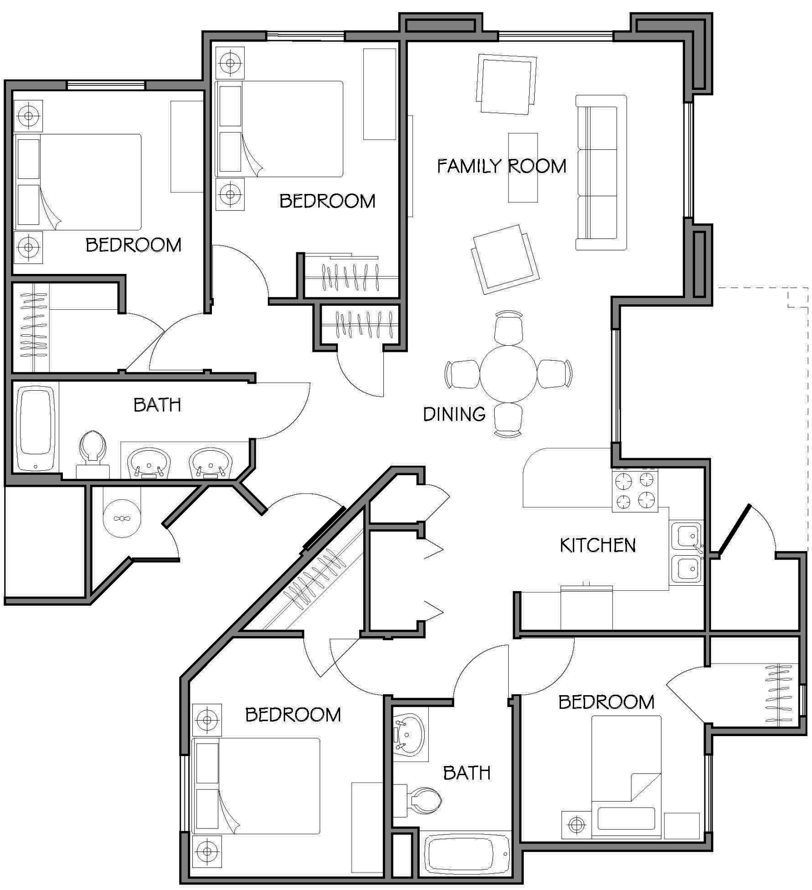
FLOOR PLAN - 1 BR



FLOOR PLAN - 3 BR



FLOOR PLAN - 2 BR



FLOOR PLAN - 4 BR

Building Envelope – Air-tightness

The Colonial House project construction is built to the high energy-efficiency standards of *Energy Star for Homes v2.0* [3] with complete *HERS measures*[4] implemented. However, multifamily housing is not required by Energy Star or HERS certification to have air-tightness testing, nor are there guidelines offered by the California Energy Commission, because it is possible to have air leakage between adjacent units although the unit is well-sealed to the exterior. So, verifying airtightness with a Blower Door Test would not yield meaningful results. However, the construction was required to undergo *QII Inspection*[5] as part of the certification process, which makes it likely that an acceptable level of airtightness was achieved.

Heating, Ventilating and Cooling Systems

Because of the proximity to the ocean and its cooling breezes, no mechanical cooling is installed in any of the housing units. As a result, many of the occupants utilize portable room fans to augment the natural ventilation and to provide a cooling assist on exceptionally warm days. The community rooms (laundry, manager's office and meeting room), however, are supplied with air conditioning via a package heat pump unit.

With no mechanical cooling of the individual units, heating is simplified by providing in-wall electric resistance heating, placed in the living room and bedrooms of each unit. Due to the *Energy Star* levels of insulation and inspection, the project was able to reduce initial cost by using electric resistance heating, which is unusual in high performance housing but well-suited for this temperate climate. In the first year, only two apartments needed the electric resistance heating.

Domestic Hot Water

Every unit, including the community laundry room, has a dedicated electric heat pump water heater. An innovative idea at the time, these energy-efficient water heaters, when combined with the electric ranges, allowed the design of an all-electric, zero-carbon housing project.

Daylighting and Electric Lighting

Windows are concentrated in the living areas and bedrooms, while the kitchens are open to the living spaces, so the sense of all the units is that of a light-filled apartment. In addition, high efficiency lamps are provided in all light fixtures.

Plug Load and Equipment

All appliances are Energy Star, including the washers and dryers located in the community laundry facilities. Cooking is done by electric ranges (not induction ranges)..

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[3] *Energy Star Certified Homes Program* The ENERGY STAR Certified Homes program helps homebuyers easily identify homes that are significantly more energy efficient than standard construction in the marketplace. For certification requirements, see: https://www.energystar.gov/index.cfm?c=bldrs_lenders_raters.homes_guidelns.

[4] *Home Energy Rating System (HERS)* is a series of energy code verification procedures that are used to confirm that certain building features are meeting their full performance during construction. See the discussion in the Introduction to this book for more details about the HERS Rating System in California.

[5] *QII Inspection* is "Quality Installed Insulation Inspection", which means it was carefully inspected throughout construction for proper air tightness sealing (all cracks, penetrations, wall junctures) and careful insulation installation. There is no testing associated with this inspection, however.

(Below, Left) View of central shared common area.


PHOTO: GLEN MCDOWELL

Control Systems

No *smart* systems are installed to provide automated control of various energy-using systems, but a home energy monitoring system is standard in every unit. This simple monitoring system provides an indication on a wall-mounted device of the total electricity use. The device provides a color graphic indicator of both the instantaneous use in watts and the cumulative use of energy in kWh over the course of the day. The tenants are therefore given real-time information about high levels of energy use and gives them the opportunity to take corrective action.

(Opposite page) Initial size and layout of the solar PV system on the roofs and trellises needed to realize ZNE performance of the housing and community building. (Courtesy Coastal Architects).

Renewable On-Site Energy Supply

The large solar PV array was sized based on the results of the computer simulation of the annual energy consumption of the 44 housing units, assuming average energy use patterns prescribed by the software. (See energy modeling discussion below.) This analysis yielded an annual energy use of 216,000 kWh, which was determined to be the minimum required output for ZNE performance. This was calculated as that produced by a 147 kW(DC) system with the Oxnard project’s configuration.

The decision was made to install solar PV panels on all available roof space as limited by code and fire access restrictions and on the three trellis features in the community open space. Initially, the solar PV system planned consisted of 523 panels mounted at 10° tilt angle on the roof arrays (housing and community building) and 147 panels mounted flat on the trellises, as shown in the drawing on the opposite page. This system design would have a total of 670 panels of SunPower module (Type E) with an output of 240 watts (DC) and a total installation of 160.8 kW. With that output, the housing project would have been expected to perform at ZNE as measured during occupancy.

(Below) Solar PV system as installed. (Courtesy of Redwood Energy).

The actual system installed consists of 304 SunPower modules with an output of 327 watts (DC) for a total installation of 99.8 kW. This essentially means that when all units are taken together, the total energy produced on site annually would not offset the annual energy consumption total.

