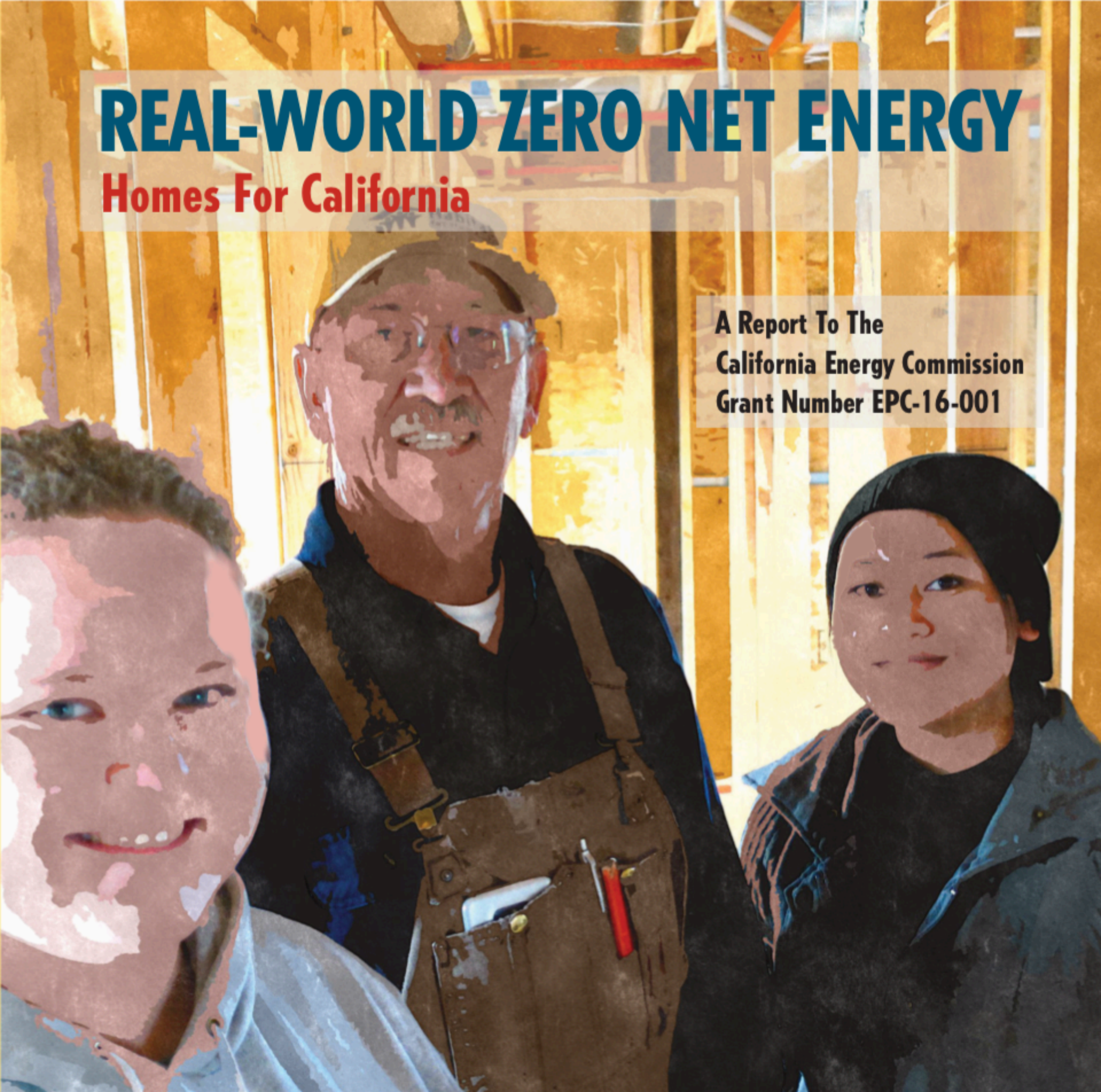
REAL-WORLD ZERO NET ENERGY

Homes For California

A Report To The
California Energy Commission
Grant Number EPC-16-001



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Gas Technology Institute
Davis, California
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ABSTRACT

This report was supported by funding from the California Energy Commission, the Gas Technology Institute and the San Joaquin Valley Habitat for Humanity program. It describes simple and economical designs, means and methods for building moderate-cost new houses that can generate approxmately as much energy as they consume, over the course of a typical year. The information is based in large part on lessons learned through the 10 year process of planning, designing, building, operating and measuring the performance of houses in the Zero Net Energy Dream Creek neighborhood in Stockton, California. Dream Creek is a 14-home development planned and built by the San Joaquin County Habitat for Humanity organization, with George Koertzen as the Principal Designer and Construction Project Manager. Supplemental technical commentary and detailed advice for builders was provided by a team of California design, construction and engineering professionals.

KEYWORDS

California Energy Commission, residential new construction, Zero Net Energy, residential design, residential engineering, residential construction management, best practices, home performance, Habitat for Humanity, Stockton CA, Gas Technology Institute

CITATION

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THIS BOOK IS FOR YOU

This book is for builder-developers, their purchasing agents, project managers and their major subcontractors. It is also written for the support team: architects, engineers, HVAC designer-installers and energy raters. We assume you are an experienced professional in a position of authority who intends to design, build and market successful zero net energy houses at a sustainable profit.

PURPOSE

Zero Net Energy is California State policy. We assume that if you are reading this book you are already working to achieve zero net energy homes, or expect to be changing towards that goal in the very near future. If ZNE is not your goal, or if you would like suggestions for ZNE that do not require new designs and new construction practices, you may prefer to look elsewhere for advice.

PROJECT

The principles and practices described in this book apply to a wide variety of market-rate ZNE homes. But to be clear, most of the examples, photos and diagrams described here come from the San Joaquin County Habitat for Humanity's Dream Creek development in Stockton, California.

That project is an especially useful source of examples of best practices for ZNE because any builder can apply them, no matter at what price point the homes are intended to sell. The houses at Dream Creek were built at very modest cost, and mostly with unskilled volunteer labor. As a result, the designs have been simplified and cost-optimized to the last possible penny, so that ZNE could be reliably achieved at equal or lower costs than past practices. By applying the approaches outlined in this book, profitable market-rate ZNE can be a reality without its former complexity, waste and cost.

CONTRIBUTING AUTHORS

As an experienced construction professional, you probably want to know who's responsible for the information that ended up in this book. The principal team members who helped structure, write and edit the text include:

George Koertzen

George is the designer, construction manager and site superintendent of the Dream Creek development. His 45 years of construction experience also includes production site-built homes and manufactured housing. Most of the construction details and best practices described here come from his decades of cost-optimizing and simplifying designs and processes to get rid of waste. He regularly achieves ZNE within the constraints of limited budgets and the real-world skill set of modern workers. The fact is, George is ***really*** *tight with a dollar. So if it's in this book—it's a tried-and-true, robust, reliable and inexpensive way to achieve a great result.*

Rick Chitwood

Rick is a mechanical engineer. With his 40 years of experience as a design engineer, mechanical contractor, builder, home performance contractor and trainer, he is an expert in energy-efficient residential building construction, diagnostic testing and performance evaluation. Now retired, he served as a consultant for projects funded by utilities and by the California Energy Commission. Rick provided field measurements and on-site investigation of energy features that contribute to updating California's Title 24 Energy Code. He is also the author of Measured Home Performance, *a book published in 2012 that has become a standard reference for energy retrofit of existing homes. For his long years of service to the industry, Rick was recently inducted into the Building Performance Industry Hall of Fame.*

Bruce King

Bruce King is a Civil Engineer who has provided structural engineering services around the world since 1978. He has also developed standards and building codes for low-carbon construction, and for fire-safe construction in the American West. He is cofounder and Director of Ecological Building Network (EBNet) a non-profit coalition of engineers, builders, and architects. Bruce is also the author of four books, Buildings of Earth and Straw *(1996),* Making Better Concrete *(2005),* Design of Straw Bale Buildings *(2006) and* The New Carbon Architecture *(2017).*

Bill Dakin

Bill is Director of Engineering at Frontier Energy (earlier known as the Davis Energy Group). He served as energy consultant for the well-known West Village Community project of the University of California at Davis. Over the last 25 years, he has served as engineering manager for modeling and remote monitoring verification of many of the design features of buildings and systems that have become part of California's Title 24 energy code. His decades of comparing policy goals and design intent to measured field results over time provides a rich understanding of the thermodynamic behavior of occupied buildings in the real world.

Steve Easley

Steve is a nationally recognized expert in design for constructability and in construction process optimization informed by building science. His guidance and training programs focus on avoiding common but costly mistakes that lead to construction defects and call backs. For more than ten years in the earlier part of his career, Steve was a tenured Professor of Building Construction and Contracting at Purdue University. Steve provides design review, building science training, conflict resolution, forensic investigation and expert testimony in California and throughout North America.

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Rob is Senior Engineer at the Gas Technology Institute in Davis, California. Rob is the manager of the project under which this book was developed; Zero Net Energy for California Homes, (CEC grant number EPC-16-001). In addition to his decades of experience as an energy engineer, Rob is a recognized expert in renewable energy production at commercial and utility scale. For five years he served as CEO of WINDprove, providing wind turbine expertise in aerodynamics, structures, composites, controls, dynamic load simulation, and data analysis, as well as installation design, test, and repair.

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Ann is an architect and national expert on green home design and construction. She is a net-zero energy home expert, as well as a principal author of the US Green Building Council's LEED for Homes Rating System. *Ann served as Chair, Green Building Construction Task Force for the tri-national (US, Canada, and Mexico) Commission for Environmental Cooperation. She also served as juror for the US DOE 2015 Solar Decathlon and 2016, 2015, & 2014 Housing Innovation Awards. Among many other publications, Ann is the author of* ENERGY FREE Homes for a Small Planet *(2009) and the* Zero Energy Primer, *published in 2018 by the California Council of the American Institute of Architects.*

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Mike MacFarland is the hands-on founder and CEO of Energy Docs Home Performance, a retrofit company in Redding that also provides workforce development and new construction consultation to utilities and builders. He is a licensed General Contractor with more than more than 20 years experience. He practices what he teaches, measuring and monitoring the long-term energy performance of his own projects and those of his consulting clients. Mike pioneered the "ring4club.com", a national organization committed to achieving zero measurable duct leakage on every system, which has helped maintain his track record of 30-80% annual utility bill savings for his clients.

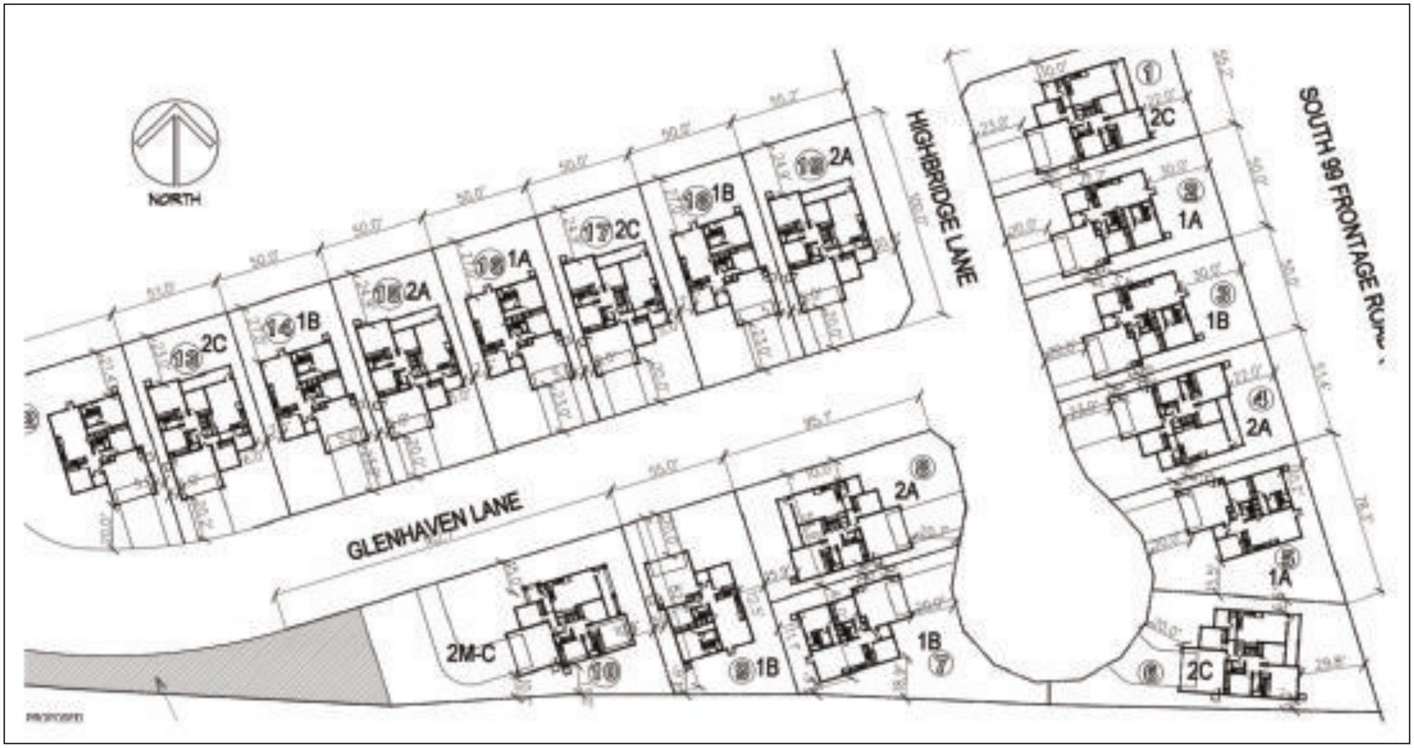

Fig. P.1 Site plan for the Dream Creek Development, Stockton, CA
This book is focused on the design and construction features of this ZNE development, built by San Joaquin Valley Habitat for Humanity.

Lew Harriman
Lew is retired after 34 years as Director of Research at Mason-Grant Consulting. His experience includes HVAC design and field evaluation of the performance of building systems and enclosures. He is an ASHRAE Fellow and Distinguished Lecturer, and was elected to the Indoor Air Quality Hall of Fame in 2018. Lew served as lead author for major reference books published by ASHRAE, as well as for three chapters of the ASHRAE Handbook. For this project, he gathered input from the team and from our generous contributors. Lew is responsible for most of the writing as well as the layout, typography, illustration and production of press-ready files for this book. So if you find mistakes, he's probably the guy who made them.

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Chapter 1

Overview

ZNE Homes are Different

Fig. 1.1 Hands-on development and use of best practices for ZNE: George Koertzen, Master Builder
The foundation for successful ZNE includes willingness to learn and change the patterns and practices of the past. The advice in this book is focused on the designs and construction management by George Koertzen of the San Joaquin Valley Habitat for Humanity, shown here with two of the construction professionals who volunteered to help him at the Dream Creek development in Stockton, CA.

Yes. Zero Net Energy Homes Are Different

Zero Net Energy buildings are relatively new in the world of market-rate homes. And there are "many flavors" of ZNE buildings, a fact that quickly leads to confusion about how much these buildings cost, what is really meant by "zero net energy," and how they can be built by real-world businesses that have real-world subcontractors. Builders approaching this challenge are generally cautious, and more than a little bit concerned about whether these homes will really be ZNE, and if so whether they can be built and sold at a profit.

That caution is a good thing. It opens the mind, sharpens the wit and focuses professional creativity on the technical and managerial changes that make profitable ZNE a matter of "well of course we do it that way" instead of "that's not the way we do it here." Yes. Residential ZNE at market-rate prices does mean changes. But it's California State policy. So the future is now, and let's get to it.

Setting Expectations: What's meant by "Zero Net Energy"

An ideal goal for zero net energy would be that utility bills all net out at zero by the end of the year. And when consumers hear the term ZNE, that's what some may be thinking. The reality is a bit different, because of two factors: there will always be a utility connection charge for grid-connected homes, and consumers often increase electrical consumption through their use of appliances, cell phones, game consoles, security cameras, computers and in some cases, charging electric scooters, bikes and cars. So absolute zero net annual utility cost is not entirely within the builder's control, which means it's not a reasonable expectation for the home buyer.

However, if we do the building well, the homeowner can come close. To build market-rate, near-zero net energy homes (meaning that annual utility costs net out at zero apart from plug loads and grid charges), it's all about keeping lighting, heating, cooling and hot water loads low. And those loads are indeed within the builder's control.

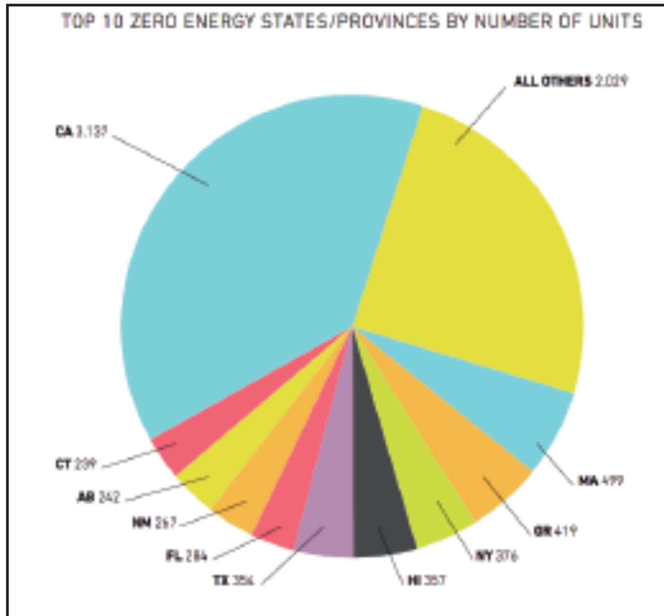


Fig. 1.2 California leads the nation
California uses less energy per capita than any other State (including automotive energy). So it's not a big surprise that we have led the nation into the future of buildings, as shown in this chart, published by the Net Zero Energy Coalition[1] in 2016.

Here's why loads ensure success or failure with respect to zero net energy. The cost of land is the enormous and unavoidable challenge faced by California builders. Given the high cost of land in California, keeping the selling price within reason means that the solar array for a market-rate homes must fit on its roof. It's not going to be in the yard, and it's rarely going to be on an adjacent lot. Extra land is simply not likely to be part of a market-rate property. Consequently, the annual costs for lighting, heating, cooling, ventilation and hot water need to "fit into" the power budget that a rooftop array can produce, over that same year. This means that all loads must be really small, to keep the grid-purchased power and gas to a minimum. And the solar array (and therefore the roof) must be sized and oriented to maximize the amount and value of electrical production. The measures described in this book will help you do all of those things.

ZNE can be cheaper, better and faster than current practices. But it demands architectural creativity

Low loads are possible only when the enclosure is compact, airtight and superbly insulated, and when windows are minimized by locating them for productive illumination as well as visual delight, and whenthey have glass and shading that keeps solar heat out of the house. Given such a low-load enclosure, HVAC equipment can cool and heat the house very evenly, with no more than a 3°F temperature difference throughout the home during all seasons. And the HVAC system will provide such superior comfort using very little energy, even though the system is small, simple and surprisingly inexpensive.

In addition, the floor plan layout and space allocation must provide the centralization of equipment that allows short runs of both duct work and hot water piping. That way, distribution energy waste is kept low. Also, water waste is minimal, because hot water arrives at the shower or the tap in less than five (5) seconds.

Such thermally-informed architectural creativity is the essential foundation for ZNE houses from which everybody benefits economically and which are effortlessly comfortable.

ZNE demands subtractions and reallocations

Get rid of the idea that ZNE needs more technology and "new stuff." Instead, to achieve market-rate ZNE at a profit, *subtract* the expensive extra stuff that drives up costs and reduces profits: excess material, expensive HVAC, big PV arrays, sloppy framing, wasteful insulation and unplanned design changes by subcontractors.

Subtractions that *improve* rather than reduce the value of the house can only happen when the purchasing agent and construction manager allow flexible reallocation of the budget. The necessary increases in one subcontract or component must be balanced by savings in other areas. For example, when framing is always 24" on center, it saves labor and lumber costs. And with uniform and standard widths for insulation, labor is also less expensive. Installation can fast, certain and without wasted trim-cuts. Based on those improvements, the framer's and insulation installer's contracts can (and must) cost less, so the money can be used to offset the cost of the better glazing and similar higher-grade components that provide ZNE, without increasing total costs.

Modeling must show the design can achieve ZNE. But modeling does not provide results.

Modeling is important (and required by code in California). But ultimately the annual utility bills show whether near-ZNE has really been achieved. After the utility bills arrive it's much too late to improve the building. So although pre-permit modeling is important, we measure installation quality *during* (not after) construction.

Figure 1.3 - In-process verification. For example, the fog machine

Achieving profitable market-rate ZNE homes demands new patterns of workflow, supported by new tools. Some of these tools are expensive and unfamiliar. But big improvements come trusting workers (and requiring them) to test and measure the results of their work, as they work. In this photo, a blower door is used to positively-pressurize the building. Then a fog machine generates fog inside, and is held near suspect joints. From outside, the worker can locate air leakage points by the escaping fog. Then those can be sealed up, immediately. From the immediate reduction in air flow through the blower door, air tightness is measured in real time—instead of long after the crew has left the job and it's too late to seal the leaks.

After low-energy design… installation quality is everything. So we measure it.

To achieve ZNE, installation quality must be excellent. Now to be clear, excellence does not mean perfection. But it does mean getting thousands of details right. Given a baseline of thousands of correctly-installed details, it does not matter as much if a few details get installed wrong.

To ensure that the vast majority of details are installed correctly, have the workers themselves measure the result, *before each subassembly is covered up*. In-process measurement is a new and unfamiliar process for most installers. It means new instruments, more trust in workers and choosing subcontractors based (in part) on their *measured* installation results. This seems expensive, until you consider how cheaply, effectively and quickly it provides relevant technical training. Measuring results in-process speeds up the construction completion of an excellent building; one that delivers comfort and energy efficiency at a profit, and without callbacks.

Marketing can be based on measured excellence, with confidence that tangible benefits will endure over time.

One of the big benefits of ZNE is that excellence is measured by utility costs and by in-process installation metrics rather just by expectations set by computer modeling. *Measurements* provide a firm foundation for marketing that demonstrates how ZNE homes are better and are therefore worth more than others that look similar. And the marketing can highlight the fact that the benefits endure for decades, unlike add-on decorations or complex technology that quickly becomes obsolete and needs to be replaced after a few years.

Success or failure for ZNE depends on changing people, not on adding new gizmos

The patterns and practices of the past have not provided (nor can they ever provide) zero net energy buildings. There's no escaping the fact that our potentially strongest asset; our workforce, has been trained and accustomed to past practices that simply don't deliver ZNE homes in volume at affordable prices.

Figure 1.4 - Count Leo Tolstoy (Who might have suggested...)
"Profitable market-rate ZNE homes are possible, but only if your most experienced people are willing to change!"

ZNE begins by recognizing that big changes must happen now. What were seen by experienced professionals as acceptable standard practices in the past are now the biggest obstacles to success in the future. Leo Tolsoy had it right when he said: "The most difficult subjects can be explained to the most slow-witted man if he has not formed any idea of them; *but the simplest thing cannot be made clear to the most intelligent man if he is firmly persuaded that he knows already, without a shadow of doubt, what is laid before him.*"

Keeping that problem in mind, let's get started by discussing just what changes are needed in each area, beginning with people.

References

1. Net Zero Energy Coalition, 2017. *To zero and beyond - Zero energy residential buildings study - 2016 Inventory of residential projects on the path to zero in the U.S. and Canada.* NetZeroEnergyCoalition.com

The People

ZNE Success Requires Cultural Change

Fig. 2.1 For ZNE results (at a profit) cultural change is necessary
Bart Leammel has been a carpenter and builder for 25 years. He had this motto permanently tatooed on his arm, to help his organization keep in mind that for ZNE, any worker's "long experience" is no substitute for the truth (measured installation excellence).

Our People Need To Change

High performance homes are California policy. So it's time for straight talk about the biggest elephant in the room: the changes needed to deliver market rate high performance homes, every day, for every new home, without adding costs or an entirely new workforce.

Both people and organizations will need to change, and this is hard. Today's successful builder or skilled construction worker became successful by following patterns and practices that rewarded fastest completion and lowest cost ***above all other*** criteria. But for delivering actual ZNE homes (at market rates and at a profit), speed and economy alone are no longer enough. Our people, and their patterns and practices, need to shift focus so that measured installation excellence is a cultural norm and understood to be critical to success. To make this happen, installation quality needs to be measured and monitored as a standard practice through the entire construction process, and the results rewarded accordingly.

Does this really apply to me?

As you read this, you might be thinking… "My homes perform just fine. We always pass the building department inspections. We also pass our HERS verifications, and we earn Energy Star certification. So our organization does not need to change to achieve ZNE." But here's the thing. ***Those are useful indicators of intent, but they don't ensure that houses perform.*** California has always had some of the strictest energy codes and verification procedures in the nation. But measurements of actual houses have proven over and over that design and high-efficiency equipment don't provide post-construction results. Much more is necessary and it all requires cultural change.

This is unwelcome news to every architect and builder, who all intend to—and believe—that they make excellent homes. So let's consider some specifics that prove the point.

Measurements of 80 houses located throughout the entire state have shown that:

- HVAC system air flow resistance is far too high. The code calls for 0.5" WC or less, but not a single one of the 80 homes measured met that (relatively lenient) code requirement. With such high resistance, fan energy is excessive for the entire 50 to 100-year life of all those homes.
- AC system air flow is far too low for efficiency and comfort: Not one of the 80 homes achieved the 550 cfm/ton needed for dry climate efficiency. In fact, the average of all 80 homes was only 326 cfm/ton—even lower than the manufacturer's minimum requirement of at least 350 cfm/ton to achieve rated performance. Such low air flow leads to poor energy performance, early equipment failures and the all-too-familiar hot spots, cold spots and over-dried air that makes homes so uncomfortable.
- Actual delivered cooling is less than 50% of rated capacity. This is one reason that HVAC contractors so often install much larger equipment than needed for the load, wasting space and construction dollars for the builder and wasting energy dollars for the owner—for the entire life of the home.

The sad truth is that programs and regulations have failed to achieve real-world results. They fail when on-site inspections do not demand measurements of actual performance of installed systems. Codes and voluntary program inspections enforce minimums, at least in theory. But in fact they have not even achieved minimums in the past, much less ZNE performance. And if this track record of intention vs. results seems too depressing to believe, use the QR code below to download the report of post-occupancy measurements of 80 homes. Bottom line: we really do have to change organizations and people, to achieve market-rate ZNE homes at scale.

Download the report that proves the point
Field measurements show that 80 newly-built, code-compliant homes did not achieve ZNE-grade results.
CEC Public Interest Energy Research (PIER) Program
Final Project Report CEC 500 2012 062

OK. So what are some changes that can work?

We'll begin this discussion with three examples of critical aspects of ZNE construction that often require cultural and organizational changes. After these examples, the chapter will continue with a few suggestions, tips and traps from people who currently deliver ZNE homes, every day, at a profit.

Architectural drawings must call out air sealing targets plus placement of every stick and every joint, gasket and sealant. Chasing air leakage can ruin profits on every job if exact locations and types of framing lumber are not defined on drawings, and if those drawings are not physically available to the workers on site. Organizational structure, on-site tools and job assignments need to align so that:

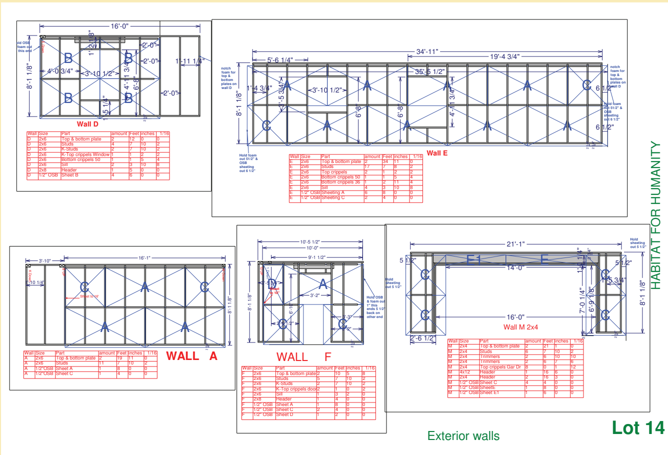
- The framing crew is not forced (or allowed) to make "creative" on-site modifications of the details that ensure that air tightness is achieved quickly and with certainty.
- The purchasing department is not tempted (or allowed) to substitute lower-cost framing lumber that has more knots, twists and camber than the dead-flat and straight members that allow air tightness to be achieved quickly and with certainty.
- The site construction manager needs to clearly understand that unless air tightness is achieved immediately after the framing stage, it's not likely to reach target at any later stage. Adding insulation and gypsum board on top of leaky exterior walls makes it really expensive to fix problems and achieve air tightness at a production building pace.

Air tightness is critical. Measure and correct leakage during construction. Otherwise, air tightness probably won't happen. ZNE is made possible when HVAC equipment is small, and does not need to run at high speed. But if the house is not air tight, the loads can be so high that both comfort and ZNE are no longer aligned. You can always throw energy at comfort problem. But then ZNE becomes impractical because electrical consumption from the grid goes way up. That's because equipment must operate at high speed, right through the most expensive time-of-use rate slot. The work force structure, on-site equipment and job responsibilities need to change so that air tightness happens on every project. To accomplish air tightness all the time, on every job:

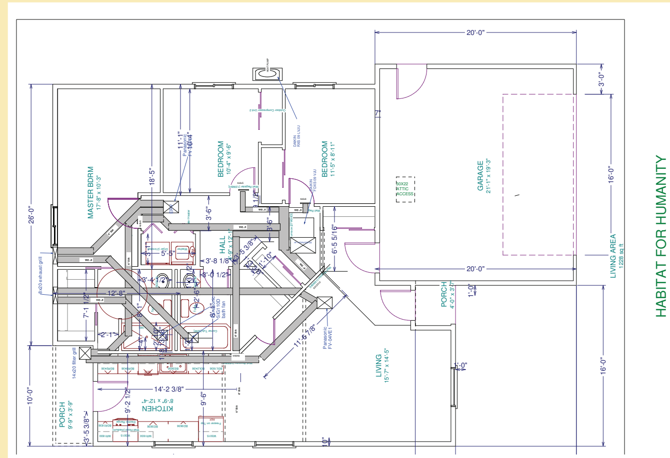
- At least one individual who is on-site or nearby, is specifically trained for and charged with responsibility for using blower doors, duct blasters and theatrical fog generators for leak seeking and real-time measurement. That person will measure air leakage and identify leak locations so they can be fixed without delay. After the building enclosure is closed-in air tightness needs to be measured (and immediately improved) without delaying the project.
- HVAC system airtightness measurements are also critical, after equipment and ductwork is installed and connected. The air leakage of the HVAC system must be measured and reduced, while it's still accessible for air sealing.
- A full set of building and duct work air tightness diagnostic tools must be on-site, available and in working order. If not already owned, expect to allocate between $7,000 to $9,000 (in 2020 dollars) for a blower door set with digital micromanometer, theatrical fog generator, duct blaster and powered flow hood, along with the necessary time-saving supplies and accessories.
- Before insulation and gypsum board are installed, the framing/siding/window crews need to know the air tightness they have achieved (or failed to achieve) in real time, during every project. And their job performance should be rewarded accordingly. If construction speed is the only criterion for evaluating performance, workers will know that. You'll get it fast—but without the air tightness you need to deliver ZNE.

Correct HVAC air flow rates to each space are critical. Measure and adjust these during installation, so they really happen. If there is too much or not enough supply air in a given space, somebody (or maybe everybody) will be uncomfortable. Then say goodbye to ZNE as the system runs flat-out most of the time, chasing thermostat set point changes by occupants. Adjust the organizational structure, on-site equipment and job responsibilities so that:

- The HVAC designer performs a comprehensive ACCA Manual J room-by-room load calculation, and clearly specifies the supply air flow values for each space on the construction documents.



Detailed Wall Framing
No confusion about exactly where each stick must be placed



Exact ERV placement and duct routing
Speeds correct installation of complex, two-ERV design

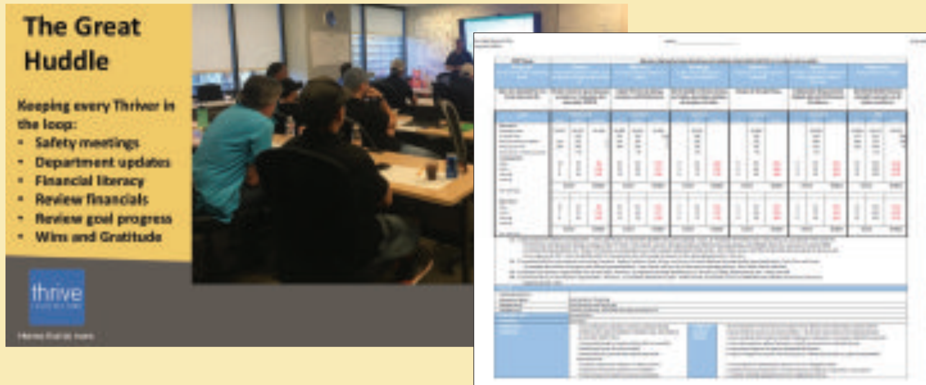
Fig. 2.2 Easy-to-read detailed guidance on site, for each trade
Designers need to deliver detailed drawings for each trade, with non-relevant visual clutter removed.

- Floor plans with HVAC duct layout and the air flow rates for each space are available on-site, for the easy reference of both the HVAC crew and the site construction manager.
- The HVAC crew is equipped with and trained in the use of a powered flow hood, so they can measure and set all air flows to the values laid out on the HVAC plans.
- HVAC crew is required to achieve air tight systems, including air tight connections to grilles, wall board and air handlers. The same is true of the heat recovery ventilation system. HVAC installers need a duct blaster, tape and cardboard to seal grilles during the test, and a theatrical fog generator to locate leaks.
- Your on-site construction manager makes sure the measured supply air values and system air tightness match the design (and are recorded) before the HVAC subcontract is signed off.
- Compensation for the HVAC subcontract reflects the success (or lack of success) in delivering the required supply air values, air tightness and system pressure called out by the design.

Cultural changes for ZNE

Builders who have made the switch to ZNE in recent years usually say that the transition can be bumpy. But after the organization internalizes the fact that patterns and practices are now—and will remain—different, it's not difficult to achieve ZNE as an everyday norm. Award-winning ZNE builders attending two national conferences in 2019 (EEBA and RESNET) suggested a few cultural and structural changes that their construction and marketing departments found effective.

Reporting demonstrates that culture must change. If some parts of the organization don't recognize that patterns and practices need to change (right now), achieving ZNE will be painful and take a long time. The messaging needs to be consistent, and needs to start at the top. One good way to start is for upper management to begin asking for (and circulating internally) the measured air tightness values vs. targets for both the building enclosure and the HVAC system. If you don't get those, it's a reliable indication that something is still



"Transparency and trust built the foundation for our economic success. Our business plan is a single page. At a short meeting every week, every employee sees the financials—for the company as a whole and for their assigned project. We all know what happened last week & what must happen next, to ensure quality and profit on every house... and for our trade partners."

Fig. 2.3 Bill Rectanus - V.P. of Operations - Thrive Builders
Bill's boss, Thrive CEO Gene Myers has built a profitable and award-winning company based on the memorable mantra: "Do the right thing." Thrive closes over 250 ZNE-ready houses per year—every one of which earns the EPA's EnergyStar and IAQ-Plus certifications.

wrong: perhaps the measurements are not specifically assigned to any single person, or the measurement equipment is not really on site, or perhaps nobody has been fully trained. In any case, when executive management asks for these values every day, it becomes clear to the organization that ZNE is here to stay. If the numbers aren't right, something needs to change so that air tightness actually occurs and can be measured and reported as an everyday practice.

