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Deep Energy Retrofits—Eleven California Case Studies

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Disclaimer

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Abstract
This research documents and demonstrates viable approaches using existing materials, tools and technologies in owner-conducted deep energy retrofits (DERs). These retrofits are meant to reduce energy use by 70% or more, and include extensive upgrades to the building enclosure, heating, cooling and hot water equipment, and often incorporate appliance and lighting upgrades as well as the addition of renewable energy. In this report, 11 Northern California (IECC climate zone 3) DER case studies are described and analyzed in detail, including building diagnostic tests and end-use energy monitoring results. All projects recognized the need to improve the home and its systems approximately to current building code-levels, and then pursued deeper energy reductions through either enhanced technology/ building enclosure measures, or through occupant conservation efforts, both of which achieved impressive energy performance and reductions. The beyond-code incremental DER costs averaged $25,910 for the six homes where cost data were available. DERs were affordable when these incremental costs were financed as part of a remodel, averaging a $30 per month increase in the net-cost of home ownership.

Building enclosure performance was poorer than expected, though the average HERS (2006) score was 49. Air leakage was greater than 5 ACH_{50} in seven homes, and only five projects installed insulation beyond 2008 California Title 24 code minimum levels. Increased airtightness was the most obvious place for improvement in most homes. 50% energy reductions were proven possible in Northern California climates without superinsulation or extreme airtightness, but these measures allowed for greater variability in user behavior while still achieving deep energy savings. Some DERs used overly complex, custom engineered HVAC solutions, which did not perform as expected, and sometimes required replacement or major service. These features cost more, used more energy and resulted in comfort issues. DER should target current energy code requirements in new homes for envelope and equipment.

Indoor environmental quality in the DERs was mixed. None of the project homes were verified as meeting all requirements of ASHRAE Standard 62.2-2010, and only four out of eleven projects provided whole house continuous mechanical ventilation. While all homes installed kitchen and bathroom exhaust fans, failure to meet 62.2 airflow requirements occurred in 10 out of 20 bathroom fans and three of nine kitchen systems. Indoor temperatures were also extremely variable. Some homes maintained very consistent, comfortable temperatures, and others actively used cooler winter temperatures as a way to reduce energy use. A number of homes spent significant portions of the year above the recommended 60% relative humidity limit, though no specific moisture issues were observed. DER should comply with ASHRAE 62.2 requirements.

Average post-retrofit net-site energy, net-source energy and carbon dioxide equivalent emissions (CO_2e) were 9,552 kWh, 18,453 kWh and 4,480 pounds, respectively. Average reductions relative to a typical CA single family home were 52%, 49% and 52%. Five DERs with pre-retrofit data achieved weather-normalized average reductions of 15,966 kWh (58%), 16,918 kWh (43%) and 6,423 pounds (54%). Homes with pre-retrofit net-site usage <15,000 kWh had average absolute reductions of 6,546 kWh, whereas those using >30,000 kWh pre-retrofit averaged a reduction of 22,246 kWh. High usage pre-retrofit homes were much more successful at achieving large absolute net-site reductions, despite having higher average post-retrofit usage (13,797 vs. 6,314 kWh). Net-site savings >60% did not guarantee satisfactory net-source performance in homes that switched from natural gas to electricity. Net-source energy increased

12% in one case and was only reduced by 7% in another, while net-site reductions were 31% and 61%, respectively. Furthermore, even without fuel switching, homes experienced negative changes in relative rank going from net-site to net-source energy, if net-electricity made up more than 45% of their total net-usage. DER should be assessed in terms of source energy and CO_2e emissions, in addition to site energy, preferably on a regional basis. Per house or per person, not per square foot metrics should be used.

For homes where heating and hot water were disaggregated, usage averaged 2,088 kWh and 2,031 kWh, respectively. Average appliance usage (2,446 kWh) was greater than either disaggregated heating or hot water, and plug loads were just slightly lower (1,717 kWh). Lighting was on average 916 kWh. Combined HVAC-hot water averaged 6,444 kWh (54%), and combined plugs-lights-appliances averaged 4,856 kWh (46%). Combined HVAC-hot water exceeded combined plugs-lights-appliances only in those homes with either very low heating energy or exceptionally high appliance usage and low heating energy. Baseload electricity consumption averaged 203 Watts, for an estimated 1,778 kWh per year, or 22% of total average net-site consumption. Baseload was a clear opportunity for deeper reductions in nearly all homes.

Based on these results, the following basic approach for DERs is recommended:

1. Bring building envelope to current IECC requirements for project climate zone.
2. Tighten building envelope to reach <3 ACH_{50} if replacing interior or exterior cladding, or <5 ACH_{50} if not replacing cladding. If applicable, either insulate and air seal forced air ductwork, or bring it into conditioned space or eliminate it.
3. Change all water fixtures to low-flow.
4. Install simple, non-customized, high efficiency systems for heating, hot water and ventilation. Ventilation systems should comply with ASHRAE 62.2. Commission and verify performance.
5. Replace all lighting with either CFL or LED.
6. New appliances to Energy Star or better.
7. Manage plug loads with power strips, whole house off switch, etc. Consider post-retrofit electricity audit.
8. Install PV system aiming for zero-net electricity (optional).
9. Provide feedback to occupants for whole house energy use.

1 INTRODUCTION

In 2009, the residential building sector consumed 22% of the United States (US) annual energy (RECS, 2011). There is a growing trend towards increased energy efficiency in new homes through building codes and standards; California's Title 24 (CA T24) is a great example, having saved $56 billion in energy costs since its implementation in 1978 (California Green Building Strategy, 2010). These codes and standards do not sufficiently address energy use in existing buildings. In 2009, the American Housing Survey (AHS), administered by the US Census Bureau, reported that there were 130,112,000 existing housing units in the country (American Housing Survey, 2009). Meanwhile, new construction is at an all-time low. Dramatic energy reductions in existing homes are needed to reduce the overall impacts of the residential building sector.

Weatherization and energy efficiency retrofit programs have proven that 10 - 20% energy savings in existing homes is easily attainable (Fuller et al. 2010) (Goldman, 1985), yet deeper energy reductions are being targeted at national and state levels. The Federal government has recognized the importance of significant energy reductions within the built environment. The Department of Energy's (DOE) Building America program aims to save 50% of the energy in all participating homes by 2015 (Building America Program Goals, 2011). Since 2009, over $5 billion of stimulus funding has been allocated towards energy efficiency programs, including research funding to establish guidelines of how to effectively save more energy than has historically been achieved in weatherization and retrofit programs. In 2010, an interagency working group, headed by the Office of the Vice President, announced plans that were intended to lay the groundwork for a strong, self-sustaining home energy efficiency retrofit industry. Programs launched included a home energy-scoring tool (Home Energy Score), energy efficiency financing option (FHA PowerSaver) and workforce guidelines for home retrofit workers and healthy indoor environments during home energy upgrades (Office of the Vice President, 2010).

In addition to these Federal goals, some states are introducing their own legislation. Leading the charge is California (CA), which passed state law Assembly Bill 32 (AB 32) in 2006, committing the state to reducing greenhouse gas (GHG) emissions to 1990 levels by 2020 (a 30% reduction of projected emissions) and an 80% reduction from 1990 levels by 2050 (California Green Building Strategy, 2010). The Scoping Plan explains that California's existing buildings will have to be 40% more energy efficient by 2020[1], and zero-net energy (ZNE) by 2050. It also plans to monitor the performance of selected low energy homes, and to achieve a 70% energy reduction from 2008 levels in 25% of the existing homes in California by 2020 (CPUC, 2008).

The goals outlined above are very challenging. To further complicate the problem, there is a lack of understanding in the field as to how much energy retrofit programs have actually saved, as the performance monitoring and reporting has been inconsistent and insufficient. Furthermore, the difference between site energy savings and the reduction of GHG emissions is not well

[1] All new homes in California are intended to be zero-net energy by 2020.

understood in the industry and is essential in order to meet the goals of AB 32 and to curb global climate change. A new paradigm in home energy efficiency—Deep Energy Retrofits (DERs)—has the potential to achieve energy and carbon reductions in existing homes consistent with these aggressive goals.

A DER is a home energy upgrade, aimed at energy reductions above and beyond those achieved in traditional weatherization or home performance programs. These ambitious projects take existing, inefficient homes and transform them into very energy efficient, comfortable, low-energy homes. Often sustainability, historic preservation and occupant comfort, health and safety are intertwined with the energy reduction goals. These drastic energy cuts are typically achieved using a combination of building enclosure air sealing, additional insulation, window replacement, HVAC and domestic hot water system upgrades, lighting and appliance replacement, and sometimes the addition of renewable energy technologies, such as photovoltaics (PV) or solar hot water. These building upgrades are often combined in varying degrees with occupant conservation efforts.

While the exact definition of a DER is not yet clear, most working in the field consider energy reductions of 50% to 90% to be readily achievable with existing technologies, materials and construction practices (Wigington 2010) (Henderson et al. 2008). Published definitions of DERs range from 30% to 75% of annual energy use compared with a pre-retrofit baseline (PNNL, 2011) (Thousand Home Challenge 2010). Lubeck and Conlin (2010) define a DER as a process of super-insulating and air sealing an existing home, as well as upgrading the heating and cooling systems, with the intent of reducing energy consumption by 50% or more. The Affordable Comfort Institute (ACI) sets the bar even higher by defining a DER as 75% or greater energy savings by comprehensively improving the entire building enclosure, HVAC and domestic hot water systems (Thousand Home Challenge, 2010). ACI has been leading the way in promoting DERs, and in 2010 it began the Thousand Home Challenge (THC) initiative, with the plan to get 1,000 homes across America to meet the challenging goal of 75% energy savings. Energy reductions can be achieved by THC participants using either behavioral or retrofit measures. Given advances in minimum building codes and the general DER objective to make significant changes in energy use, we believe that the most appropriate DER definition should be on the high end of the published definitions at the 70% level. This threshold was used in this research.

California's AB 32 has committed the state to a zero-net energy (ZNE) future, requiring drastic changes current patterns of consumption. As shown above, the greatest potential for drastic energy reductions is in the existing building stock, and DERs will play a key role in achieving real reductions. Metrics and methods for designing, building, monitoring and reporting site and source energy, as well as GHG emissions are needed in order to provide informed guidance for successful implementation.

Deep Energy Retrofits (DERs) are at the cutting edge of US efforts to reduce energy use and curb global climate change. In this report, we chronicle the performance of eleven[2] case study homes in California, which have targeted energy reductions of 70% or more. We look at the use of various metrics for assessing whole house DER performance, investigate energy end-uses, examine the impact of occupants on attempts to save energy, and provide guidance and recommendations for future DERs.

There has been very little continuous monitoring of the energy used by deeply retrofitted homes – particularly end-use breakdowns. In order to better understand how energy is being used in these homes, eleven DER case studies in Northern California (International Energy Conservation Code (IECC) climate zone 3) have been equipped with wireless energy monitoring equipment, providing one-minute resolution on each electrical and gas energy end use, as well as temperature and relative humidity. This live data stream was made available to the home occupants via a web application. The analysis and case studies that follow include data from this continuous monitoring, as well as home inspections, diagnostic testing, and input received from the occupants, designers and contractors. Each home was retrofitted by the homeowner prior to joining the research project, so the study had no influence on the retrofit measures taken. The project goals, strategies used and results achieved represent actual results of the homeowners', designers' and contractors' approach to a high performance retrofit.