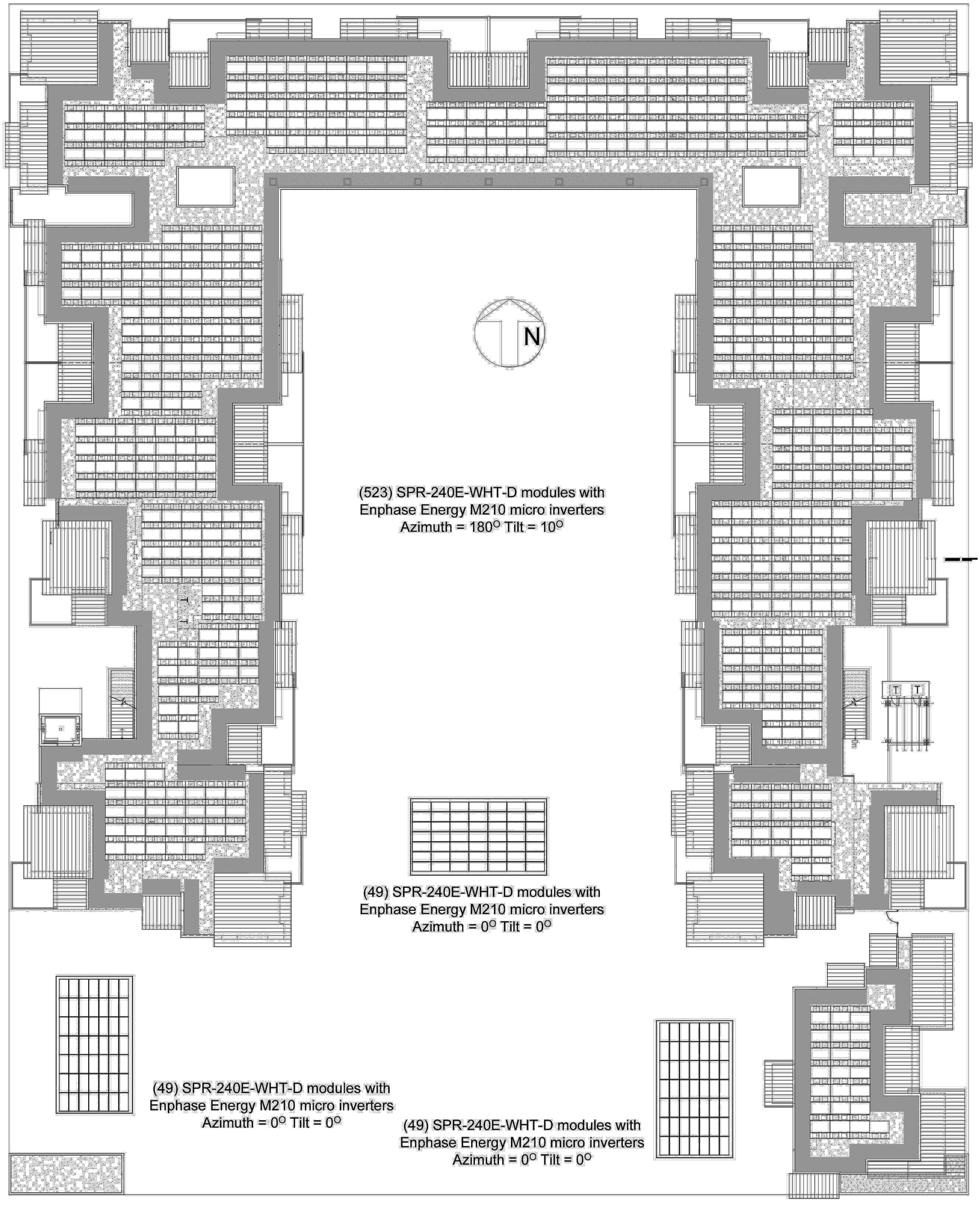

N
(523) SPR-240E-WHT-D modules with
Enphase Energy M210 micro inverters
Azimuth = 180° Tilt = 10°
(49) SPR-240E-WHT-D modules with
Enphase Energy M210 micro inverters
Azimuth = 0° Tilt = 0°
(49) SPR-240E-WHT-D modules with
Enphase Energy M210 micro inverters
Azimuth = 0° Tilt = 0°
(49) SPR-240E-WHT-D modules with
Enphase Energy M210 micro inverters
Azimuth = 0° Tilt = 0°

PHOTO: GLEN MCDOWELL

Energy Design Analysis and Energy Performance
Modeling versus Post-Occupancy Measurement

Energy Modeling

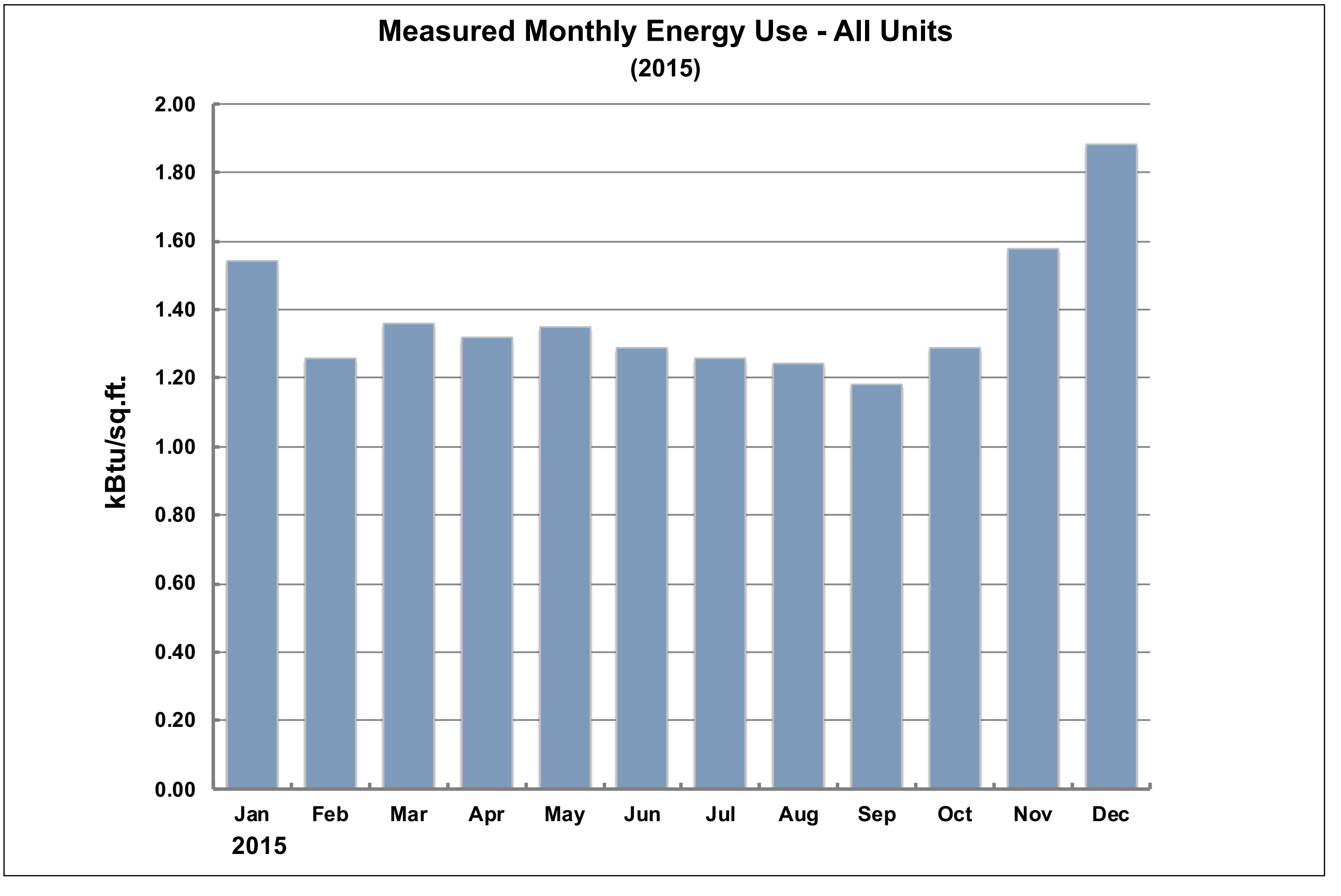
Energy Pro modeling software, approved by the California Energy Commission (CEC) for showing compliance with state energy standards for residential projects, was used to estimate the energy performance of the Colonial House project. Because of the affordable housing component, a project-specific *utility allowance* was required to be calculated for each unit, which is included in the maximum-allowable rent calculation. This is done using a CEC-mandated software tool known as the *California Utility Allowance Calculator (CUAC)*[6].