Designers need to generate detailed drawings by trade, printable on separate sheets. In the past, the specifics of where framing members are placed and how many to use where, were left to the framing crew. But now, air tightness and effective insulation are imperatives. "Creative" framing and extra lumber "to make it more sturdy" make it difficult or impossible to make the building effectively insulated and air tight, economically and on time. Also, air leakage problems multiply when electricians, plumbers and HVAC folks start punching through walls and ceilings in an effort to get their jobs done as quickly as possible. The only way to prevent profit-crippling on-site framing decisions or plumbing and electrical holes is to have really well-detailed, trade-specific drawings on site. There must be no question about exactly where components must be placed, and exactly where ducts, pipes and wires must be routed.

That means that designers of architectural features and electrical, plumbing and HVAC systems have to generate more detailed drawings than in the past, printed out as separate sheets for each trade. Composite sheets that combine electrical on top of mechanical air flows and plumbing layouts are too cluttered to read and understand quickly—especially if your native language is not English.

Supervisors and workers must work to the plans. Once the plans are adequately detailed and easily available on site for quick reference, the supervisors and workers need to understand that the building really must be built to those plans. Ad-hoc or "creative improvements" cause problems for other trades. This is not because of any power trip on the part of the managers or the designers. It's

"Here in the Central Valley, summer temperatures have risen dramatically over the last 20 years. Recently, one of our unexpected marketing assets has been referrals from our homeowners. They tell friends that their ZNE houses have stayed comfortable in the summer—without the locally-notorious problem of punishingly high utility bills.

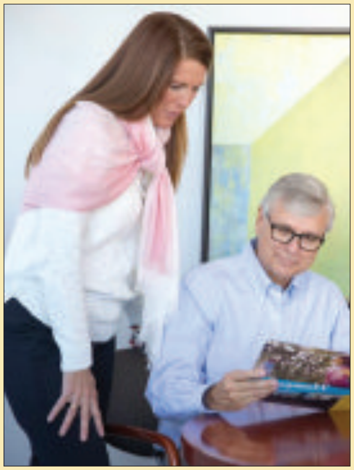
Fig. 2.4 Brandon DeYoung - DeYoung Properties - Clovis
Brandon, a third generation builder, has brought the company to the forefront of the local construction community by focusing on ZNE homes

simply the fact that if components are not installed in a way that makes it fast and easy to achieve ZNE, there won't be any profit at the end of the job. And without profits, ZNE construction is not sustainable. At the same time, if the plans are going to be strictly enforced, there must be an effective conduit and procedure providing updates and corrections to drawings.

Provide a process that corrects and distributes drawings so they remain worthy of enforcement. Your supervisors and workers are plenty smart. If you tell them to build details that make no sense, they know you don't really want or care about ZNE. Enforcing details that no longer make sense (or were wrong from the start) destroys the credibility of ZNE within the organization. So updates and corrections need to happen quickly. The feedback/correction loop between site supervisors and designers must be continuous.

Sometimes, the designers will need to explain that although the design requirement looks wrong, it's actually correct for reasons not obvious to those whose experience relates to older designs. And in other cases, the site super will see things that require corrections or redesigns with respect to thermal efficiency and/or constructibility. So expect that during the transition, highly-detailed drawings will be changing. You can't just set'm and forget'm.

Don't assume that ZNE requires technology or higher-cost materials. Misimpressions driven by high-tech and HVAC marketing are a big problem for the industry. ZNE does not require sexy, expensive materials and complex technologies like ground-source heat pumps, or remote control switches via smartphone apps. None of those things guarantee ZNE—but they do add costs. The features that actually ensure ZNE include: everything air tight, insulation that is effective, window selection, and placement that minimize heating and cooling loads and floor plans that centralize hot water distribution and HVAC ducts. These are not sexy, but they do provide the essential foundation for ZNE.



"Our primary buyers tend to be 35-year-old mothers, the CEO's of their families. They want to be sure they are doing the best for their families. Health of children is constantly in her mind. ZNE home certifications address that concern clearly and powerfully."

Fig. 2.5 Susan Elovitz, VP Marketing with Gene Myers, CEO - Thrive Builders
Thrive ZNE homes also carry EPA certifications. These help remind buyers that materials and HVAC have been selected and designed for health.

Marketing and sales for ZNE

Marketing imperatives will probably change as ZNE becomes the baseline assumption for new home buyers. But for the moment—during the transition to ZNE-everywhere—the consumer sees many apparently attractive "green" features of new homes that shout for attention. Here are four tips that may be helpful to the sales staff and marketing department, as they make the transition to selling ZNE homes:

The relative value of a ZNE house rises with utility rates, while non-ZNE houses lose value with every rate increase. Because ZNE houses generate electricity on-site, the homeowner is much better protected from the rate increases that come with time-of-use surcharges. Similar-size houses in the same neighborhood that are *not* ZNE will *lose* value over time, because the utility bills of non-ZNE homes rise as rates keep climbing.

ZNE homeowners enjoy whole-house comfort. With an airtight, perfectly-insulated enclosure and windows exclude 70% of excessive solar heat, the hot spots and cold spots so typical of homes in the past simply don't happen. The indoor air temperature stays more uniform throughout the house. And because the walls are so well-insulated, they won't get too hot or cold during weather extremes. For most home buyers, these are unfamiliar but very welcome benefits. You can make this benefit more real to home buyers by alluding to houses of the past that have some rooms that are: "just never at the right temperature." Nearly all home buyers have lived in houses that suffered from hot and cold spots. With ZNE, they'll be able to keep all their loved ones comfortable in all weather and in all parts of the house—while using very little purchased energy.

ZNE homes come equipped for excellent indoor air quality. Airtight ZNE homes keep out millions of the small outdoor particles that are so damaging to long term human health (PM2.5). ZNE homes all have engineered systems that bring in appropriate and measured amounts of ventilation air by design, rather than by accident.

Gizmos do not equal green. High-efficiency equipment and electronic gadgets don't achieve ZNE. Sales pros selling new ZNE homes need to clearly understand and communicate this fact, because it's a matter of confusion for many consumers. Marketing of tech products and "revolutionary" HVAC equipment creates the

This is George…

…This is George when he thinks you're wasting money by adding needless cost or complexity.

"ZNE doesn't have to cost more. Ask for and enforce designs that use every bit of material. Judge the quality of the design and your site supervision in part by how much material ends up in your dumpster."

Fig. 2.5 George Koertzen - Habitat/San Joaquin County
Using a strict grid of 24" x 24" for the floor plate and walls, George's designs use every possible inch of every sheet and every stud.

illusion that you get magical energy reduction by simply adding the latest technology to any new house. But energy reduction only happens through *installation that keeps the **loads** low*.

For example, installing a high-efficiency AC system on a poorly-insulated house that leaks air is like trying to make a refrigerator out of a cardboard box sitting on a hot driveway; it might take less energy to run than other equipment, but it's still not going to be either effective or energy efficient. Unless a building enclosure has *inherently low heating and cooling loads* (as do ZNE homes) it's going to take a lot of electricity to keep it cool in the summer and warm in the winter. High efficiency equipment and fancy thermostats won't change that fact.

Another example is the energy and water consumption of the hot water system. Unless the architectural design makes the plumbing "compact" (short distances between the water heater and all points of use), then the labeled efficiency of the water heater is not going to reduce the amount of water used, nor will it make much improvement in the amount of energy needed to produce hot water.

So sales pros and marketing materials need to clearly communicate that it's the *combined effect of all* the features of a ZNE home that allow the homeowner to save energy while staying comfortable—not highly-rated equipment, nor any add-on gadget or appliance controlled by a smartphone.

Ultimately, the homeowner controls the ZNE outcome. Over-promising utility bill reduction is a trap that sales and marketing promotion should try to avoid. ZNE homes are designed and built based on a reasonable engineering estimate of HVAC loads, occupant behavior and preferences. But there are also "plug loads" imposed by occupants' uncontrolled appliances, lights and electronics that can overwhelm solar production. So to avoid buyer annoyance with utility bills, it's useful to tactfully mention that the actual annual consumption—"your mileage"—may vary, based on plug loads.

Chapter 3

Architectural Design

Inherently Low Costs for Energy & Construction

Fig. 3.1 Thermally-informed architectural creativity

For zero net energy homes, the definition of architectural creativity includes designs that keep thermal loads small—without sacrificing visual delight and robust functionality. For best results, the architectural and mechanical designers work and rework the floor plan together, so that energy consequences of architectural decisions are immediately apparent.

Creativity Focused By Thermal Reality

Achieving zero net energy depends first on architectural design. And ZNE design is *really easy* to do without any changes to past practices—provided you have an unlimited budget along with a huge lot, so you can buy and have space to install a really *big* solar array.

But without that mythical unlimited budget and plus-size lot, achieving zero net energy in market-rate homes on mass-market-sized lots is more of a challenge. Real-world ZNE demands a new focus for architectural creativity—designs that reduce thermal loads and water waste to an absolute minimum.

ZNE Design: What Stays The Same

Customers' perceptions of beauty and utility will always remain the first imperatives, after good location and reasonable cost. Those realities never change. If a house is zero net energy—but cramped and ugly—it won't sell and it won't last long. To be truly sustainable (meaning they will last for generations) houses will always need to be visually appealing and well-fitted to the needs and wants of their owners. Those attributes ensure they receive the care and maintenance that allows them to endure over time.

So nothing changes with respect to the importance of visual appeal and functionality. And of course nothing changes with respect to meeting minimum code requirements. What *does* change is the rather large challenge of meeting these market realities while keeping lifetime energy consumption near net zero, with the same or lower construction costs. Low energy consumption used to be "nice to have" but now it's imperative. So, how to accomplish this?

ZNE Design: What's Different

To sell market-rate ZNE homes at a profit, the construction budget needs to remain economical. This challenge is not new. To paraphrase a 19th century construction expert: "An architect can do for a dollar what anyone else could do with two."[1] Architectural design has always been about creative cost trade-offs. So here are some suggestions for the designer, based on what has worked well when designing houses with exceptionally low thermal and hot water loads.

1. Face the roof southwest

Solar energy is most valuable during the late afternoon and early evening, when electrical loads peak as occupants return home. So at the very beginning of the design, angle the largest clear roof surface south or southwest (Between azimuth 180° and 225°).

You can quickly estimate the differences in peak and annual solar production between different orientations by entering the project location ZIP code into "PVWatts Calculator," a no-cost, public, browser-based software tool provided by the US Department of Energy's National Renewable Energy Laboratory. Figure 3.2 shows the output from that tool for a 4 Kw array facing south (180°) in Turlock, CA. Also at this site, a single click on the output page downloads a spreadsheet that documents the detailed hourly data that support each summary. This and many other useful suggestions are detailed in the Zero Net Energy Primer, published in 2018 by the California Council of the American Institute of Architects.[2]

Fig. 3.2 Estimate solar production early, to establish roof orientation
Web-based calculator - National Renewable Energy Laboratory.

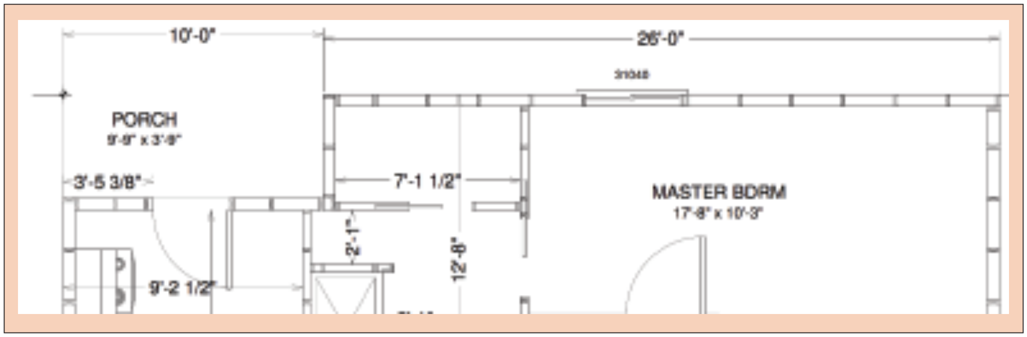


Fig. 3.3 Floor plate based on exterior wall studs set 24" on center
To avoid needless expense, poor thermal performance and air leakage, make sure the lengths of exterior walls consist of even increments of 24" stud bays.

2. Air tight, perfectly-insulated envelope

In the past, the exact design of these critical features were often left in the hands of the framing crew. But for ZNE, air tightness is an imperative, and success requires detailed architectural drawings that include check numbers for air tightness. That's because air tightness and insulation must be accomplished at low cost—not the high costs imposed by either ad-hoc on site framing, or by architectural designs that cannot be made air tight except by spending lots of time and wasting large amounts of material.

George Koertzen's successful ZNE designs begin with highly-detailed construction documents for exterior wall framing, based on studs set 24" on center. Fenestration is also located and dimensioned to match the 24" grid. When all exterior wall cavities have a uniform width of 24", economical glass fiber insulation can be quickly installed correctly: tight to all six sides of the cavity of every stud bay. A standard 8' x 24" batt then fits perfectly, with zero wasted material and zero time to measure width, and trim or fit. When each batt is in full, uncompressed contact with all six sides of the cavity, the labeled insulation value will be achieved without time-consuming efforts on the part of the construction crew, and without the need for expensive and labor-intensive spray foam to fill leftover cavities.

More framing details and connections are described in Chapters 5 and 6, because seismic considerations and further thermal considerations are just as important as the 24" spacing of wall studs. But the main point here, in the architectural design chapter, is that for greatest economy, wall lengths and the distances between windows (and window dimensions themselves) should fit the framing grid. Each deviation of either fenestration size or placement means adding framing members that will break the grid, increasing costs in a series of negative consequences that fall like dominos. First, HVAC loads increase. From that, equipment sizes increase. That means a larger budget for equipment, and larger equipment connected to the electrical system means higher power consumption under peak loads, which means larger solar panels to reach net zero on an annual basis. Not only that, but larger equipment demands more space for ducts and equipment. And that space is expensive, because inside the conditioned space is where equipment and duct work needs to be in any production-built, moderate-cost ZNE home. Then, square footage in the floor plan increases... which means there is more exterior surface area exposed to heat and cold, which increases loads still further... and so on. In short: when you need to deliver designs that achieve moderate-cost ZNE homes at a profit, don't break the 24" grid.

3. Window design governs mechanical system cost and thermal comfort

One of the reasons that refrigerators use so little energy is because they are air airtight, they have a thick and continuous layer of insulation on all six surfaces without any voids or thermal bridges and.. they don't have any windows. On the other hand, very few humans like to live in refrigerators. So we need windows in houses.

But here's the deal with windows. They are a visual delight and an obvious design imperative. However, they are too often a thermal

Fig. 3.4 Low SHGC keeps solar heat out of the house
The window on the right has a solar heat gain coefficient of 0.27. The window on the left has a SHGC of 0.58. The thermal images show how much more heat is transmitted to the black cardboard that hangs from the inside of the window frame. To keep the HVAC loads low enough for ZNE, use windows rated at SHGC 0.23 or less (in fact a minimum requirement of Title 24, effective January 2020).[2]

catastrophe. Without thoughtful placement and thermally-aware selection by the architectural designer, they are essentially big holes in the wall that leak large amounts of heat in both directions. Here are some ways to maximize the many wonderful benefits that windows bring, while minimizing the cooling loads they create:

SHGC below 0.23 The requirements of Title 24 that went into effect on January 1st, 2020 are clear on this point.[3,4] For everywhere in California except the North coast and high Sierras, the journey to low HVAC loads begins by specifying glazing that has a solar heat gain coefficient (SHGC) of less than 0.23. Solar heat gain is what really drives up the size of the cooling equipment and it's duct work. It's possible to overcome any cooling load, of course. But then comfort requires bigger cooling equipment, more air flow and bigger duct work, along with more solar panels to power it. So if the solar heat gain through windows is less than 23% of the sun's radiant heat, everything mechanical becomes more smaller, more economical and easier to install to achieve the same level of comfort. Figure 3.4 shows the difference between glass that has a solar heat gain of 0.27 compared to glass that has a solar heat gain of 0.58. The low solar heat gain glass keeps the indoor surface temperature of the cardboard 30°F lower than the old-style glazing. Keeping that heat out of the house allows the HVAC system to be smaller, less expensive and less complicated, so it can fit inside the conditioned space rather than being forced into the attic or garage—a result that would force still larger increases in AC capacity and therefore the number of solar panels.

To minimize mechanical cost, minimize West-facing glass. West-facing glass adds the greatest cost to the cooling system and its duct work. That's because peak cooling loads occur in the late afternoon and early evening, after the building has had all day to warm up in the hot air that surrounds the house. And it's the peak—not the average load—that sizes the cooling system. So when windows are located on the west side of the house, on a per-square-foot basis they force a larger-than-average increase in the size of the cooling system.

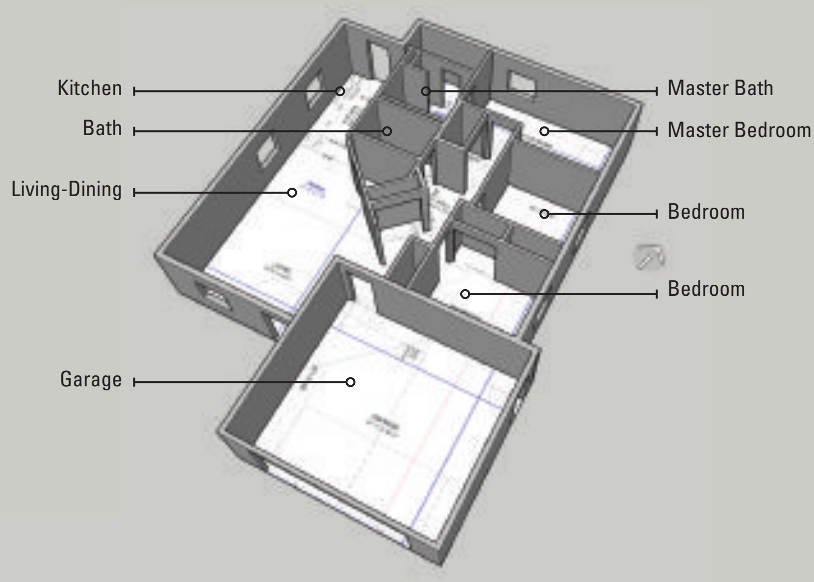
Whenever possible, minimize the amount of glass surface that faces west. And when the west face really has the most valuable views, use

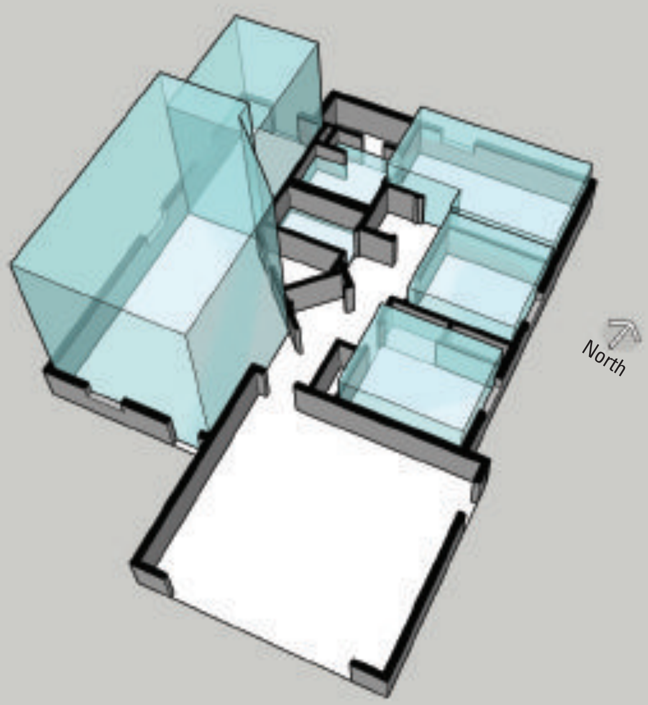
Fig 3.5 Minimizing West-facing Windows
The modest-sized houses of the Dream Creek development provide examples of thermally-informed architectural creativity. Note the peak cooling load of less than one ton of AC for 1,200 ft² of living area.

Also note that the cooling load is still highest on the west side of the building, in spite of very minimal window surface, and excellent thermal performance of those windows (less than 0.3 solar heat gain and less than U-0.3 sensible heat transmission).

West-facing glass often dominates the peak cooling load. So the fewer and smaller windows on the west elevation, the smaller and more energy-efficient the HVAC system can be.

Benefits of minimal west-facing glass cascade through the project. Because the system is small, it fits inside the occupied space. Keeping duct work out of the hot attic allows the system to provide comfort while avoiding a 27% increase in equipment capacity.





PEAK HVAC LOADS

	Heating (Btu/h)	Cooling (Btu/h)
Living	2,562	2,876
Master BR	1,301	1,002
Kitchen	1,267	2,254
Hall/Storage	1,118	1,306
Bedroom 1	870	1,016
Bedroom 2	663	958
Master Bath	559	316
Bath 1	103	90
Other Equipment	366	291
Humidity		603
Total	**8,809**	**11,006**

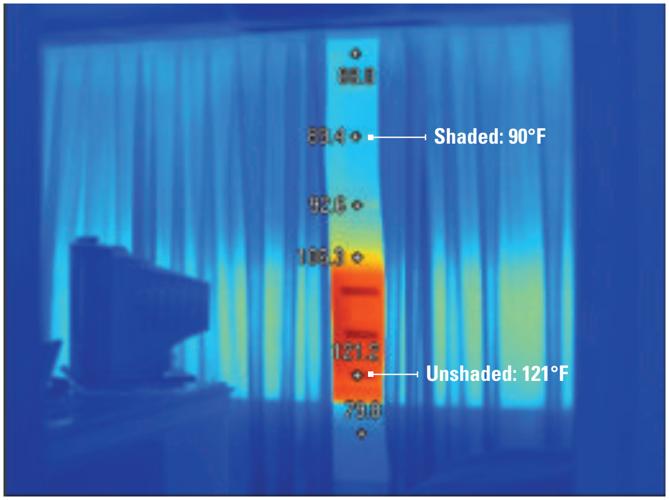


Fig. 3.6 If some windows must face West.. shade them.
The surface temperature measurements on shaded (90°F) vs. unshaded (121°F) glass illustrate the potential cooling load reduction that comes from shading west-facing glass. The peak load sizes the cooling equipment, and that peak load happens in the afternoon, when the sun is blasting through any West-facing windows. Smaller peak load = smaller and less expensive HVAC equipment. Shading the glazing is good.

solar shading both beside the window and above it, to minimize the number of hours and the amount of surface area that will be exposed to high solar heat gain.

To illustrate the value of shading, Figure 3.6 shows the temperature differences between shaded and unshaded portions of window glazing that faces the afternoon sun. The inside temperature of the shaded glass is nearly the same as the outdoor air temperature. But the unshaded glass surface temperature is over 120°F. When a window must face West, the larger the percentage of its glass that is shaded, the larger that window can be, without increasing the cooling load.

Avoid overheating: shade glass on South, East and West. Here's a subtle but important point. The most difficult seasons for comfort are often Spring and Fall. That's because when the sun is at a low angle, it can blast through glazing on the East, West and South faces, adding unwanted heat to a few spaces—right when the building *as a whole* does not need heating or cooling. So without the HVAC system operating, air can overheat spaces in which there is no thermostat. In the middle of Winter, this is less of an issue even though the sun is at its lowest point on the horizon. That's because in the winter, there will be more frequent calls for heat. Solar overheating is more commonly a problem during the swing seasons.

To avoid this issue, common in high performance houses, shade any glass on the East, West and South faces, reducing the potential for overheating during Spring and Fall. Figure 3.7 on the next page shows the benefit of solar shading during the Fall. The first photo shows the view during the Winter. The sun is at a low angle, so it adds heat to the house—not a bad thing. Next look at the second photo, take in late September. The shading is helpful, reducing the number of hours when overheating could be a problem when the outdoor air temperature is nearly perfect, from a comfort perspective. The shading looks great, and makes for better comfort all year long.

4. Central collocation of HVAC equipment and hot water heater

When air and water have to be pushed around corners and over long distances, the equipment and its peak energy demand gets bigger and more expensive. That money that can be saved when the floor plan allows the mechanical equipment and hot water heater to be together in the middle of the home.

For HVAC, central location allows duct runs to be short and straight. That simple fact provides the foundation for a series of HVAC details that allow lower energy costs, less equipment and better comfort. There's a series of benefits that begins with central location of mechanical equipment. With little or no friction from long runs and sharp corners, it costs nearly nothing to have constant-volume recirculation. In other words, air circulates throughout the house at all times, 24-7. Constant air flow allows effective sizing of supply air diffusers so that air is always well-mixed throughout the house, and located in parts of each room where drafts will not disturb occupants. Constant air mixing means that any ventilation air is well-distributed,

Late September - Shading is especially useful for comfort
Shading helps avoid ***overheating*** *the indoor air when the outdoor temperature is perfectly comfortable.*

Mid-Winter - Shading not effective, but also not needed
Solar heat gain is not all bad, at this time of year when cold outdoor temperatures often call for heating.

Fig. 3.7 Shading is especially important to avoid overheating during Spring and Fall.

Photos courtesy of Steve Easley

and otherwise hot and cold spots are eliminated. When temperatures stay even throughout the house instead of having "islands of hot and cold air" in different rooms, everybody is more comfortable. Thermostats can stay set at constant values rather than being tweaked up or down as one person or another becomes uncomfortable in an overheated or over cooled space. Figure 3.8 shows a floor plan that allows these benefits.

In contrast, the photo and caption in figure 3.9 illustrate a negative consequence of two architectural design decisions for HVAC equipment, energy and thermal comfort. The first architectural decision was for a long, unsupported span to avoid support columns. And the second decision was to locate the mechanical space far from the areas it serves. Those two decisions led to the need for a deep steel beam and a long duct run, which in turn led to four right-angle bends in the duct work to get around the beam. Those four right-angle turns make the air flow resistance over these three feet about 300 times greater than it would have been if it had been a simple 3 ft. section of straight duct. That energy waste will now last as long as the building itself. Waste will occur during every day and every hour that the HVAC system needs to operate, for its entire life.

Returning to the positive consequences of thermally-focused architectural decisions, central location for the hot water heater is another beneficial feature of the floor plan in figure 3.4. In this design, the longest run of hot water pipe is 14 ft. from the heater to any point of use. This arrangement provides two big benefits. First, hot water arrives at the faucet or shower head in five or six seconds. Then, because water arrives hot in seconds instead of minutes, there's much less water that runs down the drain while the occupant waits for water at the right temperature. Less hot water waste saves the homeowner twice: less money to heat water, and lower monthly costs for water and sewer use. Also, short hot water runs save money for the builder as well: less material and faster installation.

All these benefits accrue because the architectural designer provided central locations for the mechanical equipment and hot water heater, and located the bathrooms and laundry rooms near the center of the house.

Fig. 3.8 Save energy and water by central location
This layout allows short, straight duct runs to each conditioned space, which means the air flow resistance is very low. This in turn allows the system to circulate air continuously, without the usual energy penalty caused by long runs and sharp turns.

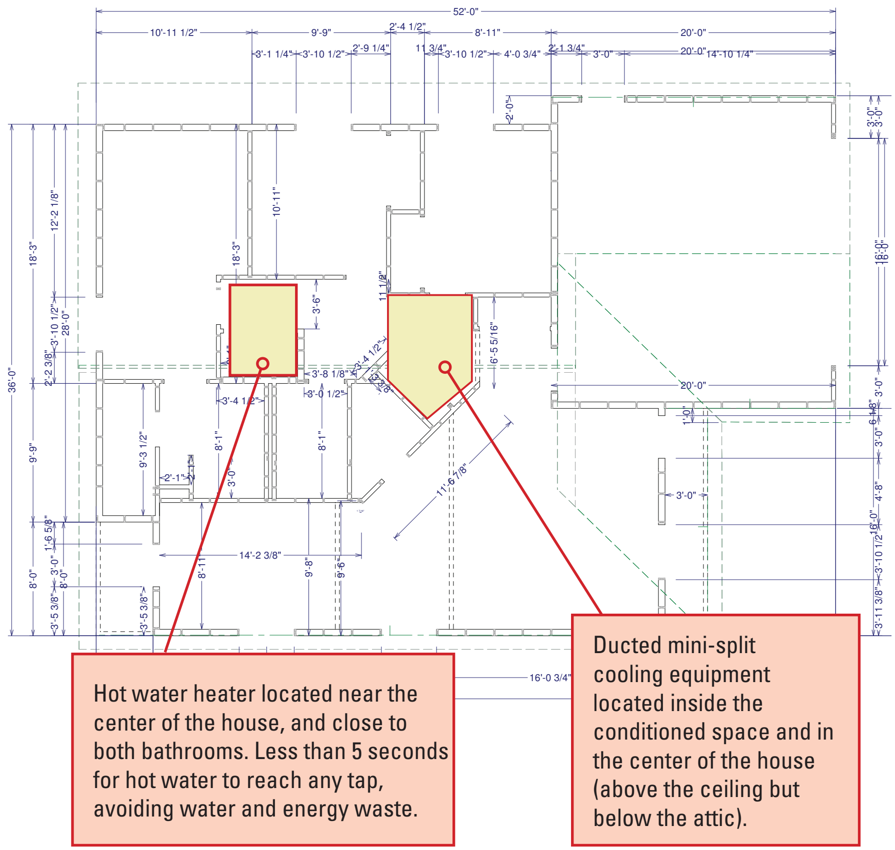


Fig. 3.9 Don't do this! Big energy waste.
The architectural decision to use a deep beam forced the HVAC duct to make four right-angle turns. That decision multiplied the air flow resistance of these three feet of duct by a factor of 100.

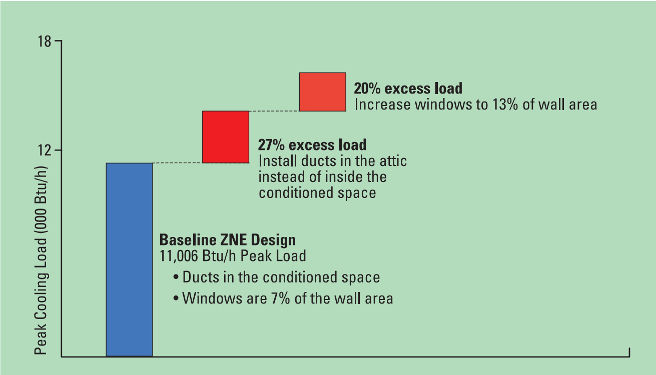


Fig. 3.10 Keep ducts out of the attic!
Attic ducts would increase cooling equipment by 27%. So keep them out of the attic. Also, resist the temptation to increase window sizes, unless they are well-shaded.

5. Ducts and mechanical equipment inside the conditioned space

In the past, the high cost of California real estate and the natural desire of homeowners for more usable space at affordable costs combine to work against energy efficiency and thermal comfort. That's because high per-square-foot costs of housing encouraged the thermally and economically catastrophic practice of placing mechanical equipment and duct work in the attic. Now, better building enclosures allow locating air distribution and mechanical equipment *inside* the air barrier and insulation, instead of up in the hot attic. There is a chain of reasons why locating the equipment inboard of the insulation is now economically practical in ZNE homes.

With ZNE's low cooling and heating loads, the enclosure will have excellent air tightness, continuous insulation and windows that have a low solar heat gain coefficient. Given those ZNE imperatives, the heating and cooling equipment is *far smaller* than in the past... so it can fit inside without taking up much space.

For example, consider that in the past it would not have been unusual for a 2,000 ft^2 house to have an cooling system of 5 tons or more. Now, a cooling system of less than 1/3 that size makes the house even more comfortable than the larger system—provided that the system does not also have to overcome the loads imposed by locating equipment and duct work on the other side of the insulation, in the attic.

Smaller HVAC equipment saves installation and operating costs. And smaller electrical loads enable ZNE homes with smaller solar arrays. That's the benefit that comes from thermally-excellent enclosures, which are the result of air-tight construction and careful window placement, selection and shading—all of which are decisions that fall into the category of thermally-informed architectural creativity.

Summary

Architectural design provides enormous personal and professional satisfaction: ideas become three-dimensional reality that endures for *generations*. ZNE buildings are even more satisfying. Their thermally-informed architectural creativity ensures a low energy, low-cost, comfortable and beautiful indoor environment over those generations.

References

[1] Arthur Mellen Wellington (December 20, 1847 – May 17, 1895) was an American civil engineer. The saying that "An engineer can do for a dollar what any fool can do for two" is attributed to him. Wikipedia 2018

[2] Zero Net Energy Primer. 2018. American Institute of Architects, California Council

[3] California code of regulations, Title 24, Part 1, Chapter 10 and Part 6 (2019 California Energy Code) California Energy Commission Docket no. 17-BS TD-20 January 19, 2018. http://www.energy.ca.gov/title24/2019standards/rulemaking/

[4] California climate zone map 2017. http://www.energy.ca.gov/maps/renewable/building_climate_zones.html

No-Cost ZNE Resources for Architectural Design

California Energy Code Ace

Provided by the California Statewide Codes & Standards Program, the site offers free energy code training, tools and resources for those who need to understand and meet the requirements of Title 24, Part 6 and Title 20. (https://energycodeace.com)

US DOE - Tour of Zero

The site provides documentation and virtual tours of specific ZNE homes that were independently certified to meet DOE Zero Energy Ready Home guidelines, constructed by both custom and production builders. The database includes homes in all parts of the US. As of January 2019 it contains more than 400 case history examples in California. (https://www.energy.gov/eere/buildings/doe-tour-zero)

Net Zero Coalition - Current Inventory of ZNE homes

Designers and builders in the Net Zero Coalition provide this nationwide inventory of completed residential ZNE projects. (https://teamzero.org/inventory-of-zero-energy-homes/)

PDF Library at Building Science Corporation

A rich resource that helps answer your building science questions, based on decades of hard-learned lessons from the real world of production building and building forensic investigation. (https://tinyurl.com/y6ruuauj)

US DOE - Building America Solution Center

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Construction Management

In-Process Measurements Can Reduce Costs and Speed Completion

Fig. 4.1 Is it actually any good, or is it just... "finished?"

*Homeowners may judge ZNE results by their utility bills. Delivering on the implied promise of that label, George Koertzen manages by **measuring key results in-process** rather than just hoping the numbers will "look pretty good" after completion.*

Tips and Traps for ZNE Construction Management

As a builder, you're not new to construction management. You know what to do, and how to do it. In short, the budget and the schedule are always sacred. But with ZNE, installation quality must also be sacred, to achieve the promised result.

On the bright side, high quality in the ZNE world does not have to mean expensive materials and complex, schedule-busting installation. In fact, quite the contrary. Profitable market-rate ZNE can use simple systems and simple materials rather than adding fancy HVAC or "smart home technology" to the home. The most effective and lowest-cost strategy is to *make the cultural changes* that reduce formerly-acceptable waste and rework, rather than substituting cheaper materials or pushing workers to finish work in a less-than-practical time frame. Well sure, everybody would like that general approach. But how about some specifics? Here are a few tips from those who have achieved ZNE results.