Each DER is documented in detail, providing total and end-use energy consumption data, reductions achieved by each project, and discussions of the relative successes and failures of the homes. The eleven case studies are then compared side-by-side, and overall trends in DER methods and performance are highlighted. The influence of energy performance metrics (site energy, source energy, carbon emissions, etc.) on "success" is also explored. The goals of this project are to: (1) document the strategies and efficiency measures used in California DERs, (2) report their detailed energy end uses, (3) provide general design and construction suggestions for those in pursuit of deep energy reductions in homes, (4) suggest example DER specifications that will provide reliable results, and (5) determine how DER performance and success should be measured.

1.1 DER Definitions and Metrics

As described above, DER definitions vary widely. Yet, defining a DER requires more than simply selecting a percentage reduction target, which has been the traditional method used. Different programs use different energy metrics to measure performance, and they also stipulate the different levels of performance or energy savings that constitute a DER. It is important to remember that the metric used will drive the results obtained, particularly when the metric is used as part of the retrofit design and decision-making process, which we believe it should be. For example, if site energy is the chosen metric, then source energy and carbon dioxide

[2] One the deep retrofit projects included in this research was a co-housing group, which consisted of two detached homes on the same property. Both homes were moved from their previous locations and were deeply retrofitted side-by-side. These homes are referred to as P6-North and P6-South, consistent with their relative locations on the site.

equivalent (CO_2e) emissions could increase, despite efficiency improvements in delivered energy use.

DER definitions and performance metrics can include site energy, source energy or carbon emissions, each of which can be normalized per house, per person or per square foot. Total energy use per house is most often used, but end-use reduction targets are also possible. Many past programs have targeted large heating energy reductions, for example. Energy performance can be reported as: (1) percentage reduction, (2) absolute reduction, (3) performance relative to reference home (e.g., HERS index or Home Energy Score) or regional average energy use, or (4) an absolute energy target (zero-net energy or Thousand Home Challenge Option B[3]). Each of these metrics measures something distinct, and the public policy, environmental, energy cost and project design implications are significant.

In addition, a single DER definition may not be possible or desirable. Most DER definitions assume that pre-retrofit energy use can be determined or modeled, and that these values can be meaningfully compared with post-retrofit performance. This is not the case in many DERs. A number of our project homes did not have available pre-retrofit energy use data, and those that did often incorporated significant changes—new occupancy, layout, floor area, window area, fuel type, comfort, etc.—that make before and after energy use comparisons impractical or meaningless. Furthermore, site energy may be the easiest metric to understand for occupants and designers, but it fails to account for potentially critical environmental and societal impacts of energy consumption. Finally, homes that begin with relatively low energy use can have a very difficult time meeting a percentage or absolute reduction target, despite being a very low energy home. For these reasons, at the very least, DER definitions must allow both a target reduction from pre-retrofit and a target post-retrofit energy use. This provides the most flexibility, and we recommend this approach.

Due to the complexity of the projects and multiple performance metrics, the assessment of DER project performance is not necessarily straightforward. Do we measure energy, carbon or cost savings? Do we consider percentage savings per house, per person, or per square foot? Do we use site energy or source energy in these comparisons? Is performance based upon a reduction in energy use, a comparison to a reference design or an absolute post-retrofit energy target? Is a DER an asset or operational term[4]? A number of projects in this research did not have pre-retrofit

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[3] The Thousand Home Challenge Option B Threshold determines how much energy a "very low energy" home would use with similar size, occupancy, fuel mix and location. It is used in the ACI Thousand Home Challenge to generate an annual site energy target, when pre-retrofit consumption is not available.

[4] DERs could be defined as "assets" with certain performance levels using existing home energy rating schemes, such as Home Energy Rating System (HERS), Home Energy Score, etc. Asset ratings are based upon the physical structure and its systems, and variation in occupant behavior is not considered. Ratings are generated using energy simulations and established procedures.

data available. How are these projects to be assessed? Can we honestly compare homes before and after that have different families living in them, different sizes, fuel types, comfort levels, etc.? All of these issues are important to consider when judging the effectiveness of a DER, and each can tell a different story. Energy goals and targets that consider all of the above issues are essential to achieving real-world performance in DERs. They guide the design and construction team in their decisions, and they also provide motivation and feedback to the occupants in their pursuit of deep energy reductions.

"Operational" ratings of DERs are based upon non-simulated energy use, which includes actual variations in weather, behavior, etc.

2 BACKGROUND

From 1994 to 2008 an average of 20,000,000 homes per year in the U.S. underwent renovations. Totaling just over one quarter of all owner occupied households, averaging $8,000 per year, or a total of $160 billion (American Housing Survey for the United States: 2009, 2011). Of these 20,000,000 renovations, 28% reported some level of energy efficiency improvements (Joint Center for Housing Studies, 2011). Many of those were inadvertently related, in that people had to replace their windows or HVAC equipment and the more energy efficient products were selected or mandated by codes and standards. The truth is that people rarely remodel their home for purely energy related reasons, but are motivated more often by aesthetics, emotions, utility, safety and comfort (Fuller *et al.*, 2010) (Novikova *et al.*, 2011). Despite this, policy makers, utility companies and home performance contractors have pushed the concept of energy efficiency “retrofits” as a way to save energy and money in what Fuller et al. (2010) would call an unsuccessful attempt to motivate homeowners to participate in their programs. Even if these programs have not fully succeeded in motivating homeowners, they have produced an abundance of data and information regarding the successes and failures of retrofit programs. The following literature review explores some of the most pertinent research and retrofit program results to date, followed by a brief history of DERs, and a review of recent trends in the field and indoor environmental concerns in retrofits. Finally, barriers to achieving deep energy savings are identified. This review is meant to provide an historical context for DERs, while highlighting the important role they can play in the current fight against climate change.

2.1 Traditional retrofit programs

Policy-backed home improvements are nothing new to the United States. *Operation Home Improvement* was a campaign of President Eisenhower in 1956, which emphasized the rehabilitation of existing buildings as opposed to new construction. The effort claimed to have prompted over 5,000,000 major home renovations in a two-year period (Ennis 1956) (Stern 1957). Although energy was not a concern at the time, it shows the early involvement of government in improving the state of our existing building stock, boosting the economy through job creation, as well as improving homeowners’ comfort and satisfaction.

Energy consumption in our homes first became a topic of concern during the oil crisis of the 1970’s. The Weatherization Assistance Program (WAP) was created under Title IV of the Energy Conservation and Production Act of 1976. During a period of staggering increases in energy prices following the 1973 oil crisis, the program was designed to save imported oil and cut heating bills for low-income households by air sealing to reduce infiltration, insulating the attic, and sometimes walls, floors, ducts and pipes as well. In the past 33 years, WAP has provided weatherization services to more than 6.4 million low-income households (Weatherization Assistance Program, 2010). In addition to government programs, utility companies have also offered financial incentives for retrofits. This is generally due to the fact that growing energy demand requires them to increase production capacity, which has sometimes proven to be more expensive than demand-side management, wherein customer energy use reduction replaces new energy generation facilities (P. C. Stern *et al.*, 1986). In a recent review of 126 whole house retrofit programs, utility companies sponsored 113, or 90% of the programs (LeBaron & Rinaldi, 2010).

Goldman (1985) compiled building performance data from 115 retrofit programs across the US. The data was put into four general categories: utility-sponsored conservation programs, low-income weatherization programs, research studies and multifamily buildings. The sample size for each project varied widely, ranging from individual buildings to 33,000 homes. Retrofits to the building shell, principally insulation of exterior surfaces, window treatments, and air infiltration reduction measures were most common. Space heating energy savings achieved were typically 20% - 30% of pre-retrofit space heating energy use although large variations were observed both in energy savings and in costs per unit of energy saved (Goldman, 1985). Much higher savings were predicted in nearly all of the programs than were actually achieved, and whole house energy savings were not reported. The prediction errors in this case were suspected to be mostly due to "variances in occupant behavior, physical differences among houses prior to retrofit, variations in product and installation quality, and errors in measurement" (Goldman 1985, 145).

The Hood River Conservation Project (HRCP) was a $21 million weatherization research and demonstration project funded by the Bonneville Power Administration in Hood River, Oregon from 1984-1986. The intention was to test the upper limits of energy savings through cost-effective retrofit measures in electrically heated homes (E. Hirst *et al.*, 1987). The measures were focused on improving the building shell and water heating system, no heating or water heating equipment was replaced. Predicted energy savings were greater than 50%, but the actual reductions averaged 15%. The discrepancies were attributed to several factors: (1) Electricity use was significantly reduced in the area before the retrofits were implemented due to a dramatic 40% increase in electricity prices. This resulted in an increase in the use of firewood to heat homes instead of electricity, and homes were also kept cooler on average. Increased unemployment was also thought to add to this problem. (2) Some of the homes had already been retrofitted under previous programs but were still included in the study, as they wanted to have very high participation numbers; these homes did not save much energy and lowered the average. (3) Behavior is unpredictable, and predictions of energy use have not been able to account for how people use the home (E. Hirst *et al.*, 1987).

In addition to the problems listed above that may result in lower than predicted energy savings, issues have also been raised regarding the quality of data from retrofit programs. These have often relied on partial annual utility bills or energy data, and have lacked a consistent methodology across different programs. For example, Fuller et al. (2010) reviewed fourteen large-scale retrofit programs, and electricity savings of 10-20% were reported, but these did not include the majority of the heating and hot water energy uses attributed to natural gas. Furthermore, performance metrics were inconsistent, and the electricity savings are only reported for five of the fourteen programs. This is a very important issue that to date has not been adequately addressed. Not only are retrofit programs failing to report consistent performance metrics, but many also fail to measure actual performance. Instead, they rely on predicted energy savings, which have historically been proven inaccurate.

There is a vast discrepancy between the predicted savings based on "technical potential" and the actual savings achieved. Retrofit programs have not typically submetered energy uses, monitored indoor temperatures, or accounted for any type of occupant behavior or occupancy variations, leaving a lot of room for error in the analysis (Goldman 1985).

The majority of traditional retrofit programs have not used whole house approaches to save energy, but have instead focused on one or two cost-effective measures per home, such as attic insulation and nominal air sealing. LeBaron and Rinaldi (2010) distinguish between a traditional retrofit and a whole house retrofit, because the level of complexity in our buildings requires an holistic approach to reducing energy. They claim that whole house retrofits with existing technology could potentially save 40% of the energy in existing homes, but they also fail to report actual measured whole house energy reductions.

Holistic, whole house approaches are often referred to as "house-as-a-system" thinking. The concept of house-as-a-system is fundamental to the achievement of greater, more consistent energy reductions than those of the past. A whole house retrofit systematically addresses the interaction of all aspects of the home, as opposed to focusing solely on those that are cheapest or easiest. A simple example that is often used is to first insulate and air seal your home, and then purchase a new heating and cooling system that can be downsized to meet the new reduced load. The new system is also higher efficiency, thereby saving far more energy than just insulating would. This new system may be attached to improved ductwork, and it may operate less frequently, leading to reduced infiltration, and so on. LeBaron and Rinaldi (2010) also emphasize the need to address health and life safety through comprehensive building diagnostics and energy audits by certified technicians. An energy audit is an assessment of the home by a certified energy specialist trained in building science principles using visual and diagnostic test methods to evaluate the best approach to save energy in a home (Weatherization Assistance Program, 2010).