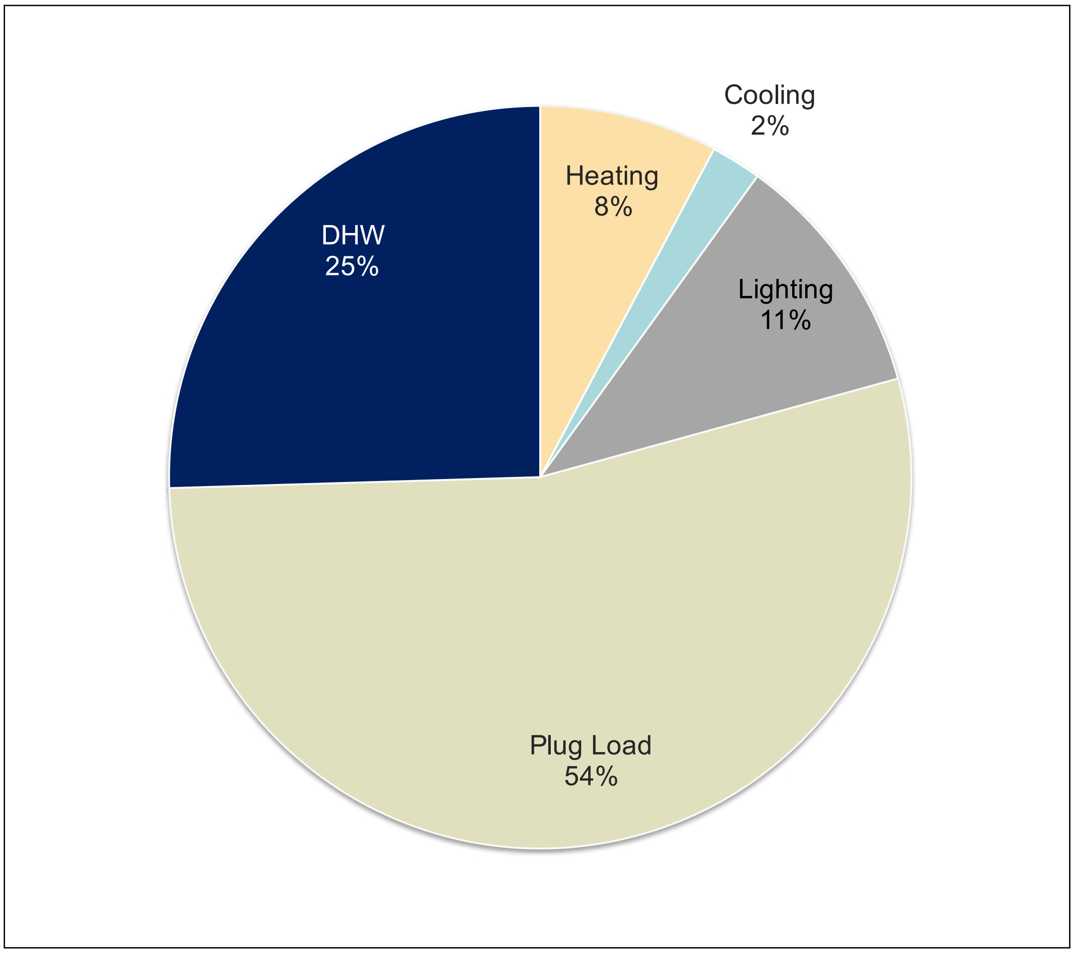
The energy modeling results using the CUAC-prescribed input values for the project as a whole and the average 3BR unit are shown on the folllowing pages, broken down by category of energy use (heating, cooling, lighting, plug load and domestic hot water (DHW). Both total annual and monthly modeling results for all units taken together are shown on the opposite page..

Energy Use—Monitoring and Measurement

Each one of the 44 units is individually monitored for energy use along with the energy produced by the large solar PV array. This data has been recorded routinely since 2014. When the total monthly energy consumption of all units of housing are tabulated for 2015, the results are as shown in the chart below. This can be compared with the energy modeling results for all the units of housing taken together, shown on the opposite page *(bottom)*.