1. Purchasing managers must insist that installation time savings balance the increases in other categories

Successful ZNE requires that savings in some subcontracts be applied to cost increases in other categories. Because there will be some cost increases. Purchasing will need to reallocate some dollars from one line item to another, to keep the overall budget within bounds. Here are a few examples from the Dream Creek project:

- **Wiring notches at the base of each wall stud save time for electricians and insulators.** Their contract costs should reflect that time savings. A tiny increase in cutting time for the framing crew saves a great deal of installation time for the electricians, and allows much faster and more effective installation of insulation in wall cavities. The purchasing department can (and must) enforce a lower subcontract price for faster wiring and insulation, so that savings can be applied to other contracts.
- **LVL or LSL top and bottom plates save framing (air sealing) labor.** The framers or the siding crews save time because single LVL/LSL top plates and bottom plates are smooth, straight and dead-flat.[1] Time to achieve air tightness is reduced. That fact needs to be reflected in the framing contract.
- **Framing 24" on center saves lumber costs.** There will be a 30%+ reduction in lumber as a result of advanced framing of exterior and interior walls at 24" on center vs. framing at 16" on center. Material and labor costs need to reflect that savings.
- **Horizontal drywall with OSB-backed, off-stud splices saves material and labor.** Ending sheets between studs using OSB-backed splices saves a lot of wall board. This detail reduced the number of drywall sheets from 37 to 17 in the 1200 ft2 houses at Dream Creek, for a 53% savings in material. The detail also reduced labor. With fewer joints and more factory sheet edges there's less measuring and cutting, and less time needed to mud and sand the interior. The detail is fully permitted by code, as discussed in chapter 6. Material savings, plus the labor savings of mudding and sanding fewer joints needs to reduce the cost of the drywall contract.
- **HVAC equipment and installation is smaller.** ZNE homes have very low heating and cooling loads because of the airtight building enclosure, low SHGC windows, exterior insulation and airtight duct work. That reduction needs to be reflected in the HVAC equipment sizing and its installation cost.
- **Keeping HVAC ducts and equipment out of the attic saves installation time**. This speeds installation time and simplifies the task of making all connections air tight and adjusting supply air flows. Equipment and duct work inside the air barrier also eliminates the need to seal duct penetrations into the attic. These labor savings must reduce the HVAC subcontract cost.
- **Compact plumbing saves material and labor.** Architectural design that locates "wet rooms" close together (aka: compact plumbing design) reduces both material and the labor needed to run pipes. The savings from that architectural decision should be reflected in the plumbing subcontract.

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1. These abbreviations refer to laminated veneer lumber and laminated strand lumber—engineered wood products that are manufactured in a highly uniform process.

Job Site Plan Station
Accessible to all workers

Rolled Plans In Open Tubes
Easy to find and refile

Every Stud Is Located On Wall-By-Wall Drawings
Avoids problematic ad-hoc redesign by workers

Fig. 4.2 Full set of plastic-laminated detailed drawings—on-site and accessible to all workers—reduces confusion and speeds completion

2. Trade-specific, plastic-laminated drawings—easily and obviously available to workers—reduce rework.

The super can't be everywhere, at all times. But achieving high quality results at low cost strongly depends on the clarity and availability of guidance to on-site workers. In-person guidance can be enhanced with simplified (trade-specific) architectural, electrical and mechanical drawings.

This is especially important for ZNE details that may not be what workers are expecting. For ZNE, the house must be built according to the design and the specific details that have been proven to achieve ZNE—not built with details that are improvised on site. Trade-specific drawings are important not just for the supers' reference, but also for the workers in each crew. "Where—exactly—is that set of 24"-on-center wall studs supposed to begin and end on that front wall around the main entry door? How—exactly—is the plumbing supposed to run from the water heater through that cramped bathroom-laundry room combo?" Simple, clear drawings can answer these key questions—now. Not later, after it's been done the wrong way and has to be taken apart and redone to get ZNE-grade results.

These visual diagrams are especially helpful for newer workers, many of whom may not have grown up speaking English as their primary language. Given the workforce demographics of California, a duplicate set in Spanish is a useful tool, especially since it's so inexpensive to produce with the aid of web-based translation. Por ejemplo, "Google Translate" es disponible gratuitamente a todos. No hay un aumento significativo en el tiempo de diseño para generar un conjunto de dibujos en Español. Reconocer la realidad de una fuerza laboral multiculturál no solo es una señal de respeto, sino que también reduce los costos al reducir la confusión. La inclusión de dibujos con instrucciones en Español mejorará en gran medida la velocidad y la calidad de la instalación, además de reducir los costosos reprocesos.

3. "Creative redesign by the trades" can ruin profits and ZNE

There's a trap that can come from old, familiar habits. "Trusting the worker" used to mean let him or her get the job done in the way that's most familiar. But until each and every worker's "most familiar way" evolves into the way that ensures ZNE, worker creativity must be constrained and guided by the design. And if the design documents do not locate every stud and every duct run and every wire and outlet of plumbing, wiring and supply air, then that set of design documents needs to be improved before it's ready for ZNE construction.

Successful ZNE demands that design details be worked out—in advance of construction—to ensure low cost and to prevent interferences between assemblies installed by different trades. (e.g., All those extra holes drilled in air barriers and structure by electricians and plumbers, because wiring and plumbing runs were not clearly defined and located on the drawings.) Construction management needs to ensure that details are correct and current, so that the trades do not need to "get creative," driving up costs with problematic details that prevent the speedy installation and full function of other subassemblies.

4. Less rework when site supers explain why, when and how to *measure* successful installation

Measuring performance in the work flow (rather than after substantial completion) saves time and rework. But this is a change from past practice, when key measurements were only made by 3rd parties. It helps when supervisors clearly explain that:

- **Measuring in-process saves time and keeps the schedule on target.** Installation makes or breaks ZNE. And there's always, always some sort of adjustment that will need to be made to achieve air-tight buildings, air-tight duct connections, fully-continuous insulation and the correct air flow to each conditioned space. The sooner corrections are made, the less expensive it will be to make those corrections. Measuring and fixing later generally requires taking things apart for access. That means more than one trade has to be involved with rework. Making sure each trade measures its success—or lack of it—greatly reduces the cost and disruption that comes from finding and fixing problems after the fact.
- **Measuring in-process provides real-time feedback and self-education to workers, helping them avoid rework in the future.** Having the workers themselves perform the testing is ideal. They develop a gut feel for successful installation that improves their speed as well as their certainty of success. And it gives them the pride and self confidence that comes only from *measured*—rather than assumed—excellence.

5. Measurement instruments need to be on-site, in working order and available to workers—along with training

There are some key instruments that most tradespeople cannot afford to buy and own. But they are critical to measuring success in-process. So for ZNE, the builder needs to make the necessary investment in instruments and training. Each site supervisor needs all of these items available and on-site:

- Blower door kit including micromanometer
- Fog machine with glycerine and distribution hose
- Duct blaster kit with micromanometer
- Return air flow plate
- Supply air (powered) flow hood
- Training + experience using each instrument

That last item—often overlooked—is very important. Until the workforce culture has fully adapted to the imperatives of ZNE, there's no guarantee that workers will know how to use the instruments that test their own work and document the degree of success they have achieved. And even in the future when all tradespeople understand the value of measurements, human nature being what it is, some workers may be tempted to report "optimistic" testing results if their site super does not know how to use the measurement equipment.

6. How and when to measure installation quality

Table 4.1 shows critical measurements and when they should be made, along with check values that indicate successful ZNE-grade installation. The table also includes QR codes to access generic video clips that provide a brief audiovisual summary of each measurement. Note, however that the video clips were not produced for this project. So keep in mind that they illustrate the basics of the instruments and how measurements are made—***not*** the specific check numbers and procedures that assure ZNE.

CRITICAL IN-PROCESS MEASUREMENTS BY WORKERS (OR SITE SUPERINTENDENT)

What to Measure	Target	Acceptable	**When to Measure**	How to Improve	YouTube Example ***See commentary for important cautions***
Enclosure Air Leakage	Less than 2 ACH_{50}	3 ACH_{50}	After windows, doors, ceiling and floors are all sealed—but **before** insulation and wall board	Locate leaks using blower door to create positive pressure indoors, forcing theatrical fog out through any gaps, cracks and holes	
Installed HVAC Pressure Drop (Supply + Return)	Less than 0.2" W.C.	Less than 0.3" W.C.	After ducts are installed **and connected but not sealed** to air handler, grilles and supply nozzles	Locate and fix obstructions, kinked ducts or closed dampers. If still above 0.2" W.C. the design is faulty, or contractor has installed the wrong size ducts or grilles, or the duct has extra lengths, elbows or T's.	
Duct Leakage	Zero (too low to measure)	Less than 15 cfm @ 25Pa	After all ducts are installed **and sealed** to all grilles, supply air nozzles and air handlers	Locate leaks using positive pressure with duct blaster, forcing theatrical fog out through joints	
Air Flow Leaving Each Supply Jet Nozzle	CFM as specified by design ±10CFM	CFM as specified ±15CFM	After HVAC is **measured, meets criteria above** and is connected to power	Adjust air flow control dampers funtil supply air flow for each space meets its design target.	

Table 4.1 In-process installation quality measurements and check values

ZNE results are more easily achieved when things don't have to be pulled apart and fixed. These measurements, made by workers themselves, will help the site super make sure things are right—before each assembly is closed up and no longer accessible.

Air tightness of the enclosure

Air tightness is critical to achieving ZNE results. It eliminates hot and cold air infiltration and drafts, which improves comfort. It also greatly reduces HVAC loads, which in turn reduces electrical consumption so that the solar array can cover a larger portion of the demand.

The best time to measure and correct air leakage is after the windows, doors and ceiling of the space below the attic are complete and sealed up—and before any interior insulation and gypsum board is installed on the exterior walls. With that timing, any gaps and holes are easily located and sealed up. No need to pull down walls or remove cavity insulation to find leakage locations. To reinforce the point made earlier in the chapter, the best results come from having the framing crew measure their own work. If you are the super, you'll want to cross check results yourself, of course. But by having the framing crew do the blower door testing, they will quickly see how they need to do the next house more effectively.

But before anybody tests, you'll need to seal all the seams and joints. Rarely, if ever, will it be possible to meet air tightness requirements without sealing every joint with tape or foam. This includes all the seams and joints in the exterior wall, all the seams around and under windows and doors, plus all the seams where exterior walls meet the interior gypsum board of the ceiling of the space below the attic. In addition, every joint in that ceiling needs an effective bead of sealant to keep air from leaking out of or into the attic.

Comments & cautions - Video of air leakage testing (Table 4.1)

The clip illustrates many useful points, in just 5 minutes. Note that the blower door test is done twice: first at the stage recommended above (after exterior walls and doors and windows are complete) and then again later, after the interior gypsum board has been installed and all wiring, plumbing and HVAC are complete. In almost all projects, finishing the interior and installing plumbing, electrical and mechanical systems will open some holes or gaps or cracks that need to be sealed again to ensure adequate air tightness (less than 2 ACH/50).

In the final-stage test shown by this video, you'll note that air leakage from the attic came down through an interior wall and out through the lock set of an interior door. This illustrates how important it is to have a tight seal on the attic side.

At the same time, there are aspects of that video example that are less applicable for the ideal case:

- The house is a custom home, and did not use advanced framing. With advanced framing—such as studs 24" on center and other features—there are fewer leak points.
- The video is conducted by a 3rd-party consultant, as required for the intended certification. But ideally, the workers do these tests themselves, providing the real-time measurements that help them improve speed and quality of their air tightness (while also providing the opportunity for bragging rights).

Air tightness of both HVAC systems

Just as we have always pressure-tested plumbing, all connections between ducts and HVAC fixtures need leak detection and correction. If air leaks into or out of duct connections, bad things happen: hot spots and cold spots instead of nice, even temperatures, and of course higher electrical demand—for the life of the building.

HVAC air leakage testing can't happen until all ducts are connected to all components and fixtures, because most of the leakage will come out at the joints.

Also keep in mind that the energy recovery ventilation system needs to be air tight, just like the primary AC and heating system. Air leakage around the ventilation heat exchanger via duct connections destroys any savings that this subsystem can achieve. In general, ERV's and HRV's operate continuously, unlike the main heating/cooling system. Continuous operation means that any leakage will also be continuous for the life of the building. So be sure that the ERV system is installed air tight, including all connections at its inlets and outlets.

Once again, the most effective plan is to have the HVAC crew make the air tightness measurements. That way, they become fully aware of what needs to be done better the next time, saving you (and them) valuable time, while providing the owner with a system that is measured—not assumed—to be air tight.

Comments & cautions - Video of duct leakage testing (Table 4.1)

The video clip shows the basic steps involved with duct leakage testing in less than 12 minutes, but this overview does not include finding aßnd fixing of the leaks. For that, you'll probably need to rely on theatrical fog injected into the duct system via the duct blaster.

In most systems, you can expect to find leaks around and out of the air handler casing. Air handlers sold in the US are not fabricated to strict air tightness standards, such as those that apply in Europe. So in addition to leakage at duct connections, the air handler panel seams often will need to be sealed up, so that the system as a whole will meet the criterion of less than 15 cfm leakage at test pressure. Also, watch out for leakage at the collar where the supply air diffusers or jet nozzles connect to the supply ducts. The same caution applies to the connection between the return grille(s) and the return duct.

Most importantly, note that ZNE results demand more stringent criteria than what are shown in this video. For example, the target whole-system leakage for ZNE is less than 7 cfm, with an upper limit of 15 cfm. The 125 cfm leakage of the system tested in the video is far too high and would be simply unacceptible for ZNE.

Measuring HVAC system pressure drop

Measuring the air pressure differences across components and across duct sections will uncover obstructions and shortcomings of duct installation. The total external static pressure (the sum of the supply static pressure plus the return static pressure when measured across the air handler) should be less than 0.2" W.C. Higher static pressure indicates there's too much resistance in the system, which could happen for many reasons:

- Crushed or kinked supply or return ducts
- Sharp bends in the duct runs
- Extra flex duct, i.e: loose loops and bends with highly-corrugated interior surfaces rather than short, straight and smooth runs.
- Ducts that are not large enough for the design airflow
- Return grille that is too small
- Return filters that are clogged or not deep enough (e.g., 1" deep rather than either 2" or 4" deep)

Any such shortcoming needs to be corrected before the interior finish is complete, because after everything is buttoned up it will be very difficult to correct any duct work problems. If not corrected, these issues cause needless fan energy consumption, for which the owner will have to pay for the life of the building.

Comments & cautions - Video of HVAC system pressure test (Table 4.1)

Excessive static pressure is a bad thing in any HVAC system. It means that fan energy is being wasted. This 11-minute video provides a useful hands-on overview of pressure measurements, along with troubleshooting examples that can help locate specific shortcomings. The system shown in the video is generic. It's installed and operating in a teaching lab.

Note, however that the test pressures used to demonstrate the measurement techniques are far higher in this video than appropriate for a system in a ZNE house. For example, the target total system pressure described by this video is 0.5" W.C. That target was typical in the past, reflecting many manufacturers' default recommendations for maximum static pressure. But an efficient ZNE residential system should need no more than 0.2" W.C. external static pressure when operating at the air flow rate needed for comfort.

Measuring and adjusting correct supply air flows to each space

Measuring and setting the very low supply air flows of an efficient, low-load house is tricky. Measuring larger air flows would be easier. This video helps the non-expert understand the overall process of measuring air flow as it enters a room, and makes the very important point that the flows need to be compared to—and then adjusted to match—the air flows called out on the HVAC floor plan. Do that right, and the system will rarely—if ever— need adjustment. Do that wrong, and the owners will always be complaining about hot spots, cold spots and inadequate capacity. And of course such comfort complaints and callbacks steal profits and clog up your production schedule.

Comments & cautions - Video of measuring supply air flow (Table 4.1)

The video demonstrates the use of the only currently-available powered flow hood for small air flows. At a cost of $3,000 as of early 2020, it's clearly an expensive item. But it provides the accuracy needed for the very low flows of all ZNE homes. Other flow hoods do not perform reliably for flows that are often below 75 cfm. Further comments and cautions about this video include:

- This video clip is roughly 6 minutes long. The narration during the first 2 minutes, 30 seconds provides less-than critical introductory remarks. So you might consider fast-forwarding to minute 2:30 before starting to view the commentary.
- The narration between 2:30 and 4:30 demonstrates the use of the powered flow hood when *measuring* low air flows.
- Beginning at about 4:30, the narrator shows the use of the hood when *adjusting* air flows, so the measured value matches the design supply air flow for each room.
- The video is not a model of either succinct narration or excellent sound engineering. But it's "handcrafted" look and feel still provide an excellent introduction and real-time demonstration of tmeasuring and setting small air flows with relevant precision.
- If your systems are built like those at Dream Creek, then flow adjustments are made with dampers located near where air distribution plenum connected to the air handler. This is a much better location than at the face of the diffuser, which then impedes air mixing and can lead to noise. Bit when located back at the plenum, the dampers may get hidden behind interior gypsum board. So it's important to set the air flows before those dampers become more difficult to access.

Summary

No brief chapter such as this one can explain everything construction managers must understand to be successful and profitable with ZNE-grade construction. The items noted here are just the tip of the iceberg. But if any of these items are ignored, it will be difficult to succeed. So consider these tips the beginning rather than the end of a journey to ZNE.

Chapter 5

Building Enclosure

Economical, Highly Detailed, Well Insulated, Air Tight... and TESTED

Fig. 5.1 Economy and speed require detailed design and rigorous site supervision
Note the level of framing detail in the plans. Next, note that these sheets are laminated and available on-site for constant reference. Finally, note the sharp-eyed and continuous supervision by the site super. He's ready to firmly enforce exact placement of each framing component, avoiding any costly habit of adding extra lumber.

ZNE Enclosures

The ZNE enclosures in the Dream Creek development in Stockton, California provide the examples discussed in this chapter. They are different from traditional enclosures in many important respects:

- **Much less lumber.** They use one-half to one-third of the lumber used in similar homes.
- **Very little heat leakage.** Exterior wall framing factors are about 12%, rather than the 25-30% framing factors of conventional houses. (Framing factors measure the percentage of the exterior walls that leaks heat through the framing, bypassing exterior insulation. This is also called "thermal bridging.")
- **High performance windows.** These reduce solar heat gain to less than 20% and the overall heat leakage to a U-value of less than 0.28. Said another way, these windows have an R-value of 3.6, compared to traditional R-1.5 windows.
- **Continuous exterior insulation.** A continuous layer of extruded polystyrene insulation covers the entire outboard face of exterior wall. Inboard from that layer, the 6" deep stud bays of exterior walls are insulated with fully-fitted batts, boosting the net thermal resistance up and over R-25. The under-floor insulation over the crawl space is identical to the exterior wall insulation. The blown-in attic insulation reaches R-42.
- **Air tight.** Leakage of the completed buildings is always less than 1.7 air changes per hour at a pressure difference of 50 Pascals. In fact, most buildings at Dream Creek leak less than 1.5 ACH_{50}.

These improvements add up to great thermal comfort all year long: no drafts and no hot or cold rooms. So it's perfectly comfortable to sit near windows at any time of the day or year. And the other good news is that this superior comfort needs only small HVAC equipment—not the big clumsy stuff of the past. In these houses, "small HVAC" means less than one ton of AC capacity per 1500 ft^2 of floor area, compared to the typical 2.5 to 3.5 tons/1500 ft^2 of past practice.

Keep in mind, however, that as admirable as these results may be, success in keeping the *construction budget* within profitable boundaries strongly depends on four new cultural imperatives.

1. Highly-detailed design documents

Pre-construction drawings define and locate every stick and every connection. This is quite different from the traditional practice of simply ordering the pre-engineered roof trusses and then providing the framing crew with the floor plan and roof plan. Such minimal architectural design leaves detailed design and the connections between assemblies to the workers and/or the carpenter in charge of the crew. That traditional approach has usually been adequate for structure. When in doubt, carpenters' cultural bias is to add more framing and more fasteners. And certainly, robust structure is a good thing... until the concept falls over the cliff into wasted material during construction, followed by *decades* of energy waste over the life of the building. Excessive framing wastes energy, because it leaks heat.

To avoid lumber waste and to ensure that ZNE is not accidentally ruled out by on-site framing decisions, the framing needs to be defined clearly for all to see, in construction documents that call out every framing member and its location. And these documents need to be readily available on site at all times, as shown in figure 5.1.

2. Strict installation with continuous on-site verification

The next imperative in pursuit of ZNE is constant checking of installed results against detailed plans—every hour of every day. This is really hard for many organizations. Material substitutions to meet schedule, shortages of both supervisory staff and trained craftspeople, language barriers and even the sometimes misplaced pride of experienced workers can all become obstacles to achieving ZNE. But deviations from structurally economical and thermally excellent framing plans can add up very quickly to become insurmountable obstacles to either profits or ZNE, or both.

ZNE buildings cannot be built using "creative on-site adaptations." If construction documents are not explicit, they leave thermal and structural details of design to craftspeople. That's a mistake. Workers need to and want to focus on completion speed and quality rather than on long-term building energy consumption. Vague construction documents are simply not adequate to guide craftspeople during the difficult challenge of achieving market-rate ZNE at a profit.

3. Commit to the specified materials and subcontractors

Traditionally, the purchasing agent needs and is given autonomy to substitute materials or subcontractors to keep the project within budget and meet the target completion date. Those functions don't change with ZNE construction, except in two essential respects:

- Before any substitutions are made, both managers and purchasing agents need to be fully aware of—and fully compensate for—all of the energy and installation quality consequences of the planned substitution.
- Savings in one assembly, material or subcontract must be allowed to balance the higher-than-traditional expenses in other areas.

To achieve ZNE, some items and some subcontracts will be more expensive than in traditional construction, while many others will be less expensive. The usual flinty refusal to prohibit any one category to go above a budget set by long years of experience with traditional construction won't work with ZNE. Now, most categories will need different budgets than before. Some must be allowed to rise while others need to fall, to keep the overall budget on target. For example, lumber savings from advanced framing and labor savings from speedy installation of insulation will need to be applied to the higher cost of thermally-excellent windows and the cost of additional insulation.

4. Measure and correct air leakage before exterior drywall

With ZNE, measured results really do matter. And with respect to the enclosure, air tightness is a critical parameter. Leaky buildings can't reach ZNE within a reasonable budget. They just can't. That's because they would need a huge solar array and large mechanical equipment to meet the loads imposed by air leakage. Big arrays and large mechanical systems don't fit into a market rate lot or modest budget.

" Take this and make it much more difficult than it needs to be. "

Fig. 5.2 Don't make it complicated!... simplicity provides profits
The key to profitable market rate ZNE is taking stuff out, not adding expensive gizmos.

Further, to keep the building profitable, construction must go fast. And it can't go fast if the construction crew is chasing air leaks after drywall is installed. By then, they simply will go nuts trying to find the leaks. And when (or if) they eventually find them, they'll have to tear things apart to fix them. And then put it all back together. No fun at all.

There is no substitute for testing. "Happy thoughts and regulations" do not make buildings air tight. The evidence is clear. After regulations requiring air tightness went into effect, the California Energy Commission measured leakage in a state-wide sample of 80 new homes, with results expressed as air changes per hour, when the house pressure is 50 Pascals higher than outdoors (ACH50). The leakage varied from 30.0 ACH50 in the leakiest home to 2.0 ACH50 in the tightest home. Not even one met the ZNE target of 1.7 ACH50. Leakage must be measured, located and *fixed before interior insulation and finish* to make homes tight enough to achieve ZNE.

Detailed design locates every stick...
... construction goes quickly, with no wasted lumber.

Without detailed design, they'll figure it out on site... but it won't provide profitable ZNE.

Fig. 5.3 Detailed design avoids waste Photos courtesy of Steve Easley

When every stick is placed on the design documents, framing moves faster, while using less material and avoiding thermal bridges that block insulation. Faster construction, less heat leakage and less wasted material—all from simple, code-compliant framing via detailed drawings.

Fig. 5.4 Single LSL top plate: 36 ft. long

Fig. 5.4 Exterior wall studs set 24" on center

Exterior Framing - Keep it Simple

The exterior of the enclosure needs to be a six-sided, air tight, perfectly-insulated box. That's a tough standard, especially since the building is made of sticks and sheets, with big punched holes for doors, windows, wires and pipes. All those gaps, cracks and holes make it tough to maintain air tightness, and even more difficult to avoid gaps in the insulation. So here are some specific suggestions about the exterior of that ideal enclosure.

1. Exterior wall studs set at 24" on center saves lumber cost, speeds insulation installation and reduces the heat-leaking framing factor

Framing at 24" on center is not an absolute imperative for ZNE construction, but it sure saves time, trouble and material cost, while improving insulation effectiveness and reducing energy consumption.

Fig. 5.5 Stacked roof trusses
This design saves time and lumber, and it's fully code-compliant.

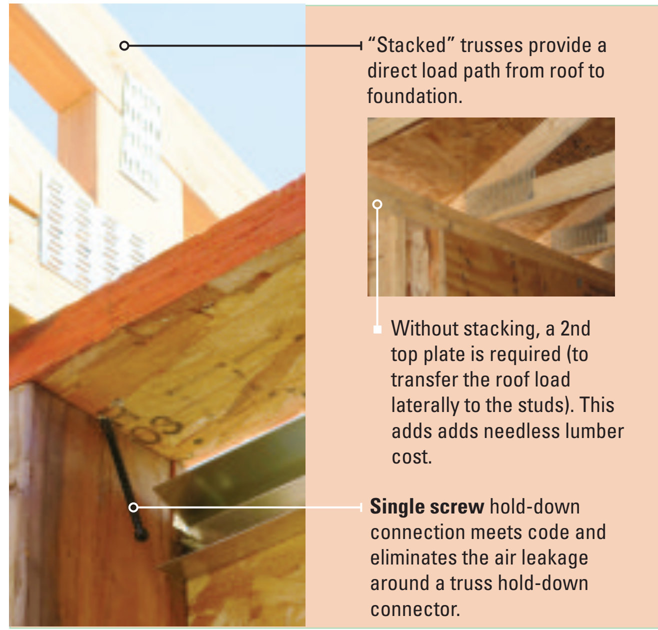


Fig. 5.6 Single screw hold-down is stronger than a twist tie
Faster to install, less expensive and overall—it's simply better.

2. LSL top and base plates: flat and straight avoids air leakage

Most air leakage comes through the long joints between the base of the exterior walls and foundation, and between the top plate of the walls and the roof with it's support structure. That's partly because fresh cut lumber twists and warps slightly as it dries during construction and over the life of the building. So, engineered lumber like LVL (laminated veneer lumber) or the slightly lower cost LSL (laminated strand lumber) is a better choice (see fig. 5.4). These are available in long lengths for use as top and bottom plates. Such perfectly flat and perfectly straight lumber greatly simplifies the task of air sealing those long, and otherwise very leaky joints.

3. "Stacked" roof trusses set above studs at 24" OC add further savings

As shown in figure 5.5, roof trusses placed 24" on center and set directly above wall studs ("stacked") meets code and saves the cost of extra trusses. And in most cases, stacked trusses eliminate the need for a double top plate and/or a header across the length of the top plate. If this is not a familiar detail, be sure to check out Chapter 6 for the commentary of a California Civil Engineer about how structural codes apply to this and other details. Eliminating that long extra top plate and/or header saves money and reduces heat leakage through framing.

4. Single screw connection between top plate and roof truss avoids air leaks and is stronger than a twist tie

See figure 5.6. A perhaps surprising fact is that a single screw connection is stronger than a connection made with the usual truss hold down connector. The single screw (provided it meets the SDS25412 specification) provides 2% greater uplift displacement resistance, and 56% more lateral displacement resistance compared to a "hurricane clip" connection. Without hold down connectors in the way, the interior gypsum board can lie dead-flat on the side of the top plate,

Fig. 5.7 Removable headers reduce insulation gaps
The header is installed with screws. Then it is removed temporarily by insulators, so they can insulate the cavity behind.

instead of creating the usual air gaps where the gypsum board lays over the metal connector. Placing a single, long, self-tapping screw takes much less time than fiddling a connector into place and fastening it with four screws.

5. Removable single-piece headers screwed into notched wall studs allow insulation behind, in full contact with the exterior sheathing

See figure 5.7. At Dream Creek, the headers on the exterior wall are set into the trim studs of the windows on their interior edges. They are fastened with screws that can be removed, so that the insulators can get behind them to place layers of insulation behind the header and in full contact with the exterior sheathing. This detail provides full structural code compliance, and avoids the usual heat leakage from lack of insulation at the headers above windows and doors.

Fig. 5.8 Two-stud exterior wall corners
Eliminating the usual extra studs in the corners allows more complete insulation, improving comfort with less energy consumption.

6. Two-stud corners avoid wasted lumber and heat leakage, and they speed insulation installation

The traditional over-built exterior corners allow heat leakage because of the difficulty of insulating between the studs. Two-stud corners such as those in figure 5.8 are fully code-compliant, and allow for insulation all the way into the corner. This saves lumber, reduces seasonal heat loss and improves comfort by avoiding those annoying "cold corners" in winter and "hot corners" during the summer.

7. Run the wiring down on the bottom plate, to avoid crushing insulation and slowing down its installation

Another neat trick from Dream Creek is illustrated in figure 5.9. Precut studs have V-notches or half-holes where they land on the bottom plate. Wiring runs through those notches along the bottom plate and

Fig. 5.9 Notches for wiring, cut into the base of exterior studs
Avoids crushing or squeezing insulation with mid-cavity wiring.

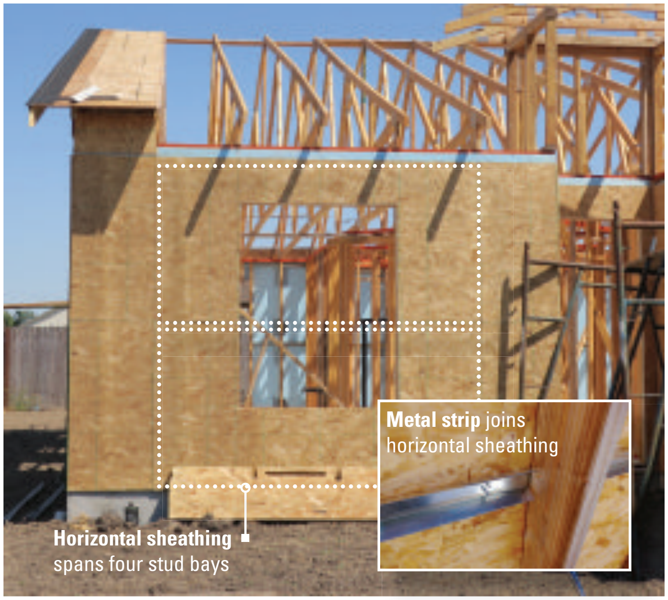


Fig. 5.10 Horizontal sheathing joined by metal strips
The assembly was developed at Dream Creek by George Koertzen, the project designer and its construction manager.

up the sides of the studs, eliminating the usual crushing of cavity insulation when wires cross the cavities. That way, standard-width batts can be quickly and perfectly installed, in full contact with all six sides of every 24" stud bay.

8. OSB sheathing installed horizontally improves structural strength

Figure 5.10 shows another useful design detail: sheathing set horizontally. When studs are set 24" on center, horizontal 4' x 8' OSB sheets span four rather than two stud bays, improving shear resistance. While this detail does have the disadvantage of making the upper horizontal panel more difficult to place, the top of that second panel at 8' means that the width of the third and final panel is an even dimension (16"), which helps eliminate wasted trim pieces. The relative lightness of that narrow panel also makes it easier to lift it into place, which helps make a tight fit between and around the roof trusses.

The innovative notched metal strip shown in Fig. 5.10 connects the OSB sheets along their horizontal joint. This detail was developed for Dream Creek by George Koertzen, the project designer and construction manager. The notched strip helps enforce the 24" spacing between studs, while also adding strength to the wall assembly by connecting the horizontally-mounted OSB sheets.

This innovation does have a downside. Although certainly strong, the detail is not described or discussed in the building code. While used for the Stockton project by agreement with local code officials, the fact that the assembly is not mentioned in the code means that in areas of higher seismic risk than Stockton, testing would probably be required before it would be approved for use.

9. Pre-assembled gable end trusses carry loads that would otherwise require headers

The pre-assembled gable end trusses shown in figure 5.11 provide another lumber cost reduction as well as an insulation improvement. Any header would leak more heat than these fully-insulated cavities.

Fig. 5.11 Pre-assembled gable-end truss - lifted as a single piece

Fig. 5.12 The right time to find and fix air leaks
Get the air barrier sealed up tight BEFORE drywall goes onto the exterior wall. That way everything is still accessible and visible. So the crew can easily see and seal up the gaps, cracks and holes—and find and fix any leaks.

Also, the entire gable end assembly can be fabricated on the ground and then lifted into place by a crane, eliminating the need for gable-end scaffolding. Working on a scaffold always presents the risk of a fall from that height by less-experienced workers.

10. Effective air sealing is least expensive after doors, windows and ceilings but before insulation and gypsum board on exterior walls

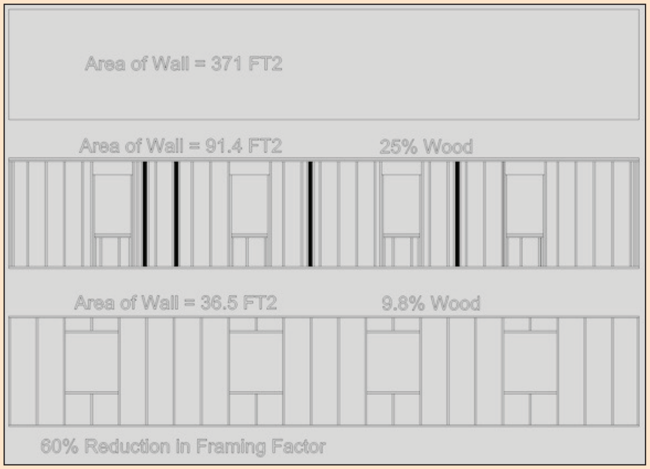
The best way to save time and money while still limiting air leakage to less than 1.7 ACH_{50} is to complete—and test—the air barrier before installing any cavity insulation or any wall board on the interior face of exterior walls.

After windows and doors are in, install the ceiling drywall and seal it to the top plate of the exterior wall and top plates of all interior partitions (Fig. 5.12). Also install drywall on one side of the wall between the house and the garage. At that point, a leakage test can be performed while the entire air barrier is both visible and accessible for any sealing touch up. And by using a fog machine while the building is kept under positive pressure, the exact *locations* that need to be sealed become quite apparent. That fog machine really saves a lot

Fig. 5.13 Use a theatrical fog generator to find leaks
Crews work from both sides of the walls. Blower door pressure forces theatrical fog outwards through any gaps or holes, so leakage can be seen, located and sealed up tight. The blower door quantifies the leakage—so there's no doubt about sucess or failure to meet the ZNE target of less than 1.7 ACH_{50}

of time and reduces uncertainty.

As many readers will be aware, having the workers themselves perform the blower door test pays off in a big way. When the framing crew actually measures the results of their work while they are still on site, the knowledge they gain is immediately available to each and



Extra wood means extra cost and wasted energy over decades, because wood framing displaces insulation.

Advanced framing at 24"OC meets and often exceeds code, while reducing construction costs and then saving energy for generations of homeowners

Real-world project comparison - Redding, CA.

Traditional framing = Higher construction cost and higher annual energy waste

Framing Lumber
320 studs
48 trimmers
Doubled 2 x 6 top plates
(5) 6 x 6 posts
(8) 6 x 12 headers

Old-style framing for 1,565 ft²

Photos and data courtesy of Mike MacFarland

Advanced framing = 70% less lumber than project above, but 35% MORE living space! Annual energy measured LESS than zero. (July 2017 - June 2018)

126 studs, 11 base plates, 1 header

Perimeter top plates

Advanced Framing for 2,400 ft²

Fig. 5.14 Advanced framing saves lumber and labor costs during construction, then it saves energy for homeowners—for about 100 years.

every one of them on the next project. And when you measure your own results, you're naturally curious about how your work compares with that accomplished by other crews. A little pride goes a long way towards improving results and speeding the work on the next project. Everybody realizes that their numbers and reputation *might* become the subject of discussions around the lunch truck.