While the traditional retrofit programs have indeed saved energy and created a greater awareness of the importance of residential energy efficiency, they have also left a lot to be desired, particularly when the results are compared with the technical potential estimates of engineers. Both the achieved savings and reporting methodologies have been criticized in the literature. The programs that have monitored energy performance do not use consistent reporting metrics, and have time and again fallen short of the predicted energy savings. However, these programs have been a necessary step towards deeper energy savings and have recently gained significant financial and political support, resulting in greater media attention for saving energy in our existing homes.

2.2 Recent retrofit policy

The Federal Government has revitalized government support for energy efficiency and invested significantly in the potential of home retrofits to create jobs, reduce energy and improve the quality of the nation's housing stock. The American Recovery and Reinvestment Act (ARRA) and the Better Building programs have enabled states, municipalities and utilities to expand and develop large-scale retrofit programs, significant tax incentives and $5 billion of stimulus funding was awarded to weatherization work. However, the industry is having a difficult time spending that money for a variety of reasons and is falling far short of the original goal to weatherize 1 million homes a year (Office of Inspector General, OAS, 2010). Vice President Biden has also been involved in laying the groundwork for a residential retrofit industry. His Middle Class Task Force requested that the White House Council on Environmental Quality (CEQ) develop recommendations for federal action to lay the architecture for a self-sustaining home energy efficiency upgrade industry. The outcome was the *Recovery Through Retrofit* report. Outcomes from this effort have included the development a Home Energy Score program and a PowerSaver loan program to assist in financing energy improvements. In addition, guideline documents were developed such as the *Workforce Guidelines for Home Energy Upgrades* from NREL and the US EPA's *Healthy Indoor Environment Protocols for Home Energy Upgrades* (Council on Environmental Quality, 2009)

However, without proper experience and training, a retrofit can in fact create unhealthy conditions in buildings, such as mold and moisture issues (Manuel, 2011). Although the knowledge and technologies exist, there is a lack of experience and a poor track record of actually achieving the levels of efficiency expected or desired. Also, the human-social element may actually be more problematic than the technical implementation in homes. Important new research (Fuller et al. 2010) has been geared towards the marketing approaches used by retrofit programs, and how to more effectively sell energy efficiency.

Ten to twenty percent energy savings is indeed a step in the right direction. But, if we are to make an impact on greenhouse gas emission reductions, far greater savings are needed. Much deeper energy savings have been proven possible through what are now known as DERs.

2.3 Deep energy retrofits

2.3.1 History

DERs are not a new concept, however only recently have they resurfaced as a topic of interest in the building industry. There has been a recent surge of new DERs publicized in the media; ranging from do-it-yourself blogs by homeowners and even Lowe's home improvement store (Schlereth, 2010), to federally funded DERs participating in the Building America program. The THC (discussed above) has supported deep retrofit development in the US through training, outreach, publications, case study development and webinars on deep-retrofit technologies and strategies. The state of Massachusetts is leading the way with NSTARs Deep energy retrofit Pilot Incentives program, offering up to $42,000 for homeowners performing DERs, and more if they meet Passive House, THC, or zero-net energy standards (NSTAR Deep Energy Retrofit Pilot Incentives, 2011). While all of this is exciting, the architecture, engineering and construction (AEC) industry in the U.S. is still far away from being able to reliably deliver such high energy savings, and homeowners are reluctant to pay the high up-front costs of a DER, as well as accept the important role that their behavior may play in achieving deeper energy savings.

A DER is quite different than the energy efficiency upgrades normally performed by a home performance upgrade contractor or the WAP mentioned above. They require different approaches and have had distinct histories. Although both share the goal of saving energy, a

DER is a far more comprehensive approach, more analogous to a whole house remodel or sometimes even new construction, as opposed to reducing air leakage and adding insulation.

In the early 1970's, small groups of engineers at Princeton, Danish Technical University and the University of Saskatchewan, Canada were simultaneously building super-insulated homes with air barriers and homemade heat recovery ventilators, and were testing them with makeshift blower doors (Holladay, 2010).

From 1978 to 1981, the US Department of Energy (DOE) awarded more than 2,000 small grants to research and demonstrate appropriate technologies. Almost 60 percent of the projects awarded were for active and passive solar heating of buildings (Quivik, 1984). This research and development, combined with published results of the weatherization programs, led to the realization that there is a limit to the amount of energy that can be saved using conventional home weatherization techniques and solar heating systems in existing housing. The air leakage cannot be adequately addressed through normal weatherization techniques, and some homes are not well suited for solar due to orientation, shading, massing etc. In response, researchers were led to a few of the small groups of engineers at the previously mentioned Universities, who were doing "Major Energy Retrofits." The DOE funded a series of reports related to these projects, and a few books were published, describing the comprehensive retrofit measures. These measures included adding more depth to the walls and ceilings for added insulation, the addition of airtight vapor barriers, heat recovery ventilators and higher efficiency HVAC equipment (Quivik, 1984).

These retrofit ideas were researched, tested and published by a range of engineers, builders and academics. The results of this work included books such as: *Superinsulated Houses and Double-Envelope Houses* (Shurcliff, 1981a), *Superinsulated houses, a survey of principles and practice* (Shurcliff, 1981b), *The Superinsulated Retrofit Book* (Argue & Marshall, 1982), and *The Superinsulated Home* (Nisson, 1985). Numerous other works on the same subject were published within this short timeframe, reflecting the high level of research and general interest in super efficient homes during that time period. By 1985, arguably all of the information and technologies needed for DERs was available, tested and proven. However, oil prices dropped dramatically and funding for energy efficiency programs was reduced. The US is only now recovering from this sudden change of course in residential building energy efficiency.

2.3.2 DERs in Europe and Canada

In Europe, interest in DERs continued at a high level. Dr. Wolfgang Feist, the founder of the Passiv Haus Institute (*Passive House* in the United States), acknowledges these superinsulation pioneers in the United States and Canada as the origin of his work. The Passive House concept has become very popular in Germany over the last few years, particularly in multi-family projects. It is also getting a lot of recognition in the United States, although few projects have been built here successfully, due to the challenging performance standards and more challenging climatic conditions. There are three required elements of Passive House construction: (1) Space heating annual site energy not to exceed 15 kilowatt-hours (kWh)/m^2-yr (1.4 kWh/ft^2-yr; 4755 Btu/ft^2-yr), (2) Whole house annual source energy not to exceed 120 kWh/m^2-yr (11.1 kWh/ft^2-yr; 38 kBtu/ft^2-yr), and (3) Building airtightness tested below 0.6 air changes per hour at -50 Pa pressure (ACH_{50}), measured with a blower door test ('What is a Passive House?', 2011). These performance metrics are typically achieved using superinsulation, triple glazed windows, strict air barrier detailing, mechanical ventilation with heat recovery and passive solar design. The performance of a Passive House is modeled using the Passive House Planning Package (PHPP), and predicted energy performance is used for certification. The Passive House standard is intended to result in extremely good building envelopes and super-efficient buildings, which achieve cost-effective performance by reducing the need for expensive space conditioning equipment (ibid).

In order to better accommodate the challenges inherent in existing buildings (where a retrofit to the full Passive House standard may not be cost-effective), the International Passive House Association (IPHA) has recently created the Quality-Approved Energy Retrofit with Passive House Components (EnerPHit) certification program. The main differences between Passive House new construction requirements and the EnerPHit retrofit standard is that the space heating demand is a maximum of 25 kWh/m^2-yr (2.3kWh/ft^2-yr; 7925 Btu/ft^2-yr) and the air leakage, as tested with a blower door, can be up to 1 ACH_{50} ('International Passive House Association', 2011).

The International Energy Agency (IEA) is an autonomous body within the framework of the Organization for Economic Co-operation and Development (OECD) based in Paris, France. It was established in 1974 after the first "oil Shock," and supports international collaboration in energy technology research, development, and deployment. A total of 49 tasks have been initiated, 34 of which have been completed (*Advances in Housing Retrofit Processes, Concepts and Technologies*, 2011). IEA task 37 produced a report titled "Advances in Housing Retrofit Processes, Concepts and Technologies," which goes into great detail about a variety of topics related to the current best practices and cutting edge research of DERs in Northern Europe. Topics covered include cost benefit analyses of DERs, new innovative insulation materials and applications, ventilation strategies with and without heat recovery, and heating technologies including combined domestic hot water (DHW) and heating (or "combi-") systems, and solar thermal/biomass district heating. Sixty buildings from Europe and Canada are documented and analyzed. The most common retrofits implemented were 6" – 12" of exterior insulation and a new façade including high performance windows, a new balcony structure to eliminate thermal bridges and create more useable floor space, tightening the envelope and adding mechanical ventilation with heat recovery, replacement of the heating system, addition of a solar system and redesign of the existing floor plan to enhance living quality. Of the 60 projects, ten met the Passive House standard, and three almost met it. Fifty-one had mechanical ventilation with heat recovery, 39 of those were central systems. Performance was measured in pre vs. post source energy savings; the sixty projects averaged 76% savings, and the single-family homes averaged 74%. The main conclusion was that a DER is not cost effective if only looking at the payback due to energy savings, but if the replacement of these components were to happen anyway, then the incremental costs of high performance components become cost effective. A brochure was made for each case study and the task participants hope to inspire other homeowners to learn from these examples and implement the successful strategies themselves (*Advances in Housing Retrofit Processes, Concepts and Technologies*, 2011).

Not all of the projects had detailed monitored energy performance data, so a sub-set of German buildings with detailed measured data was examined in greater detail. All of the German case studies were multi-family homes and apartments that were renovated between 2003 and 2007. The main findings were that reaching Passive House levels of performance is possible in retrofit applications, although user behavior in both hot water and electricity use is the most challenging variable (Herkel and Kagerer 2011, 8).

England has launched an exemplary DER project titled "Retrofit for the Future." It was created in 2009 and was funded by the Technology Strategy Board who put forth £17 million to design, build, monitor and study as many DERs as possible. The first phase in 2009 saw 194 design and feasibility studies, while phase two took 86 of these studies and funded the implementation of the proposals. Generally speaking, the program focuses far more on reducing CO_2 emissions than any other certification program, with targets based on an 80% reduction in CO_2 from an average 1990 baseline for a typical $80m^2$ semi-detached house of 97 kg CO_2/m^2-yr. The criteria for certification includes: A CO_2 target of 17 kg/m^2-yr (if modeled in the Standard Assessment Procedure, or SAP) and 20 kg/m^2-yr (if modeled in the PHPP), a primary energy target of 115 kWh/m^2-yr, and no specific space heating requirement but if the above targets are met, then the space heating energy should be necessarily low, around 40 kWh/m^2-yr ('Low Energy Buildings Project', 2011). In addition to implementing the program, they have also created a very valuable "Low Energy Buildings Database." This database is a collection of UK low energy building case studies, including both Retrofit for the Future and Passive House examples. There are currently 122 projects and counting. A similar database could be created for DER case studies in the United States.