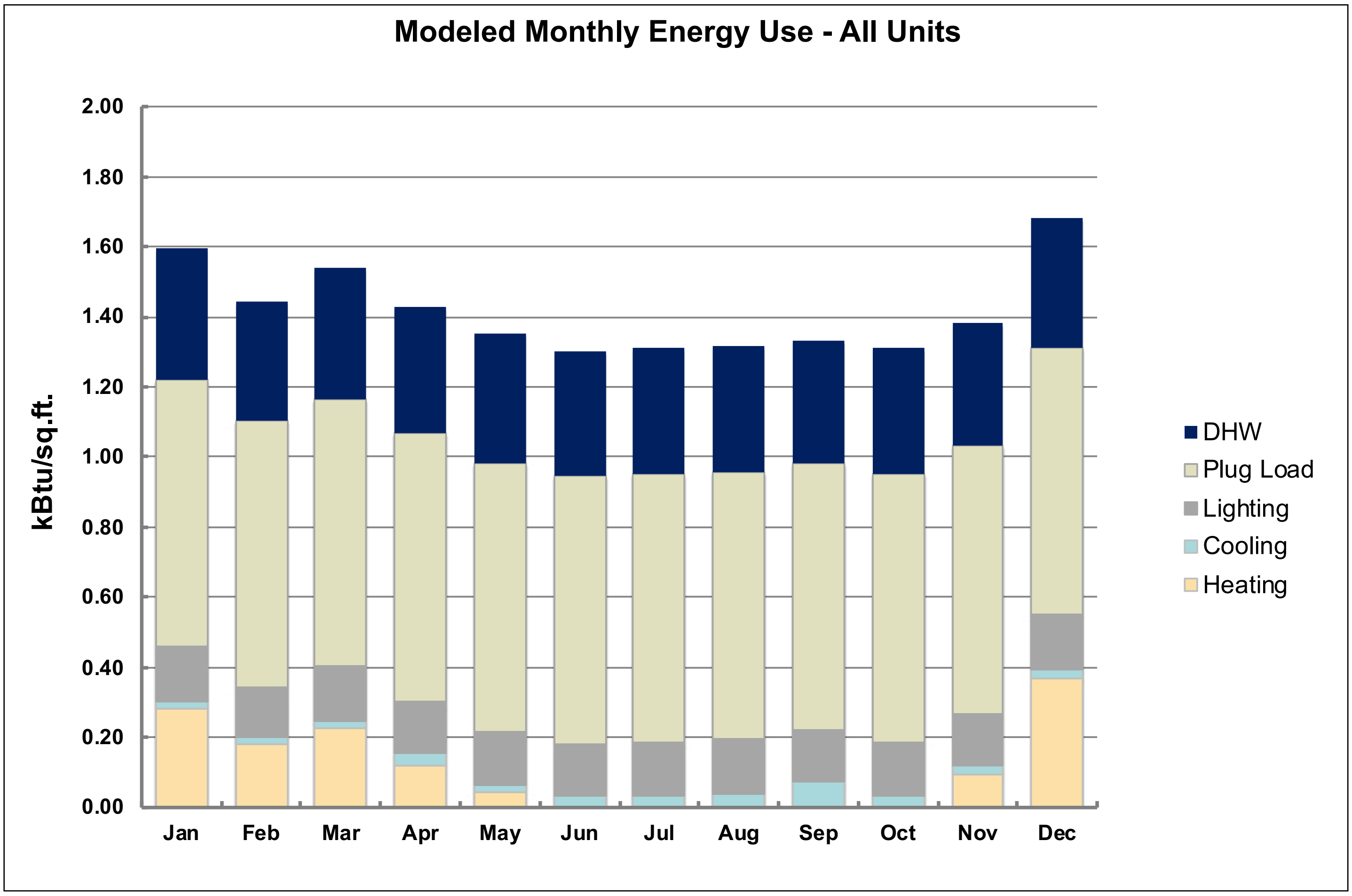
[6] The U. S. Internal Revenue Service (IRS) regulates the application of the *Low Income Housing Tax Credit (LIHTC)* for affordable housing projects and has authorized the use of CUAC in California to determine the utility allowances. See http://www.gosolarcalifornia.ca.gov/affordable/cuac/index.php.