Insulation

Now, on to insulation. Much of the usual discussion on insulation is focused on exterior walls. That's understandable, since walls are probably the most complex assembly from the perspective of installing insulation. It's tricky to do well. Walls have lots of awkward cavities that take time and effort to insulate, compared to the more open—and arguably simpler—attic and crawl space insulation.

But it's useful to keep in mind that image of a six-sided box, perfectly air tight and perfectly insulated without any gaps or voids. And when you visualize that box, with it's nice, thick, continuous insulation, you'll be immediately aware that your design can't really be that simple. You're going to punch through it in many places, leaving holes that can't be insulated. Such unavoidable punched holes are called windows and doors.

1. High performance windows: SHGC 0.20 and U-value below 0.28

To come as close as possible to the ideal insulated box, keep in mind that windows need to be as thermally-resistant as possible. They will still be something like a weak R-4 or maybe an R-6—compared to the robust R-26 of the clear walls and floors at Dream Creek, and rather embarrassing compared to the magnificent R-42 in the attics.

So keep in mind that windows need to be as thermally-terrific as windows can be, in order to keep the goal of ZNE within reach. Some numbers can help to reinforce the point.

The cooling load imposed by the sun is about 250 Btu/ft^2. So, let's say one side of the building has a total of 48 ft^2 of glazing area. Unless the solar heat gain is drastically reduced by those windows, it will require *one entire ton of AC capacity* (12,000 Btu/h) to remove the solar load from those windows alone. Considering that the houses

Photo courtesy of Steve Easley

Fig. 5.15 Window performance certification label
The National Fenestration Rating Certification (NFRC) Label shows this window—installed at Dream Creek—has a low thermal leakage rate (0.28 U-value) and resists 80% of the excess heat from solar radiation (Solar heat gain coefficient of 0.20).

at Dream Creek are heated and cooled by equipment that needs *less than* one ton of capacity to remove *all* the cooling loads from the entire house and all it's people, meal prep, appliances, lights and consumer electronics, it's apparent that their windows are not large, and are thermally excellent. That's why Dream Creek homes can achieve ZNE.

Here are some easy numbers to keep in mind. Windows should have a solar heat gain coefficient of 0.20 or less (which means they only allow 20% or less of the solar radiant cooling load to leak into the home). And they should have a U-value (heat transmission rate) of 0.28 or less. That's an R-value of at least 3.57. (U 0.28 ÷ 1 = R 3.57)

2. Exterior insulation totals R-26, so continuous insulation is a must

To avoid the thermal losses when heat leaks through framing, the building needs to be "wrapped in a sweater." It's not good enough (as in traditional buildings) to only "pull apart the sweater and stuff the wool between the ribs" of the exterior wall. The exterior walls need two separate layers of insulation: a continuous layer outside the structure ("the sweater") plus a much thicker layer inside the wall.

That thicker inside layer will necessarily be interrupted by the wall structure itself: the vertical studs and the bottom and top plates. The metric that quantifies that interruption is the "framing factor." It's the percentage of insulation that is eliminated by framing. In typical wall construction of the past, 20 to 30% of the insulation would be displaced by excessive framing. At Dream Creek, the framing factor is reduced to less than 13% by placing studs 24" on center, and by using single-piece headers that have insulation behind them, in full contact with the exterior wall sheathing. As shown earlier in figure 5.14, that 24" spacing reduces lumber cost while reducing thermal losses.

For the continuous exterior layer of insulation, two designs have been used at Dream Creek: placement outboard of the sheathing, or placed further inside, between the sheathing and the framing (Fig. 5.16). These have been lightheartedly nicknamed the "outtie" and the "innie" by Bruce King, our consulting team's Civil Engineer.

The advantage of the "outtie" is structural. With no insulation between sheathing and framing, the connection between the two is stronger. It's disadvantage is that with insulation on the outside, there's more work and complexity when attaching the exterior cladding (stucco, clapboards or other).

The advantage of the "innie" is that it's much easier to add the exterior water barrier and then the cladding over the full-width support

Fig. 5.16 Exterior insulation layer—two alternatives

"The Outtie"
Exterior insulation on the outside surface of the sheathing

"The Innie"
Exterior insulation between sheathing and framing

of a continuous OSB surface. The disadvantage is structural: the connection between sheathing and framing must go through about 5/8" of insulation, so during shaking events, the fasteners may twist. The connection is less robust from a seismic perspective. For further discussion, read Bruce King's commentary on this detail in chapter 6.

Inside the walls at Dream Creek, unfaced batts of either glass fiber, recycled denim or mineral wool are (lightly) press-fit into each stud bay, taking care to fill the cavities' vertical dimension and their front-to-back dimension perfectly. This attention to installation is critical for ZNE homes, which are equipped with much smaller heating and cooling capacity than the usual oversized, uncomfortable and inefficient HVAC systems. Crushing the batt, or leaving an air gap around the batt quickly reduces the R-value from R-21 when perfectly installed to R13 or even lower, depending on how badly the batt is crushed, or how wide an air gap exists between the batt and any of the six sides of each stud cavity. So while the insulation design matters, what matters even more is that *installation* does not destroy the thermal effectiveness of that insulation.

Fig. 5.17 Interior insulation layer—installed perfectly
Regardless of which choice is used for the exterior insulation, the interior layer must be installed tight to all six sides of each stud bay.

Fig. 5.18 Roofs have radiant barrier sheathing
Shiny aluminum helps keep solar heat from radiating into the attic.

3. Attic floor is air tight and its insulation is R-42. The roof has radiant barrier sheathing.

The thermal effectiveness of the attic begins with the "attic floor", which is also the ceiling of the occupied space. The assembly needs to be air tight, because it forms the top of that ideal "six-sided, air tight and well-insulated box." Exterior attic access is preferable to help air tightness with respect to the occupied space, and to limit the temptation to go into and out of the attic for storage, which could compromise insulation. Any interior attic access hatch must be well-gasketed, air tight—and measured to be so, using a blower door.

There are two strong reasons to keep that attic air tight with respect to the occupied space: mold prevention and thermal comfort. With thick insulation and radiant barrier sheathing, the attic insulation and the roof support structure is cooler during the winter than traditional thermally-inefficient construction. But cooler attic surfaces can lead to mold, if humid air from the occupied spaces is allowed to drift upwards during the colder months. Keeping the attic floor air tight avoids this problem.

Now, it's worth highlighting the fact that construction sequence matters with respect to attic insulation. At some point, you might need to remind the super and/or the subcontractors *why* it's critical to make the attic floor air tight *before* insulation. Just ask them to think about how much aggravation and time (labor cost) will be wasted trying to locate and seal up air gaps —while wading through 18" of loose-fill cellulose or fiberglass inside the hot attic. No fun at all. So... *first* the air sealing, *then* the insulation.

Next, note that the "raised heel" trusses at Dream Creek shown in figure 5.18 allow a full 18" layer of insulation to be installed on the attic floor, all the way out to the eaves. The truss height at the eaves allows enough space *above* that 18" of insulation to let outdoor air ventilation flow into, up and out the attic through vents at the roof eaves and ridge.

Finally, to complete a thermally excellent attic, the roof sheathing is equipped with a reflective radiant barrier. Shiny metal surfaces have a very low emissivity—they don't emit much heat into the air. That means the sheathing of Dream Creek roofs leak a smaller percentage of solar heat into the attic and then into the occupied space.

4. Crawl space insulated and sealed like exterior walls

Air sealing and insulation for the floor above the crawl space will complete the six-sided box. Again, air sealing the floor comes before insulation. Use your blower door with a fog machine to locate and seal up any gaps, cracks or holes.

The design for crawl space insulation at Dream Creek is (nearly) the same as insulation for exterior walls. Moving down from the inside: first the rough flooring is fastened to the floor joists. Then 6" unfaced insulation batts are set between the joists. Those batts are held in place and supported from below by a 1" layer of rigid board insulation nailed to the bottom of the joists. This design provides R-26 insulation between the occupied house and its crawl space.

Two additional components help make that crawl space clean, dry and impermeable to rodents. First a class 1 vapor barrier (Perm value less than 1.0) is laid down wall to wall between the footings. Then a concrete rodent barrier slab is placed on top of the vapor barrier. In addition to improved durability, sanitary benefits and mold risk reduction, by code this assembly allows reduction of crawl space ventilation down to one square foot per 1,500 square feet of floor area. Fewer crawl space vents means fewer "doorways" for unwelcome visits from critters and insects over the life of the building.

Interior walls and gypsum board

At Dream Creek, interior walls are non-load-bearing. This provides opportunities for savings in lumber and wall board. The savings are used to offset part of the cost of other components, such as windows.

1. No headers for non-load bearing walls

Interior walls carry no loads other than their own weight, so there is no need to headers above doorways beyond the framing needed to support the door assembly.

2. No extra stud at interior-exterior wall intersections

Where interior walls meet exterior walls, past practice has added studs to the exterior wall at the connection. This is not necessary. See figure 5.19. The interior wall is firmly connected to both the floor and the bottom of the roof trusses, so no extra stability is gained by an extra stud in the exterior wall. And that excess stud would increase heat leakage, by blocking space needed for exterior insulation.

Fig. 5.19 Interior wall connects to exterior—without extra studs

Metal splice plate joins top plates together, in a robust and code-compliant connection.

No need for extra studs that add cost and block the space needed for insulaiton.

Fig. 5.20 Horizontal drywall with OSB-backed splice
Rather than landing on a stud, the sheetsare spliced and backed securely using OSB off-cuts, saving a surprising amount of wall board.

3. Drywall clips eliminate extra studs in interior walls

Rather than adding wall studs on which to "land" the interior gypsum board at joints, at Dream Creek, drywall clips are used to support the ends of the drywall sheets. This saves lumber and is code-compliant in Stockton's seismic zone. At the same time, it probably allows more movement than traditional practices. Some may decide that the "firmer feel" of gypsum board edges landing on vertical studs adds value in return for the higher lumber costs.

4. Horizontal drywall with OSB-backed splices

Gypsum board waste in traditional construction is high. Dumpsters full of off-cuts were common on jobsites in the past. At Dream Creek, this waste has been nearly eliminated. Interior drywall is set horizontally, and never cut until the end of the wall. Any hanging edges between vertical studs are joined and backed by OSB off-cuts, as shown in figure 5.20. By not trimming all the drywall to land sheet-ends on studs, the number of sheets are reduced by a surprising amount. For example, the modest-size 1200 ft^2 homes at Dream Creek needed about 32 full sheets of drywall when installed vertically. Now, with horizontal sheets that have joints backed by OSB off-cuts, the sheet count has dropped to 16. Any such 50% cost reduction is attractive, even for low-cost wall board.

And there are further benefits. When the 8' sheet spans four 24" bays rather than only two (as when installed vertically), the longer attached sheet improves racking resistance of the wall. A final benefit comes when finish the walls. There are fewer joints to tape, mud and sand. Fewer joints and smoother edges helps make taping and sanding a bit faster, providing some labor savings in addition to less wall board and fewer off-cuts going into landfills.

Structural Commentary

Low Cost , Code-Compliant Structural Details for ZNE

Fig. 6.1 Structural details depend on seismic imperatives

Advanced framing is critical to the economics of market-rate ZNE, for all the reasons detailed in other chapters. However, seismic imperatives are even more critical, especially for houses in California.

Four members of the project team for this book met on site to view and assess framing and connection details designed by George Koertzen, from the perspective of a California structural engineer. Bruce King has over 40 years of experience designing, investigating and assessing seismic issues in all California seismic zones, as well as throughout the US and other countries.

Structural Commentary

By Bruce King, PE

This is a review of some of the novel framing techniques developed by Habitat for Humanity (H4H) for new homes in Stockton, California. These homes are built partly with donated materials and in large part by semi-skilled labor. The techniques discussed here are said to cost less to build and facilitate more certain construction of a super energy-efficient building envelope.

This commentary provides a structural engineer's perspective on the essential details, how they relate to the 2016 California Residential Code (**CRC**), and how they might be adapted to different levels of seismic risk, or different wood building types such as custom residential, multifamily, and light commercial.

If you're a builder, an engineer, or a building official, you will likely have specific concerns about "advanced framing." This chapter is an effort to identify and address those concerns. But first, some general comments.

Prescriptive design

The CRC spells out in some detail how to frame a house in ways that do not require an engineer's review and stamp. Prioritizing economy over design flexibility, homes built earlier in the Dream Creek subdivision stay within those prescriptive guidelines, avoiding the cost of an engineer. Comments that follow are also aimed at staying within those guidelines. Having a project engineer gives much greater flexibility to this design team. Generally however, the best parts of these details (from an energy efficiency perspective) can be made to work almost anywhere.

Seismic risk

In recent decades we have learned a very great deal about earthquakes and their effects on buildings. One result is a vastly more refined and demanding set of guidelines. Structural engineers now assesses risk to a specific project based on soil type, building structure type, size and irregularity of shape, occupancy, and "importance". Of particular (and easy-to-understand) impact is proximity to known active faults. We now know that about 90% of damage and loss of life from an earthquake happens within about ten miles of the source fault. The building codes reflect that fact.

First and foremost, always ask this question about a new project: "Is it near a major fault, or not?" Given the geology of the west coast of North America, the question for California structures becomes: "Is the earthquake risk merely *high*... or is it *severe*?" In California, areas of severe risk are generally along the coast; along the transverse ranges; in some of the desert areas east of Los Angeles and also along the crest of the Sierras. In the mountains, the risk is exacerbated by the nontrivial possibility of having a lot of heavy snow on a roof when the ground moves.

The building code reflects this generalization. Sometimes, as when in articulating prescriptive framing requirements, it asks (essentially) the same question: "Is the structure within 10 miles of a major fault?" In those cases, two levels of seismic detailing are assigned according to the answer. Stockton, where these study homes are located, is not near a major fault. So the requirements are more relaxed than they would be for the same house located 40 miles west in the Bay Area or 100 miles east in the Sierras (seismic design categories D). Most of the details described here would need further assessment for use in areas that have a higher level of risk.

Building Typology

Generally, one-story (and to a lesser extent two-story) wood-framed houses are very stable. In most cases they suffer their most direct damage during earthquakes because they lack anchor bolts, or have excessive openings on any one side, eg: garage doors or picture windows. However, in hilly, wooded, or densely-built neighborhoods earthquakes also cause indirect damage from the fires that usually follow the shaking. And it bears noting that those fires are much exacerbated by the pressurized and fragile natural gas lines running to each structure.

The risks are different for taller, longer, larger, or more irregular structures. Seismic forces can be both greater and more concentrated on particular parts of the framing in such buildings. Then the code is quite clear: you'll need an engineer to design the framing. With these

Fig. 6.2
Exterior wall studs 24 in. on center, aligned under framing above

general observations in mind, we'll now examine some of the specific details used for the two single-story project houses at Dream Creek.

Exterior framing 24″ on center (Fig. 6.2)

Place exterior wall studs at 24 inches on center. Show each on the floor plan. Define doors and windows to fit the module so as to avoid extra studs, and align framing members above to bear over studs.

Relevant CRC provisions

R602.3.1 Stud size, height and spacing

The size, height and spacing of studs shall be in accordance with Table R602.3.(5). Exceptions:

1. Utility grade studs shall not be spaced more than 16 inches (406 mm) on center, shall not support more than a roof and ceiling, and shall not exceed 8 feet (2438 mm) in height for exterior walls and load-bearing walls or 10 feet (3048 mm) for interior non load-bearing walls.

2. Where snow loads are less than or equal to 25 pounds per square foot (1.2 kPa), and the ultimate design wind speed is less

TABLE R602.3(5)
SIZE, HEIGHT AND SPACING OF WOOD STUDS[a]

STUD SIZE (inches)	BEARING WALLS					NONBEARING WALLS	
	Laterally unsupported stud height[a] (feet)	Maximum spacing when supporting a roof-ceiling assembly or a habitable attic assembly, only (inches)	Maximum spacing when supporting one floor, plus a roof-ceiling assembly or a habitable attic assembly (inches)	Maximum spacing when supporting two floors, plus a roof-ceiling assembly or a habitable attic assembly (inches)	Maximum spacing when supporting one floor height[a] (inches)	Laterally unsupported stud height[a] (feet)	Maximum spacing (inches)
2 × 3[b]	—	—	—	—	—	10	16
2 × 4	10	24[c]	16[c]	—	24	14	24
3 × 4	10	24	24	16	24	14	24
2 × 5	10	24	24	—	24	16	24
2 × 6	10	24	24	16	24	20	24

For SI: 1 inch = 25.4 mm, 1 foot = 304.8 mm.

a. Listed heights are distances between points of lateral support placed perpendicular to the plane of the wall. Bearing walls shall be sheathed on not less than one side or bridging shall be installed not greater than 4 feet apart measured vertically from either end of the stud. Increases in unsupported height are permitted where in compliance with Exception 2 of Section R602.3.1 or designed in accordance with accepted engineering practice.

b. Shall not be used in exterior walls.

c. A habitable attic assembly supported by 2 × 4 studs is limited to a roof span of 32 feet. Where the roof span exceeds 32 feet, the wall studs shall be increased to 2 × 6 or the studs shall be designed in accordance with accepted engineering practice.

than or equal to 130 mph (58.1 m/s), 2-inch by 6-inch (38 mm by 14 mm) studs supporting a roof load with not more than 6 feet (1829 mm) of tributary length shall have a maximum height of 18 feet (5486 mm) where spaced at 16 inches (406 mm) on center, or 20 feet (6096 mm) where spaced at 12 inches (304.8 mm) on center. Studs shall be minimum No. 2 grade lumber.

R602.3.3 Bearing studs

Where joists, trusses or rafters are spaced more than 16 inches (406 mm) on center and the bearing studs below are spaced 24 inches (610 mm) on center, such members shall bear within 5 inches (127 mm) of the studs beneath.

Commentary

Spacing wall studs at 24 inches is explicitly allowed by the CRC, which all by itself substantially reduces the framing factor and its attendant thermal bridging (that erodes the R-value of the composite wall). At the same time, wider spacing also, of course, makes for a less robust structure. The code carefully defines where 24" spacing is—and is not—acceptable practice. The code further constrains stud spacing where walls are resisting lateral forces (Table R602.3(3)).

The common notion of a sheathed, stud-framed wall is a sort of solid plate which can be penetrated or loaded almost anywhere. With wider stud spacing, especially in combination with a single (vs. double) top plate, the structure becomes more of a light post and beam frame in which each piece plays a more defined and specific role; it requires more care in both design and construction.

Testing has shown that OSB or plywood-sheathed walls with 24 inch stud spacing carry only slightly less force than equivalent walls with studs at 16 inches spacing Consequently, the code generally doesn't penalize the practice. Still, in severe seismic risk locations like the upper Sierras where heavy snow weight may coincide with a big shake, it is wise to consider carefully the trade off between better thermal performance of 24" spacing vs. the better (more robust) seismic performance.

Also, there is the matter of durability. As structures get old, they are subject to wetting in its many forms—but hopefully will dry out before mold and other decay sets in. When modern moisture barriers and higher insulation values are used without an effective moisture design strategy, energy-efficient structures become moisture traps; we contain the heat but rot the framing. Where that is the case, fewer studs means less time before the structure is rendered unserviceable. This is not an argument against 24 inch stud spacing so much as a caution against building energy efficient structures without understanding where moisture in its many forms can enter and exit the assembly (dry out).

Durability is also a function of construction and occupancy, and the degradation of framing that accompanies both. Part of the innovation of the Stockton H4H houses is the careful layout of electrical and mechanical systems so as to minimize runs, interference with insulation, and generally of framing penetrations. But all too often systems are not that well thought through, or changes and mistakes are made, or for any of dozens of reasons studs get drilled or notched during construction or occupancy. Studs don't get un-notched, and with time walls can be severely weakened by the cumulative effect of installing or changing utility lines. This effect is hard to predict, and certainly varies with the building type and expected occupancy, but to some extent does raise caution about the practice of wider stud spacing.

Finally, there is an ill-defined and mostly non-structural effect that we could call the "Fist Thump Check." If a wall feels flimsy or weak when struck, it can affect occupants attitudes and therefore their care of the building over time. If it "feels cheap," people often won't treat the structure well, or bother to maintain it. That can mean it doesn't last, and in the long run was that much less energy efficient. The loss of "solidity" stemming from wider stud spacing can materially affect longevity, but can be countered by using thicker gypsum board, such as 5/8" Type X, around interior surfaces. That modest extra cost will make for a quieter, longer-lasting and more fire-safe structure.

Fig. 6.3 Single top plate

Single top plate (Fig. 6.3)

Instead of a double top plate of matching lumber, the Stockton H4H projects use an engineered lumber (LSL, laminated strand lumber, or LVL, laminated veneer lumber) continuous along each wall run. LSL/LVL lumber can be ordered in lengths up to 60 feet, so horizontal splicing can usually be eliminated.

Relevant CRC provision

R602.3.2 Top plate

Wood stud walls shall be capped with a double top plate installed to provide overlapping at corners and intersections with bearing partitions. End joints in top plates shall be offset not less than 24 inches (610 mm). Joints in plates need not occur over studs.

Plates shall be not less than 2 inches (51 mm) nominal thickness and have a width not less than the width of the studs. Exceptions: A single top plate used as an alternative to a double top plate shall comply with the following:

1. The single top plate shall be tied at corners, intersecting walls, and at in-line splices in straight wall lines in accordance with Table R602.3.2.2.

2. The rafters or joists shall be centered over the studs with a tolerance of not more than 1 inch (25 mm).

3. Omission of the top plate is permitted over headers where the headers are adequately tied to adjacent wall sections in accordance with Table R602.3.2.

TABLE R602.3.2
SINGLE TOP-PLATE SPLICE CONNECTION DETAILS

CONDITION	TOP-PLATE SPLICE LOCATION			
	Corners and intersecting walls		Butt joints in straight walls	
	Splice plate size	Minimum nails each side of joint	Splice plate size	Minimum nails each side of joint
Structures in SDC A-C; and in SDC D_0, D_1 and D_2 with braced wall line spacing less than 25 feet	3" × 6" × 0.036" galvanized steel plate or equivalent	(6) 8d box ($2^1/_2$" × 0.113") nails	3' × 12" × 0.036" galvanized steel plate or equivalent	(12) 8d box ($2^1/_2$" × 0.113") nails
Structures in SDC D_0, D_1 and D_2, with braced wall line spacing greater than or equal to 25 feet	3" × 8" by 0.036" galvanized steel plate or equivalent	(9) 8d box ($2^1/_2$" × 0.113") nails	3' × 16" × 0.036" galvanized steel plate or equivalent	(18) 8d box ($2^1/_2$" × 0.113") nails

Commentary

Use of a single LVL top (and bottom) plate conforming to code provisions should give a better-performing wall system than its double top plate counterpart. One reason is that with bearing studs aligned under joists or trusses above (as defined by code above), the plates experience no bending loads, also, they are much less compressible than softwood lumber. The three (total) 2x plates of conventional lumber can lose as much as ½ to ¾ cumulative inches in thickness to drying, putting stress on interior and exterior sheathing. LVL plates, by contrast, experience essentially zero shrinkage.

Further, the seismic loads that potentially put the plate in tension are much better resisted by the prescribed metal plate connectors, for two reasons: LVL is denser by about 12% than softwoods, and a metal plate-to-wood connection is usually tighter than a wood-to-wood connection. (Theoretically, the typical corner splice of double top plates has zero value, because the code disallows fasteners in cross-grain tension—too brittle.)

It bears mentioning that the metal plates prescribed by code for corner and "T" connections correspond to standard sizes in manufacturer catalogues. In contrast, the prescribed plates for butt connections are not standard products; another reason to use full length LVL top plates and dispense with butt joints. Finally, the sizes of metal plates allow them to be located inboard of framing, thus getting better bearing and avoiding the small gaps that make for air leakage.

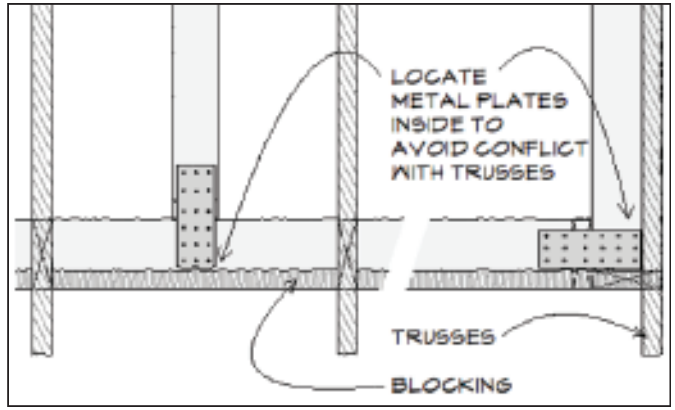


Fig. 6.4 Top plate splices
Using continuous long lengths of LVL or LSL engineered lumber for top plates helps avoid the need for splices along the length of the top plate. This simplifies installation, and reduces the challenge of achieving air tightness under the time pressure of the construction schedule. However, keep in mind that splices are still required at T-connections. Metal rather than wood plates allow locating the plate inboard of framing edges, as shown here.

Fig. 6.5 Frame to minimize interference with batt insulation

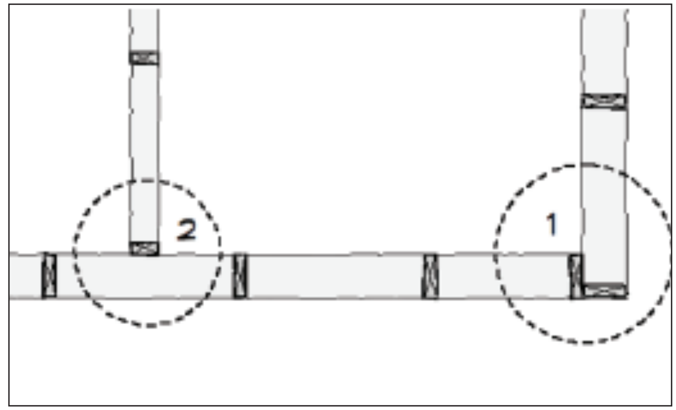


Fig. 6.6 Framing with installation and thermal advantages
By avoiding extra studs at corners and intersections, exterior wall insulation can be installed quickly, in full contact with all six sides of each cavity, using standard 24" unfaced batts.

Two-stud corners and clips (Figs. 6.5 - 6.8)

Frame to minimize interference with batt insulation:

1. At exterior corners, frame with only two studs as shown, and secure the unsupported sheetrock edge with light gauge drywall clips
2. At interior intersections, add no framing studs to exterior wall; secure the unsupported sheetrock edge with light gauge drywall clips.

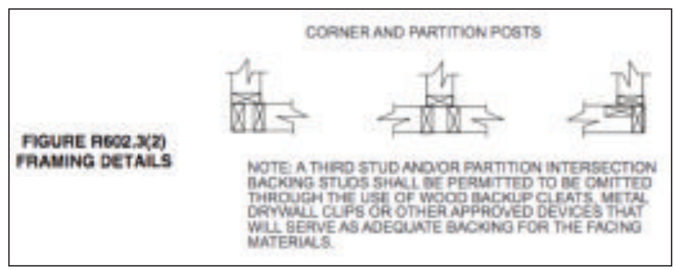


TABLE R602.3(1)
FASTENING SCHEDULE

ITEM	DESCRIPTION OF BUILDING ELEMENTS	NUMBER AND TYPE OF FASTENER[a, b, c]	SPACING AND LOCATION
		Wall	
8	Stud to stud (not at braced wall panels)	16d common (3 1/2" × 0.162")	24" o.c. face nail
		10d box (3" × 0.128"); or 3" × 0.131" nails	16" o.c. face nail
9	Stud to stud and abutting studs at intersecting wall corners (at braced wall panels)	16d box (3 1/2" × 0.135"); or 3" × 0.131" nails	12" o.c. face nail
		16d common (3 1/2" × 0.162")	16" o.c. face nail

Fig. 6.7 Drywall clips in place of extra studs
By avoiding extra studs to support the edges of drywall, lumber cost is reduced, at some reduction in racking strength of the wall.

Fig. 6.8 Clear cavities for fast and uncompressed installation of low-cost, high-performance batt insulation

Relevant CRC provisions

Note the prescriptive requirements defined by CRC figure 602.3(2) and table R602.3(1) on the facing page.

Commentary

Some of the comments regarding 24 inch stud spacing apply here. That is, elimination of some studs at intersections makes for better thermal performance, but less robust seismic performance.

The code recognizes that gypsum board, though not usable as a primary seismic force resisting material, does nevertheless provide some stiffness and energy absorption. Not adding it to interior wall surfaces makes for a reduction in allowable wall loads.

If sheetrock edges are supported by clips rather than studs, the wall is less robust during seismic racking—less able to absorb energy and protect the occupants. But, all in all, removal of redundant studs makes for only a modest reduction in wall strength, but a substantial improvement to thermal performance.

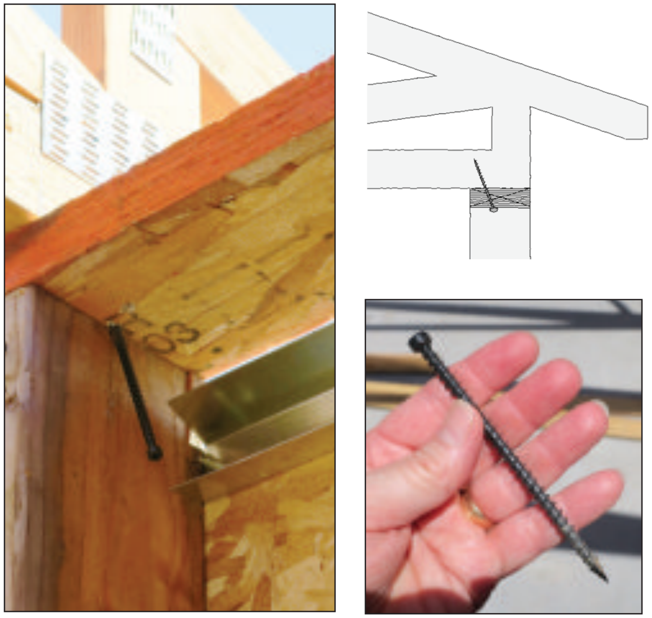


Fig. 6.9 Single truss holddown fastener

Single truss holddown fastner (Fig.6.9)

Instead of the more common light gauge metal twist ties, or the triple toe nail stipulated in the code, secure truss ends to the top plate with a single self-tapping ¼"Ø screw of at least 4 inch length, extending up at an angle from the bottom of the top plate and into the truss bottom chord. This eliminates the more common twist tiedown strap, which takes longer to install and makes for air leakage gaps where sheathing crosses over.

Relevant CRC provisions

Prescriptive requirements are defined in table R603.3(1) below. An engineered solution using a single screw improves seismic resistance beyond these requirements

Commentary

Self-tapping screws have taken over many parts of everyday framing because they are so strong and easy to install. In this application, a single screw applied from below replaces either three toenails driven from above (as per the code table below), or the more common light gauge twist clips such as Simpson H3 which require a total of eight nails driven into plate and truss—and can interfere with insulation installation.

The table below compares the approximate load capacities of twist-clips and structural screws when installed in Douglas fir truss chords. While these values vary with lumber moisture content, density, nail type and other factors, the structural capacity of the screw in both uplift and lateral load is comparable to or better than that of the nails or twist tie, so the screw is usually a better structural connection.

APPROXIMATE LOAD CAPACITY (LBS)

	Lateral (Side to side)	Tension (Uplift)
Hurricane twist clip (H3)	160	415
Structural screw (SDS25412)	**250**	**420**

TABLE R602.3(1)
FASTENING SCHEDULE

ITEM	DESCRIPTION OF BUILDING ELEMENTS	NUMBER AND TYPE OF FASTENER[a, b, c]	SPACING AND LOCATION
		Wall	
8	Stud to stud (not at braced wall panels)	16d common (3½" × 0.162")	24" o.c. face nail
		10d box (3" × 0.128"); or 3" × 0.131" nails	16" o.c. face nail

Fig. 6.10 Wall openings

No need for king stud+jack stud at openings (Fig. 6.10)

Instead of the more common king stud + jack stud framing at the sides of openings, design all doors and windows to fit within the 24 inch stud module, and limit their widths to 46 inches. Limiting the width of windows to four (nominal) feet allows for removal of the jack stud, and is generally part of an energy-conserving strategy.

Relevant CRC provisions

602.7.5 Supports for headers.

Headers shall be supported on each end with one or more jack studs or with approved framing anchors in accordance with TableR602.7(1) or R602.7(2). The full-height stud adjacent to each end of the header shall be end nailed to each end of the header with four 16d nails (3.5 inches × 0.135 inches). The minimum number of full-height studs at each end of a header shall be in accordance with Table R602.7.5.