Europe is ahead of the United States in examining total life-cycle energy of buildings, including in their assessment of performance in deep energy retrofits. The more efficient a building becomes, the greater impact the embodied energy of the materials and construction has on the lifecycle of the building. Dodoo et al. (Dodoo *et al.*, 2010) examined the entire lifecycle of a Passive House retrofit in Sweden, under the premise that the "energy used for building production becomes increasingly significant as measures are implemented to reduce operating energy" (Dodoo *et al.*, 2010). By using the PHPP, they calculate the primary (source) energy used in the initial construction, the retrofit, operation and demolition of an apartment building in southern Sweden. Building maintenance energy was not included. The retrofit included improved envelope, efficient DHW and heat recovery from ventilation. The findings show that the type of fuel used to heat a home pre- and post-retrofit plays a very large role in assessing the life-cycle savings. For example, if an existing home that used district heating were retrofit to a Passive House standard using electric resistance heating, the original building would have lower life-cycle primary energy use. This point is particularly important for this research, as several of the case study homes have replaced natural gas furnaces with electric resistance heating. Although not as drastic of a difference as district heating to electric resistance, the source energy of electricity is much higher than that of natural gas.

Zero net energy buildings are the ultimate goal of the building industry in order to reduce greenhouse gas emissions. While there is actually an array of definitions of ZNE, the overarching goal is to produce as much energy as is consumed on site throughout the course of a year. In a Canadian study to determine the feasibility of ZNE retrofits, the authors found that existing technologies allow for a 70 – 90% reduction in energy use, and the remainder can usually be met by PV and solar thermal to reach ZNE in existing Canadian homes (Henderson & Mattock, 2008). They based their research on a series of energy models using HOT2000 for several types of homes in six Canadian cities to establish a baseline. A series of energy reduction measures was applied to each house type in each city, emphasizing improved efficiency through building enclosure improvements, upgrading HVAC and DHW, new appliances and lighting. Then PV and solar thermal were added when economically feasible. The bungalow style home was found to be the most appropriate house type for ZNE, as it has a simple form, resulting in better air sealing and insulation, and a long roof area, most suited for large PV and solar thermal arrays. Obvious differences between climatic regions influenced the ability to achieve ZNE (Henderson & Mattock, 2008).

In the same report, the authors emphasized that deep retrofits require an understanding of the house as a system, and that any change to one element of the home will affect how all other elements of the house perform. If upgrades are made as the homeowner can afford to do so, measures such as insulating and reducing air leakage will necessitate additional mechanical ventilation, and will likely result in oversized heating and cooling equipment as the reduction in load will reduce the efficiency of the existing equipment due to short cycling, since it will longer be operated at its optimum operating conditions (Henderson & Mattock, 2008).

The Canadian Mortgage and Housing Corporation (CMHC) also tested different DER packages in five, 1 ½ story, post World War II homes. Retrofit costs in the five homes ranged from $31,260 to $56,172, PV costs not included. Electrical energy reductions ranged from 17.4% to 42.7%, and gas reductions ranged from 43.2% to 60.1%. The two homes with solar PV are on the path to zero-net annual energy cost (Charron, 2011).

2.3.3 DERs make a comeback in the United States

In 1990, Pacific Gas and Electric's (PG&E) *Advanced Customer Technology Test* (ACT^2) research funded the R&D, design, construction, monitoring and analysis of eight different case studies in northern California, including two residential retrofit projects that achieved 54% and 51% weather-normalized energy savings. The project hypothesized that greater energy savings could be achieved through the "synergistic interaction of individual energy efficient measures than would be realized if the measures were implemented individually" (Brohard *et al.*, 1998). The study concluded that energy audits, strict budgets, highly experienced design and construction staff, reliable equipment, performance commissioning and on-going maintenance provisions were required to achieve successful results.

In a review at the commencement of this research, we identified 24 existing DER projects that were described in publications or online. This number has grown since, but an updated catalogue does not exist. The review identified the Northeast of the U.S. as the most popular region for DERs with 58% of the reported projects. The average age of the DER homes was 97 years old, far older than the U.S. average of 35 years. Similar improvements as have been discussed above were made to the building enclosure, HVAC and DHW systems. Under-slab insulation averaged R-11, foundation wall insulation averaged R-22. Average insulation in exterior walls was R-31, and R-53 in the attic. Every project replaced the windows; all but two projects used double pane, low-e coatings and gas filled units. The other two used triple pane high performance glazing. There was a lack of consistent performance reporting methodologies in both energy use and air leakage. Many of the projects used pre- and post-retrofit energy models to predict energy savings, citing no measured performance. Even amongst homes reporting usage, the performance metrics varied greatly, making comparisons impractical. This trend was also found throughout the traditional retrofit and weatherization programs. This important topic will be further discussed in the methods section of this report.

Another important finding was that there has been very little monitoring of performance in DERs and no published data was found on monitored end-use energy data. "Clear, consistent, and accurate performance metrics help researchers understand what drives building energy performance, help designers and owners build and operate more efficient buildings, and help policy makers formulate meaningful performance goals and track progress toward those goals" (Deru & Torcellini, 2005, p. 5). Unfortunately, retrofits have not historically reported performance, leaving a significant gap in the knowledge. This research aims to address this problem with extensive end-use energy monitoring and thorough documentation of energy performance, using a metric that will allow for the extrapolation of any desired metric. This will be further discussed in the following methodology chapter.

The Building Science Corporation (BSC) has published numerous DER case studies as well as extensive research on high R-value insulation strategies, durability issues, and lifecycle cost benefits of DERs in its work as USDOE Building America partner. The case studies include pre- and post-retrofit energy comparisons as well as construction cost data. These case studies can be accessed on their website www.buildingscience.com. One of their informative research papers on DERs is "Residential Exterior Wall Superinsulation Retrofit Details and Analysis" (Ueno, 2010a). Three residential DER case studies are analyzed with a particular focus on exterior wall insulation details. Ueno helps demystify the process through the case studies, including guidance on air barriers, fenestration details and hygrothermal simulations of moisture penetration through the walls.

An exterior insulation retrofit is an expensive undertaking. Ueno points out that this type of retrofit is especially applicable if the home already needs to be re-clad, and if so, then exterior foam board insulation is preferable to a double stud wall. Exterior insulation eliminates all thermal bridges, including at the rim joist, and reduces the risk of condensation as the detail used in each of these case studies places the most of the thermal resistance outside the condensing surface (the interior face of the existing sheathing). One lesson learned from these case studies was that complex building geometries result in a lower chance of successfully retrofitting an exterior air barrier, and that using the exterior insulation as an air barrier is very challenging. Additionally, the hygrothermal simulations point out that 4" of exterior polyisocyanurate insulation can reduce the ability of the wall to safely dry if incidental water leakage occurs, perhaps by a factor of two (Ueno, 2010a, p. 11). This highlights the importance of very careful water management details, especially around windows. For a more detailed analysis of BSC's high R-value wall assemblies and waterproofing details see (Straube & Smegal, 2009). The work from BSC highlights the importance of careful building science design, as well as proper installation by the contractor; which is required if the transfer of air, heat and moisture is to be adequately dealt with in order to be successful in a DER.

The Passive House standard has been used repeatedly as a tool in the design and construction of DERs in the US, but it has also come under criticism. The climate-independent energy targets and questionable cost-effectiveness of US Passive Houses have been challenged by several researchers and building scientists like Straube (2009a), Brinkley (2007). Taking into account climate variability and the constraints encountered in existing homes should allow for easier and cheaper DERs than solely following Passive House requirements. Consistent with these concerns, the Passive House Institute US recently announced that its committees would be developing a new energy standard that is appropriate for US climate zones (Holladay, 2012b).

Massachusetts has been leading the way in DERs. Not only do they have some of the best publicized and studied DERs in the United States, but their National Grid program is using a marketing based approach to promote DERs, offering technical assistance and $42K incentives, or more if meeting the Thousand Home Challenge or Passive House standards. They are working with the Building Science Corporation, who reviews all projects prior to commencement, after an initial screening by National Grid. Energy modeling is used as a decision making process during the design phase and multiple HERS inspections are carried out throughout the process, ensuring construction quality is maintained. In 2009, after the first year of the program, they had 94 serious inquiries and 32 applicants. Of those 32, nine projects were awarded funding, averaging $32K each. The incentives are for strictly energy related upgrades, and do not include siding, finishes, structural or aesthetic upgrades. Total costs of retrofits often exceeded $100K ('Deep Energy Retrofit', 2011). The program is a great model for helping first adopter's meet DER goals, and is helping create a larger set of case studies and data to learn from.

In 2010, the New York State Energy Research and Development Authority (NYSERDA) funded 4 DER case studies, investing around $100,000 each. They are documented through both pre- and post-retrofit utility data, as well as photo documentation of the process. Each project demonstrates the whole house DER techniques required for achieving deep energy reductions. First, the building enclosure is aggressively improved with thermal and air barriers in order to reduce the space-conditioning load. This includes 4" of exterior foam insulation on walls and roof, new windows, air sealing and insulating of the foundation and below grade walls, and sealing roof to wall connections with spray foam insulation, which also acts as an air barrier. Following this, the mechanical and DHW systems are replaced with downsized, ultra efficient equipment and a whole house ventilation system ('NYSERDA - Deep Retrofit', 2011). Only air leakage improvements and heating energy reductions are reported; the heating energy was reduced between 47% and 62%. Photo documentation of each project makes this an informative resource for further understanding the construction process of a DER.

A substantial number of DERs have also been constructed and documented as part of the US DOE Building America (BA) program. Numerous case studies and research reports can be found on the BA website for projects carried out by BA partners throughout the country. A notable example is the collaboration between ORNL and the Tennessee Valley Authority on 10 occupied DER projects targeting 40-50% energy reductions (Boudreaux *et al.*, 2012). Sacramento Municipal Utility District (SMUD) has partnered with NREL, and they have implemented and are measuring performance in 5 DERs in California's Central Valley. Results are somewhat mixed, with occupant-driven electricity use being 150% and 200% more than predicted in two projects, and electricity savings of 9% and 57% (Keesee, 2011).

Affordable Comfort Inc. (ACI) launched the Thousand Home Challenge (THC) initiative in order to get 1,000 homes across America to save 70-90% of their energy through DERs. The founder of THC, Linda Wigington, also founded ACI and is a leader of the DER movement. In order to meet the THC a homeowner must monitor their energy for one full year post-retrofit and either a) save a minimum of 70% of your total household energy based on a full year of utility bills prior to the retrofit, or b) meet the "Thousand Home Challenge Option B Threshold," which is a whole house energy allowance in kWh per year. The number is produced using a simple engineering analysis that is currently implemented in an excel spreadsheet, "The Option B Threshold Calculator," in which you enter the home's finished floor area, occupancy and zip code (Wigington, 2008). The kWh value returned from this spreadsheet reflects what the designers of the 1000 Home Challenge estimate would be extremely low energy usage for the home[5]. The Option B Threshold is also used as an alternative for those projects whose energy use was quite low prior to the retrofit, which could make achieving a 70% energy reduction either impossible or impractical.

As part of the THC, the NorCal Collaborative (NCC) was formed in Northern California in order to advance the science and practice of achieving deep energy reductions in existing homes in northern California, as well as to help promote and implement 40 DERs in the area. The mostly volunteer group includes leading professionals in building science, home performance, utility services, energy and resource conservation, environmental protection, finance, state and local government, public interest research, trade associations, workforce and community development, affordable housing, social marketing, media and communications. Various members have been both directly and indirectly involved in the ten case studies presented here.