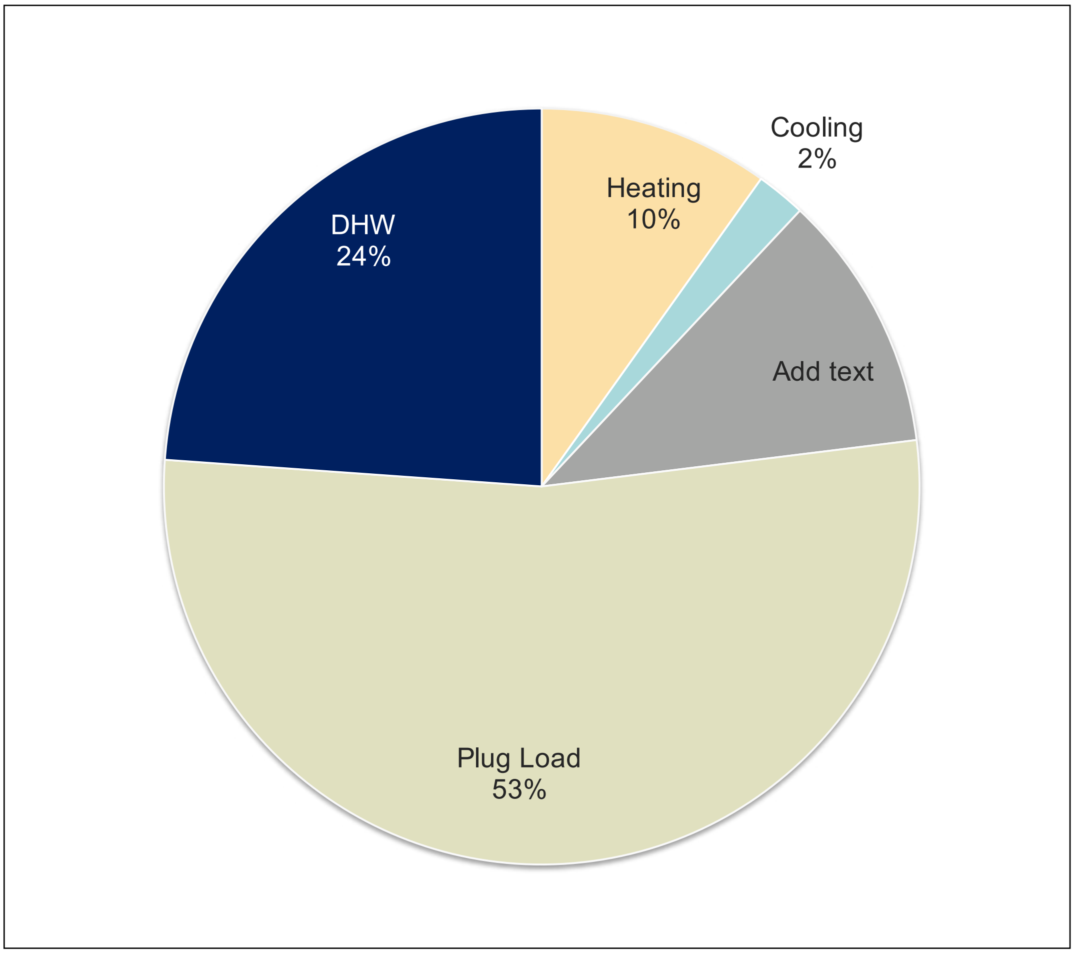
Modeled Annual Energy Use All Units

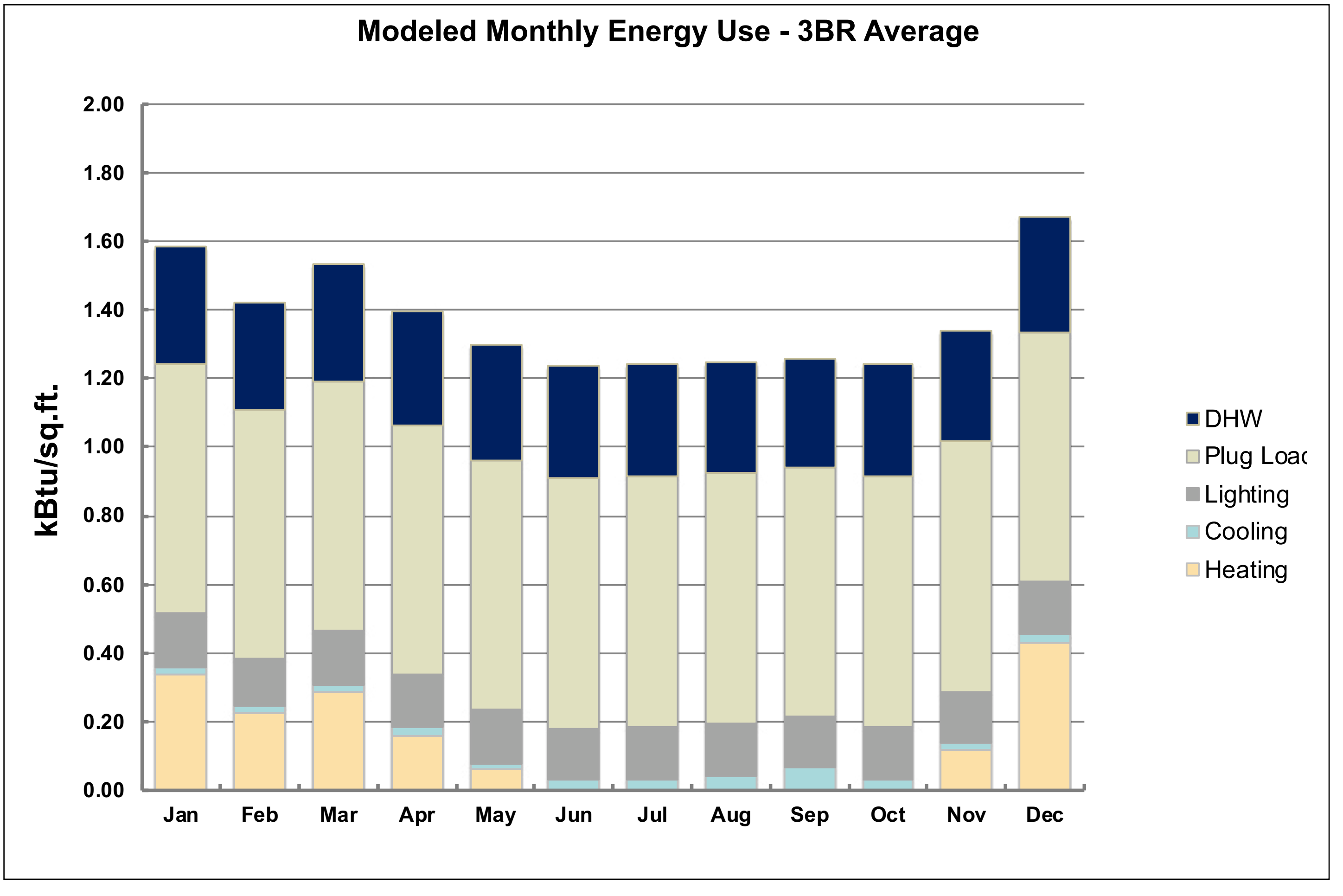
232,000 kWh/year
Measured EUI = 17.0



Modeled Annual Energy Use 3BR Average

7,100 kWh/year
Measured EUI = 20.1

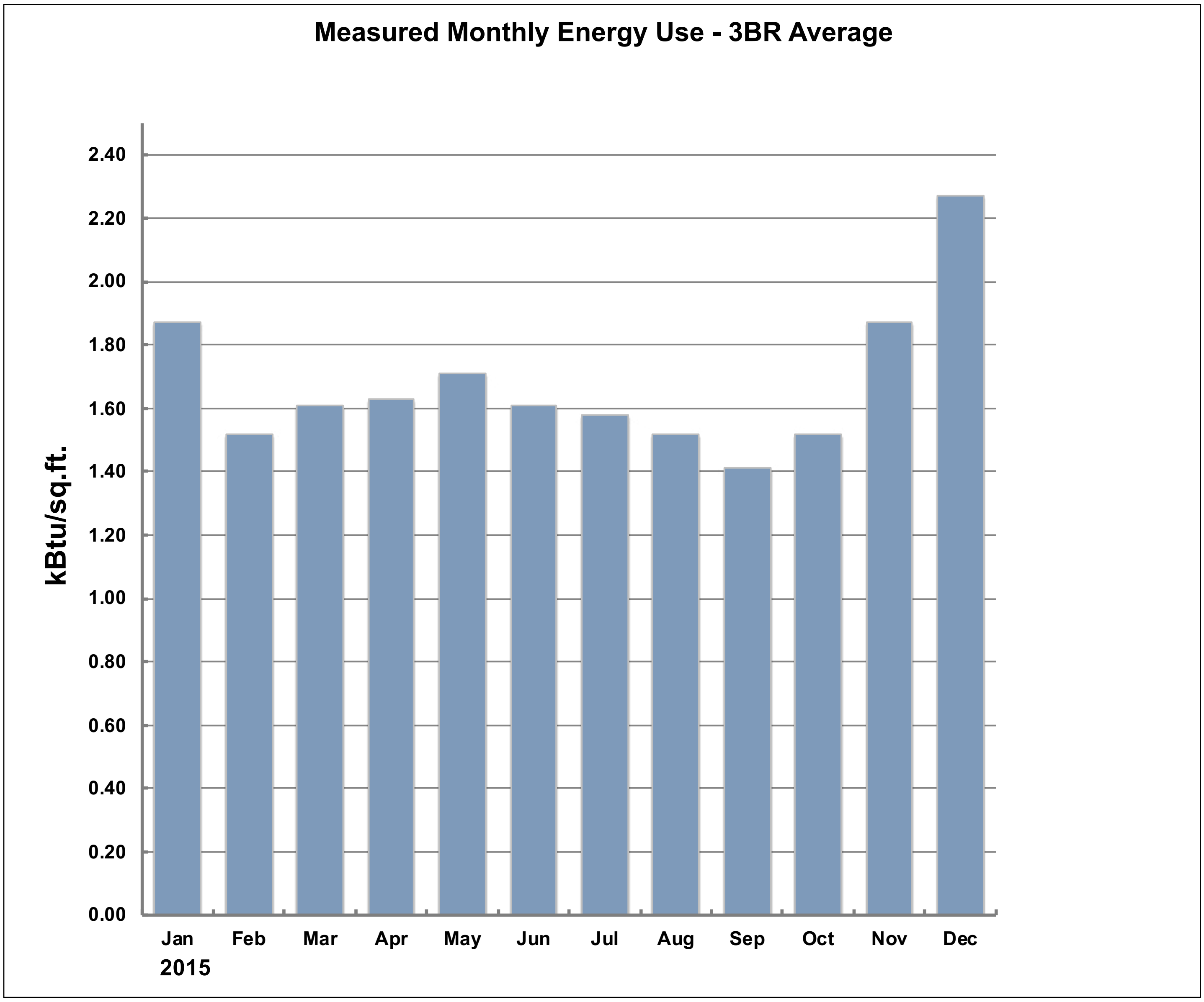




The total measured monthly energy use in 2015 can also be charted according to type of unit (1BR, 2BR, 3BR, 4BR), showing higher energy use in the 3BR unit on a per-square-foot basis. The case of the 3BR unit is highlighted with the comparison of the modeled and measured charts shown on the opposite page and below.