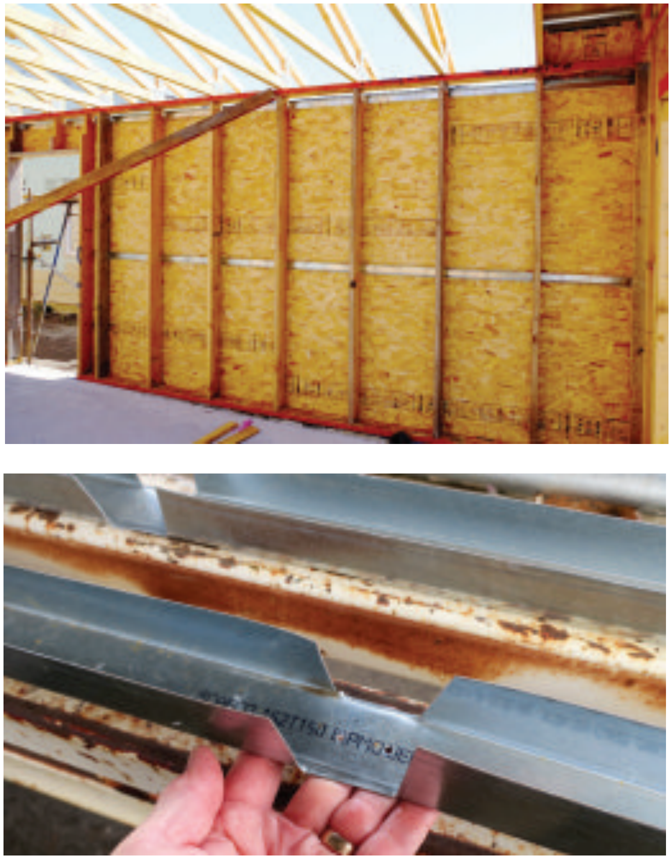
TABLE R602.7.5
MINIMUM NUMBER OF FULL HEIGHT STUDS AT EACH END OF HEADERS IN EXTERIOR WALLS

HEADER SPAN (feet)	MAXIMUM STUD SPACING (inches) [per Table R602.3(5)]	
	16	24
≤ 3'	1	1
4'	2	1
8'	3	2
12'	5	3
16'	6	4

TABLE R602.7(1)
GIRDER SPANS[a] AND HEADER SPANS[a] FOR EXTERIOR BEARING WALL
(Maximum spans for Douglas fir-larch, hem-fir, southern pine and spruce-pine-fir[b] and require

GIRDERS AND HEADERS SUPPORTING	SIZE	GROUND SNOW LOAD (psf)[e]																	
		30						50											
		Building width[c] (feet)																	
		20		28		36		20		28		36		20		28		36	
		Span	NJ[d]	Span	NJ[d]	Span	NJ[d]	Span	NJ[d]	Span	NJ[d]	Span	NJ[d]	Span	NJ[d]	Span	NJ[d]	Span	NJ[d]
Roof and ceiling	1-2 × 8	4-6	1	3-10	1	3-5	1	3-9	1	3-2	1	2-10	2	—	—	—	—	—	—
	1-2 × 10	5-8	1	4-11	1	4-4	1	4-9	1	4-1	1	3-7	2	—	—	—	—	—	—
	1-2 × 12	6-11	1	5-11	2	5-3	2	5-9	2	4-8	2	3-8	2	—	—	—	—	—	—
	2-2 × 4	3-6	1	3-2	1	2-10	1	3-2	1	2-9	1	2-6	1	2-10	1	2-6	1	2-3	1
	2-2 × 6	5-5	1	4-8	1	4-2	1	4-8	1	4-1	1	3-8	2	4-2	1	3-8	2	3-3	2
	2-2 × 8	6-10	1	5-11	2	5-4	2	5-11	2	5-2	2	4-7	2	5-4	2	4-7	2	4-1	2
	2-2 × 10	8-5	2	7-3	2	6-6	2	7-3	2	6-3	2	5-7	2	6-6	2	5-7	2	5-0	2
	2-2 × 12	9-9	2	8-5	2	7-6	2	8-5	2	7-3	2	6-6	2	7-6	2	6-6	2	5-10	3
	3-2 × 8	8-4	1	7-5	1	6-8	1	7-5	1	6-5	2	5-9	2	6-8	1	5-9	2	5-2	2
	3-2 × 10	10-6	1	9-1	2	8-2	2	9-1	2	7-10	2	7-0	2	8-2	2	7-0	2	6-4	2
	3-2 × 12	12-2	2	10-7	2	9-5	2	10-7	2	9-2	2	8-2	2	9-5	2	8-2	2	7-4	2
	4-2 × 8	9-2	1	8-4	1	7-8	1	8-4	1	7-5	1	6-8	1	7-8	1	6-8	1	5-11	2
	4-2 × 10	11-8	1	10-6	1	9-5	2	10-6	1	9-1	2	8-2	2	9-5	2	8-2	2	7-3	2
	4-2 × 12	14-1	1	12-2	2	10-11	2	12-2	2	10-7	2	9-5	2	10-11	2	9-5	2	8-5	2

TABLE R602.7.5
MINIMUM NUMBER OF FULL HEIGHT STUDS AT EACH END OF HEADERS IN EXTERIOR WALLS



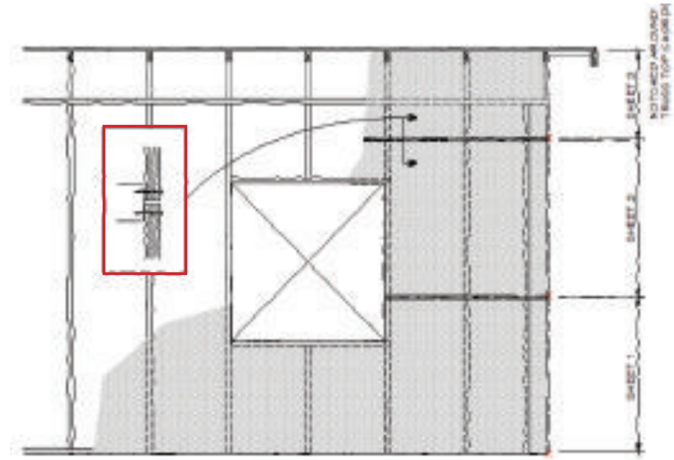


Fig 6.11 Horizontal exterior sheathing spliced with metal channels

Horizontal sheathing spliced with metal channels (Fig. 6.11)

Instead of the more customary full-depth 2x blocking at panel edges, the H4H Stockton projects use a continuous 1½" x 1½" 18 gauge metal C-channel as backing and splice. This gets rid of the thermal bridging and insulation interference caused by a 2x block, and also provides a guide, with its pre-notched flanges, for keeping studs aligned at exactly 24" oc. The channel is attached to both upper and lower wall sheathing panels, with self-tapping screws at 6 inches on center. The channel spans the gap between those panels.

Relevant CRC provisions

There are no CRC provisions. This is an untested system only made code-acceptable by severely limiting door and window openings. The CRC, like other codes, in a sense prefers wall sheathing attached with the strong axis across the supports—that is, horizontally—but allows the much more common practice of applying sheathing vertically to save labor.

Commentary

In this case, H4H mixes systems—wood and light gauge metal framing—to achieve the dual purposes of thermal efficiency and framing alignment but at the cost of mixing fasteners (nails and screws) and creating a hybrid system with uncertain code status.

This is one of those rare details about which George Koertzen and I cheerfully agree to disagree. George likes the horizontal application because it is much less likely to "cup" under moisture and thermal changes. I believe that applying the wall sheathing vertically, as is far more customary in California, is just as effective structurally and a lot less cost & trouble. Moreover, the use of the screws and custom steel channels is probably very strong but is as yet untested; in higher seismic risk zones many building officials would likely require expensive verification testing. Where there are concerns about the sheathing cupping between studs 24 inches on center, then, I say, use thicker sheathing.

Fig 6.12 Removable header

Fig 6.13 Raised heel truss

Removable header and raised-heel trusse (Fig. 6.12 and 6.13)

Locate and design headers for minimal interference with insulation. Provide engineered header of LVL lumber, let-in to the inside face of studs and attached with screws. After fitting, remove it to allow installation of insulation behind the header on indoor face of the exterior sheathing. Reinstall the header after insulation is in place. Provide roof trusses that have "raised heels," to allow fully-expanded insulation (100% of rated R-value) where the roof slants down at the eaves.

Relevant CRC provisions: See figures R602.7.1(1) and (2) below.

Commentary

There is nothing here at odds with the code. These are simply smart details for energy efficiency. Note, however, that the lack of a jack stud to support headers means that the upper plate defining an opening must be supported at the king stud with a light gauge metal framing bracket or shelf. The raised heel truss is a simple, no-cost solution, but the let-in header does add some labor time to the project.

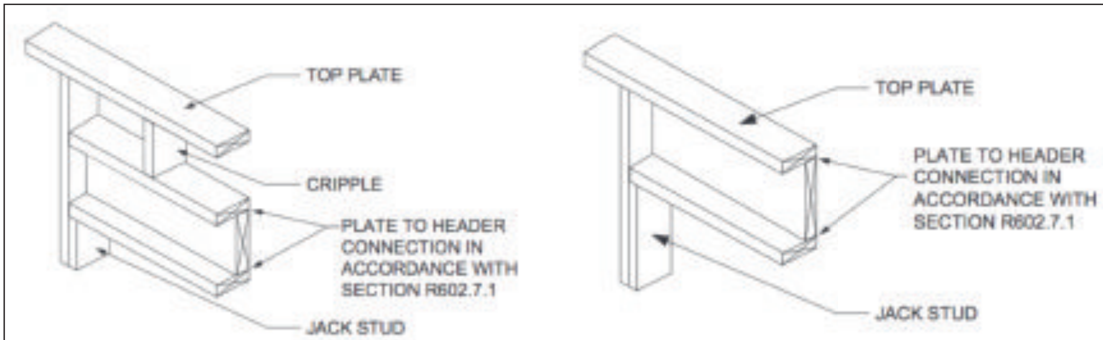


FIGURE R602.7.1(1)
SINGLE MEMBER HEADER IN EXTERIOR BEARING WALL

FIGURE R602.7.1(2)
ALTERNATIVE SINGLE MEMBER HEADER WITHOUT CRIPPLE

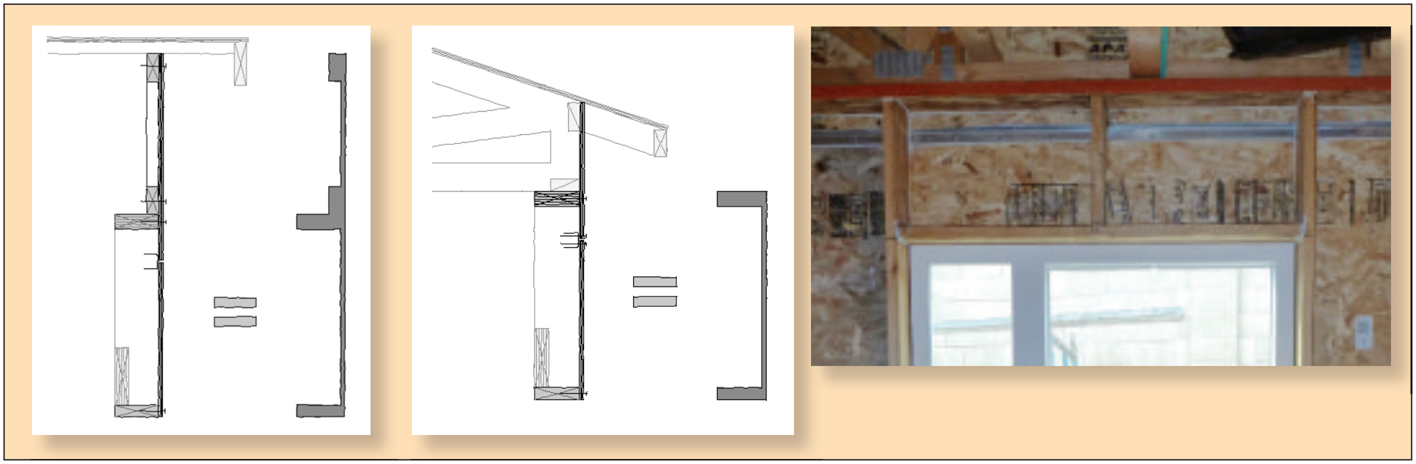


Fig 6.14 Gable end structure & wall sheathing above framing as headers

Gable end structure + sheathing as header (Figs. 6.14 - 6.15)

Where possible, use structure already in place to serve as headers for door and window openings. Based on the specific framing and construction details of houses at the Dream Creek subdivision, two assemblies can serve this purpose:

1. Gable end trusses as headers. Provided that wall sheathing is attached reasonably well to framing and the face of the end truss, it becomes a very sturdy "plywood 'C' beam" capable of carrying even fairly heavy roof and snow loads.
2. Wall sheathing over framing above as header. In like manner, if there is sufficient wall height above an opening—as is usually the case, especially with these H4H projects and their raised heel trusses—the combination of wall sheathing and horizontal plates makes for a field-built header capable of carrying most loads.

For these reasons, though prefabricated gable end trusses often come with diagonal members like neighboring true trusses, the diagonals are rarely necessary and can be a wasted expense.

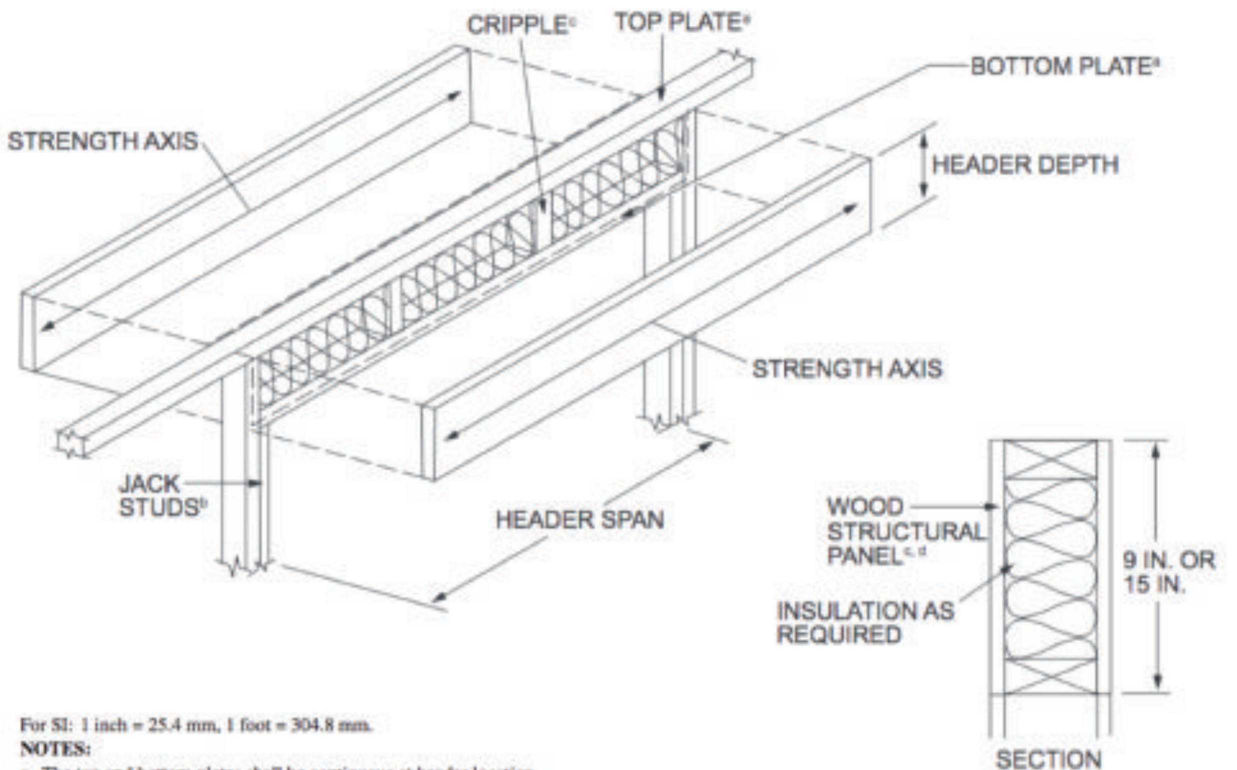
Relevant CRC provisions & commentary

See Table R602.7.3 and Figure R602.7.3 on the facing page. The code provides prescriptive guidelines which are conservative but do cover most conditions for one-story wood-framed construction. These guidelines are not specifically useful for gable end truss conditions, nor for the depth provided by raised heel trusses, but often reasonable arguments can be made based on the similar conditions described by code, as used at Dream Creek.

TABLE R602.7.3
MAXIMUM SPANS FOR WOOD STRUCTURAL PANEL BOX HEADERS[a]

HEADER CONSTRUCTION[b]	HEADER DEPTH (inches)	HOUSE DEPTH (feet)				
		24	26	28	30	32
Wood structural panel–one side	9 15	4 5	4 5	3 4	3 3	— 3
Wood structural panel–both sides	9 15	7 8	5 8	5 7	4 7	3 6

For SI: 1 inch = 25.4 mm, 1 foot = 304.8 mm.
a. Spans are based on single story with clear-span trussed roof or two story with floor and roof supported by interior-bearing walls.
b. See Figure R602.7.3 for construction details.



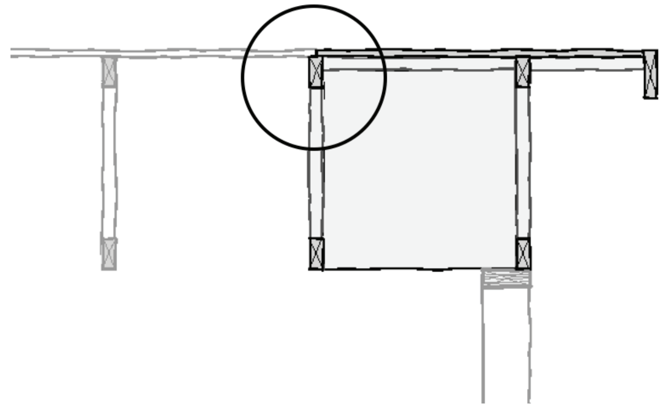
For SI: 1 inch = 25.4 mm, 1 foot = 304.8 mm.

NOTES:

a. The top and bottom plates shall be continuous at header location.
b. Jack studs shall be used for spans over 4 feet.
c. Cripple spacing shall be the same as for studs.
d. Wood structural panel faces shall be single pieces of $^{15}/_{32}$-inch-thick Exposure 1 (exterior glue) or thicker, installed on the interior or exterior or both sides of the header.
e. Wood structural panel faces shall be nailed to framing and cripples with 8d common or galvanized box nails spaced 3 inches on center, staggering alternate nails $^{1}/_{2}$ inch. Galvanized nails shall be hot-dipped or tumbled.

FIGURE R602.7.3
TYPICAL WOOD STRUCTURAL PANEL BOX HEADER CONSTRUCTION

Fig 6.15 Ground-assembled gable end trusses



Ground-assembled gable end trusses (Fig 6.15)

The logic for this design is explained by Rick Chitwood: "With conventional building techniques, a lot of construction labor occurs on the first two trusses at the gable end – often with laborers 10 to 25 feet off the ground. On this project all that work – two trusses, lookouts, fascia, roof sheathing, venting, gable end sheathing, and house wrap was done on the ground, increasing both speed and safety. (OSHA identifies falls as the leading cause of death in the construction industry.) The end units were then set, along with the rest of the trusses, with a truck-mounted crane. An additional benefit on this project—since it has a 4/12 roof pitch—is that the roof worker safety harnesses that would normally be required within three feet of the gable ends are not needed, because the surface at the gable ends was pre-sheathed on the ground."

Relevant CRC provisions

The CRC is silent about what is a process, not material, innovation. But, as noted above, certain Federal safety regulations are avoided (and workers kept safer) by assembling end trusses on the ground. The associated expense and delays of compliance are also avoided.

Commentary

The assembly described requires stiffening webs of ½" OSB at eight feet oc between the two trusses, along with blocking for attachments; roof sheathing is applied (unlike the rest of the roof) with strong axis parallel to the slope, spanning across 2x4 outriggers at four feet on center. This should make, if anything, a stronger diaphragm edge and seismic assembly, so long as the sheathing edges at the inboard truss (**circled**) are carefully nailed.

Fig 6.16 Wall board connected with OSB splice strips

Wall board conected with OSB splice strips (Fig 6.16)

Rick Chitwood explains the logic and benefits of this innovation from his perspective: "The industry standard installation technique is to cut drywall so that a sheet ends on a framing member to which the end of the sheet is attached. Instead, using splice strips avoids the need to measure and cut a piece of drywall, until reaching the end of the wall. This is accomplished by fastening drywall screws through the face of the gypsum and then into 4 inch wide OSB scraps placed behind the joints where two sheets come together. Benefits include:

- Reduced material cost because of less waste. In the 1200 ft2 houses at Dream Creek, the total number of drywall sheets dropped from 32 to 17, for a 53% material cost saving.
- Reduced labor—less measuring and cutting
- Reduced waste disposal cost
- Easier to finish, since there are more factory sheet edges
- Stronger joints, since each sheet edges has 2 inches rather than ¾" of backing.

Relevant CRC provisions

See table R702.3.5 below. The CRC neither discusses nor prohibits this detail.

Commentary

This is almost a non-structural issue, in that it has no bearing on life safety. However, as described for drywall clips (vs. solid framing support), the robustness of drywall installation matters to overall performance during an earthquake. Even if not part of the primary lateral system, drywall in one and two-story structures contributes noticeably to stiffness and energy absorption.

Taking some exception with Rick Chitwood's last comment above, the spliced drywall joint may be stronger in some ways than its conventional counterpart (drywall screwed to wood), although probably weaker in other ways, particularly vis-à-vis seismic shaking. A fairly simple side-by-side test of the two joint types under cyclic loading would demonstrate how much, if at all, the H4H spliced drywall joint is less effective. Overall, since all sheets are attached at all framing members, the effect is probably trivial on the performance of the structure.

Another caution is that the joint may be less satisfactory if impacted: if the splice lands midway between stud supports, it will be a hinge—weaker than if the joint landed on a stud. But, unless there is a strong impact, the consequence may be no more than a hairline crack in the paint.

TABLE R702.3.5
MINIMUM THICKNESS AND APPLICATION OF GYPSUM BOARD AND GYPSUM PANEL PRODUCTS

THICKNESS OF GYPSUM BOARD OR GYPSUM PANEL PRODUCTS (inches)	APPLICATION	ORIENTATION OF GYPSUM BOARD OR GYPSUM PANEL PRODUCTS TO FRAMING	MAXIMUM SPACING OF FRAMING MEMBERS (inches o.c.)	MAXIMUM SPACING OF FASTENERS (inches)		SIZE OF NAILS FOR APPLICATION TO WOOD FRAMING[c]
				Nails[a]	Screws[b]	
Application without adhesive						
$^3/_8$	Ceiling[d]	Perpendicular	16	7	12	13 gage, $1^1/_4$" long, $^{19}/_{64}$" head; 0.098" diameter, $1^1/_4$" long, [illegible]
	Wall	Either direction	16	8	16	
	Ceiling	Either [illegible]				

(continues)

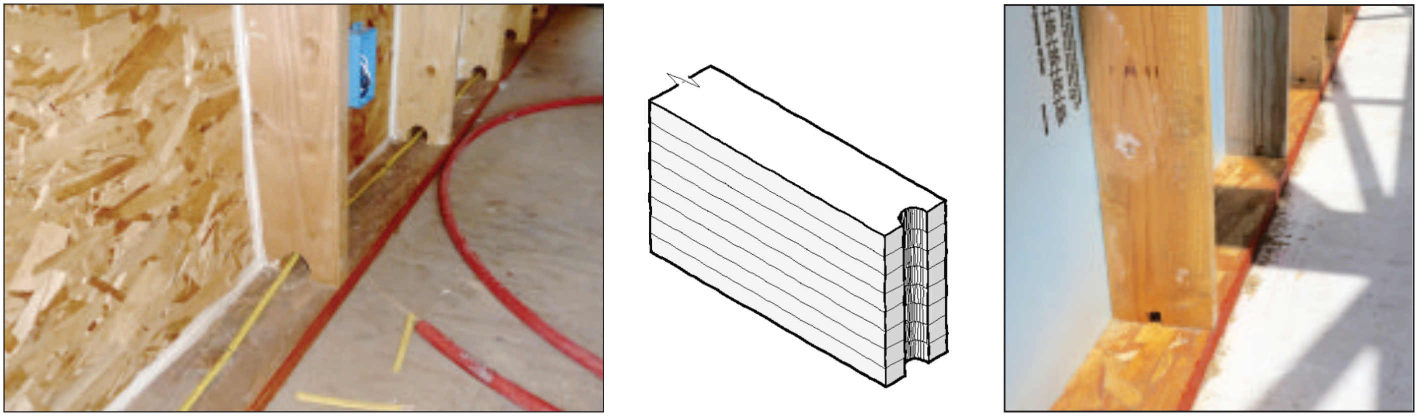
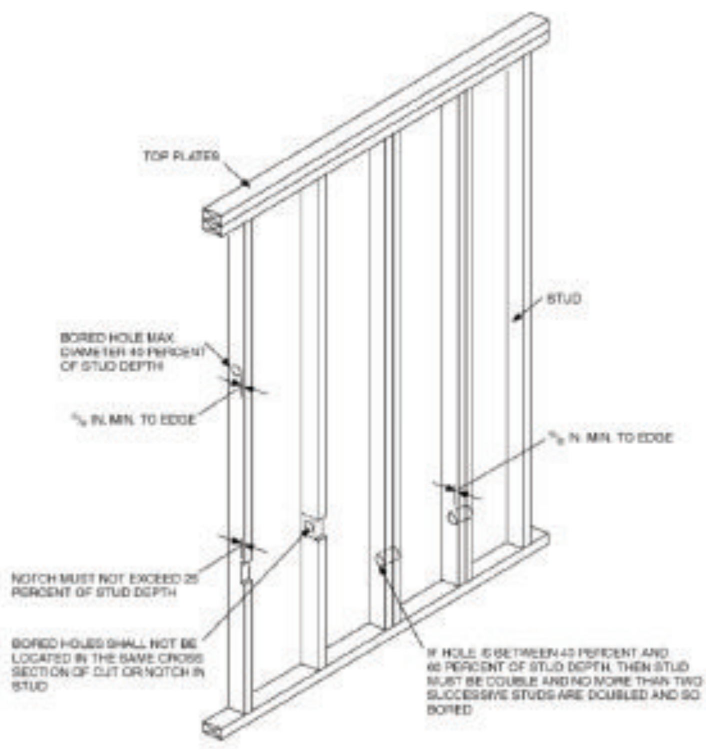


Fig 6.17 Stud bases pre-drilled or notched for wiring



For SI: 1 inch = 25.4 mm.
Note: Condition for exterior and bearing walls.

FIGURE R602.6(1)
NOTCHING AND BORED HOLE LIMITATIONS FOR EXTERIOR WALLS AND BEARING WALLS

Wall stud bases notched for wiring (Fig 6.17)

In the H4H Stockton project, the bases of wall studs are notched or drilled for electrical access, before they are unbound from delivery. This provides multiple benefits:

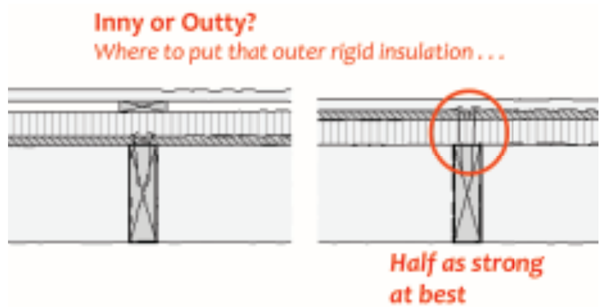
- The electrician need not drill individual studs after framing.
- Electrical lines are kept at the sill plate, keeping them out of the way of insulation.

Relevant CRC provisions

See figure R602.6(1). The CRC provides clear guidelines defining what is or is not acceptable with respect to notching or drilling studs, and the project's holes at the base of studs easily falls within those guidelines.

Commentary

This is another process innovation with no real bearing on structural performance; it saves money and helps insure that batt insulation can be installed in full contact with all six sides of the cavity without crushing its face.



Inny v. outty exterior insulation (Fig 6.18)

Design of high performance building envelopes very often leads to adding a "jacket" of exterior rigid insulation, an energy performance boost now recognized and even codified in more and more places around North America. First generations of this system simply put the rigid insulation outside of the structural sheathing, but that made attaching siding or plaster more difficult. Such difficulty sometimes leads to installation defects that degrade moisture and thermal performance. In response, many builders have attached the rigid insulation directly to the framing, and then the structural sheathing over that. There are even manufactured versions such as Zip System that provide the OSB sheathing with plastic foam factory-bonded to the inside face of OSB.

Relevant CRC provisions

This "Inny" assembly, with rigid insulation between the framing and structural sheathing, isn't addressed in the 2016 CRC. ICC approval of the Zip System, for example, explicitly excludes its use for resisting lateral forces in the highest-risk seismic zones.

Commentary

Testing to date shows that an Inny wall's structural strength against wind and especially dynamic seismic forces is very much degraded because the fasteners must bend and wiggle in ways they are just not so good at. Although installed in the Dream Creek houses in Stockton, the code status of this assembly in areas that have higher levels of seismic risk is indeterminate. As further testing emerges for this novel assembly, we may refine our understanding. For the present, installing rigid insulation between sheathing and structure is not a viable option where the ground shakes hardest.

Mechanical Systems & Equipment

Using Smaller Equipment, ZNE Saves Energy While Improving Comfort and IAQ

Fig. 7.1 Designing and installing for HVAC for ZNE: "You can't un-learn this stuff"

Richard Hiteshew, Larry Waters and Casey Kinnard of A1-Guaranteed Heating and Air Conditioning, at the Dry Climate Home Performance Forum in 2018. Richard's approach to running his business reflects his 30+ years of experience. Focusing on careful load calcs and in-process measurements of installation quality provides great HVAC for the owner, a powerful marketing advantage and better-trained techs—and therefore more pleasant and profitable conversations with customers.

For ZNE homes, HVAC is very different

We all know that good HVAC design and equipment selection depends on the loads and *where* they occur within the house. How much heat will each space be losing or gaining and therefore how much air will be needed to keep each space comfortable? In theory, all HVAC systems are designed and installed in response to those loads and where they occur.

But let's face some facts about our HVAC design culture. It doesn't always work that way. Often, the designer looks at the plans, approximates the floor area and then sizes equipment and designs duct work based on space constraints and cost, guided less by room-specific loads and more by "experience plus a safety factor." But that approach is neither legal in California nor is it effective for ZNE homes. ZNE homes are different because the enclosure loads are *exceptionally* small. That means that to avoid discomfort and occupant complaints, the HVAC must be *much* smaller than in the past—but not too small. And the air ducts must be a bit larger—but not too large. In short, HVAC systems in ZNE homes must be "just right." Deviations on either side of that knife edge—too big or too small—will create much bigger problems than in earlier houses. Here are four reasons why ZNE homes are so different from an HVAC perspective:

1. **The enclosure is excellent, so loads are tiny.** ZNE homes are superbly insulated and air tight, with excellent windows. So they don't leak the amount of heat lost and gained in previous homes. As shown in table 7.1, one 1,200 ft^2 home at Dream Creek has peak loads of 11,000 Btu/h for cooling and 8,800 Btu/h for heating. That's right: *less than one ton of cooling at peak temperatures and a heating load that could be met by running two hair driers during the coldest winter weather*.

2. **The whole HVAC system is inside the conditioned space.** When ducts and HVAC equipment are in the attic, the cooling loads go up dramatically. In the case of houses at Dream Creek, attic equipment and air distribution would increase loads by about 27%. Avoiding that load means smaller, less expensive systems, smaller ducts and better air distribution.

3. **Air tight houses must be well-ventilated.** Air tight houses are energy-efficient, but they need an engineered ventilation system that recovers energy and that operates whenever the home is occupied. With that system in operation, indoor air quality is much better in ZNE homes than in non-ventilated homes of the past... while still consuming much less power. No more "funky was here" aroma in bedrooms and bathrooms.

4. **In California, HVAC systems need great filtration.** Because of urban pollution and rural wildfire smoke, as of January 2020 California Title 24 requires air filters with a minimum efficiency rating of MERV 13 or higher. (MERV = Minimum Efficiency Reporting Value). In California the outdoor air is often heavily-loaded with the small particles that pose the greatest risk to health (PM2.5 = The total mass of particles in the air sample that have a diameter of 2.5 millionths of a meter and smaller.) To provide that level of filtration while still keeping fan energy low, the return air grille needs to be big, for low resistance. Fortunately, it's easier to find space for right-size grilles in ZNE

HVAC LOADS - 1,200 FT^2 ZNE HOME		
	Heating (Btu/h)	Cooling (Btu/h)
Living	2,562	2,876
Master BR	1,301	1,002
Kitchen	1,267	2,254
Hall/Storage	1,118	1,306
Bedroom 1	870	1,016
Bedroom 2	663	958
Master Bath	559	316
Bath 1	103	90
Other Equipment	366	291
Humidity		603
Total	**8,809**	**11,006**

Table 7.1 Loads in one 1200 ft2 house at Dream Creek, Stockton, CA

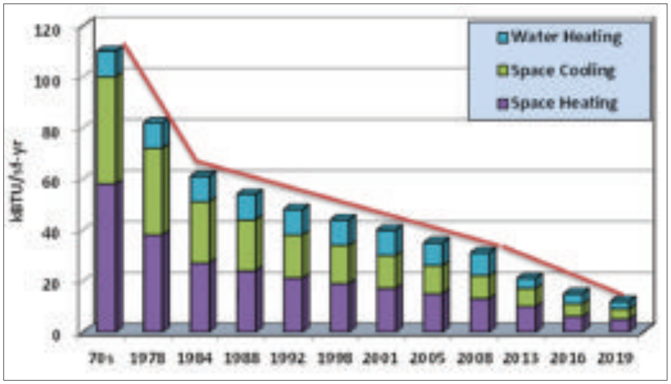


Fig. 7.2 Don't use old load assumptions for homes in 2020
*Title 24 cooling loads are required to be **90% less in 2020** than in 1978. Therefore in theory, if you installed a 3-ton system in a 2,000 ft^2 house in 1978, you should install a 0.3-ton system on that same size house today. So although that's certainly too low, it's no surprise that loads are now very small in air-tight, well-insulated house with great glazing. (See table 7.1 for real-world example.)*

homes. The loads are small, so air flows are also small.

In sum, ZNE homes offer a (potentially) great package for both HVAC contractor and homeowner: smaller and simpler equipment and duct work, uniform temperatures throughout the home, easy access for filter changes and great indoor air quality through high-efficiency filtration and continuous ventilation. Now let's dig into the details for each element, to turn those ZNE potentials into reality.

Equipment selection and system design - for small loads

Begin by considering the tiny loads described by table 7.1. Can those be real? Less than one ton of cooling for a 1,200 ft^2 house in the Central Valley where the 1% design outdoor temperature is 98°? Well yes… in fact those loads are probably *larger* than what has been measured in similar houses, *provided* that several things are true:

- All the equipment and the duct work is in the conditioned space. (Even if ducts in the attic were buried under attic insulation, the cooling load would be 27% higher than table 7.1)
- The window solar heat gain is less than 23% (SHGC = 0.23)
- Measured leakage of the enclosure is less than 1.5 to 2.5 air changes per hour at test pressure (50 Pa, 0.2" W.G.).
- The walls and floor are wrapped with exterior insulation and cavity insulation totaling R-24, and the attic insulation is R-38 or higher.

Now granted, table 7.1 is still a calculation—an engineering estimate of peak loads. That estimate, based on a *typical* year, may not capture the peak during an *extreme* year. And any estimate of plug loads is an educated guess about occupant's uses of appliances and electronics. So placing a one-ton unit (12,000 Btu/h) on a house that has a calculated load of 11,000 Btu/h at peak design would normally be a reasonable decision for houses built according to standard industry practices. But it would be a poor selection in a ZNE house, for two major reasons.

First, keep in mind that by definition, peak cooling loads are those that (might) be exceeded for only 1% of a typical year—35 hours that probably occur randomly throughout the cooling season rather than all at the same time. Said another way, HVAC systems sized for the peak load are grossly oversized for 99% of the year (8,725 of 8,760 hours in a year). Oversized systems are hard to control. They start up… then stop after only a short run-time. This leaves the house with long periods of no cooling and no dehumidification. The result is thermal discomfort; hot and cold spots and "thermostat wars" between occupants rather than a comfortable uniform temperature and humidity throughout the house.

Second, *the rate* at which a ZNE house heats up or cools down is very slow. The "thermal time constant"of a ZNE house is *much slower* compared to houses that leak air and have ineffective insulation. Slow response is a good thing. A long time constant indicates the house is thermally excellent. The building does not heat up quickly when the outdoor air temperature rises. But it also means that even a careful load calculation based on ACCA Manual J greatly over-estimates the cooling requirement. A fast response to outdoor air temperatures was perhaps not a bad strategy for inefficient houses of the past, which may help explain why Manual J calculations show a consistent bias

Fig. 7.3 Like clothes. For ZNE homes, bigger HVAC is NOT better
Systems that are too large make it difficult to keep the system and its ducts inside the conditioned space. Moving HVAC into the attic would make everything much, much worse: the budget, the schedule and thermal comfort. And the house would have to "wear that floppy suit" for next 50 to 100 years. Design the HVAC system so that it meets—and does not exceed—the peak loads.

in favor of excessive capacity. But in ZNE houses during hot summer days, any significant rise in the indoor temperature may take five or six hours, rather than only one or two. By the time the peak afternoon cooling load is finally penetrating the enclosure and heating up the indoor air, the outdoor air is already cooling down the outside of the house in the evening. So extra capacity becomes a distinct liability. Short cycles lead to discomfort and needless energy expense.

Based on experience of the last few years, it's best to "think small" when calculating loads and designing systems for ZNE homes. Rick Chitwood, one of the contributors to this book, has more than 15 years of experience observing occupied ZNE-style houses compared to load calculations, and also 10 years of measurements taken in research houses. That real-world experience confirms that a typical Manual J calculation over-estimates the peak cooling load of a ZNE house by as much as 25 to 30%. So although the Manual J loads shown in table 7.1 indicate 11,008 Btu/h, a better equipment selection for that house is probably 9,000 Btu/h of cooling capacity. Consequently, it would be a real mistake to put a 2-ton or a 3-ton unit on that house, as might have been common practice in the Central Valley in the past.

This is all rather technical, involving rates of change and equipment behavior that are difficult to keep in mind, let alone calculate accurately. These phenomena are certainly not intuitive. And based on their experiences in non-ZNE houses, most owners (and too many contractors) generally assume "bigger equipment is better" with respect to comfort. So it's useful to review why that's *not* the case with HVAC in ZNE homes.