In some ways, the industry has come so far in the successful implementation of energy efficiency retrofits since the early days of the WAP. And, with examples such as Massachusetts' National Grid Program, both policy and utility companies are seeing DERs as a logical solution to our

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[5] The THC Option B Calculator version 1.3 (2/6/2009) uses user inputs, weather data, and a number of key assumptions to generate usage allowances. Assumptions include a building shell heating average u-value of 0.028 (R-35.7), a cooling "pseudo u-value", hot water consumption per person, and estimates of non-space conditioning and hot water usage by applying per home, per square foot and per person terms. Per home (400 kWh), per square foot (0.2 kWh/ft^2-yr) and per person (1&2) and 3+ (500 kWh/person and 200 kWh/person, respectively).

surmounting energy challenges. However, there are many barriers to overcome before enough early adopters will perform DERs to make an impact on the industry. And perhaps more importantly, we still don't really know how they are performing, as there is a lack of thorough energy performance monitoring, especially in regards to energy end-uses.

2.4 Indoor Environment in DERs

Indoor environmental quality (IEQ) improvements are a critical part of the deep energy retrofit process. Energy upgrades to existing homes have been argued to enhance occupant health, comfort and safety, particularly when these upgrades are applied to distressed, low-income housing (Kuholski *et al.*, 2010). The National Center for Healthy Housing (NCHH) and the Green and Healthy Homes Initiative (GHHI) have been demonstrating, through research, case study development and training, the potential for indoor environmental improvements from low-income weatherization and provision of green affordable housing. Mills and Rosenfeld (Mills & A. Rosenfeld, 1996) provide an extensive discussion of the non-energy benefits of efficiency measures, and they suggest that non-energy benefits play a large role in motivating consumers to adopt energy efficiency technologies. At the same time, energy upgrades in homes have also been widely identified as posing a potential health risk to occupants (Manuel, 2011). DERs are major home interventions that have the potential to both improve IEQ and to worsen it, and care should be taken by those pursuing deep energy reductions that energy cuts do not come at the expense of occupant health and comfort.

Temperature

Indoor temperature is a critical element of the indoor environmental quality achieved by a DER. Temperature and humidity have been shown to have a strong and significant impact on human perception of air quality, with increasing air enthalpy[6] being linked with decreasing acceptability across a variety of pollutant levels (Fang *et al.*, 1998). In addition, the temperatures maintained in a DER will have a great impact on the energy consumption of the home, as well as on the comfort of the occupants, and the susceptibility to condensation and other moisture problems. An increase in thermal comfort, through better temperature control and evenness of temperatures, can be one of the primary occupant benefits of a DER.

Relative Humidity (RH)

Indoor ambient RH is a very important element of IEQ in DERs, because of its direct and indirect effects on occupants and on the building itself. DERs provide an opportunity to remedy moisture problems in existing homes through improvements in water proofing, upgrades of leaking plumbing, exhausting of moisture from bathrooms, and avoidance of condensation on interior surfaces. Unfortunately, they also have the potential to cause new problems resulting from a reduced ability to dry after wetting events, or through reductions in air exchange that potentially increase indoor humidity levels.

[6] The enthalpy of air is the total energy content of the air per unit mass, including both sensible and latent heats. It combines the effects of both temperature and moisture content. It is expressed as Btu/pound (J/kg).

The human health effects of relative humidity are elaborated upon and discussed in detail by Arundel et al (1986) and later by Arens and Baughman (1996). Several recent reviews of the epidemiological literature have reaffirmed consistent positive associations between evident dampness or mold in buildings with allergic and respiratory health effects (Fisk *et al.*, 2010) 2010) (Mendell *et al.*, 2011). The discussion below is summarized from Arundel et al (1986) and later by Arens and Baughman (1996). 'Direct effects' refers to effects that humidity itself causes, such as thermal comfort, skin and mucous membrane irritation, throat irritation, building degradation, etc. 'Indirect effects' refers to secondary effects that are related to indoor ambient RH, but cannot be said to be caused directly by RH levels. Examples include dust mite and mold growth, material chemical emissions and pathogen and viral viability. In order to create a good indoor environment, RH levels in buildings should be controlled to a range in which the direct and indirect effects are minimized. This range is considered to be in the 30% to 60% range, with some disagreement at the lower and upper bounds.

Clearly, the relationship between ambient RH and any of the effects described above is complex, and this is why specification of acceptable RH in DERs is difficult. The range of 30% to 60% is generally accepted by organizations such as ASHRAE (ASHRAE, 2010). Yet, no one writes convincingly about the consequences of duration of humidity events, nor how they are averaged or measured. Presumably one hour spent in excess of 60% RH is inconsequential, whereas 3 months spent in excess of 60% may be very important. So, not only is the RH level itself hard to specify, but its time-resolved behavior may be very important. This is further complicated by the influence of other factors on all health outcomes associated with indoor ambient RH, such as surface microclimate and moisture content, home furnishings, finishes, individual sensitization and allergic reactions. These factors can combine to make two homes with similar temperatures and RH perform differently in terms of occupant, comfort, health and exposures.

Ventilation and Indoor Air Quality

The final key parameter in DER IEQ is the ventilation techniques and air qualities achieved in each home. Good indoor air quality is an essential element of DER projects, yet this is the parameter for which designers and engineers have the least practical guidance or design tools. Ventilation can be provided in a number of ways in DERs including natural infiltration, designed natural ventilation systems, central fan integrated supplies, exhaust systems and balanced systems, some including heat recovery. As the only existing residential ventilation standard in the US, ASHRAE Standard 62.2-2010 is taken as an appropriate reference for DER projects. It has requirements for whole house ventilation, kitchen & bathroom exhaust, filtration, noise and ducting.

The voluntary minimum ventilation requirements of ASHRAE Standard 62.2-2010 have begun to be incorporated into building code by select jurisdictions throughout the US, including California and Washington (Washington State Legislature, 2010). Minnesota state energy code has developed its own ventilation requirements, which serve the same purpose (Department of Labor and Industry, 2009). It has also been used as a requirement in voluntary green building programs, such as LEED, NAHB and Build-It Green. Yet, DERs may not trigger ventilation requirements even in states where code requires it in new homes. For example, in California, the ventilation requirements of 2008 Title 24 are only enforced in remodels that add more than 1,000 ft^2 in floor area. In most cases, the requirements of the energy code will not be triggered in DER projects in CA. However, DERs certainly pose IAQ concerns similar to those in other new homes—increased airtightness, new materials and furnishings, etc. This leaves the decision of ventilation provision, if it is to be provided at all, entirely up to the occupants and design/construction team.

Fortunately, ASHRAE standard 62.2 has been extended through means other than building codes. RESNET (RESNET, 2006), the Building Performance Institute (BPI) (BPI, 2012) and the US Weatherization Assistance Program (WAP) (EERE, 2011) have all elected to include 62.2 as program requirements in their standards and work practices. RESNET certified 42% of new homes sold in the US in 2011 (RESNET, 2012). BPI and the WAP are two key players in the residential retrofit industry. This should help ensure that DER projects will meet the requirements of 62.2. We highly recommend that all DERs comply with ASHRAE Standard 62.2 whether required by building codes or not. Further suggestions for ventilation provision in existing homes in CA can be found at the LBNL RESAVE Guide website (www.resaveguide.lbl.gov), whose recommendations can be applied across the US (LBNL, 2012).

2.5 Barriers to DERs

The question remains: How are we going to meet the carbon reduction goals of California AB 32, the Architecture 2030 Challenge, and many other similar bills, measures, and pledges nationwide? A growing number of researchers are starting to focus on the social and behavioral aspects of energy consumption, as many believe that purely technical solutions are not going to achieve the necessary levels of energy reduction. In order to reduce energy in our buildings, our way of life must be changed. This is one of the most important and challenging barriers to achieving deep energy reductions. Additionally, there are very real economic challenges. It is often difficult to determine the cost of DERs, because most DERs occur at the same time as other remodeling activities. Our estimates of the additional retrofit costs in the homes we studied to achieve deep energy savings in California was between $20-30K. Without subsidies or loans to help homeowners go deeper, market penetration will be challenging. Finally, even if people did have the money and desire, the AEC industry is not prepared to adequately perform the necessary actions required for successful implementation. Current research has pointed to the consumer, the cost and the industry as the three main barriers to DER implementation. Having said all this, it is valuable to put DERs into the same context as other home improvements. The home remodeling industry is responsible for about $160 billion dollars annually ('Remodeling Magazine: Cost vs. Value Report 2011-2012', 2012). Many of these remodels are considerably more expensive than our estimate for DER costs discussed below, and they already occur in a substantial fraction of the population of homes in the US. The barrier is getting homeowners and contractors to think about DERs when other remodels are happening, and to find ways to sell the value of DERs compared to other ways the money could be spent.

The Consumer, Owner or Occupant

In order to provide sufficient background information on the subject of DERs and their significance, not only must we look at the historical evolution of the design and construction techniques employed in DERs, but also at the role of the user of these buildings and the significant impact they have on the success of a project. A DER is not a purely technological solution; it requires human participation and engagement in order to be successful. In fact, current research indicates that behavioral changes could save 20% of our national GHG emissions (Janda, 2011).

Energy experts, policy-makers and the general public have begun to acknowledge that providing energy efficiency "offers the largest and most cost-effective opportunity […] to limit the enormous financial, health and environmental costs associated with burning fossil fuels" (Thumann & Woodroof, 2004). Others have emphasized the difference between energy efficiency and conservation. Energy efficiency "provides the same service with less energy (e.g., using a more efficient furnace to warm the air in a house to 72°F) and conservation…means using less of a service (warming the air only to 70°F)" (Harris *et al.*, 2007). This distinction is important in regards to DERs. Some DERs focus primarily on very high levels of efficiency, whereas others combine moderate levels of efficiency with conservation efforts. Efficiency is technology based, and conservation is primarily a result of human behavior. The majority of US retrofit efforts have been focused on reducing heating, cooling and DHW energy through technological solutions, but in order to reduce greenhouse gas emissions, we must accept that "whole house energy" must be saved, including all of the plug loads and occupant-related energy consumption. It may be that combining efficiency with conservation is the most effective, reliable and cost-effective way to achieve deep energy reductions in homes.

Energy conservation was popularized during the oil crisis of the 1970's, but sometime in the mid 1990's, this conservation effort was changed for marketing purposes to energy efficiency (Moezzi & Diamond, 2005). The move made it a "purchase oriented rational practice, as contrasted with conservation, which was taken to mean the curtailment of needed energy services" (20).

Figure 1 - Per Capita Electricity Consumption, 1960 – 2006 (A. H. Rosenfeld & Poskanzer, 2009)

In order to understand why both energy efficiency and energy conservation are necessary, we must understand both the micro and macro level implications of energy efficiency. (Herring, 2006) explains that efficiency has not lead to reduced consumption:

> [A] wide range of energy economists […] have all maintained that increased energy efficiency at the microeconomic level while leading to a reduction of energy use at this level, leads not to a reduction, but instead to an increase in energy use, at the national, or macroeconomic level. Their arguments have been supported by the historical record for most of this century, of increasing levels of both energy efficiency and energy consumption.

Although the efficiency of homes and appliances continues to increase, U.S. energy consumption per capita has also increased. Energy efficiency efforts in CA have been substantial enough to stop this increase in per capita consumption (see Figure 1 above), but they have not led to decreases.