Energy Production versus Energy Use: Zero Net Energy Performance

As previously described, a monthly *utility allowance* (in dollars) for each type of unit (1BR, 2BR, 3BR or 4BR) is determined by the combination of the output of the solar array and the average consumption of the building during that period. Essentially this is the method of apportioning the output of the single large solar PV array to the individual tenants—not a kWh share of the monthly or annual energy production but a direct dollar credit.



It is possible to do a ZNE performance analysis using the total energy use of all units versus the energy production recorded for the entire array. This analysis is shown in the two charts on the opposite page The cumulative net energy performance of the project as a whole shows that the housing did not achieve ZNE performance in 2015, as expected due to the reduction in solar PV panels in the rooftop arrays. The performance bears out the results of energy modeling analysis.

However, it is possible to look at net energy performance of the *individual units*, as opposed to simple averages, by considering the individually metered results for the energy use and the basis for the utility allowance in kWh. The HERS Rater's site inspection carried out such and analysis in September 2017, which showed that over a period of 2-1/2 years, seven individual units had performed at net positive energy, with two more within a few percent of ZNE performance, out of the total 44 units of housing. With the exception of the 4BR units, these ZNE-performing units are representative of all unit types in terms of the fraction that are performing at ZNE.

Post Occupancy: Observations and Conclusions

The Colonial House multifamily housing project is primarily a design based on the requirements of affordable housing as prescribed by federal and state agencies, but in this case including design features corresponding to the special sustainability and energy performance goals set in the developer's brief in its funding application. These goals were met to some degree as described in the preceding sections.

Post Occupancy: Solar PV System

As noted above, initially the design of the solar PV system called for 670 panels of a SunPower module (Type E) with an output of 240 watts (DC) each for a total installation of 160.8 kW. Despite the energy modeling result that showed that ZNE performance would require a 147 kW system, the decision was made to install the smaller system of 100 kW. As expected, according to the data collected in 2015, the result was that the project as a whole fell short of ZNE performance.

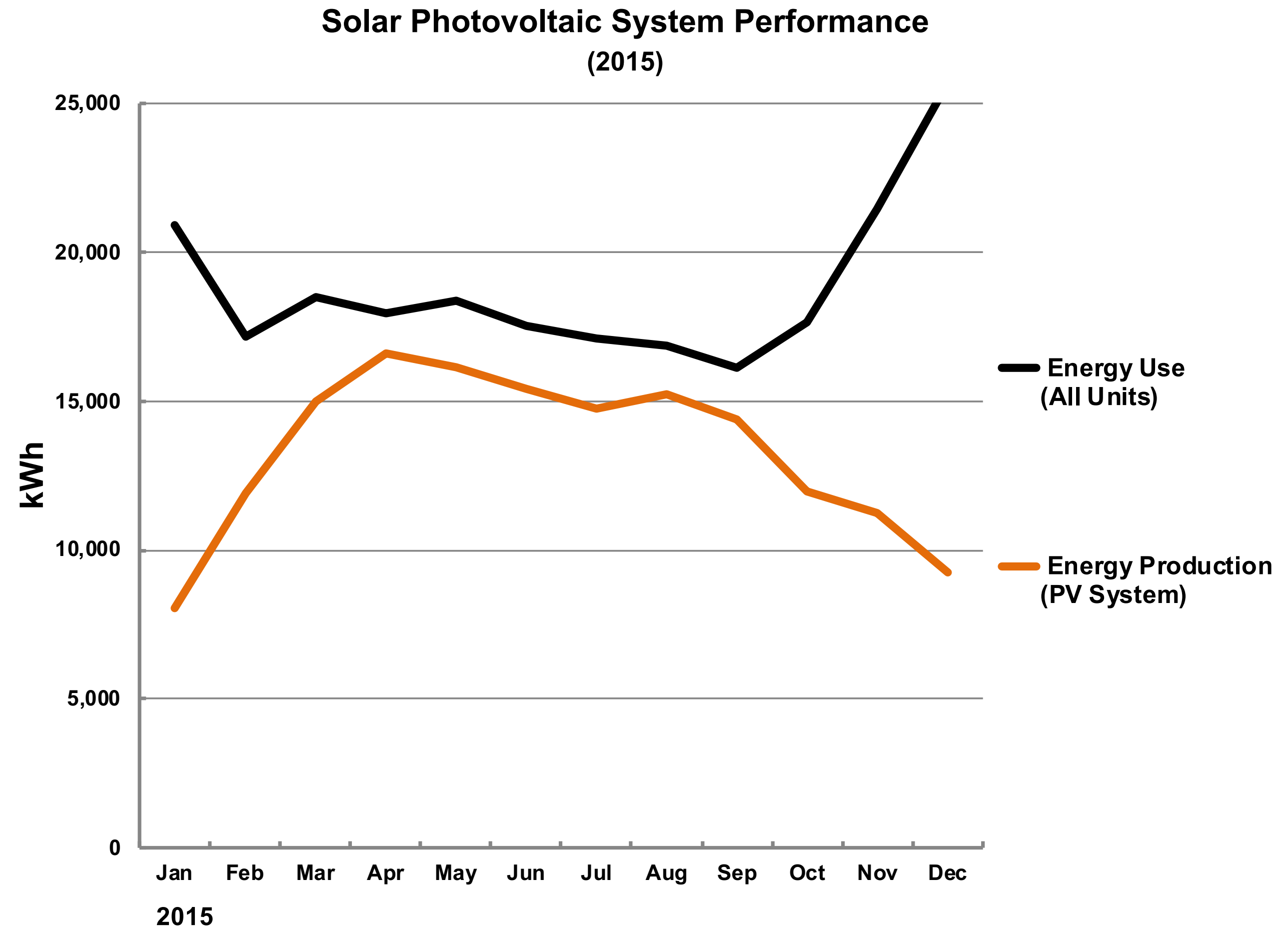
However, several individual units were found to be achieving ZNE performance that year based on the allocation of their share of the solar PV system output and the average energy consumption of all the units. The HERS Rater's site inspection in 2017 verified that seven individual units had performed at better than ZNE (net positive), with two more within a few percent of ZNE performance. The project's ZNE performance was therefore achieved for some of the project units.