Air mixing is critical. In theory, variable-speed units could compensate for over-sizing. But in practice, *oversized* variable-speed units must drop the system air flow down to its minimum to avoid over-cooling during nearly the entire year. This often means that cold air will dribble out of the supply diffusers, rather than exit those diffusers at 600 feet per minute—the speed high enough to provide air mixing and therefore uniform temperatures throughout the room.

Temperature uniformity requires constant air flow. Consider the "thermal geography" of the room when oversized systems operate intermittently. Near the windows the room stays hot, while over near the supply air grilles, the room stays cold. Based on rated capacity, an oversized system should (in theory) remove all the heat. But in practice, the compressor that provides cooling starts and stops and the air flows also vary instead of staying constant. So parts of the room stay uncomfortably hot in the summer (and cold in the winter).

Therefore when selecting equipment for ZNE homes—think small. Smaller equipment avoids the comfort problems that happen with oversized systems.

Cooling and heating equipment for small loads. It's actually difficult to find equipment that's small enough to be right-sized for ZNE homes. In the past, poorly-insulated houses that leak air and heat strongly encouraged equipment manufacturers to focus on larger systems. Today, it's difficult to find a gas-fired furnace that has a heating capacity of less than 40,000 Btu/h. And a heater that big is a bad match for a house that has the maximum load of only 9,000 Btu/h as described by table 7.1. And in fact, that 9,000 Btu/h heating load in table 7.1 is probably considerably overstated, because for unknown reasons, Manual J winter heating loads do *not* include the internal heat gains of appliances, lighting and consumer electronics. So the real-world heating load of that home will be even less than 6,000 Btu/h. Given the excessively large heating capacity of even the smallest gas furnaces, plus the exceptionally small heating loads of ZNE homes, a small, ducted mini-split heat pump is often a good choice.

HVAC based on ducted mini-split heat pumps

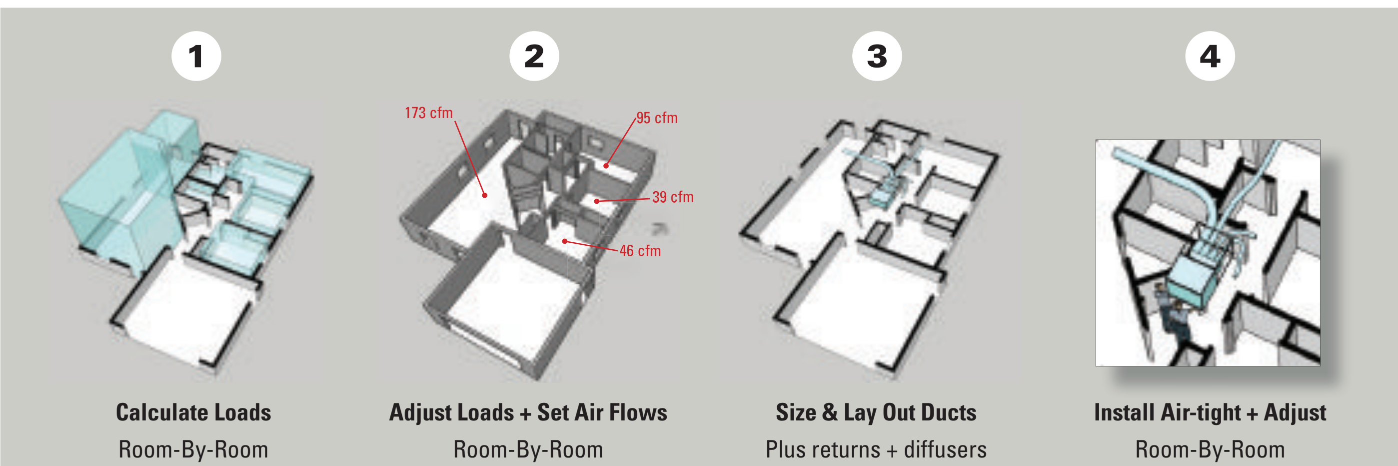
Many ZNE homes in California end up with ducted mini-split heat pumps. This class of equipment is economical and can be right-sized for very low heating and cooling loads while still providing enough supply air flow to provide air mixing in each space. Benefits include:

- Availability. These can be bought from multiple vendors, in the small sizes appropriate for low loads.
- Ducted mini-split air handlers are famously quiet. There is no need to install the air handler in a hot attic to attenuate sound. Noise is not an issue with ducted minisplits (provided that neither ducts nor supply air diffusers are undersized).
- The air handler component does not need floor space. Designers can locate the small, short air handler above a dropped ceiling, while still keeping all equipment and duct work inside the air and insulation boundary (out of the hot attic). Ceiling-mounted equipment provides a further bonus by freeing-up a bit of floor space that the occupants can use for other purposes.
- Most ducted mini-splits can reduce their cooling/heating capacity to 33% of full load. That way, they fit the very low running loads typical of most hours during the year, *while still maintaining air flow* at 75% of maximum, for good air mixing.
- California-specific residential energy modeling software has subroutines for calculating energy consumed by ducted mini-splits, which simplifies documenting compliance with Title 24.

But please keep in mind that everything depends on keeping all equipment and duct work inside the conditioned space.

Design and Installation Sequence - Some Suggestions

Fig. 7.4 Design and installation sequence that avoids problems



HVAC TARGET VALUES				When to Check		
Variable	Target	Acceptable	Inadequate for ZNE	At Design	During Installation	Sloppy Current Practices (These Must Change)
Cooling Size	2,000 ft^2 per ton	1,500 ft^2/ton	Less than 1,500 ft^2/ton	X		600 ft^2/ton and even less
Cooling Airflow	600 cfm/ton	550 cfm/ton	Less than 550 cfm/ton	X	X	Often less than 350 cfm/ton
Supply Velocity	600 fpm	500 to 700 fpm	Less than 500 fpm or over 700 fpm	X		Sometimes even less than 300 fpm
Return Grille + Filter	3 ft^2 per ton AND 2" thick	2.5 ft^2 per ton AND 2" thick	Less than 2.5 ft^2 per ton OR less than 2" thick	X		Often less than 1.5 ft^2 per ton and only 1" instead of 2"
Filter Rating	MERV 13	MERV 13	Less than MERV 13	X	X	MERV 8 that should be 6x larger
Heating Size	10 Btu/h ft^2 or less	18 Btu/h ft^2	More than 18 Btu/h ft^2	X		Often over 40 Btu/ft^2
Duct Leakage	Zero (Too low to measure)	Less than 15 cfm @ 25 Pa	More than 15 cfm @ 15 Pa		X	5% of flow - Often more than 60 cfm for a 3-ton system

Table 7.2 HVAC Check numbers

Check out figure 7.4. Sequence matters. HVAC success does not happen by just buying new components. To avoid problems and callbacks, the stages of HVAC design and installation need to follow each other in a logical sequence. Also, installation is not complete until the system as a whole is measured and adjusted to *verify* each aspect of its performance. Here are some specific suggestions to help make the process simpler, faster, more effective for the owner and more profitable for the contractor.

Step 1 - Room-by-room load calculations for ZNE homes

Title 24 requires load calculations. But there are many ways to comply that do not really help design an efficient and effective system. With ZNE homes, that all-important first step of load calculation is tricky, because the real loads are so very small. And load calculation software has a strong bias towards over-sizing in dry climates. So "being small" does not happen through automatic calculations.

For example, in non-ZNE homes, systems have certainly been oversized for decades. Recent ASHRAE research confirms that the average residential system operates between 18 and 25% of the hours in a year. That research is based on data donated by an international manufacturer. They have more than a million web-connected smart thermostats that log start and stop times for heating and cooling, in 15 second increments 24-7-365 (*Nest Division - Alphabet Corp).* Benefits increase with longer run times (70 to 80% of the hours is much better). This only happens by installing a smaller, right-sized system.

With long run-times, the system provides good mixing, plus ventilation and filtration for better indoor air quality and even temperatures throughout the house.

System oversizing is not always the result of Manual J's oversizing bias. Frequently, it happens because the person working the software relies on defaults or on past experience of similar-looking houses without really entering the home-specific data for building orientation, air tightness, framing factor and the U-value and SHGC of the installed windows.

So, suggestion number one is to enter all those values for the exact home in question, using the measured air tightness and insulation values of the home, and the actual orientation of each window, room-by-room. The result will often surprise a professional who may have long familiarity with load calculations for typical houses in the past—but who may have less direct experience with ZNE homes.

Suggestion number two is to compare the calculated results with the check numbers described by table 7.2 (the peak load capacity requirements for heating and cooling). If the calculated results don't match or improve on these target numbers, consider the reasons why. Then either adjust the inputs to come closer to the physical realities of the home—or make adjustments to the architectural design so that the house has a better chance of reaching ZNE (without a solar array so large that it won't fit on the roof).

Design and installation suggestions by component

Mini-split heat pumps

Mini-splits have an indoor unit connected to an outdoor unit with insulated refrigerant tubing ("the line set"). In the case of Dream Creek houses, the air handler (indoor unit) is often mounted horizontally inside a 12" dropped ceiling in the hallway, as shown in figure 7.5. This easily accessible location is made possible by the low height of the air handler (only 8" tall, including outlet flanges). The true ceiling (which is the air barrier) is set at 8 ft. above the floor. So setting the air handler below, at the 7 ft. level, avoids setting the unit on valuable floor space. The air handler is suspended and anchored to the bottom chord of a roof truss. The frame also provides support for gypsum board that forms an air-tight plenum around the air handler. That plenum is important. By making it air tight with respect to the attic and side walls, the plenum qualifies as the "ducted return" that is required by California title 24.

Large filter grilles are set into the bottom of that plenum, to clean the return air that is pulled from the hallway. In that location, the filters remain visible to occupants when they look up towards the ceiling. And the 2" deep, hinged filter frame allows easy access for filter changes from the corridor below. Given such visibility and easy access, it's more likely that filters will be replaced when they become obviously clogged.

Three-season condensate drainage

In ZNE homes, year-round condensate drainage is an important feature, and one that (in the past) has not been an obvious necessity in California's dry climate. In ZNE houses the HVAC equipment will be condensing moisture out of the indoor air more frequently. Because ZNE homes are so well sealed, indoor humidity can rise higher than in traditional California homes. Once again, that smaller-than-usual heat pump has a side benefit. It provides more continuous dehumidification, because small units run longer, to keep up with the cooling load. However, any water removed the air must go someplace! So the air handler needs a water-tight drain pan, equipped with a small condensate pump and connected to a condensate drain line to a sanitary drain or outdoor drip-drain.

Outdoor unit set above head-height on exterior wall

The outdoor unit of heat pumps is usually set on a pad at ground level. But you may want to consider mounting it instead on a bracket above head height on an exterior wall as shown in figure 7.6. That location has some useful advantages. For one, the lineset is shorter, improving performance. Also, at ground level, "stuff can happen" to an outdoor unit. Dogs like to advertise control of their territory by bathing the unit with urine, which corrodes the aluminum fins, as

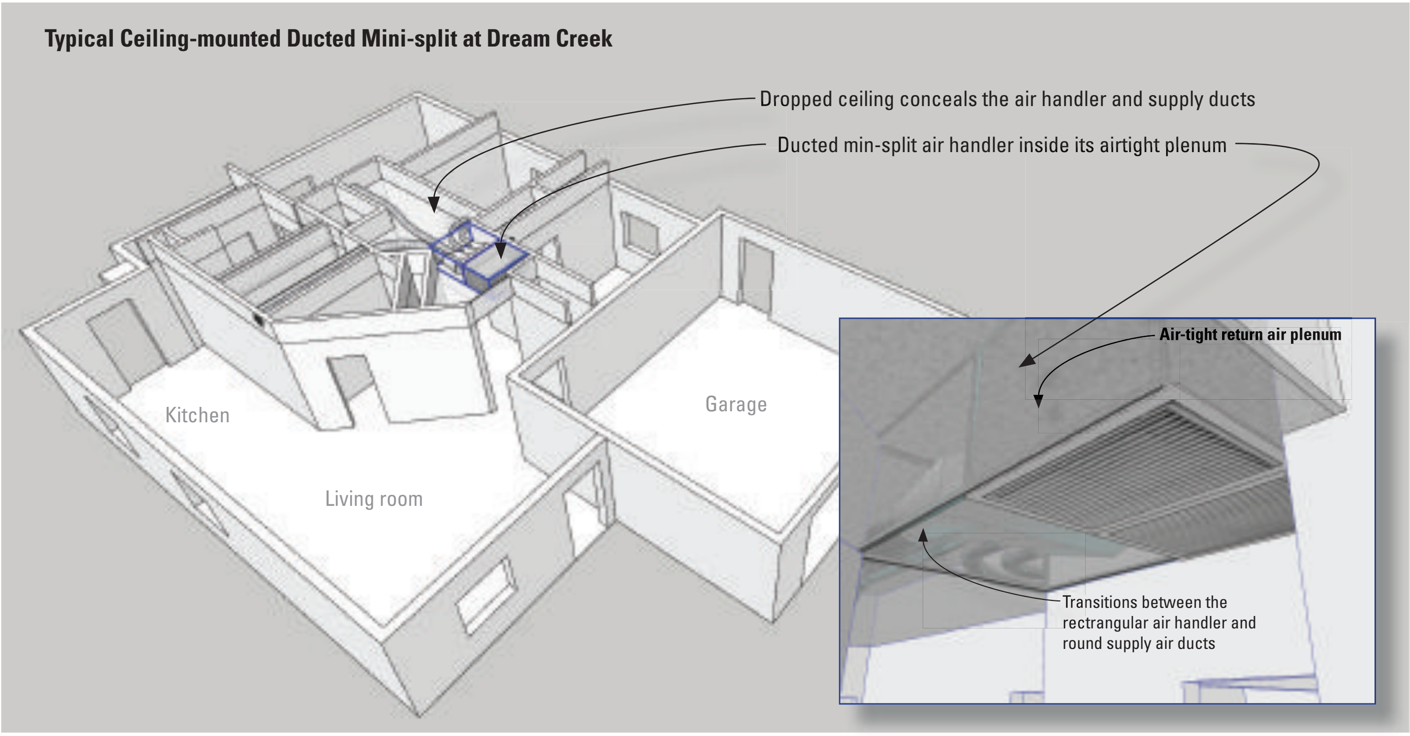


Fig. 7.5 Ducted mini-split air handler above a dropped ceiling. *Note that the space above the dropped celing provides ample space for running duct work with smooth curves intead of right angle elbows. Also note the tapered transitions between rectangular air handler and each of the round supply ducts. This design keeps presure drop low, providing energy savings for the life of the system.*

shown by figure 7.6. Also, crushing the edges of fins to make a pattern or somebody's initials often proves an irresistible temptation to kids. Fin-crushing degrades the cooling and heating capacity of the unit. Then there's the problem of grass clippings and leaves, which may obstruct the air flow or clog the fins of a ground level unit.

Mounting the outdoor unit high on the wall avoids these problems and also provides benefits. For example, the line set that connects the indoor and outdoor units is shorter. It can run through the attic under the attic insulation, exiting the building above the air barrier formed by the indoor ceiling. That routing eliminates two of the three air barrier penetrations of a typical line set. It's always good to reduce holes in the air barrier. Also, it's more difficult to steal a wall-mounted unit. Interestingly, in some jurisdictions building officials may allow side yard clearance to be measured from the wall (rather than from the edge of outdoor unit). In any case, for safety the unit should be mounted high enough for an adult to walk under it (without a hard hat!). Also, one must recognize that while the potential for "extra lot coverage" provides value, the service technician won't always thank you. A ladder will be needed for servicing that outdoor unit.

Air distribution and the importance of supply air jet nozzles

Air distribution needs more attention when the goal is zero net energy. In the past, air distribution was an afterthought rather than one of the most critical elements that govern HVAC efficiency. Even today in Non-ZNE houses, ducts are often cramped, kinked and too small, while

Fig. 7.6 Ducted mini-split outdoor unit mounted high on the wall
Keeping the outdoor unit high on the wall helps limit the amount of dust, grass and leaves that might otherwise clog the coil and reduce AC and heating capacity. (It also avoids the problem of dog urine..!)

supply air diffusers are often too big. The air leaving such diffusers is turbulent and too slow-moving for good air mixing. For ZNE, we need to avoid all of these problems and ensure smooth-flowing air that mixes air in every space very effectively. Sometimes, this may suggest slight modifications of architectural or interior design elements. For example, if side-wall jet nozzles are not permissible for aesthetic reasons (i.e., "I just don't want to look at them on that wall"), it might be useful to point out that without good air mixing, the owner can expect hot spots and cold spots and energy waste. Interior designs should respect the imperatives of comfort and low energy consumption.

Air distribution efficiency can be judged by three values. Each must be calculated at design and then assured by mid-process measurements and adjustments during installation.
Critical values include:

1. Total system air leakage
2. Air flow resistance of the entire installed system
3. Air velocity leaving the system's supply air nozzles.

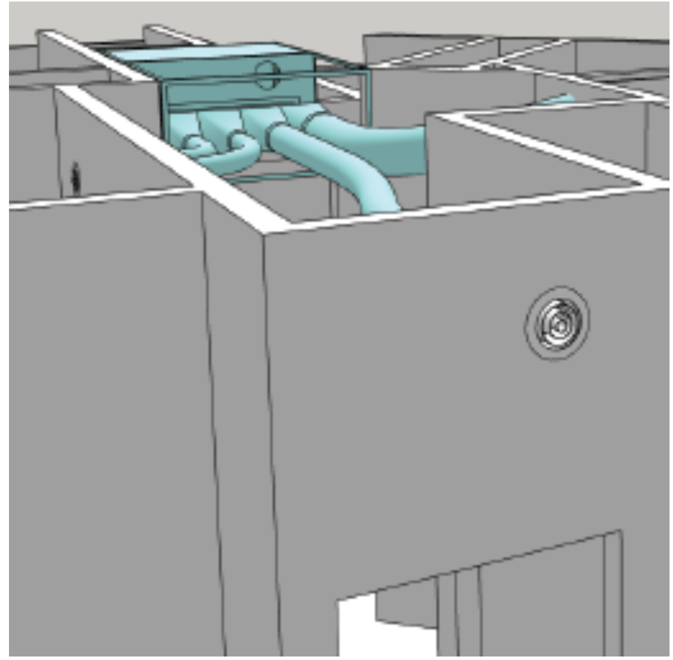


Fig. 7.7 Supply air jet nozzles set high on a side wall
Air flow is set by a fixed-position sheet metal disc set into each branch duct, back near the air handler. There is no need for a damper at the nozzle, which avoids turbulence and noise. Also, the flat concentric nozzle blades do not deflect the flow, so the supply air enters the room straight and smooth, at full velocity (500-650 fpm). This provides excellent air mixing throughout the whole room.

Air leakage should be so low that it cannot be measured even when using digital micromanometers (less than 10 cfm). Air flow resistance of the installed system should be less than 0.1" W.G.. Supply nozzle exit velocity should be no lower than 500 feet per minute and no higher than 700 fpm. (Table 7.2 summarizes target values for these and other key variables.)

To achieve those values we can turn again to examples provided by the houses at Dream Creek. First, check out figure 7.7. Note that the interior design includes a dropped ceiling that extends all the way down the corridor from the living room to the master bedroom. The 12" space above that dropped ceiling allows enough room to run insulated and air-tight supply air ducts to each conditioned space—without the need for tight duct turns or 90° duct connections. Also the diameters of the supply air ducts can be large enough to minimize air flow resistance. With larger ducts, air flow velocities are all less than 600 feet per minute, greatly reducing air flow resistance compared to the typical 800-1000 feet per minute velocities of old-school cramped-and-kinked duct systems. Also, note the smooth transitions from the rectangular supply air outlet of the air handler into the round ducts that carry supply air to each space. With only smooth turns and smooth transitions as duct diameters change, the supply side air flow resistance is less than 10 Pascals! (less than 0.04" W.G.)

Next, consider the design of the supply air grilles and their locations in each space. Common practice in the past has been to use a rectangular double-deflection supply air grille with a built-in air flow damper. That hardware is problematic in several respects. First, it requires a round-to-rectangular transition, usually called a "boot" These are relatively short and abrupt transitions that increase air flow resistance. Also with that hardware, balancing the system requires throttling down the air flow by adjusting the position of the damper in the supply air grille. And it's difficult to find a grille small enough for the small air flows of a ZNE home. So the damper position is often so-far-closed that its difficult to avoid the whistling sounds that comes from excessive velocity. The lever position difference between too-open or too-closed might be less than 1/10 inch. The relatively crude damper linkage levers in outlet grilles simply don't allow such fine adjustments. Finally, the double-deflection feature is intended to distribute air evenly across a wide area. In theory, that would facilitate air mixing. But in practice the much better way to achieve good air mixing is by using a jet nozzle—a high-velocity air stream that is not interrupted by double-deflection supply air vanes. (Figure 7.7)

In older houses (with little insulation and windows that allowed excess solar heat gain) the supply air discharge was usually located over or under windows, way out at the edge of the building. But with thermally-efficient architectural design and excellent windows, there's no need to push the supply air out to the edge of the house. The jet nozzle grilles can be installed on an inside wall, closer to the air handler. Shorter ducts without twists and turns reduces pressure drop, which in turn reduces both noise and energy consumption. Then the high speed of air leaving the jet nozzle generates a convection current within the room near the ceiling, entraining room air into the supply air flow. With horizontal, high-level, high-velocity mixing, the upper air flows gently and smoothly down into the occupied lower portion of the room, providing even, comfortable temperatures.

Another benefit of round jet nozzles in place of rectangular deflection grilles is their reduced air flow resistance. There is no need for any boxy rectangular "boot" connection between a round duct and round nozzle.

Finally, although it seems counter intuitive, there's less risk of noise from jet nozzles than from the usual double-deflection grilles that include dampers. The air flow-setting adjustments are accomplished back at the air handler permanently, during commissioning. This is done by covering a bit more—or a bit less—of each duct connection port, using a simple sheet metal disc. So any possible noise from air turbulence is generated far away from the occupied spaces rather than by dampers that generate turbulence at the supply grille.

Big return grille with 2"deep MERV 13 filters

For ZNE, the return air path must be larger than the undersized, cramped and convoluted return ducts of the past. At Dream Creek, two features provide improvements in the return air system:

1. An air-tight, ceiling-mounted plenum contains the air handler and also acts as the ducted return mandated by Title 24.

2. The return air filter grille is wider and deeper than in the past—so it can accommodate a large, 2" deep MERV 13 filters.

Figure 7.8 shows a view of the return air grille mounted in the ceiling of one of the houses at Dream Creek. Figure 7.9 shows how the return air grille relates to the rest of the HVAC system: the air handler, its supply duct transitions, and the framework around the air handler. The air handler pulls air from the corridor through the large filter

Fig. 7.8 Large air grill holds MERV 13 filters
Filters are large for very low resistance and excellent removal of the small particles that represent the greatest health risk.

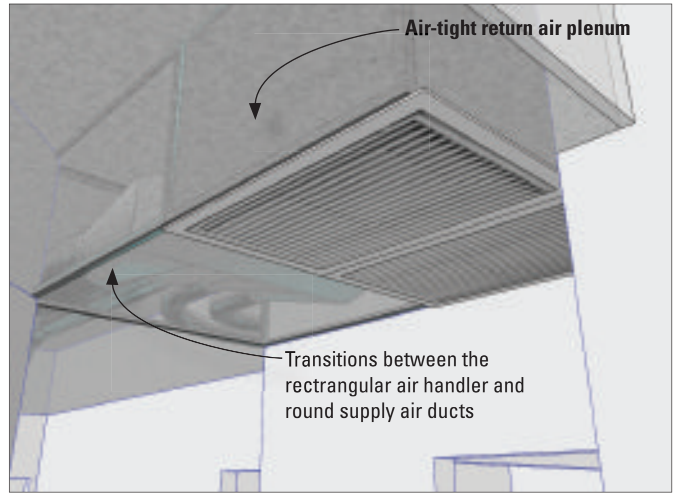


Fig. 7.9 Grille + filters form the base of the air-tight return plenum
The air handler is mounted above the grille, inside an air-tight plenum. This arragement satisfies Title 24, which now requires air tight return air duct work.

grille that is set into the dropped ceiling to form the under side of that air tight plenum. This arrangement qualifies as a code-permissible "ducted return." The location (close-coupled to the air handler) along with the large size of the return inlet (40" x 30" = 8.3 ft^2) helps keep air flow resistance to an absolute minimum. The system in the house shown in figure 7.8 provides a total of 400 cfm of supply air. That means the velocity through the return air filters is far slower (therefore much less resistance) than undersized returns.

Because the return is so large and the filter frame is so deep, there's no problem using a 2" thick air filter rated at MERV 13. This improved filtration does not restrict or reduce the supply air flow (a common problem when better filters are added to older, undersized returns). In a typical house, that large and deep filter will probably need replacement only twice a year.

Filtration has become recognized as public health issue, and one of particular concern in California. In much of the State, the outdoor concentration of small particles often exceeds national ambient air quality standards (NAAQS), as illustrated by the map in figure 7.10. That map was generated from data recorded by U.S. EPA environmental monitoring stations located throughout the State. The values shown are the annual average mass concentration of small particles (PM2.5 - Particles with a diameter of 2.5 millionths of a meter and smaller). Those are small enough to bypass defenses in the upper respiratory tract and penetrate deep into the lungs. Over time they accumulate, burdening the immune system with toxins and carcinogens. Building occupants (especially infants and the elderly) should not breathe large amounts of these small particles. Consequently both the State of California and the U.S. Environmental Protection Agency have established MERV 13 as the minimum for residential filters.

To qualify as MERV 13, the filter must remove at least 50% of PM2.5 from the air that passes through the filter. The lower the velocity through the filter, the higher the small particle removal effectiveness. In fact, the large filters installed at Dream Creek probably perform even better than MERV 13 - perhaps more like a MERV 14 or 15. The small heating and cooling loads of ZNE homes make it possible to have small air flows—which in turn allows ducts and filters

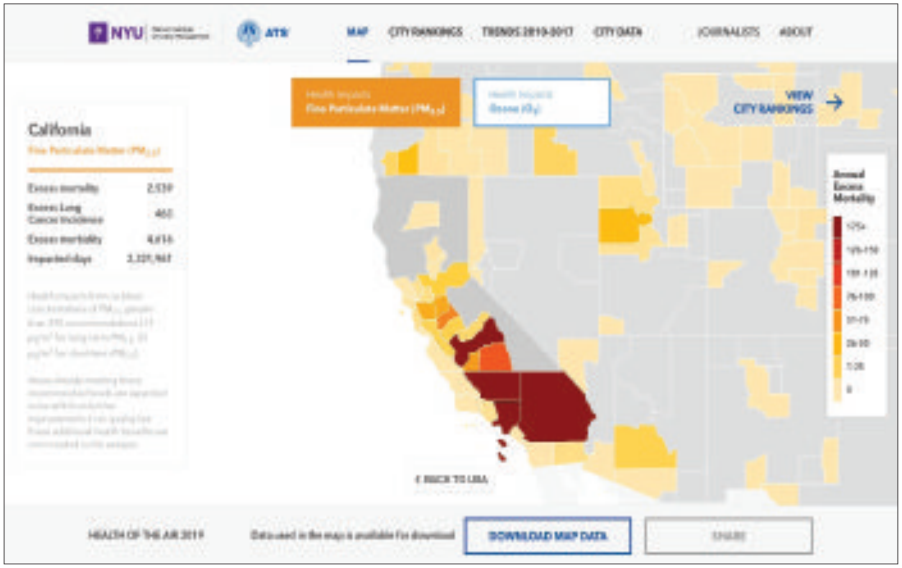


Fig. 7.10 Particle count ($PM_{2.5}$) is high in California
That's why Title 24 requires filter efficiency of MERV 13 or higher in new homes. (Source: US EPA data as displayed by healthoftheair.org)

to be large compared to the air flow. Because the filter face area is so large, a MERV 13 filter often performs as well as the more expensive MERV 14, removing more than 85% of small particles.

HVAC based on combined heat + hot water

George Koertzen originally planned the HVAC for the Dream Creek development based on ducted minisplit heat pumps. Ducted mini-splits are a good choice for heating and cooling for the reasons outlined earlier in this chapter. But in California, natural gas is often the more economical and popular choice for domestic hot water and heating. So a design for a ZNE house using gas heat and hot water was a logical addition to this research project.

Currently however, selecting gas-fired equipment for heating ZNE homes is challenging. High-efficiency gas water heaters are suitable for smaller homes, but there are fewer options for furnaces. The challenge is even greater for the very small heating loads in Stockton. In the mild winter climate of the Central Valley, outdoor temperatures are well above freezing for 99% of the hours in a typical year. According to a careful load calculation using ACCA Manual J, the highest heating load of a ZNE house in the Dream Creek development on a design day is just 8,800 Btu/h. And the actual maximum heating load is probably even smaller, because in accordance with ACCA guidance, the Manual J load calculation excludes internal heat sources. In other words, the calculation must be based on an empty house with all lights and all appliances turned off; an odd circumstance that rarely (if ever) occurs. So under normal occupied operation, internal heat sources will reduce that calculated 8,800 Btu/h load to an even lower number.

It's hard to find gas-fired furnaces with a heating capacity less than 40,000 Btu/h. Some two-stage or modulating models are available, but these still have a minimum firing rate of about 26,000 Btu/hr. That's much too large for low-load homes. One small Canadian manufacturer (Dettson Industries) offers a 95.6% AFUE 15,000 Btu/hr furnace that can modulate capacity down to 6,000 Btu/hr. Such a product could be a suitable option. Unfortunately, as of 2020 this product was not available in California.

At Dream Creek however, necessity often sparked innovation, and that has held true for gas-fired HVAC design. Experts on the consulting team for this project (contributors to this book) helped guide the

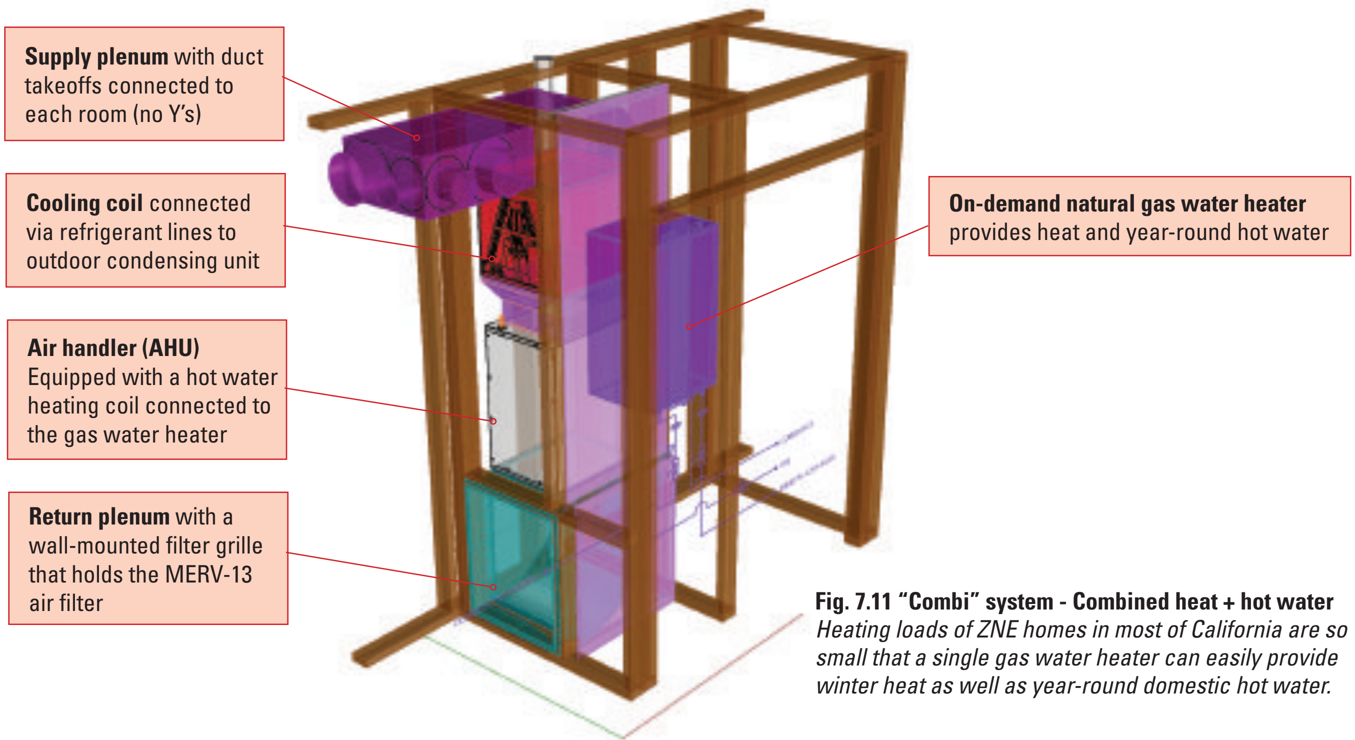


Fig. 7.11 "Combi" system - Combined heat + hot water
Heating loads of ZNE homes in most of California are so small that a single gas water heater can easily provide winter heat as well as year-round domestic hot water.

design of an innovative "combi" system for Dream Creek houses—a combined heat and hot water system that uses a tankless gas water heater. Such synergistic combinations are very efficient, providing a match for the very low heating loads of ZNE homes. Figure 7.11 shows the combi system designed for Dream Creek. The system includes:

1. **Hydronic air handler (AHU) with hot water coil**: The AHU is equipped with a hot water heating coil instead of the usual electric heating elements or gas-fired heat exchangers of traditional forced-air furnaces. A fan circulates air through the heating coil and into the home's air distribution network. While in heating mode, a pump circulates hot water between a water heater and that heating coil.

2. **On-demand condensing gas water heater.** The high-efficiency water heater serves two purposes. First, it provides domestic hot water (DHW) for use throughout the home. Second, when the thermostat calls for heat, a circulator flows some of the hot water from that heater through the coil in the AHU.

3. **Cooling coil and outdoor condensing unit**. A cooling coil is mounted in the usual "bonnet" enclosure mounted above a short transition duct connecting to the air handler. The coil is connected through refrigerant lines to a condensing unit outdoors, mounted on a wall, well-above head level.

4. **Hot water buffer tank**. The small, insulated hot water buffer tank is sized to meet the load requirement.

This design for a combi system system provides several advantages. All the key variables are controllable: air low rate, water flow rate and water temperature can each be controlled independently. Air flow is maintained at a level high enough to ensure good mixing in the space; the water temperature can be raised or lowered, depending on the season and the hot water flow rate can be varied in response to the actual heating demand. Also, combined systems use a single combustion appliance, which simplifies venting.

One challenge with combi systems is to ensure that water heating efficiency stays high under low load conditions. Efficiency partly depends on condensation of the combustion gasses to recover waste heat. The combi system's controls must adjust the air flow and pumping rate through the air heating circuit to extract enough heat from the hot water to keep the temperature of water returning from the AHU low enough to maintain condensing operation in the heater.

Another challenge is commissioning. Field-engineered combi systems require more care, and more in-depth understanding on the part of the HVAC contractor. For example, some traditional combi systems have only on-off control based on a fixed heating capacity. The hot water flow and its temperature are fixed. A valve either starts or stops the flow to the hot water coil in the AHU, in response to a thermostat. But the advanced combi system implemented at Dream Creek includes optimized modulation, to increase the annual HVAC efficiency. The control system's algorithms establish a variable heating capacity curve for air. The maximum capacity is set by the heating demand at Stockton's winter design temperature. The local outdoor air temperature is measured continuously. Then based on the algorithms, the system's central controller modulates a combination of supply airflow, hot water flow, and water temperature to match the heating demand at the current outdoor temperature.