The fundamental problem is the consumption of goods, rather than how efficiently they are consumed. Making the situation worse, the average American residential home has increased in size since 1980, while the number of occupants per home has decreased. At the same time, energy consumption per household has grown due to increased saturation of appliances and equipment, especially computer and entertainment systems (EERE, 2008). The trend in the US has been towards larger homes with fewer occupants, containing far more appliances and services that are constantly consuming energy. This represents an increase in material and energy consumption, resulting in rapidly increasing greenhouse gas emissions from the residential sector as a whole.

User Behavior

User behavior is becoming a well-researched topic in the industry. In order to understand energy use, one has to understand both the technologies that are consuming energy and the people who use them. In extensive evaluations of weatherization and other retrofit programs, average savings are somewhat less than predicted, but the variability is a bigger surprise: while some buildings save double what was predicted, others show substantial increases in energy use (P. C. Stern, 1985). Due to user behavior, researchers have reported differences ranging from 2:1 to 20:1 in energy use for apartments and homes in the same location with similar appliances, equipment and rates of occupancy. (Janda, 2011) (Socolow, 1978) (Diamond, 1995). One explanation is that people are governed by unconscious habit and are simply not used to making conscious decisions about energy (Lutzenhiser, 1993). “Household energy consumption is based on non-decisions; people do not decide to consume a certain amount of energy, but rather they engage in behaviors and activities for other ends that have the side effect of consuming energy. In addition, many people often assume they are performing better than the average person or that they are already doing all that they can” (Fuller et. al 2010, 29).

As mentioned above, there is a trend in the United States of increased consumption. Many associate this with a substantial increase in miscellaneous electrical loads (MELs). The latest report found on greenhouse gas emissions related to residential end-uses (Koomey, 1996) shows that MELs are the single most important area in the building sector for reducing greenhouse gas emissions. MELs are the fastest growing end-use in our homes, and they are expected to double in the next 20 years (Parker *et al.*, 2010). MELs include all plug loads, garage door openers, smoke alarms and any other load that does not neatly fit into the normal end-use categories of space conditioning, domestic hot water, ventilation, major appliances, or lighting. In order to save more than 50% of the energy in a home, these MELs must be addressed and reduced (Hendron & Eastment, 2006). The more efficient a home gets in regards to space conditioning and hot water heating, the more relative importance is attributed to MELs.

MELs are being addressed in the industry through mandated efficiencies in new products, and technological solutions, such as smart power strips and even more recently, automated demand response (Piette, 2009). These advancements are very important and have proven to be quite successful in reducing load and consumption. However, there is a lack of understanding by homeowners of how their existing and sometimes old MELs impact their electricity use, and what, if anything, they can actually do about it.

In a recent report (Bensch *et al.*, 2010) monitored 50 homes for MEL electricity usage in Minnesota and estimated that the plug-in devices consumed 15-30% of a typical home’s electric usage. Half of this is from home electronics, another quarter for portable space conditioning equipment. The standby power, also known as the “phantom load”, which is the power constantly used by these devices when plugged in even when not turned on, for display clocks and remote control response, for example, is estimated to be 20% of the electricity used by the devices, or 4% of the entire homes electrical use. Five low and no-cost ways to reduce these loads were identified:

1. Enabling computer power management
2. Manually unplugging devices that draw standby power when not in use
3. Manually turning off devices that are left on but not used
4. Using “smart” power strips to eliminate standby power consumption of peripherals (e.g., a DVD player) when the main device (e.g. television) is turned off
5. Using timers to eliminate electricity use by devices that are only used at certain times of the day

The average technical potential energy savings in Minnesota homes given the above methods was estimated by Bensch et al. to be 300 to 600 kWh per year. The largest potential impact was in home computer energy. Two thirds of the homes left their desktop computers on all the time, and unknowingly, only 80% of the homeowners had sleep/hibernate enabled for their computer, but most did for their monitor. The study estimates that simply switching the computer settings of these desktops to hibernate could save 50% of the computer energy, or 3% of the entire home’s electricity use (Bensch *et al.*, 2010). Another 30% of the savings potential was related to unplugging stereo equipment, TV and peripherals, and printers when not in use. The other finding was that many of the Minnesotan homes had secondary refrigerators or freezers. This was not originally part of the research scope but as a side note they found that 25-30% of these could be eliminated as they were being underutilized (Bensch et al. 2010, 32).

California has a far milder climate than Minnesota, and therefore less space conditioning energy is used. That also leaves a greater percentage of the whole house energy use as MELs. The 2009 California Residential Appliance Saturation Study found on average, 38% of electricity use in California homes is MELs, up 5% from 2003 (KEMA, Inc., 2010). In comparison, MELs in the average U.S. home account for 14% of electricity use (and 10% of whole house energy use) (Parker *et al.*, 2010). Therefore, a deep energy reduction project in a mild climate must identify and reduce MELs.

A recent report by Marc Rosenbaum from the South Mountain Company, *Zero-Net Possible? Yes! Energy Performance of 8 Homes at Eliakim’s Way,* reports on the annual energy performance of 8 homes designed to be what the author calls “zero-net possible”. This appropriate term is consistent with the author’s emphatic conclusion, borrowed from Andy Shapiro, that there are no zero energy homes, only zero energy families. End-uses were disaggregated at these occupied homes, and the author explores the variability amongst nearly identical, super-insulated homes. Only two of eight homes actually generated as much energy as they consumed. Energy consumptions ranged from 6,167 kWh to 11,636 kWh per year. Heating, plug and lighting energies varied by a factor of two to one, and hot water energy varied by factors of 2.4 to one. As the homes are essentially identical, this variability is mostly attributed to occupant behavioral patterns. The author observes that the two homes that achieved zero-net energy were the ones where heating energy was the largest end-use (still less than 1/3 of total). The hot water, lighting and plug energies were lowest in these homes, as a result of occupant behavior. These homes were all designed and constructed to have similar potential energy performance, yet occupant behaviors drove significant variability (Rosenbaum, 2011).

In April of 2010, the CPUC adopted a protocol to count energy savings from behavior based energy efficiency programs. This allowed for a larger scale implementation of programs that motivate behavioral change, as opposed to engineered efficiency. Behavior oriented programs have not previously been eligible for energy savings credits. The CPUC says that "As California pursues the strategies identified in the California Long Term Strategic Plan for Energy Efficiency, and seeks to make energy efficiency a way of life for Californians, it is essential that we create a regulatory environment in which potential game-changing efforts such as these innovative behavioral-based strategies can flourish" (CPUC, 2010). Some of the leading researchers on behavior have created an annual conference titled "Behavior, Energy and Climate Change Conference," or BECC. For more detailed information on the topic see conference proceedings ('Behavior, Energy and Climate Change', 2011).

This research aims to demonstrate that you cannot simply engineer deep energy savings; the building occupants play an unavoidable role in the project's success. An increased awareness and greater responsibility for the energy use in our homes is necessary in order to achieve the goals of aggressive DERs.

The Cost of DERs

The cost of DERs is often quoted around $100,000, and this is seen as a substantial barrier for widespread implementation (Holladay, 2012). In order to adequately assess the issue, it is important to put a DER within the context of a home remodel. Both are an expensive undertaking. Actual costs depend on local labor rates, condition and age of existing building, size, goals of remodel etc. The costs of a DER must be compared to the base case of a code compliant remodel, and only the incremental costs for the energy related upgrades beyond the base case should be evaluated. Additionally, comfort, convenience, utility, and even personal feel-good factors (Diamond, 2011) are often far more important in the initial remodel decision-making process for homeowners. Furthermore, the greater implications of climate change mitigation, durability, health, safety and comfort are all integral aspects of a DER, which outweigh financial concerns for people interested in pursuing deep energy savings. DERs generally make sense only when a remodel is already being planned. Additionally, it is important to understand that if these upgrades are not implemented during a remodel, then the mediocre/code-compliant energy efficiency measures may prevent deep energy savings for decades, or until another remodel is undertaken.

In order to create a context for the cost of DERs, let's first examine the remodeling data. Remodeling Magazine's Cost vs. Value Report for 2011-12 ('Remodeling Magazine: Cost vs. Value Report 2011-2012', 2012) shows that the average mid-range major kitchen remodel costs $64,209, while a high end major kitchen remodel costs an average of $119,716. A mid-range bathroom remodel costs $19,204, and a high-end costs $59,317. These numbers compared to a $100,000 whole house renovation plus efficiency (DER), with its long list of associated benefits, gives context for the perceived high costs.

However, at this time, an energy retrofit featuring air sealing and super insulation cannot compete with the appeal of a major kitchen or luxury bathroom renovation, even though they can be similar in costs (Henderson & Mattock, 2008). One aspect of whole house energy efficiency retrofits not currently addressed in the economic analyses is the value of associated 'non-energy benefits' (NEBs). Recent studies show comfort and aesthetic benefits far outweigh energy concerns, and very few homeowners assess the economic benefits of their investments by monitoring energy bills or calculating payback times (Amann, 2006). There are very important qualities of a home that cannot be justified through payback or a return on investment. In addition to aesthetics and comfort, these also include IEQ, health and safety, acoustics, convenience and reduction of greenhouse gas emissions. Therefore, in order to adequately assess the economics of a DER, these NEBs should be quantified in terms of their economic value to the homeowner. Of course the valuation of a DER depends upon who is paying for it. Utility programs or government-sponsored efforts may not have the luxury of using "soft" measures of cost and benefit to justify projects.

The American Council for an Energy Efficient Economy (ACEEE) is funding a project to better understand the value of NEBs in whole house retrofit programs. The first phase was a literature review (Amann, 2006), the second phase will be a survey of participants in NYSERDA's Home Performance with Energy Star program, and the third phase will analyze the data to help develop recommendations for improved cost-effectiveness tests that take into account the value and costs of NEBs to consumers. The first phase produced a literature review that suggests that the data and methodologies used for quantifying NEBs are not well developed, but have been estimated at 50% to 300% of annual household energy bill savings. But perhaps more importantly, Amann established that it is not only necessary to develop a more precise way to quantify NEBs, but also to understand the benefits that consumers value most, since they differ according to region and economic status.

In a survey of 2,000 households in Germany (Novikova *et al.*, 2011), the authors provide insights into the motivations for undertaking whole house retrofits. Although the study is German, the motivations appear to be consistent with studies in the U.S. (Wilson & Dowlatabadi, 2007). Aesthetics are said to be the main motivating factor for planning and starting a retrofit. However, the survey revealed that the motivations for a retrofit change as the project progresses. The further along in the process, the more important both thermal comfort and reduced energy bills become. Therefore, highlighting the aesthetic improvements of new siding and windows needed for most DERs could help motivate consumers, as well as the obvious improvements of thermal comfort and lower energy bills. Additionally, the survey revealed that upfront costs are the biggest concern for homeowners, and 75-90% of households that add or drop retrofit measures during the process, do so for financial reasons. Investment payback was the most significant financial motivator for retrofits, and increased in importance as the project progressed (this may be culturally specific, as similar research in the United States (Amann, 2006) has highlighted the importance of associated non-energy benefits as motivation for homeowners). Creative financial support would help participants' follow-through on plans, and help motivate them to pursue the added expense of a DER. In Germany they have similar goals as California of an 80% reduction in GHG emissions by 2050. The German government has been funding retrofits and the survey proved that those projects receiving funding are more likely to implement comprehensive DERs and to follow through with the original scope of the retrofit. In the United States, the National Grid and NYSERDA programs provide complimentary examples.