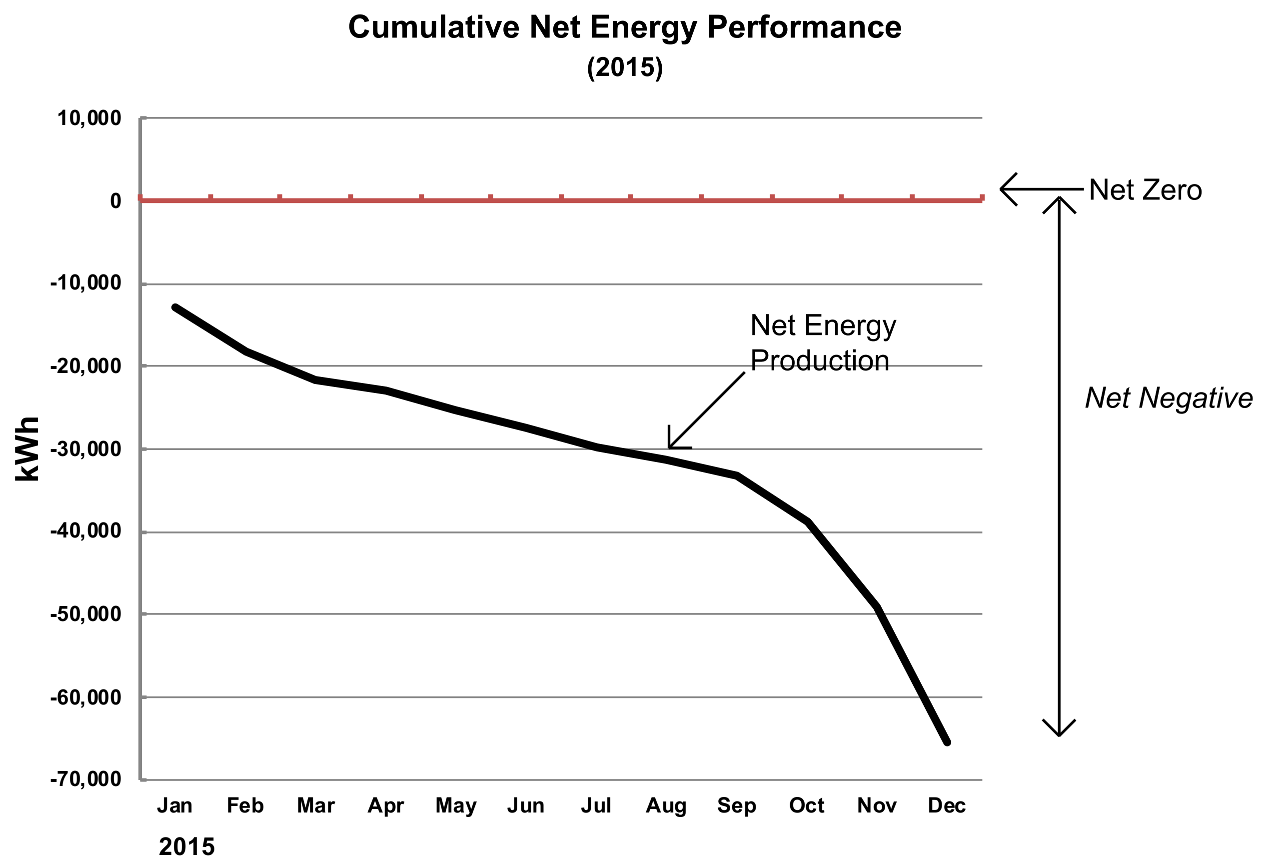
Post Occupancy: User Behavior

In the informal post-occupancy interviews, the tenants' observations about the project's design concerned those aspects unrelated to the energy goals. Since the cost of energy is included in the rent calculation by formula, unless their energy use is particularly high to cause an increase in the individual utility cost, there is little incentive to modify behavior based on energy use. There was some awareness of the home energy monitoring system, which is standard in every unit and gives visual cues to the occupants about possible excessive energy use, but the wall-mounted indicators in the units visited during the interviews were not operational.

Locating the laundry facilities in a central building was actually a design strategy to lower energy use. In general, laundry dryers are used only half as often when located in a central shared facility than when located within the individual unit, primarily for user-behavior reasons. Since the effect on marketability was not considered large in this case, the central location was chosen[7].

[7] S. Armstrong, M. Winkler, "The Impact of a Home Laundry on Energy Consumption", (2012) https://www.redwoodenergy.tech/publications/


Solar Photovoltaic System Performance
(2015)
25,000
20,000
15,000
10,000
5,000
0
kWh
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2015
Energy Use
(All Units)
Energy Production
(PV System)


Cumulative Net Energy Performance
(2015)
10,000
0
-10,000
-20,000
-30,000
-40,000
-50,000
-60,000
-70,000
kWh
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2015
Net Zero
Net Energy
Production
Net Negative

Conclusion ▷

Observations

This first zero-net-energy (ZNE) case study monograph about residential buildings, *Zero Net Energy Residential Buildings, Volume 1*, examines the design and performance of five very different types of ZNE housing design, ranging from simple renovation of a single-family home to a low-rise multi-family project. The initial goal of each project is ZNE performance, so all the case study projects have the installation of a solar PV system that offsets the annual energy demand as a base component of the designs. The projects differ, however, in the choice of energy-efficiency design strategies utilized to minimize that annual energy demand, which are based on financial criteria peculiar to the type of project. These criteria depend on whether the project is to be owner-occupied or, as is the case for three of the projects, if the house or unit is to marketed for sale or rent. Not unlike other design features of the particular housing project, the perceived marketability and expected profit margins are a determining factor in the choice of system or feature.

Yet, even though the decisions made may reflect different financial or marketing criteria, there is also a commonality among the case study projects for technical choices because of the basic similarity of construction type (generally wood-frame, “Type 5” construction) and the common “program” of spaces. In this regard, it is possible to observe and compare some differences in the design choices made and their relative success, which are informative for other ZNE residential projects.

Observations from the Case Studies in this Volume

Single-Family Residential

This type of housing, representing four of the case study projects, has the same basic type of construction and each utilizes similar energy-efficient systems and features that are unusual when compared to standard housing construction. The most significant such feature, which is not found at all in standard construction, is described in the case studies as *air-tightness* of the overall construction. Furthermore, for each ZNE case study project, this characteristic was actually measured by physical testing of the completed house and rated on a scale according to its rate of air leakage. What is remarkable about this is the importance placed on this aspect of design for all of the case study projects and the recognition that air leakage is the major cause of heating and cooling demand in a highly-insulated house.

The second observation is that the design of each of these case study houses recognizes the importance of indoor air quality when air-tight design is a characteristic of the construction. However, none of the projects include real-time monitoring of indoor air quality or installation of more elaborate ventilating systems, which may be advisable for extremely air-tight construction.

All of the single-family case study houses utilize electric heat pumps, either air-source or air-water type, for energy-efficient heating and cooling. This is preferable to traditional gas-fired furnaces for heating combined with a conventional air-conditioning system for cooling. Heat pump technology has made perhaps the largest advances in energy efficiency, practically doubling in COP in the last ten years. Cost effectiveness has also improved and will continue to do so, making heat pumps the logical choice for future ZNE residential projects.

Furthermore, in all but one single-family case study house, electric heat pump water heaters were used instead of the standard gas-fired water heaters. This is more energy-efficient, is easily supported by the solar PV system and brings the house closer to an all-electric (zero-carbon) design. With the one exception, the cooking appliances in these case study houses are electric powered—either electric range or induction cooktop with electric oven—achieving that zero-carbon design.

Low-Rise Multifamily Residential

The one multifamily housing project utilizes many of the same systems and features of the single-family case study projects. The air-tightness characteristic was recognized as important by the designers, but testing was not possible in this case because of shared walls between units. This design feature needs further study in the case of multifamily residential construction because of its importance in the size of heating/cooling loads.