Another feature of the advanced combi system is continuous water circulation through the heating loop. This provides a sort of "thermal flywheel" effect, allowing the system to supply much small amounts of heat when space heating loads are below the 15,000 Btu/hr minimum firing rate of the water heater. With this arrangement, the combi system controls maintain comfort in the space even when loads are very low, while at the same time keeping the firing rate in the efficient range, independent of the size of the current load.

Ventilation and energy recovery system

Zero net energy houses are air tight. That's how they provide better comfort, eliminate drafts and save energy. This also means that ventilation air cannot drift in randomly through gaps, cracks and holes as in past houses. Instead, ZNE homes have engineered, energy recovery ventilation systems such as that shown in figure 7.12. The preconditioned ventilation air is ducted to the inlet side (the suction side) of the air handler. That arrangement mixes fresh air into the recirculating air *before* it divides into separate ducts for each room. That way the occupied spaces share the fresh air evenly. And even if the air handler is not operating, the fan in the energy recovery ventilator pushes the fresh air through the supply air duct work into all the rooms.

Most of the time, however, the main system is going to be running. The nearly continuous run-time provides nearly continuous filtration—part of the value of a smaller-than-typical AC and heating system. The smaller the system, the longer it will need to run to keep up with the heating and cooling loads. And the longer it runs, the more small particles will be removed by the filters, and the more consistently the ventilation air will be distributed throughout the home.

There are two types of heat exchangers used in ventilation systems: those that recover heat only (HRV - Heat recovery ventilators) or those that recover both heat and moisture (ERV - Energy recovery ventilators) In much of California, HRV's are more common than ERV's, in part because the incoming outdoor air does not usually need much drying compared to more humid parts of the country.

In California's Central Valley, the choice of a ERV or HRV could go either way. In the summer and fall, there are many hours when the ventilation air is quite humid. When weather is either very dry or very humid, an ERV moderates the extremes. In the case of the Dream Creek Habitat for Humanity development, three factors favored the choice of ERV's rather than HRV's: the local climate, the equipment available through donation and the fact that ERV's have no need for a condensate drain, because in winter they transfer moisture to the dry incoming air stream rather than condensing moisture in the unit.

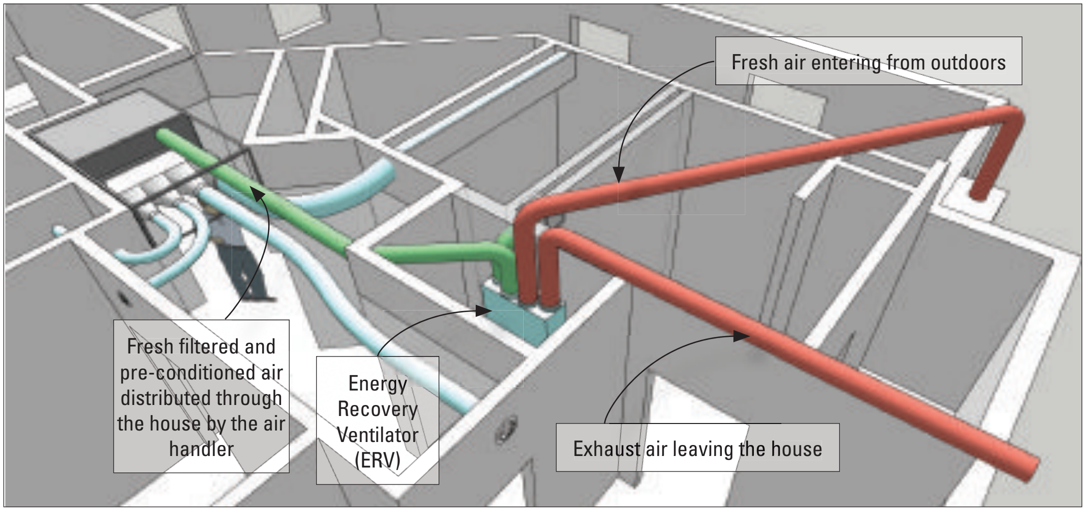


Fig. 7.12 Energy recovery ventilation (ERV) system
The system provides clean, pre-conditioned air from outdoors to all parts of the house, while saving about 70% of the energy that would otherwise be needed to heat, cool and dry and filter that fresh air.

Figure 7.13 shows the locations of the exhaust and ventilation inlets and outlets. The inlet grille for outdoor air is on the north side, under the porch roof. Exhaust comes from the two back-to-back bathrooms. The ERV pulls exhaust air from bathrooms continuously. That slight suction from bathrooms pulls in a small but steady flow of conditioned air from other parts of the home. This keeps toilet odors and shower humidity from flowing out of the bathrooms into the living spaces.

Figure 7.14 shows the heat and humidity performance of an energy recovery ventilator installed in one of the completed homes at Dream Creek during the last day of July and the 1st day of August in 2018. The top graph shows that the enthalpy heat exchanger cools the incoming air dramatically. The bottom graph shows the ERV also humidifies the incoming air substantially, helping to keep the indoor environment at a comfortable temperature and humidity every hour of every day.

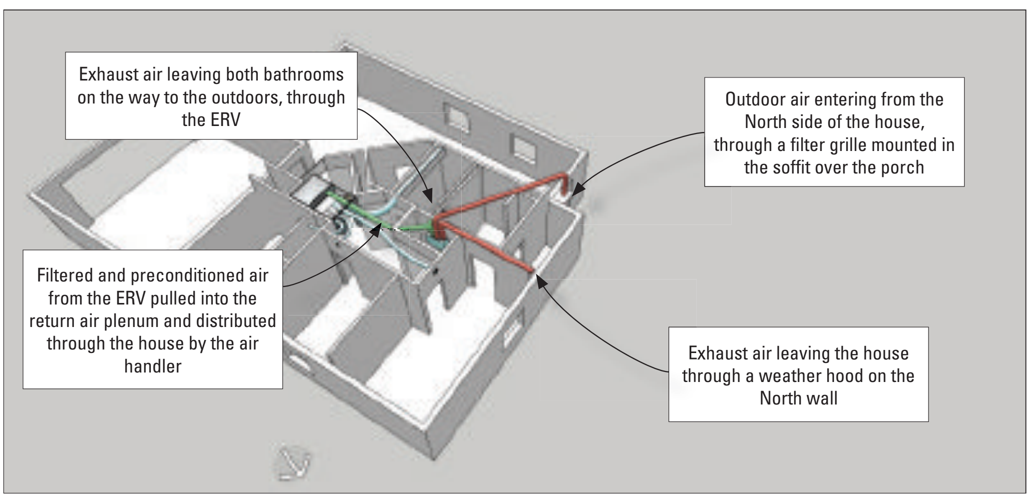


Fig. 7.13 ERV duct arrangement

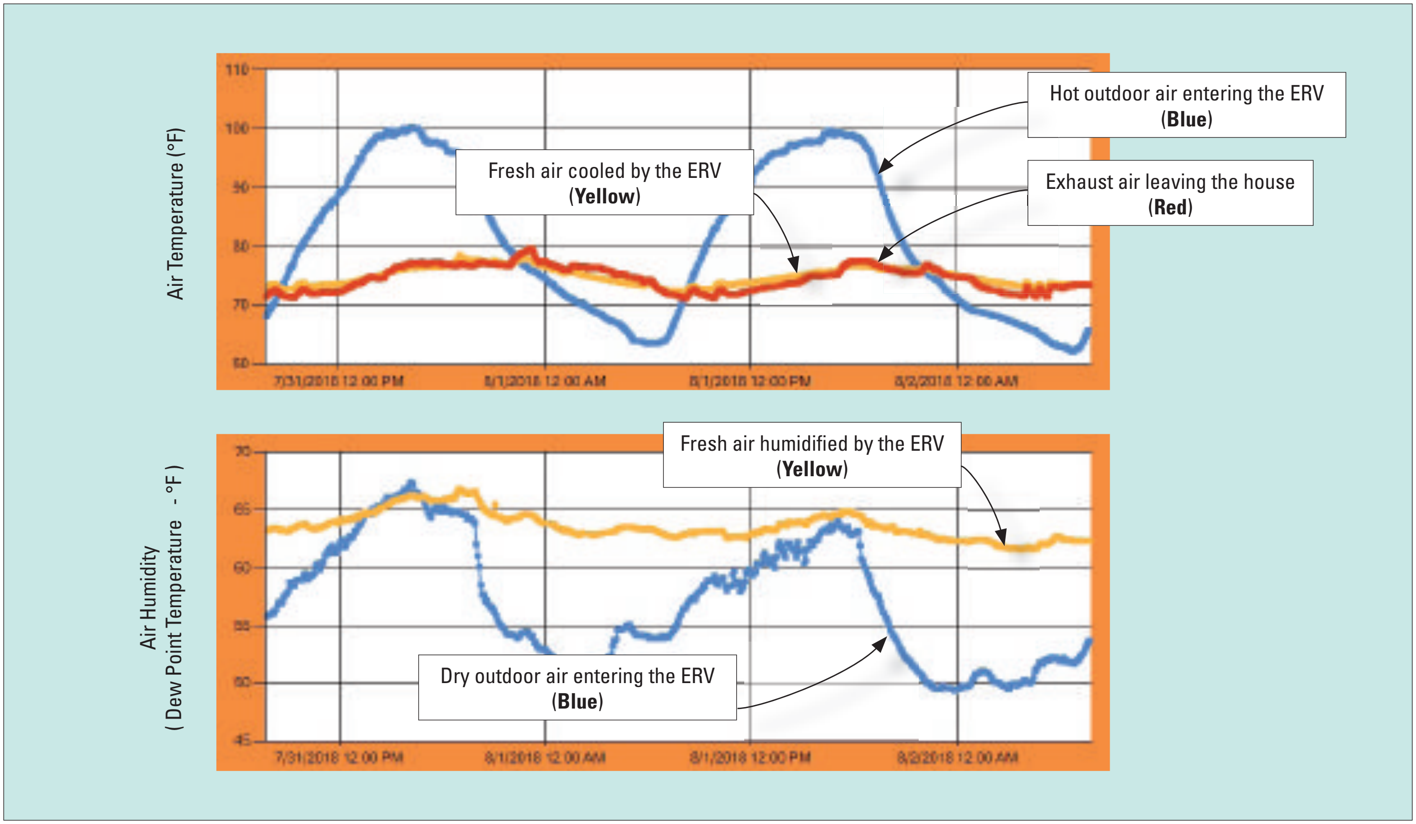


Fig. 7.14 Dream Creek ERV performance - August 2018

The savings rise and fall with the weather. Savings are greatest during the hours when outdoor temperatures is much higher or much lower than the indoor temperatures. Over the course of a typical year, this saves a great deal of energy—usually 50 to 70% of the energy needed to condition the incoming ventilation air. And the ERV accomplishes all that ventilation air pre-treatment using only the energy used by two small fans. What a bargain! And the savings really add up over time. They continue all year long, every year, for the life of the building, while providing great indoor air quality.

On the next two pages, three items to discuss with the owner, about operating and maintaining the system →

Fig. 7.15 To avoid callbacks, help the owner understand the system
Experience at the Dream Creek development suggests that most frequently, HVAC callbacks for comfort complaints are caused by clogged air filters, or by expectations of fast cooling response in the evening, after systems are shut off all day long "to save electricity."

O&M tips for new ZNE homeowners

Chapter 10 of this book is designed to help owners understand the best ways to use and enjoy the house. As the HVAC sub, you might consider using chapter 10 to generate your own guidance for homeowners—or simply leave them a printed copy of that chapter. But there are three key messages they should also hear from you in person, because you're the HVAC expert that created their new systems.

ZNE houses and their HVAC systems are quite different from conventional, non-ZNE houses. Consequently, habits about operation of the HVAC systems need to change in order to realize the benefits. For owners who are new to ZNE houses, these changes are not intuitive. The builder or HVAC subcontractor can explain three key points, to help reduce comfort problems caused by obsolete habits.

1. Let it run.

Please don't turn off the system and expect it to quickly heat or cool the building. It won't do that.

In old-style houses, systems are really big and expensive to operate. So they are often turned off or reset when occupants leave for the day. Then, in order to accomplish a rapid temperature change in a leaky building when occupants return at the end of the day, they have to be grossly oversized. Good for speed of response—but bad for thermal comfort and very bad for energy consumption. Sort of like driving a diesel dump truck to do your grocery shopping. Lots of extra power and carrying capacity—but pretty clumsy for driving and parking, and expensive when you fill up at the gas pump.

In contrast, you can run the small, hyper-efficient systems in your ZNE house continuously—without high operating costs—because your house is air-tight and well-insulated. For example, the monthly HVAC-related electric bill at houses in the Dream Creek development are usually less than $100 per month—as long as the HVAC system is allowed to run without interruption or thermostat reset. So keep the thermostat setting the same all year long to enjoy 24-7 comfort, low energy bills, great air filtration and excellent indoor air quality.

2. Make sure your fresh air can get in.

Replace or clean air filters ***on both sides*** *of your ERV or HRV at least twice a year; perhaps before Memorial Day and Christmas:*

- **Fresh air inlet filter.** This filter is usually inside a grille located under a soffit. Reach up, turn the toggle to release the filter frame, remove the old filter and put in a new clean one. In agricultural areas and near highways, this one gets clogged up rather quickly. It may need to be changed more often than every six months.
- **Exhaust air filter.** This one is located inside the casing of the ERV or HRV. Switch it off. Open the casing and pull out the cleanable filter that protects the equipment. This will look much like the lint filter in your clothes drier. And like that filter, you can probably just roll the lint off and then put the filter back inside. Then close up and restart the unit.

3. Make sure your indoor filters are always effective.

Install clean filters in the return air grille twice a year.

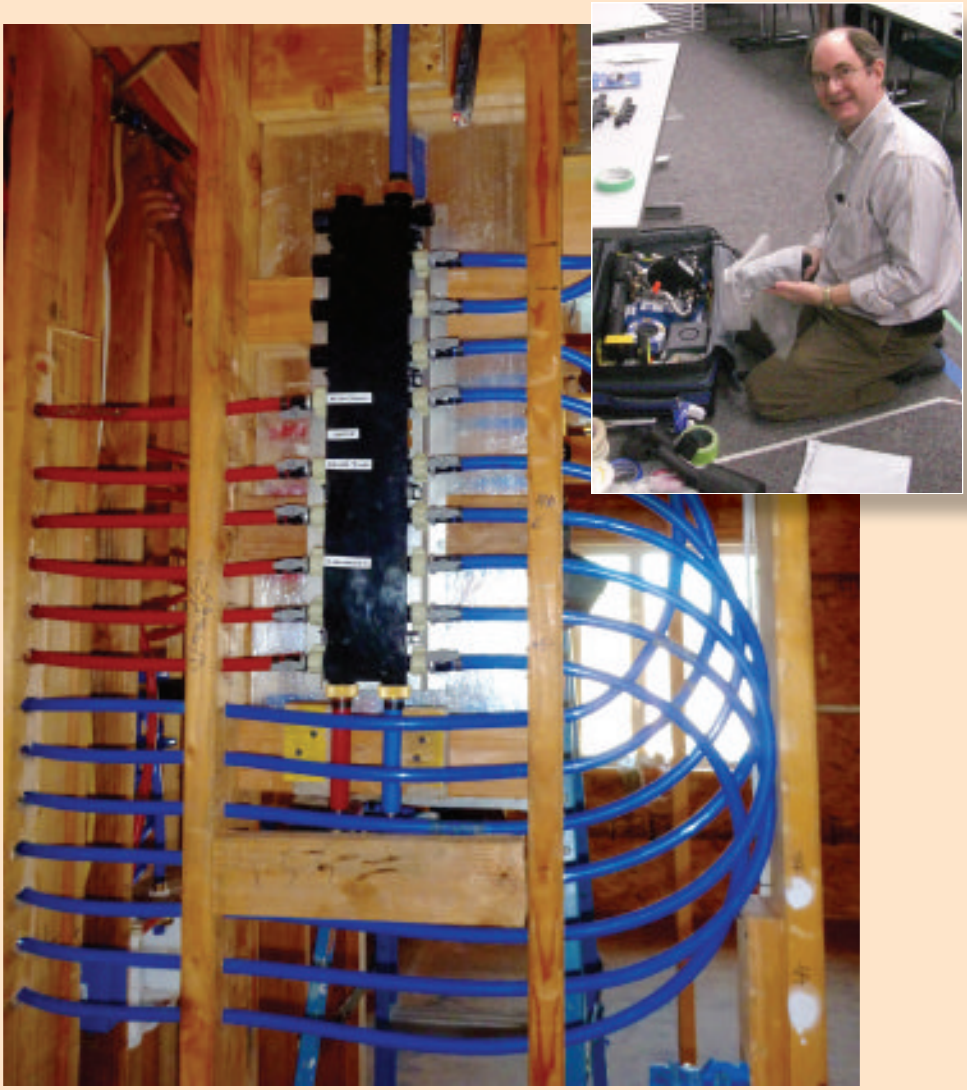
Your indoor air filters are located inside the return air grille. That's the grille mounted on the wall or ceiling near the air handler. You can see the filters (and their condition) when you shine a flashlight through the grille blades. Roughly twice every year, these filters should be replaced with identical clean ones: same thickness (2"), same rating (at least MERV 13, or Home Depot FPR-10 or Honeywell Filtrete 1900) and the same dimensions.

Always use filters with dimensions that fit snugly into the frame. That snug fit keeps dirty air from sneaking around the edges of the filters. After replacement, cruise over to the home improvement store and get a fresh set of identical filters. Then store these in a handy location so you'll have them for the next filter change.

Chapter 8

Plumbing & Hot Water

Small Pipes, with Fixtures and Appliances in a Compact Cluster



Gary Klein
Is a nationally-known hot water and plumbing design expert. He generously contributed his concepts and graphic examples that form the foundation for advice in this chapter.

Fig. 8.1 Minimizing hot water waste is a key component of sucessful ZNE

Minimizing waste begins with architecture. Short distances between heater and taps allow much less lifetme water waste. After that, the plumbing designer-installer helps by using 3/8" distribution to taps with small draws and keeping pipes below attic insulation as much as possible. Sweeping turns rather than 90° elbows reduce pressure drops and improve flow.

Water Waste = Energy Waste

To deliver water to houses south of Bakersfield, gigantic pumps operate 24-7 to lift the snowmelt and rainfall that originates in Northern California up 2,000 ft. over the Tehachapi mountains. More water is pumped over from the Colorado river. And in the Central Valley, pumps pull groundwater up to the surface and then push it through water treatment plants before it is suitable for use in homes.[1] Later—after all that water goes down the drains—even more pump power than it took to deliver it is consumed to *clean it up* at wastewater treatment plants. Bottom line?.. it takes a LOT of electricity to make clean water come out of the taps in a home.

So along with the need to conserve water during California's inevitable periodic droughts [2], we'll want to keep in mind that every drop of water that runs through our domestic plumbing has a high energy content—even before considering the energy needed to heat some of that water for bathing, cooking, washing and cleaning.

Now moving on to water heating, keep in mind there's lost water and heat every time any hot water flows through the plumbing. Heat is lost from uninsulated hot water lines. And when any hot water tap is opened, water goes down the drain (along with the heat it contains) until the flowing stream warms up enough at the tap to be useful. Later, more heat is lost as the water remaining in the hot water pipes cools down after the tap shuts off.

Wasting hot water "moves the ZNE goal post further away" by forcing more use of natural gas, or more electricity from the grid, or both. So reducing hot water waste is especially important for ZNE houses.

That's why this plumbing and hot water chapter begins by pointing out that the *architectural floor plan sometimes governs annual water efficiency and water waste* more than the type of water heater, or its fuel source or it's heating efficiency. Over the life of the building, waste is partly dictated by the distances that hot water must travel between the heater and all of the taps in the house.

The Hot Water Rectangle Highlights Avoidable Energy Waste

Gary Klein is one of the many generous California experts who have donated their hard-won experience for the benefit of readers of this book. Gary developed "The Hot Water Rectangle" to help architects and designers compare hot water distribution waste characteristics of alternative floor plan arrangements.[3] Lower numbers are better.

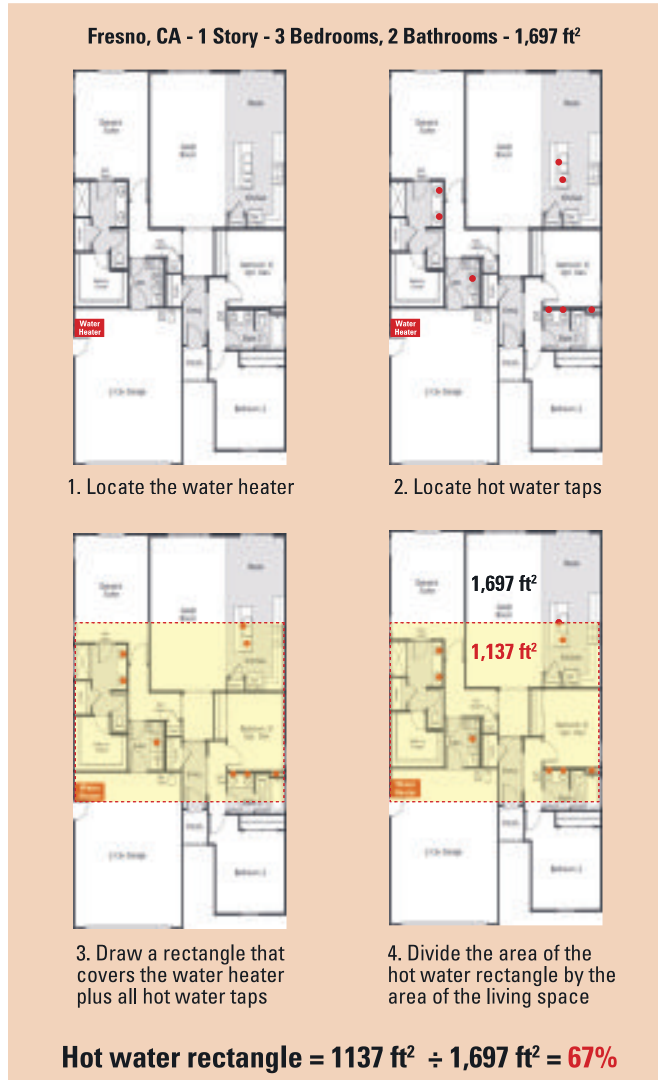
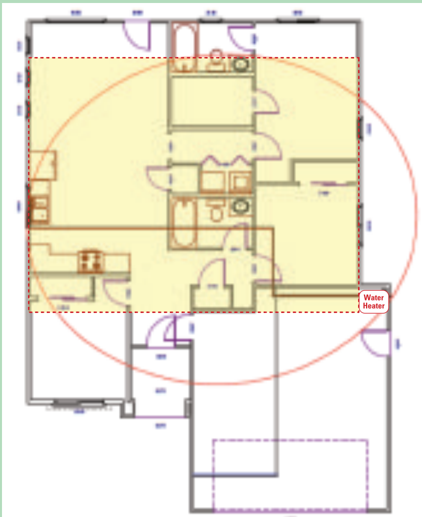


Fig. 8.2 The hot water rectangle
Helps architects minimize hot water distribution waste

Images and data courtesy of Gary Klein



In the beginning... **1279 ÷ 1619 = 79%**
3 bedrooms, 2 bath
1619 ft² living space
1279 ft² Hot Water Rectangle

"I get it"... **183 ÷ 1223 = 15%**
3 bedrooms, 2 bath
1223 ft² living space
183 ft² Hot Water Rectangle

"I can do better"... **49 ÷ 1223 = 4%**
3 bedrooms, 2 bath
1223 ft² living space
49 ft² Hot Water Rectangle

"Come to think about it"... **30 ÷ 1223 = 2.5%**
3 bedrooms, 2 bath
1223 ft² living space
30 ft² Hot Water Rectangle

"One short plumbing wall"... 10 ÷ 1245 = 0.8%
3 bedrooms, 2 bath
1245 ft² living space
10 ft² Hot Water Rectangle

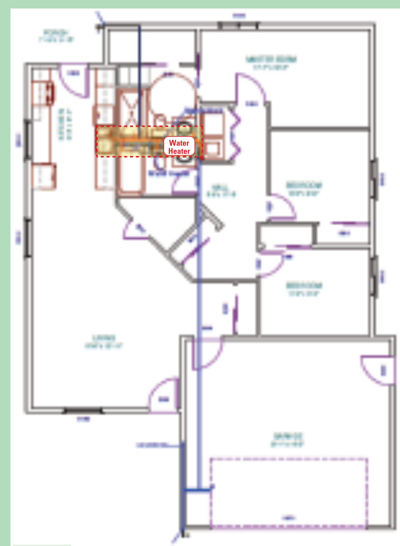


Fig. 8.3 Reducing baseline hot water waste - Hot water floor plan has improved continuously with each new house design
These five plans show the evolution of architectural designs at the Dream Creek Development. George Koertzen constantly improves his designs.

Figure 8.3 shows how George Koertzen made continuous improvements in the floor plans at Dream Creek that greatly reduce wasted water and the energy needed to heat it. The early houses where fairly conventional, with respect to the location of hot water taps and the appliances that use hot water. Using Gary Klein's "Hot Water Rectangle" as a metric, George first centralized the locations of bathrooms and the location of the washer and dryer. Then, he moved the small on-demand hot water heater out of the garage and into the laundry area—less than 10 ft away from all points of hot water use. These changes reduced the size of the hot water rectangle from 79% of living space down to 15%. Further optimization has brought the hot water rectangle of the latest design to 0.8% of living space—a truely remarkable architectural accomplishment.

The practical effect of these improvements is that hot water comes out of any tap less than five (5) seconds after the tap is opened. So the water waste on each draw is less than one (1) cup. This stands in sharp contrast to the more typical water waste of one to two gallons per draw, when hot water has to travel from the garage, up through the attic (where it gets cold in the winter) and back down into the house at multiple points of use. In other words, the lifetime architecturally-controlled hot water waste in the Dream Creek houses has been reduced by about a factor of 10—a 90% reduction from conventional architectural floor plan layouts of the past.

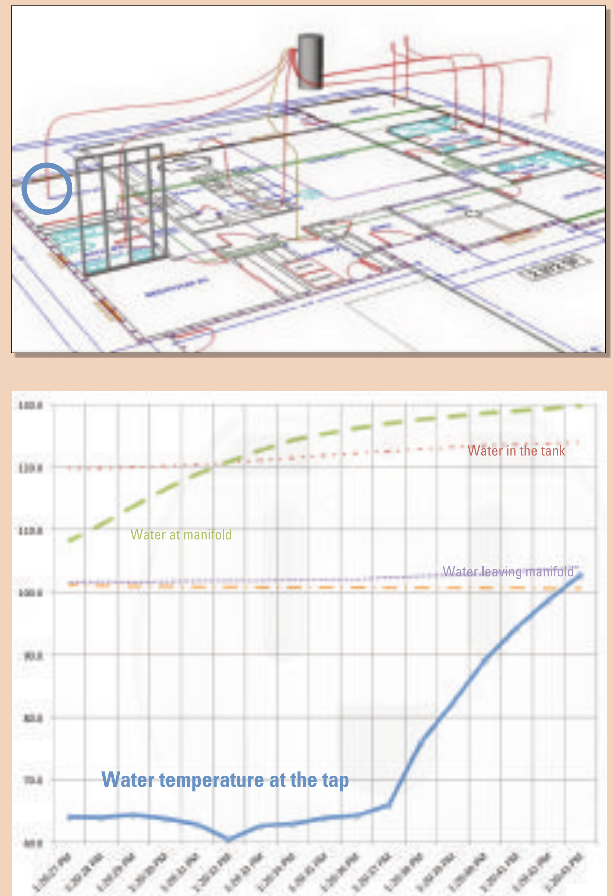
Keep Hot Water Lines Below The Attic Insulation

Another feature of the Dream Creek plumbing design is that all water distribution is below the attic insulation. That way, the hot water is not losing heat to the cold attic during the winter, and cold water lines are not becoming uncomfortably warm during the summer. Just like the shortened hot water lines described above, keeping the water lines below the insulation avoids water waste that comes from cold water coming out of hot water taps.

Figure 8.4 illustrates the thermal and water loss potential of an uninsulated hot water line located above the attic insulation. The data comes from a "less-than-zero" net energy house in Redding, CA (the PV array generated more energy in 2018 than the house consumed).

Images and data courtesy of Mike MacFarland

Hot water layout - "Below Net Zero" house - 2,372 ft² - Redding, CA



Time for hot water to reach 105° F at the far lavatory sink (seconds)

Fig. 8.4 Long pipes above attic insulation - Hot water lags

It's a great house, but improvements are still possible with respect to architecturally-infulenced plumbing design. The lines could be shorter, and they could be run *under* rather than above the attic insulation.

The vertical time divisions in Fig. 8.4 are increments of one (1) second each. Water leaving the water heater's storage tank begins it's journey out to each tap at a temperature of about 120°F. The target temperature for delivery at the tap is 105°F. As the water begins to flow, its temperature leaving the distribution manifold near the water heater starts out at about 102°F (orange dotted line), because heat is lost at the un-insulated copper manifold.

The solid blue line at the bottom of the graph shows the temperature of the water as it leaves the tap, 32 ft away from the water heater. At the start of the draw, water leaving the tap is 64°F, as opposed to the 120°F temperature of water in the storage tank. Next, note that the water temperature actually drops even lower for four (4) seconds, as the draw delivers the cool water that had filled the part of the line located above the attic insulation.

Then over the next four seconds water rises up closer to room temperature and ultimately begins a sharp temperature rise 11 seconds after the tap was opened. Another five (5) seconds are needed to bring the water at the tap to the 105°F that most consider adequate for use as "hot water." So during each initial draw, water is wasted for a full 16 seconds. The net water loss for this example is four (4) cups, or about 25% of a gallon.

To be fair, that's still much, much less than in houses of the past. You can try this at home! First thing in the morning, turn on the tap in the shower, and count the seconds until the water is warm enough to be comfortable for your shower. A count of 120 to 360 seconds would not be unusual—more than 10 times the water waste of the hot water line shown in Fig. 8.4.

Continuing the narrative, it's useful to know that the attic in this well-build house is not especially cold, and the hot water line for the lavatory has an internal diameter of 3/8" instead of the outdated practice of installing 1/2" lavatory water lines. If the lavatory water line had a diameter of 1/2"as in the past, the water waste would nearly double on each draw.

So the graph makes the point: water in hot water lines in cold attics is basically wasted, every time the tap is turned on in response to hot water demand. Take that fact, multiply it by 6 or 7 hot water taps per house, multiply the result by the number of initial hot water draws per day, per week and per month, every year for the expected 50 to 100 year life of the building, and then multiply the result of that calculation by the number of houses built each year in California (on average about 80,000). It's apparent that, as they say: "pretty soon you're talking about a lot of water waste." And that does not even count the energy it takes to heat the wasted water up to 120°F and keep it at that temperature until it flows through taps and out into the sewer.

Fig. 8.5 Water heater in the garage? Bad idea.

San Diego, CA - 1 Story - 5 Bedrooms, 5.5 Bathrooms - 4467 ft²

Hot water rectangle = 4467 ft² ÷ 6924 ft² = 155%

Keep the hot water heater out of the garage

Figure 8.5 shows the hot water rectangle of a house located in San Diego. Nice, big house. Probably very pleasant in many respects. But certainly about as wasteful as it could possibly be, from the perspective of water and water heating design. The hot water rectangle is 155% of the living space. That happened for two reasons: the bathrooms and water fixture locations are scattered all over the house, including exterior walls. And the hot water heaters are located in one of the two garages. So the area covered by the hot water rectangle includes all the garage space, in addition to every square foot of the living space.

The least wasteful location for the hot water heater and all of the hot and cold water lines, is inside the thermal boundary of the home. In other words, keep the hot water heater inboard of the insulation, as opposed to out in the un-insulated garage, or up in the attic above the attic insulation. Recall the temperature lag at the tap shown in figure 8.4. If the water heater had been located out in the cool garage, the temperartuee lag would have been much longer, and therefore the water waste would have been far greater for each and every draw—for the life of the building.

Sweeping turns waste less energy than 90° elbows

Here's an item of minimal importance to the home owner, but which translates to energy waste at the water utility. See the PEX piping manifold in figure 8.1—another feature of the Dream Creek houses. You'll notice that instead of 90° elbows, as the PEX tubing enters and leaves the manifold, it does so in long, sweeping turns. This is because measurements taken by Gary Klein in the SOCAL Edison research facility in Downey, CA found that at a bend radius of 18'', the pressure drop (flow resistance) of the tubing is equivalent to straight pipe. That fact stands in stark contrast to the flow resistance of a single 90° elbow, which is essentially 10X the resistance of straight pipe.

That 90% reduction in water flow resistance is helpful in two respects. In parts of the State that suffer from low water pressure, the lower the resistance of the interior piping, the more quickly water will flow from the tap. That's an occupant benefit. And in those same areas, the water utility can provide reasonable service at lower water pressure, which reduces the pumping energy and capital investment needed to boost water pressure up high enough to satisfy home owners.

To be clear, this energy savings is not really reflected in the homeowner's utility bill. So making long sweeping turns rather than sharp angle piping connections is a benefit that accrues to the commnuity as a whole rather than to the homeowner that enjoys the efficient plumbing. But there's still a nice side benefit for the homeowner: fewer joints mean less risk of water leakage. Less water risk is a good thing.