The NYSERDA program listed the lack of creative financing and artificially low energy costs as major barriers to greater market penetration of DERs (‘NYSERDA - Deep Retrofit’, 2011). The National Grid Program published cost data for the DERs they had completed to date. Of these, $50k was the cheapest total project cost, and $133K was the most expensive. However, NYSERDA only funded the energy efficiency upgrade portions of the retrofits, averaging $32,000 per home (‘National Grid’, n.d.). This means that the energy saving measures ranged from 24% – 64% of the total cost of the retrofits. They found that consumers are not typically renovating or refinishing their whole house, but are performing individual measures like window replacement, or new HVAC equipment as their finances permit. This staged retrofit approach is a logical solution to the financial challenges of DERs. However, if not properly designed and thoroughly analyzed, staging retrofits can be counterproductive. It is notable that the DERs performed in NYSERDA and National Grid programs were all exterior super-insulation retrofits located in IECC climate zones 4 and 5 marine and zone 6. These required very substantial façade interventions, which deviated from standard practices. Costs very well might be lower in climates where envelope measures are more in line with standard practice.

Fragmented upgrades in energy efficiency can in fact cause more harm than good in achieving a DER. But, by starting with the end in mind, a staged approach can lay the foundation for deep energy savings:

> With the focus and primary goal on cost effective energy savings, the recommendation for a home with ductwork in the attic may be to seal duct leaks and add insulation to the ducts… However, with the larger context of a deep energy retrofit, the focus would not be just on the ductwork, but on the ultimate tightness and performance of the building. Consideration would be given to moving the ductwork inside the home’s thermal boundary, moving the thermal boundary to include the ductwork, or possibly eliminating the need for the ductwork altogether (Wigington, 2010, pp. 2–344).

Wigington (2008) also points out that by placing the focus on other values, such as security, convenience, comfort, sustainability or adaptability, a specific retrofit package can be marketed more effectively. The value of eliminating GHG, saving a home from going to the landfill, or creating a more durable structure that will last far longer than standard homes is not taken into consideration in our current financial system.

When the entire lifecycle of the building is considered, Germany’s Passive Houses are now understood to be cost effective and are expected to become more so as market penetration increases; demand increases will reduce material and equipment costs, and labor costs will decrease as the industry becomes more familiar with the construction methods (*Advances in Housing Retrofit Processes, Concepts and Technologies*, 2011, pp. 2–16).

Retrofit decisions are long-term investments and must be looked at on a timescale equivalent to that of the lifecycle of the building components. In Germany, research found that insulation has a lifecycle of 50 years and windows around 30 years. When these components need to be replaced anyway, then the upgrade costs to high performance, or Passive House standards becomes cost effective when combined with the energy savings over the lifespan of these materials. These assumptions do not include the associated NEBs or the rising costs of energy, in which case the cost effectiveness is greatly improved. Additionally, if these upgrades are not implemented during a retrofit, then a mediocre renovation blocks a deeper, more effective renovation for decades (Herkel and Kagerer 2011).

Industry

The third barrier to widespread DER implementation is the AEC industry. The fundamental problem is a lack of experience in producing high performance homes across an industry that has been mainly focused on fast and cheap housing. Until contractors have an incentive to produce energy efficient homes, the market will not be transformed. The German survey (Novikova *et al.*, 2011) mentioned above shows that expert advice is as important as costs in influencing the homeowner's decision to add, drop or modify retrofit options. This reflects the important role of industry professionals in providing expertise about DERs. A DER requires high performance design and construction practices. While there is a growing cadre of competent designers and contractors, in order to have a significant impact in reducing greenhouse gas emissions through DERs, we need to develop training and performance metrics specific to DERs that can disseminate the right information effectively to a far wider audience of building professionals. This research has pointed toward four areas of focus for successful implementation within the AEC industry: simple design, high quality construction practices, good building science and increased building performance training requirements to obtain a contracting license.

2.6 Solutions to DERs

Simple Design

A DER is ideally a simple design. The best performing projects include enclosure and mechanical systems that are simplified to the greatest extent possible for long-term, high performance and robust functionality. Nearly thirty years after the construction of the Conservation House—the energy efficient, super-insulated home in Saskatchewan, Canada—project project engineer Rob Dumont stated the following: "Simple is better than complicated, passive is better than active, and moving parts fail" (Holladay, 2009). Aside from many firsthand experiences such as this one, there is a long list of reasons why an energy efficient building should be simple to use. William Bordass has been one of the main advocates of the idea of simplicity improving performance, especially in regards to the interface of users and technology. He claims, "Few occupiers want to adopt a new building-related technology if in use they need to spend more time, money and effort to nurture it. Most people seek instant, cost effective solutions and convenience" (Bordass *et al.*, 2001). Additionally, off-the shelf equipment that meets the highest efficiency standards available at the time of construction should be used. The more custom and innovative a project is, the less reliable and therefore less replicable it becomes. Customization also limits the serviceability of a system, often requiring the original designers and installers for maintenance. And finally, simple geometries can imply improved performance. Air, moisture and thermal leakage appear to increase with form complexity. Several DER case studies performed by the Building Science Corporation support this claim (Ueno 2010). The simpler the form, mechanical systems and user interfaces are, the greater the chances for deep energy savings.

High Quality Construction Practices

The devil is in the details, and the foundation for successful deep energy savings is as well. Since this is, and should be, an evolving field where both design and construction practices are constantly improving over time through iterations and lessons learned, it is essential that contractors performing DERs are up to date with the current best practices. The retrofit industry relies on external organizations to certify technicians. Nationally, the Building Performance Institute (BPI) trains whole house technicians, and the Residential Energy Services Network (RESNET) trains auditors. The National Association of Home Builders (NAHB), National Association of the Remodeling Industry (NARI) and the North American Technician Excellence (NATE) all have educational programs, including excellent green building certification programs that are integral to DERs. Trade-specific programs are also provided, for example HVAC contractors can be trained and certified by North American Technician Excellence (NATE). These are seen as valuable programs throughout the retrofit industry because they are nationally standardized and set clear expectations with contractors and technicians. BPI and RESNET also incorporate life-safety protocols, such as combustion safety testing, gas leak detection, minimum ventilation standards, etc. For these reasons and others, third party certification reduces an efficiency program's liability and enforcement tasks (CEE, 2010). However, not all subcontractors have training programs; insulation contractors, for example, are not specifically addressed by BPI trainings, but it is an important and often misunderstood trade. A Quality Insulation Installation (QII) is a common term in the industry used for what should be known as "doing the job correctly"; paying attention to details and proper installation techniques. This, however, has to be specified during the bidding process, costs more and is not common practice among insulation contractors. This type of practice within the industry must change, the service should not have a cost premium, and a basic level of quality required to become a licensed contractor. Since DERs are more like home remodels than a weatherization or typical performance upgrade, contractors must be comfortable with far more than the list of topics addressed by BPI, and a more comprehensive training program is needed.

Unfortunately, deep energy savings are going to require more than successful BPI and RESNET training programs. A shift in consciousness of the contractors and complete market transformation are necessary in order to realize drastic energy reductions in our existing building stock. Improvements in airtightness have a tremendous effect on overall heating energy use and have been heavily documented throughout the literature (Ueno, 2010a) (Wray *et al.*, 2002) (Walker & Sherman, 2003). Despite this, few architects specify airtightness details in their designs, and even when they do, it is ultimately up to the contractor to ensure proper implementation. In a DER, the contractor should be involved in the design process in order to guarantee that all team members are completely aware of every detail in the building and how its control layers interact to form a continuous barrier throughout the entire enclosure. Airtightness and thorough thermal barriers are the two construction elements that will be evaluated in this paper as indicators of high quality construction. They can be measured through blower door tests and infrared thermography. If these two items are not sufficiently addressed by the contractor, deep energy savings will be very challenging to achieve.

Good Building Science

Good building science means assembling building materials and systems in such a way that the enclosures control heat, air and moisture to produce a durable, energy efficient building (Straube, 2006). The appropriate control layers for the climate must be thoroughly addressed in the design. Air and vapor barriers, thermal bridges and water proofing details all must be sufficiently designed, detailed and specified by the architect in addition to proper insulation and glazing specifications. The Building Science Corporation has published a series of details applicable for deep energy retrofits, (Straube & Smegal, 2009) which should be clearly understood and utilized in all DERs.

In addition to proper design and construction, a high performance building is only effective if it demonstrates energy reductions during actual performance. Bordass laments, "The sad fact is that few architectural or engineering design practices consistently collect information on whether or not their buildings work, and none make the information available in the public domain. All this despite clear evidence that managed feedback produces better buildings" (Bordass *et al.*, 2001, p. 154). Improved monitoring of energy use in homes that have been retrofitted is necessary in order to establish an effective feedback loop that allows "cutting edge" or "bleeding edge" projects to serve as useful examples moving forward.

2.7 DER Background Overview

Throughout this research, the Internet has proven to be the most important source of information regarding DERs, as most of the information is relatively recent and only available electronically. The German survey (Novikova *et al.*, 2011) also mentioned the importance of the Internet for homeowners throughout the retrofit process. This public access to information represents an important shift in the industry that is not to be taken lightly. The AEC industry has historically been very slow to change, but modernization is necessary in order to keep up with the current best practices and meet the expectations of a potentially well-informed clientele who have access to the most recent DER research online. Even though the literature review shows that the information and technologies existed for DERs over twenty years ago, updated information on building products, case studies, research papers and retrofit programs is almost exclusively available online. THC education outreach has been largely through webinars, and the most current and up-to-date research is consistently coming out of websites like (Building America, greenbuildingadvisor.com and buildingscience.com, implying that researchers are not publishing their work in books, academic journals or other mainstream media sources.

Despite the recent surge in DERs, and the growing source of information mentioned above, there is still very little data regarding actual performance, and no agreed upon methodology for monitoring or reporting this performance. The effects of IEQ in DERs are also almost entirely overlooked in the literature. Furthermore, there is virtually no information available connecting GHG reduction goals and the energy saving goals of DERs. This research aims to fill these gaps by providing comprehensive case studies that go beyond basic description and energy models. Energy and indoor environmental performance is tracked over the course of a year, and the results are reported consistently and in full detail. The projects are assessed both objectively and subjectively, and their performance or success is measured across a variety of metrics.

3 METHODS

This research is a mixed-methods analysis of 11 DER case studies. It combines case study qualitative descriptions and quantitative analyses of energy, environmental and building diagnostics data. Total and end-use electricity and natural gas usage are monitored in each home for one year, as are temperature and relative humidity conditions. Inspections, diagnostic testing, input received from occupants and designers, and energy models add additional context to the gathered data. The diagnostic and long-term monitored energy data, combined with qualitative descriptions and analyses of each case study, results in a thorough documentation of the methods and results of owner-conducted deep retrofits in California.

3.1 Case Study Selection Process

The test houses were selected as a sample of convenience from local volunteers. Participants were solicited through Affordable Comfort Institute's Thousand Home Challenge, California Building Performance Contractors Association, NorCal Collaborative, Passive House CA, Bay Area Build it Green and personal contacts of the researchers. The criteria for house selection included: characteristics of the retrofits, timescale of the study, interest/willingness of occupants to participate, and location. All projects were planned, implemented and paid for by homeowners or developers, without the support or input of the research team.