Multifamily residential projects generally have a common solar PV system, with individual units assigned a share of the energy production according to some formula devised by the managing or regulatory body. If the individual unit is credited with the dollar amount corresponding to this share, then there is an incentive to reduce energy consumption, perhaps even to achieve ZNE at the unit level. Future case studies of market-type multifamily residential projects may demonstrate this.

Modeling and Measurement

As shown in these case studies, for individual single-family houses, energy modeling is usually done only when the builder is motivated to have performance information during the design phase or simply to right-size the solar PV system for ZNE performance. (California's Title-24 code compliance models the house energy performance in terms of the TDV metric but does not produce actual energy-use results.) In other cases when intended for sale, the builder provides the initial solar PV system based on assumed loads with the capacity to add panels in the future if necessary to achieve ZNE performance. As seen in the case studies in this book, the latter often results in houses or units that achieve ZNE performance and many that do not.

Energy monitoring equipment is usually not installed for cost reasons, but the owner is informed of the monthly energy performance through the utility net meter data contained in the monthly utility statement and the solar PV production data. With these two sources of data information, it is possible to determine if the house is performing at ZNE overall.

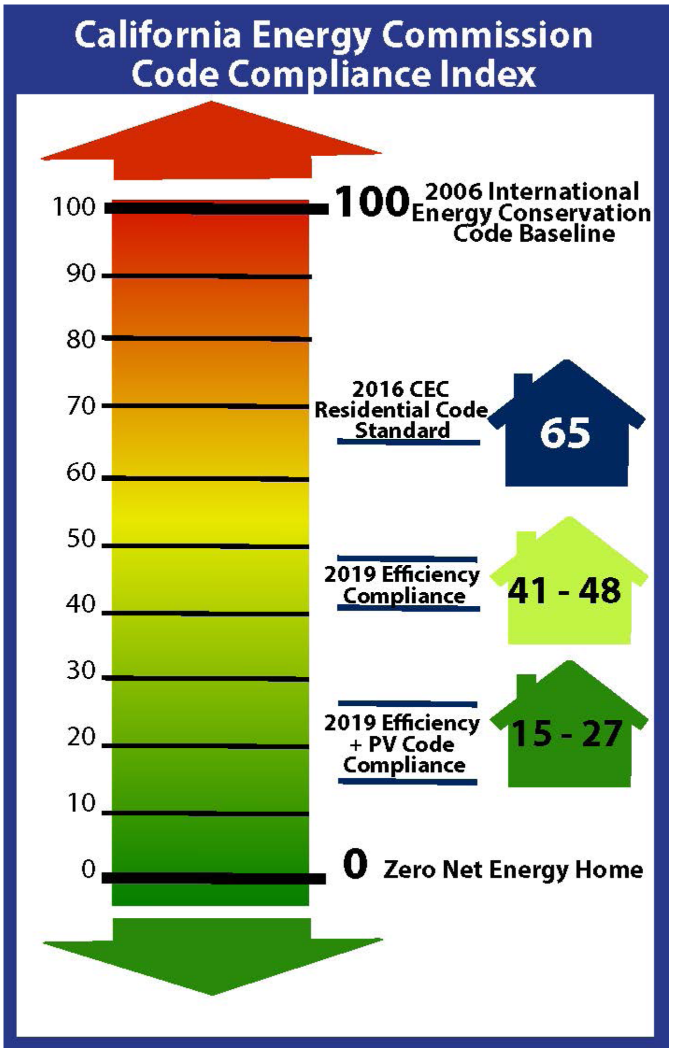
The Imminent 2020 California Benchmark Goal of ZNE Design for New Residential Construction

The five diverse types of residential construction in these case studies illustrate many of the technical and marketing-related issues pertaining to the goal of ZNE design for all new residential construction starting in 2020, a little more than one year away. Much study and discussion of these issues has occurred during the past decade and the California Energy Commission has arrived at an approach to meeting that goal in principle, which is to be discussed and evaluated further in the interim.

This approach is best described by referring to the discussion on page *viii* of the Introduction to this book, about the EDR rating of a residential project as prescribed by Title-24 energy standards. This rating on the HERS Index scale will be set at a number (not zero) corresponding to 100%-offset of the *electric* energy use of a mixed-fuel residential project (gas and electricity). See the illustration on the following page of the EDR rating requirement as described on the HERS Index scale, which will be in effect in the 2020 code. The mixed-fuel residential project is assumed to be approximately 50% electric and 50% natural gas. An all-electric home would be required to meet the same EDR rating.

This 2020 code requirement is, strictly speaking, not a ZNE standard for new residential construction. However, local agencies may adopt "reach codes" that require an EDR=0 rating per the HERS Index scale.

(Right) The California Energy Commission Code Compliance Index of EDR values. The 2019 "Efficiency + PV" code will require an EDR in the range of 15 to 27 points on the scale. Note the EDR=0 will not be required in 2020.
(Image courtesy of Redwood Energy and the California Energy Commission.)



New Design Issues for ZNE Residential

The five case study residential projects in this book were built at a time when solar power for housing and ZNE design were innovations not yet widespread in the California market. A new issue has emerged in the last couple of years that will have immediate impact on residential design and construction: *grid harmonization*. With the rapid penetration of solar power and electric vehicles in the California markets, the pattern of the electric power demand on the public utilities' electric grid has been distorted. In the middle of the day, peak solar electric production has gradually reduced grid power demand during that part of the day, while in the evening hours when the solar generation has declined, electricity demand has increased. This distortion of demand over the course of a day, referred to as the *Duck Curve*[1], normally requires the public utilities to bring large "peaker plants" online in the evening to meet the greater demand, at the cost of greater carbon production. Letting power plants maintain an idle operation during the midday hours is also problemmatic for the grid.

[1] See: California ISO, "What the duck curve tells us about managing a green grid", (January, 2018), https://www.caiso.com/documents/flexibleresourceshelprenewables_fastfacts.pdf

Grid harmonization involves flattening the electric power demand over the course of the day so that the power plants and electric grid operate more steadily and, as a result, more reliably. The component technology that can effect this desired change to the current trend is *electric battery storage.* Adding energy storage to the grid and/or the individual home will allow solar energy collected during the day to be stored for later use in the evening, thus producing the desired effect. This technology promises to have such beneficial effects that Governor Jerry Brown recently signed a bill[2] to provide almost $1 billion in rebates to customers who install batteries through 2025, which is anticipated to add three gigawatts of storage capacity to California's power grid.

This advance in renewable energy systems design will affect individual residential projects in the near future, including possibly eventual code requirements, utility time-of-day rate structures, and smart control of residential electric power use. Future case study residential projects are likely to involve issues beyond design for annual ZNE performance and include the balance of solar electric power generation and energy storage to optimize both grid performance and the cost of energy to the residential consumer.

[2] For the bill's language, see: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB700

Acknowledgments

Many thanks to the following clients, users and designers of these ZNE residential projects who gave generously of their time to provide all of the information and insights into various aspects of their design and performance. They share an obvious pride in their work and a commitment to the goal of a future of sustainably designed buildings.

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For the detailed information about the design and techniques of construction of the ZNE homes of this case study, including performance data.

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