References

[1.] California Energy Commission 2005. "California's Water–Energy Relationship" Final Report - CEC-700-2005-011-SF. https://www.energy.ca.gov/2005publications/CEC-700-2005-011/CEC-700-2005-011-SF.PDF

[2.] California Natural Resources Agency, Department of Water Resources. 2018. California Water Plan - Update 2018. https://water.ca.gov/Programs/California-Water-Plan

[3.] Klein, Gary and MacFarland, Michael. 2019. "Central Core, Pressure Drop, and Measured Hot Water Performance" Proceedings of the 2019 Forum on Dry Climate Home Performance http://www.dryclimatehomeperformance.com

Electrical Systems

Suggestions for fast and reliable installation

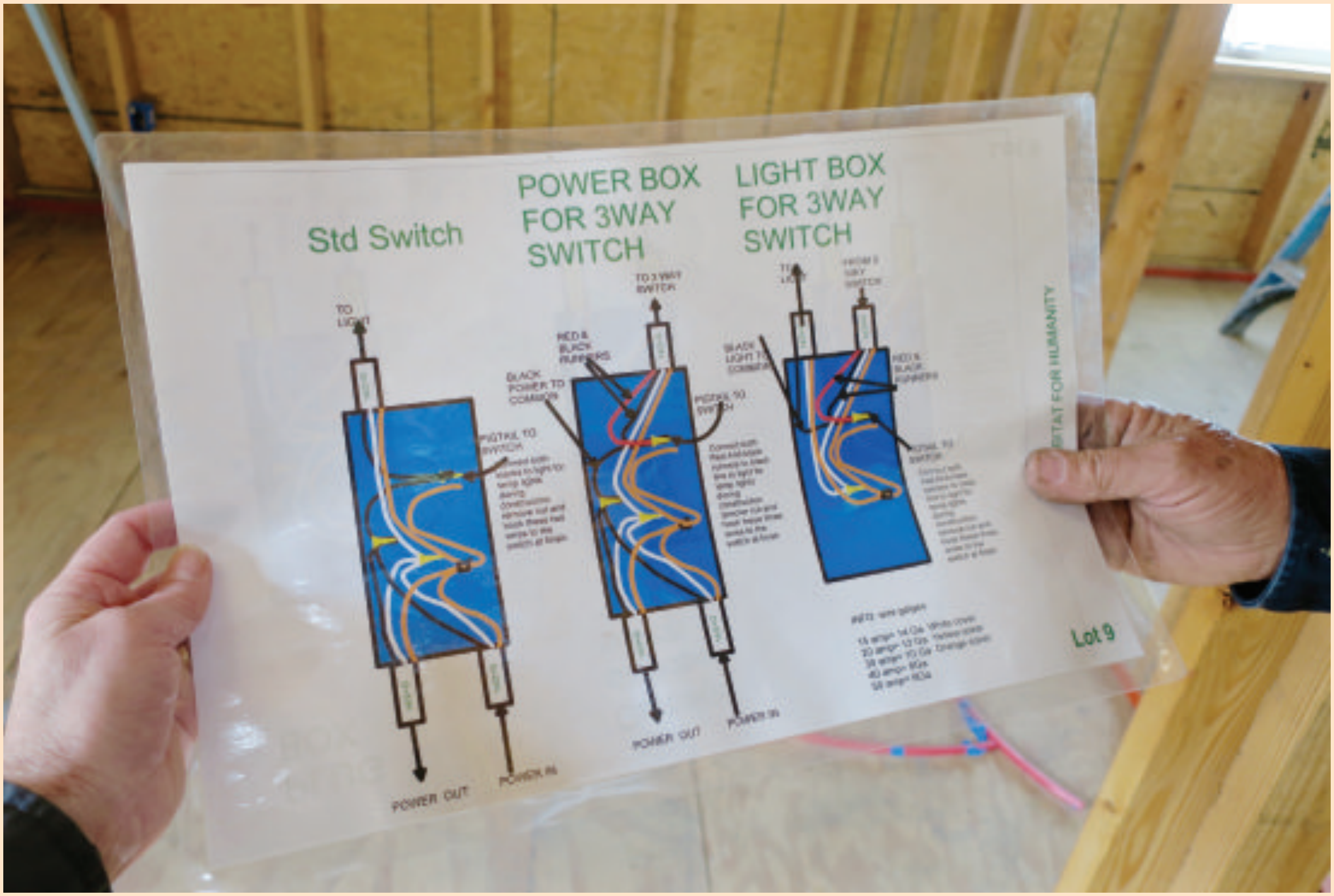


Fig. 9.1 Clear, color-coded wiring diagrams improve installation

To increase safety and reduce the need for rework, George Koertzen provides highly-detailed wiring diagrams and stores them on-site, so that the site super and any worker can refer to them quickly and easily at all times. While especially useful for his semi-skilled volunteer labor, such clear instructions can help any workforce improve its speed, safety and consistency.

Electrical Design and Installation for ZNE

This chapter provides suggestions based on George Koertzen's work at the Dream Creek Habitat development. These can help smooth electrical installation so it can go in quickly, without interfering with insulation or other key energy features. With George's thoughtful design, wire routing and consistent labeling, there's less risk of safety issues or expensive, schedule-busting callbacks. His suggestions fall into three broad categories:

- Electrical panel components and layout
- Wiring design and installation
- Beware of power parasites (Communicate to owners)

Electrical panel components and layout

Electrical design and installation at Dream Creek have benefitted from recent manufacturer's improvements in panel and breaker design, and also from clever partition of the grid-connected service.

Houses have 250A service, divided into two panels. The grid-connected service to a typical 1200 ft^2 house at Dream Creek is 250 amp. In each garage, the incoming power is divided between two circuits inside a small "splitter panel." In that panel, one 200 amp circuit is routed indoors, while a second curcuit for the garage is rated at 50 amp. The breaker for the garage circuit passes power to a single 20 amp breaker that serves four plug outlets. The garage-mounted splitter panel with the construction power plug outlets are shown in figure 9.2.

The larger 200 amp circuit continues up into the attic and onward to the main panel, which is located in the center of the house. All of the domestic wiring and the solar-generated power is connected at that main panel. During construction, the 200 amp breaker stays closed, so that all the interior wiring and the solar array can be safely connected to the main panel. During construction, the 50 amp breaker in the garage stays open, providing power for tools, construction lights, battery chargers and instruments. After construction, the garage panel continues to provide electrical service for tools and chargers through its 20 amp breaker. In the future, the face of that panel can be replaced with a 30 amp charging station for electric vehicles.

Fig. 9.2 Construction power from a splitter panel
A small "splitter panel" is mounted in the garage, where the grid-connected service enters the house. The splitter panel is equipped with a separate breaker and plug outlets to provide continuous construction power while the main panel in the center of the house stays off, to allow safe connection of all the wiring runs.

Solar-generated AC power connects directly to the bus of the main (indoor) panel. Each solar panels is equipped with micro-invertors that convert the DC power generated by the panels to AC power. One advantage of that configuration is that solar power connects directly to the bus in the main panel, rather than needing to pass through a central invertor. Another advantage is that any invertor failure takes out a single panel,rather than the whole string.

From the perspective of maximizing power generation, it's an open question as to whether a central invertor would have lower standby losses at night, compared to the losses of nine or more microinvertors. But the simplicity and labor saving of a single run from the roof to the panel allow a lower overall installation cost. Plus, interior wall space is saved by eliminating the central invertor. These benefits seem like a reasonable tradeoff for what may (or may not) be slightly larger standby losses of multiple microinvertors compared to one large invertor.

Standard panels are now available with time-saving features. The panels and AFCI breakers chosen for the Dream Creek development are available as standard items from big box home improvement stores. Some of these modern panels have useful labor-saving features, such as:

- Wire strain relief connections through the enclosure by press-fit slots. In older models, connections through the enclosure are made through knock-outs and romex strain relief inserts. In the panels selected for Dream Creek, wires are press-fit into slots that hold them securely without the need for the usual romex connectors. This enclosure design feature saves time and simplifies installation.
- Continuous ground bus under all breakers. The arc-fault circuit interrupters (AFCI breakers) have an electrical connector boss on their back surface. As the breaker is pushed into it's socket, that boss clamp down to make a secure electrical connection with a continuous ground bus underneath all the breakers. This eliminates the usual rats nest of pigtail ground wires from each AFCI breaker that usually connect to a ground bus located in a distant corner of the panel.

Wiring design and installation

Wiring design at Dream Creek helps ensure safe and reliable results by volunteers who are not experienced electricians. The design is also based on two realities: future plug loads are unknown and wiring and plumbing must not obstruct quick and complete installation of insulation. Although these suggestions are most helpful for the volunteer work force at Dream Creek, the concepts of simplifying and clarifying on-site instructions may also interest production builders, since they help reduce callbacks and rework.

Every room has its own 20 amp circuit for wall plugs. Both experience and human nature suggest that over time, plug loads vary widely. Combining plug circuits from different rooms can lead to the annoyance of tripped breakers in the future (e.g., one kiddo in a bedroom drying hair after a shower, while in another bedroom the older sibling is heating leftover pizza with a dorm-sized microwave oven.) Installing individual plug circuits for each room is easy to do during construction. It adds little cost and helps avoid needless future problems with overloaded breakers.

Fig. 9.3 Wire jacket color indicates the circuit's amp rating
White indicates a 15 amp circuit, yellow indicates 20 amps and orange indicates 30 amps. These colors allow quick and easy visual confirmation that the correct breakers are installed on each circuit.

Color coded wiring jackets indicate the circuit capacity. Wall plug circuits (and circuits for refrigerator, microwave and dishwasher) are run with yellow-jacketed #12 wire and connect only to 20 amp breakers. White-jacketed #14 wires connect to 15 amp breakers. 30 amp circuits are run with orange wire. George is seen standing by color-coded wiring in fig. 9.3. The wire jacket color codes help keep the different circuit loadings clear to workers as they run the wire (i.e., "Don't connect the plug circuit for the electric range with any wire that is not orange!") That way, at the panel the site super and the supervising electrician can tell at a glance whether the circuits are connected to the correct breakers.

Color-coded diagrams help ensure that box wiring is consistent for switches, plugs and lighting fixtures. As shown in figure 9.1, the crew is given color diagrams clearly illustrating connections and the wire routing into and out of each fixture. The diagrams greatly reduce the potential for confusion and unsafe wiring when the electrical system is partly installed by inexperienced labor. The key to success is a central location—on-site—where these easy-to-read diagrams are available at all times to workers.

Wiring on the plate through notches stays clear of insulation. Wiring starts at the panel, then goes up through the attic then down alongside a stud to the bottom platel. Wire runs then continue along the bottom plate through notched studs and back up the sides of studs to plug outlet boxes (see Fig. 9.4). Running wire on the plate helps ease correct insulation of exterior walls. No wires cross the cavity to block or partly crush insulation, which would substantially reduce its R-value for the entire 50-100 year life of the building. Confining wire to the floor plate is also helpful for interior walls. Workers can step through the wall without the hazard of a trip-and-fall injury. And equally important, tripping on the wire often tears the insulation jacket where it's held by staples. When wire jacket insulation is damaged, workers often need to replace the entire wire run all the way back to the panel—what a pain, not to mention the damage to the schedule and the wasted labor hours.

All attic wiring is fully-supported. Wiring is run on 1" x 4" wooden battens that span joist bays (aka: "rat runs") This feature helps provide durability over time in addition to speeding any necessary additions or adjustments to wiring routes or circuit density. No wire crosses the attic at an angle and all wires are fully-supported, such as those shown in fig. 9.5. It's always clear where the wiring runs are located, even after the insulation buries everything in the attic. This robust mechanical support helps reduce the risk of a worker in the attic stumbling and then snagging or snapping a wire.

Fig. 9.4 Wire on the floor plate helps avoid insulation defects
Keeping the wire from crossing the wall cavities makes it easy to install insulation quickly and correctly. Insulation has to be crushed to fit behind and around the wire, which greatly reduces its R-value. For example, look at the photo on the right. That electrician has effectively forced the owner to pay extra for heating and cooling for the entire 50-100 year life of this house.

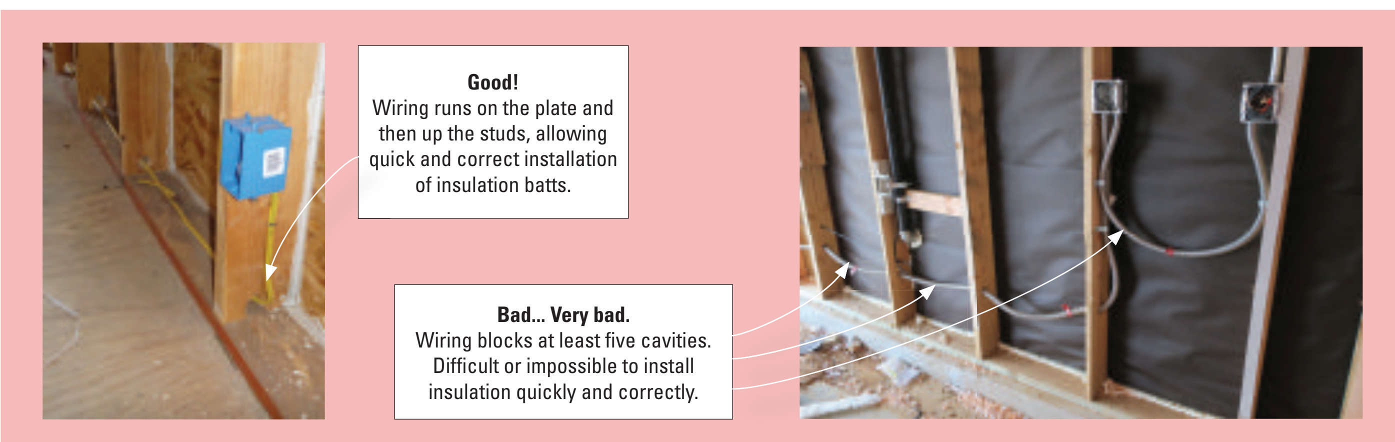


Fig. 9.5 Attic wiring is fully-supported, protected and easy to find *Wire in the attic is fully-supported by what George calls "rat runs:" 1" x 4" or 1" x 6" lumber that crosses and connects the joists or trusses. With that support, there's less risk that workers will accidentally snag and pull a wire during construction or later, after the wiring is buried under insulation.*

Lighting

All lighting at Dream Creek uses LED bulbs, providing a minimum of 50 lumens per Watt (eg: the widely-available 12W, 600 lumen bulbs). Another easy, low-cost lighting energy saver is to install interior light switches that have LED "on" indicators for all exterior lights. Garage lights, back porch lights, and front porch lights are often left on by accident, wasting energy all day long. In fact, the subject of accidental and parasitic loads deserves some brief comments for the benefit of both builders and home owners.

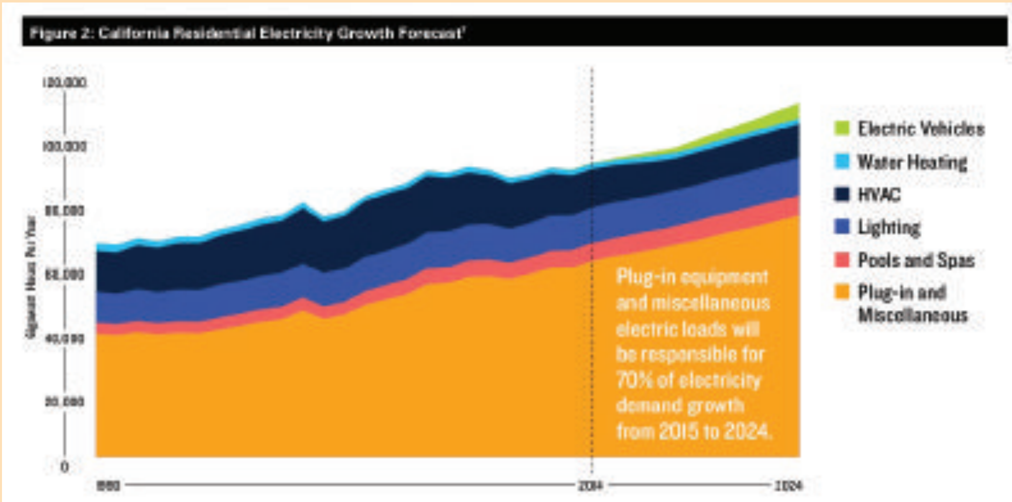
Power parasites: plug load info for builders and owners

Electronically-enhanced appliances, entertainment consoles and portable and/or wearable electronics are truely a marvel of modern civilization. They enhance our lives in many ways. But… nothing comes without a cost. Many appliances and consumer electronics come at the cost of "always-on" power consumption of their controls or digital displays, or for the plug-in chargers for battery-powered electronics like laptop computers, cell phones, tablets, watches, flashlights and power tools.

Sadly, after occcupancy begins such "always-on plug loads" waste an astonishingly large percentage of the electricity consumed by a typical household. For exampsle, in 2015 a project by the Natural Resources Defense Council, Home Energy Analytics and the Stanford Sustainable Systems Lab found that "always-on" electricity used by inactive devices represents, on average, 23 percent of northern California household electricity consumption. Their conclusion was supported by three separate data sets: smart meter data from 70,000 northern California homes; smart meter and additional information for 2,750 San Francisco Bay Area homes; and a detailed in-home audit of 10 Bay area homes.

The graph in figure 9.6 comes from the NRDC report, which can be downloaded using the QR code in that figure. Plug loads were found to represent about 70% of the growth in electrical consumption of the measured homes. And as noted above, 23% or more of plug load consumption is doing… nothing.

These data tell a rather sobering story; unless "always-on" plug loads are kept much lower by occupants, most of the efficiency gained by thermal excellence of the enclosure and low-energy heating and cooling systems may not matter very much. The astonishing waste of all those little chargers and attractive display screens on appliances and electronic devices can trash much of the potential societal benefit provided by builders who create ZNE homes. So as a builder/developer, it may be useful to point customers to the information provided for consumers in Chapter 10, the last chapter in this book.



Plug-in Equipment Efficiency
NRDC Issue Brief
IB:15-02-D April 2015

Fig. 9.6 Plug loads dominate California's residential electrical consumption... and more than 20% is wasted, by "always'on" electronics
It's important for consumers to understand that they can eliminate a very large percentage of energy waste, when get rid of old, non-EnergyStar appliances, and choose consumer electronics that do NOT use the "always-on" power that is sadly typical of most battery chargers and entertainment consoles. Useful tips, plus traps for consumers to avloid are contained in Chapter 10 of this book.

Chapter 10

Information For Owners

Comfort and Energy in Your New Home

Fig. 10.1 ZNE homes are a delight to own and to live in
And like any big investment, your house is worth maintaining to preserve its value, and to ensure low monthy expenses with optimal comfort.

ZNE Living

If this is your first zero energy home, you're probably in for a new experience. Your house is likely to be more comfortable, less expensive to operate and more durable than what you might have been used to in the past. ZNE homes are quite different. For example:

• **Indoor temperatures stay nice and even**. No more winter drafts or summer hot spots. Less than a 3°F temperature difference between any two points in the house. Your HVAC is most effective and most economical when it operates continuously—no more need to reset the thermostat to save money.

• **Monthly costs will be low.** Typical electrical bills are less than $150 per month, and can often be zero—depending on your solar production vs. your use of appliances, electronics and local grid connection charges.

• **Indoor air stays fresh and clean.** Indoor air smells fresh and clean when you arrive home and can stay that way—even overnight in bedrooms—as long as the HVAC system is operating continuously.

• **Built to last, while its relative value increases.** Your house will easily last for generations. And because its monthly electrical consumption is so low, your house is likely to be worth more than similar houses in the same market, as utility costs rise higher and higher over time.

Of course, like any new experience there are a few things to get used to about your ZNE home. Some of these may seem—at first—to be a bit odd! But very soon, you'll be wondering why all homes are not built like yours. Because in short, your house is simply better.

Here are some tips for ensuring superior comfort and economy in your house, and maintaining it to sustain its value over time.

Thermal Comfort and How To Maintain It

For maximum comfort and minimum energy, operating and maintaining your home might just a bit different from what you would expect, compared to typical HVAC systems of less efficient houses.

Leave the HVAC system on all the time, and don't set back the thermostat when you're out of the house.

You want to be comfortable when you return home after work. If you set back the temperature or turn off the system, your house will not return to comfortable temperatures quickly. It make take hours. Your system was selected according to the "Goldilocks principle": just right for the load. That means it does NOT have the wasteful excess capacity that lets it catch up quickly when the house becomes too cool in the winter or too hot in the summer. Setback increases your energy use. If the system has to struggle to catch up, it consumes much more electricity than if you had simply left it on. And if you're returning home during the evening peak between 5 and 9 PM. it will be running flat-out at maximum power consumption, at exactly the time when purchasing electricity from the grid is *most* expensive. So for reasons of both comfort and energy economy, set the thermostat where you like it when you're in the house, and leave it that way at all times.

We understand this advice may sound odd, even though field-measured data shows it to be true. If you need a more technical explanation of *why* operating the system in a ZNE home uses less power when *left on*, there's more detailed information at the back of this chapter.

Indoor Air Quality and How To Maintain It

Your ZNE home is equipped with what you need to maintain good indoor air quality. As long as you turn on the equipment that comes with the house—and keep it operating smoothly—you and your family can enjoy superior indoor air quality.

Here's a simple way to think about air quality: you don't want to breathe lots of small particles, or mold fragments or pollen. And you don't want to breathe the stuffy air and funky aromas of pets and everyday human occupancy.

So here are just a few things you might want to keep in mind that will help maintain your indoor air quality:

- Most important: install clean air filters every six months in both your AC system and your heat recovery ventilator. As long as air can flow freely through your equipment. It will clean up the indoor air while also providing the ventilation air that dilutes and exhausts the odors generated by normal occupancy. (The details of how to change filters is provided below.)
- When cooking, turn on the range hood. You can get rid of trillions and trillions of small particles produced by cooking by simply turning on the range hood exhaust fan whenever the stove is in use (and especially when frying or sautéing).
- Don't use air fresheners, and avoid frequent use of candles. These generate volatile vapors and small particles that you don't want to breathe.
- When showering, turn on the bathroom exhaust fan. By using the bathroom exhaust fan when you shower, you'll help keep moisture from accumulating inside the walls and above the ceiling. Without moisture, mold can't grow in those hidden spaces.
- If you live in an area subject to wildfires, invest in one or more portable HEPA air cleaners to keep in reserve. When wildfires hit, run portable HEPA air filters in bedrooms. Wildfires can, for a few days or weeks, drive airborne particle counts more than 10 times higher than U.S. National Ambient Air Quality Standard (NAAQS). You simply do not want to be breathing high concentrations of small particles, even for a few days.

In your HVAC system, install a clean filter at least every six months.
Keep a fresh set of filters on hand so you can change them at Christmas time, and then again when school lets out for the summer. The inlet grille of your HVAC system (the "air return" grille) has a filter that helps keep the air indoors clean and healthy. It also keeps the HVAC equipment performing at maximum capacity with minimal energy consumption. Install a new, clean filter at least every six months, and more often if you live near an agricultural area with blowing dust, or

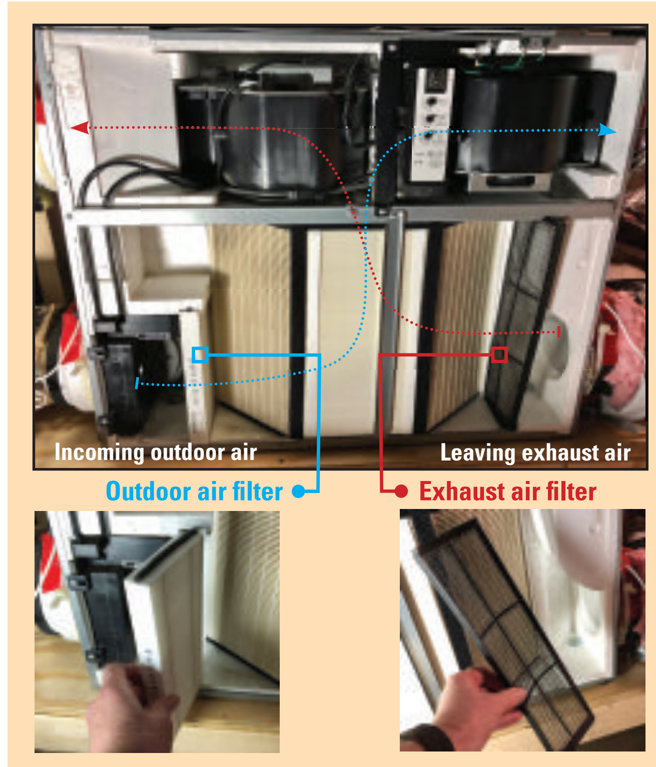


Fig. 10.2 Filter locations in a typical energy recovery ventilator

Fig. 10.3 Used v. new outdoor air filters from an ERV

Fig. 10.4 Most exhaust air filters are easily cleaned with a vacuum

near a highway where vehicle traffic fills the air with small particles. In California, standards now require that builders provide HVAC systems equipped with "MERV-13" filters. These are made to reliably remove at least 50% of the small particles that measure less than 2.5 microns in diameter ($PM_{2.5}$). Particles that small will penetrate deeply into your lungs. They are responsible for the most damaging health effects—those that affect the delicate lungs and less-robust immune systems of children, older occupants and any who suffer from athsma or COPD.

In your Heat Recovery Ventilator (HRV), install a new outdoor air filter and vacuum the exhaust air filter every six months

Over time, ventilation air filters can clog up so much so that not much fresh air gets into the home. So it's important to change or clean the HRV filters twice a year: once at Christmas and again when school lets out for the summer. Heat recovery ventilators have two filters: one for the incoming outdoor air, and another for the exhaust air that the unit ejects from the house. (Fig. 10.2).

As shown in figure 10.3, that outdoor air filter loads up heavily as it cleans the air you're about to breathe. In most HRV's, that filter must be replaced rather than cleaned. So it's a good idea to keep spares on hand.

Next, you'll see a loaded-up exhaust air in figure 10.4. That filter catches all the fuzzy stuff from indoors, so it does not clog the heat exchanger inside the HRV. Getting rid of that fuzz is easy. It's like cleaning the lint filter on your clothes drier. Vacuum that exhaust filter every six months when you install the clean filter for the outdoor air.

What can go wrong in a ZNE home?

You're now living in a new, low-energy, very comfortable and very healthy house. So what could possibly go wrong? Well.. nothing is perfect forever. And sometimes, "stuff happens." Here's a list of problems that might or might not occur your house, along with suggestions for what you could do to avoid them.

Higher-than expected electrical bill

Usually, this happens because of consumer electronics, or because the solar array is not working as originally designed, or because of heavy electrical use during the late afternoon and early evening, when time-of-use electrical rates are very high.

Some types of electrical consumption are avoidable. For example, lighting or music or game consoles don't have to be left on when nobody's home. And perhaps long showers or drying the laundry might not really have to happen during the late afternoon. Also, power can be saved by simply pulling the plug on battery chargers that have completed their jobs. Chargers for portable tools, laptop computers, cell phones, tablets and wireless headphones often chew up significant amounts of electricity, even when not connected to the equipment they serve. Further, keep in mind that any "spare" appliances drain power, and sometimes they don't need to be operating. For example, that old refrigerator and/or freezer that's still chugging away in the garage with nothing inside it that you'd really want to eat.

When bills are high, it also may be that the solar array is not working to full capacity. Homeowners can start by cleaning them off: leaves, dirt or the thin film created by blowing dust plus morning dew will reduce electrical generation performance. But if there's no improvement after cleaning, then calling the solar service company is probably the best option.

Finally, don't reset the thermostat or turn off the HVAC system unless you're going to be gone for several days or weeks. As explained earlier (and in more technical detail at the end of the chapter) just let the system run continuously at your preferred set point temperature all the time; 24-7. Because you have such a well-insulated air tight house, running the system continuously is the best the way to keep the electrical consumption of your HVAC equipment to a minimum.

- **HVAC system struggles to regain comfortable temperatures when residents return home.** Your system will not cool or heat your house quickly. That's because it's not oversized. And that's a good thing, because if it *had been* oversized, the result would be bigger energy bills and more expensive maintenance for the life of the equipment. So to avoid "comfort lag", just leave the system on with your thermostat set to your preferred temperature, even when nobody's home. That way, you never have to worry about comfort lag when you come home, and your electrical consumption is minimized.

- **HVAC system does not seem to cool or heat as well as it used to, when it was first installed.** Two common reasons for sagging performance are: increased loads from open windows and/or blocked air flow.

Since California is California, during the Spring and Fall there are sometimes periods when simply opening windows provides the comfort you need. But during heating and cooling seasons, don't expect the HVAC system to be effective when windows are open. And remember that because you have a ventilation system that provides fresh air, open windows are not necessary for good indoor air quality (IAQ).

Blocked air flow is the more common reason for poor HVAC performance. To add or remove heat, supply air must flow into and through the house smoothly, in the amounts established when the system was installed.

With respect to equipment, the solution to low air flow is obvious: remove the clogged filters and install clean ones. Then as air flows out of the supply ducts, closed interior doors might interrupt smooth airflow between the supply grilles and return air filter grilles. Closed doors mean that some rooms will get too hot while others will get too cold. Interior doors should be kept open as often as possible.

Fig. 10.5 Dirty v. clean return air filters

Finally, avoid placing furniture so it blocks or interrupts the HVAC systems' air streams. To keep the air in a room at a uniform temperature, the incoming supply air stream needs to entrain and mix completely into the much larger amount of air in the room. If there's furniture in front of the wall-mounted supply grille (or above a floor-mounted grille) it breaks up the smooth, fast-flowing supply air. The slower and misdirected supply air can't provide the air mixing that keeps the room air temperature uniform and within 3°F of the thermostat set point. So for best performance, keep furniture away from supply and return air grilles.

- **Funky, stuffy indoor air.** If the source of the unwelcome aroma is not obvious and can be easily removed (ie: those moldy yoghurt containers that your teenager forgot behind her desk, or the damp towels used to dry off that big dog after his bath, or the kitty litter that's not been cleaned out lately), then it could be that the air filters on your energy recovery ventilator are clogged and therefore prevent the normal flow of fresh air into the home. If that's the case, install new filters as described earlier in this chapter. Or it could be

Fig. 10.6 Outdoor HVAC unit and sawdust-clogged fins

that the HRV has been turned off for some reason. And if it won't turn on when you flip the switch, then call the HVAC service company so they can figure out what's wrong, and fix the problem.

Another common problem is musty odors in the bathroom. Earthy, musty odors often mean that mold and bacteria are fighting it out over the food source represented by the thin soap film that accumulates in tubs and showers or on shower curtains, or on towels that have not completely dried. Clean off the surfaces or launder the towels and shower curtains and dry them thoroughly. Such problems often go away when everything that gets damp in normal use is kept clean and is allowed to dry completely. To help prevent musty odors bathrooms, keep tub and shower surfaces clean and ask family members to remember to run the bathroom exhaust fan when showering.

Kitchen odors can also be a problem. Odors from cooking may persist and "ripen" to become unpleasant over time. This often happens if the range hood exhaust fan is not running when fish is being prepared, or when frying or sautéing pretty much anything. Once such food aromas flow through the house, it's going to take a long time to get rid of them—especially if fat or oil vapors are lifted into the air during food preparation (eg; sizzling burgers or fried chicken). When odors are not exhausted, the vapors are likely to condense on surfaces. Then walls and ceiling will need to be scrubbed off to eliminate the odors. The best solution is to remove the aromas and particles at the source. Run the kitchen exhaust hood whenever using the range or cooktop, so that odors can't escape to linger in other parts of the home.

Next, its best to avoid "air fresheners", scented candles or "advanced technology" electronic air cleaners. Burning candles generates fine particles. It's not all bad to enjoy the occasional romantic evening, but burning candles to "improve" air quality actually makes it worse, because of all the small particles that burning anything creates. Further, air "fresheners" just cover up rather than eliminate the problem and electronic air cleaners can sometimes generate ozone and/or gasses (volatile organic compounds - VOC's) as well as the fine particles that have been found to be a health risk ($PM_{2.5}$). Depending on their exact configuration, electronic air cleaners may actually *increase* rather than reduce the airborne fine particle concentration.

The real issues with electronic air cleaners is the lack of any industry consensus testing standard that could assure a user of their safety or effectiveness. If you really feel an electronic air cleaner (other than a fan-powered HEPA air filter) could be useful, be sure to check out this list of products that have been tested according to State of California requirements. These at least have been measured in one important respect: ozone. Reliable testing shows these units generate less-than-hazardous amounts of ozone in normal operation:

California Air Resources Board (CARB)
List of Certified Air Purifiers

IAQ and Wildfires

If the local *outdoor* air quality is poor due to a wildfire or periodic agricultural activities, the automatic ventilation systems (in the crawl space and bathroom) can be shut-off using the switch. Then, if you have them, use portable HEPA air filters to reduce the effect of fine particle infiltration.

Your house, being quite air tight, will be much better at excluding wildfire particles and drifting agricultural dust than other homes. But still, some will get in and it's best to avoid breathing fine particles in high concentrations. To this end, portable HEPA air filters can be helpful. Much more detailed peer-reviewed guidance about residential air cleaners is available from the U.S. Environmental Protection Agency. The guidance was written for consumers and was completely updated in 2018, based on the results of public health field studies. You can download it for free at:

U.S. EPA Guidance
Residential Air Cleaners - 2018

Variable-Speed HVAC - Technical Details

Please, operate your system any way you like. However, it's important to recognize that your HVAC system will only deliver its best performance and lowest monthly cost if it is operated continuously

Your new system has "variable speed" compressors and fans rather than the single-speed or two-speed compressors and controls of conventional systems. Variable speed components and their internal controls slowly increase or reduce power consumption in real time, as heating and air conditioning loads change by small amounts hour-by-hour, rather than turning on after the indoor temperature gets far beyond set point and off entirely after the temperature falls well-below set point. With small changes in energy additions or subtractions, the fans and compressors run slowly, taking delicate sips of energy rather than the greedy gulps they need when running flat-out. Speaking more technically, ***keeping the fan and compressor speeds low provides the major economies*** that come from engineering principals known as "affinity laws."

Here's the most important law for purposes of this discussion. Affinity law 1c states that fan and compressor power (their electrical consumption) is proportional to the cube of their shaft speed. In other words, the faster the shaft of the fan or compressor must spin, far more power will be consumed by the motor that drives that shaft. So ideally, you don't want to force the shaft to spin fast. For example, you don't want to force the heat pump go to max cooling or heating because the house has been allowed to overheat or overcool without HVAC while you were gone during the day.

Equipment specifics will vary by each make and model and according to their internal controls. But the general relationship of this power increase or reduction can be expressed by this equation:

$$P2 = P1 * (R2/R1)^3$$

Where:

P1 = Power used at the original shaft speed (Watts/min)
P2 = Power used at the increased shaft speed (Watts/min)
R1 = Original shaft speed (rpm)
R2 = Increased shaft speed (rpm)

Given this relationship, slow is good. When the variable speed system is run at 50% of full speed, its theoretical power requirement is reduced to 12.5% of full power (not 50% of full power). The systems typically installed in ZNE houses have the ability to run as low as 25% of full capacity. In contrast, if the house is allowed to get hot or cold because the system is turned off or the thermostat set back during the daytime or overnight, max power of 1,200 Watts would be needed, probably for a couple of hours, to "catch up" with the huge load of an overheated house. Over at least those two hours or... you're likely to be uncomfortable.

Here's another way to think about this great feature of variable-speed heat pumps. By leaving the system on (and set to a comfortable temperature) the entire house will stay comfortable at ***20 to 40% net cost saving over the cost of running for an hour to "cool the house back down"*** when you get home.

Now it's also a fact that this generic power relationship is always different in real life, because energy reality is constrained by hardware specifics along with the loads, which vary according to the exact configuration and use of the house. But the basic science of energy consumption at peak speed vs. lowest speed still holds. If that's not convincing enough for some of your family members, you might be consoled by this observation by the famous astrophysicist Neil deGrasse Tyson: "The good thing about science is that it's true, whether or not you believe in it."

REAL-WORLD ZERO NET ENERGY
Homes For California

A Report To The
California Energy Commission
Grant Number EPC-16-001

THIS BOOK IS FOR YOU

This book is for builder-developers, their purchasing agents, project managers and their major subcontractors. It is also written for the support team: architects, engineers, HVAC designer-installers and energy raters. We assume you are an experienced professional in a position of authority who intends to design, build and market successful zero net energy houses at a sustainable profit.

PURPOSE

Zero Net Energy is California State policy. We assume that if you are reading this book you are already working to achieve zero net energy homes, or expect to be changing towards that goal in the very near future. If ZNE is not your goal, or if you would like suggestions for ZNE that do not require new designs and new construction practices, you may prefer to look elsewhere for advice.

THE PROJECT

The principles and practices described in this book apply to a wide variety of market-rate ZNE homes. But to be clear, most of the examples, photos and diagrams described here come from the San Joaquin County Habitat for Humanity's Dream Creek development in Stockton, California.

That project is an especially useful source of examples of best practices for ZNE because any builder can apply them, no matter at what price point the homes are intended to sell. The houses at Dream Creek were built at very modest cost, and mostly with unskilled volunteer labor. As a result, the designs have been simplified and cost-optimized to the last possible penny, so that ZNE could be reliably achieved at equal or lower costs than past practices. By applying the approaches outlined in this book, profitable market-rate ZNE can be a reality without its former complexity, waste and cost.

 Davis, California

Production Notes

This book was written, designed and illustrated by Lew Harriman of Mason-Grant Consulting, who also generated the print-ready files using Adobe InDesign Creative Cloud 2021, running on a MacBook Pro (Late-2018) with 16GB RAM. Photos, illustrations and diagrams were prepared using either Trimble Sketchup Pro 2018, Affinity Designer 1.6.1 or Affinity Photo 1.6.7. The body type is Adobe Garamond Book Condensed. The heads and diagram labels are Adobe Univers Condensed. This book was specifically designed for distribution via Amazon's Kindle Direct print-on-demand service.