Homes were initially considered for participation based upon phone conversations with occupants and/or construction professionals, along with a review of construction documents. Those deemed appropriate were scheduled for an initial site visit. An initial site visit data form was filled out with detailed information such as: building geometries, construction details, window type, lighting systems, make and model of all appliances and equipment, presence of pools, spas, and other significant end-uses. Photographs were taken of the homes including all electrical panel locations and layout, as well as any other relevant details requiring photo documentation.

The ideal project had a minimum of one-year pre-retrofit utility bills in order to calculate the savings associated with the retrofit. However, only five of the eleven case studies could actually acquire the pre-retrofit utility bills for a variety of reasons, such as changes in occupancy.

The most challenging aspect of this process was actually finding viable case studies. Potential projects were not included in the research for the following reasons: inconvenient location, doubts about the extent of energy reductions, timing/scheduling conflicts, questionable status as "retrofit", and occupant disinterest. Due to the difficulties of recruitment, enrollment and deployment of equipment took longer than expected. The first energy monitoring equipment was installed in August 2010, and the final installation was completed in October 2011.

3.2 Selection and Description of the Monitoring Equipment

There are few previous examples of long-term monitoring of energy end-uses in homes, and a number of challenges had to be overcome in order to select the appropriate equipment for the job. Our main goal was to monitor electricity, natural gas, temperature and relative humidity with one monitoring system. Within that, there were numerous details that had to be considered. The energy monitoring goals and the equipment selection process will be presented below, followed by a description of the installation process, as well as the communication and data acquisition procedures.

Energy Monitoring Goal

In order to select the appropriate monitoring equipment, it was necessary to create a list of goals, which included:

- Provide real-time feedback to occupants
- Real-time access to data to facilitate detection of faults, communication failures, changes in load profile, etc.
- Use of wireless communication system to avoid running wires in the home
- Limit the intrusiveness and space requirements of the equipment
- Integrate all energy monitoring on a single platform and user interface, including both electricity and gas
- Monitor all significant end-uses at the electrical panel or gas appliance, avoiding any intrusion on living space
- Be capable of measuring net-electricity and consumption in renewable energy installations
- One minute resolution that allows precise characterization of load profiles
- Reasonable price
- Acceptable levels of accuracy and reliability
- Ability to remotely manage data collection system
- Current transformers must be small enough to fit one for every circuit inside the main electrical panel

Real-time, off-site data gathering and visualization capability was a priority for both the research team, as well as the home occupants. Many DER occupants are interested in their energy usage patterns and are actively seeking ways to reduce their consumption; access to this data at no cost was their primary compensation for participation in the project. From a research perspective, remote data access is preferred as an alternative to conventional equipment that is typically left on site and retrieved after a given time period. Upon retrieval, it is not unusual to find that due to a number of potential problems, no data was collected, or something was not setup correctly so only partial data was collected. Additionally, the large amounts of data storage required for one-minute resolution would require frequent site visits and/or a large storage device on-site. Real-time remote access to the data allows for continual data analysis, and even more importantly, it allows the research team to identify problems and errors in data collection, such as power outages, occupant tampering, communication failure, etc.

Measurement, accuracy and cost were also influences in selecting the monitoring equipment. Typically, the higher accuracy equipment has a higher cost. There are a variety of electrical loads in most homes that are difficult to measure accurately, due to low power factors, switching power supplies and phase-shifted loads. After considering the purpose of the project we determined that moderate electricity measurement accuracy was acceptable. The systems with the lowest accuracy rely solely upon measurement of AC current, using current transformers (CT), and they assume power factors of 1.0 and steady line voltage. This level of accuracy was deemed too low. The most advanced meters today use current and voltage readings, taken several thousand times per second, and they are able to accurately monitor loads with very low power factors, phase-shifted loads and switching power supplies. This level of accuracy exceeded our requirements. The monitoring equipment would need to measure both current and voltage, and would account for differing power factors, but measurement of phase-shift and power supply switching was not necessary. We sought equipment with accuracies plus or minus 2%, and a minimum resolution of one Watt.

Although there are many energy-monitoring systems available on the market, very few of them actually met our criteria. The most commonly used monitors in the research field use very large CTs (2.67" outer diameter versus desired 0.67" outer diameter). Since we were monitoring every circuit in the home, they could not fit inside an electrical panel so that was not an option. They also tend to use data loggers that contain 2 or 3 channels per device, which would have required numerous data loggers per home, creating both space and cost constraints. Additionally, wireless communication energy monitors were desirable, but few companies were offering a reliable wireless option at the time the research began. Of those that did, only one met our requirements. Most systems were not able to offer both gas meter pulse counting as well as electricity monitoring; again only one was able to actually monitor both on one user interface. Ultimately, the equipment that was selected was that which fulfilled the largest number of our project goals, with acceptable accuracy and the lowest cost. There were also some practical compromises that were made. For example, the measurement of temperature and relative humidity was most easily accomplished using stand-alone sensors. These sensors are retrieved every 6 months, the data is downloaded, and the devices are re-launched for the next 6-month period.

Selected Monitoring Equipment

The continuous energy monitoring system in each home consists of a web-connected laptop, wireless dongle, wireless energy monitors, electrical current transformers and gas submeters, where appropriate.

The selected electricity meter and data logger is *Brultech Research Inc., ECM-1240 Multi-Channel Wireless Home Energy Monitor* (ECM-1240); see Appendix A for detailed specifications of all energy monitoring equipment. Each meter has seven data channels—two primary channels and five auxiliary channels, one of which can read pulse output devices. According to the manufacturer's literature ('Brultech Research Inc.', 2011), all channels measure the true power based upon current and voltage oversampling, which accounts for power factor variations. The power resolution of the meter is one watt. The time interval between data points can be manually adjusted between 1 and 255 seconds. The accuracy of the device is plus or minus 1%, which is added to the accuracy of the CTs, which varies between 1% and 4%. Wireless communication is achieved using the ZigBee wireless protocol at 2.4 GHz, and the measurement devices within a home form a wireless mesh network. This creates a more robust wireless network, where each device acts as an interconnected node capable of sending and receiving data. According to the manufacturer, the radio frequency range indoors is approximately 130 feet and 400 feet outdoors. This range and the reliability of the network are heavily dependent on the number and quality of obstructions between the sender and receiver nodes.

In homes that use natural gas or propane, the *Elster AMCO G4 200CFH Gas Meter with pulse output* was installed and connected to the pulse-reading input of an ECM-1240. The gas submeter has an integrated pulse output of one pulse per cubic foot. Due to safety and plumbing code requirements, the installation of the meters was restricted to flexible gas connectors and located directly between a shut-off valve and the appliance itself. This installation approach also facilitates the eventual removal of the meters, and requires the least amount of plumbing time and effort.

Due to cost, time and space constraints, all gas appliances were not submetered. Monthly utility bills were used to get the total gas consumption per month, and then the sum of submetered gas uses was subtracted to get the remaining appliance's consumption. This method is unreliable on a monthly basis, due to the comparative resolutions of the utility meter and our own—therm versus ft^3. This results in inaccurate monthly end-use data, but accurate annual values for these "leftover" gas loads that are primarily for cooking.

Temperature was measured in each DER using stand-alone HOBO Temperature/Relative Humidity data loggers. Loggers were placed in one, two or three locations, depending upon the size and layout of the home. For example, P5, at ~900 ft^2 had only one sensor, whereas P7 at ~3300 ft^2 had three sensors. In two-story homes, one sensor was placed on each floor, and in single story homes, sensors were placed evenly. Temperature values were recorded on the logger every 15 minutes and were downloaded at approximately 6-month intervals.

Setup and Communication Procedure

The monitoring equipment setup procedure usually took eight hours for two researchers and an electrician. The current transformers (CTs) were placed on each individual circuit in the electrical panel by a licensed electrician, and pulse-output natural gas submeters were connected to the gas appliances. The CTs and pulse counters were then connected to the energy monitor ECM-1240. The monitors at each electrical panel and gas meter all communicate wirelessly with a central laptop computer, placed in an inconspicuous location with available Internet access in each project home.

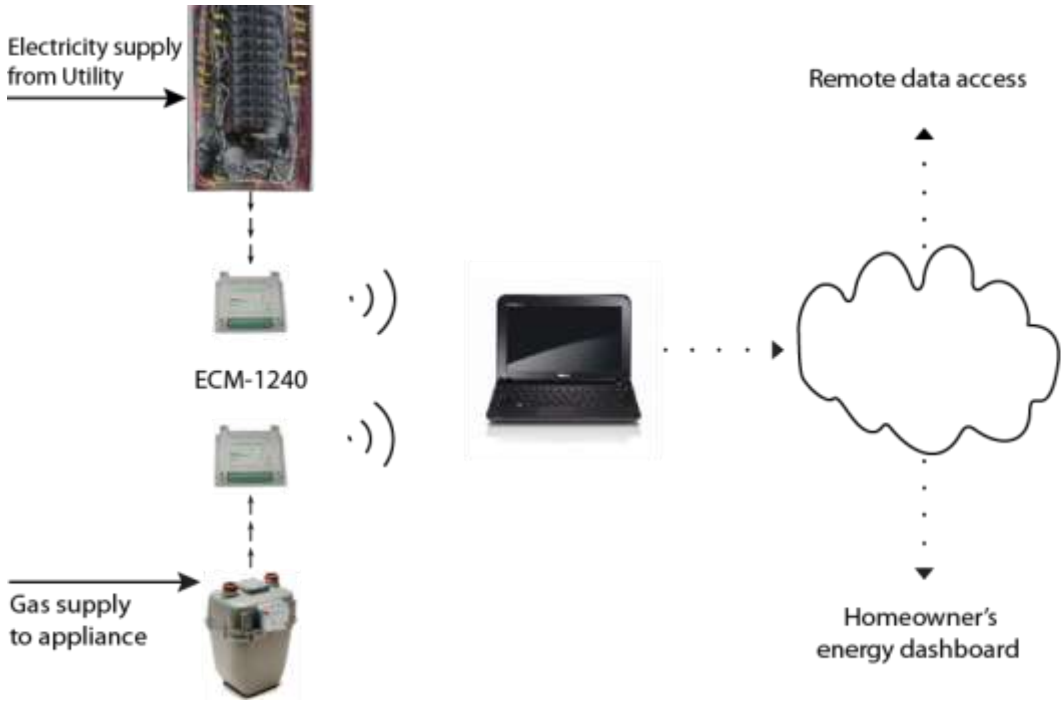


Figure 2 - Communication Schematic

During initial setup, each channel was configured based on the number of circuits and size of CTs, or as a pulse counting channel. The laptop was setup to operate continuously with the *Brultech Engine G* software application running in the background. All data is stored in a sqlite3 database on the laptop hard drive. Engine-G software was set to automatically export real-time data to Google Powermeter, an on-line energy dashboard for viewing by both the research team and the occupant. However, Google cancelled Google Powermeter in September 2011, and we have switched to a similar service provided by a company called *Check-It* ('Check-It Solutions', 2008). On-line access to real-time data was provided using a shared account, viewable by both the research team and home occupants.

Consumer laptops are not shipped with the intention that they operate reliably on a continuous basis. The central laptop computer used at each project required configuration to ensure proper operation and reliability. This set up was typically done prior to installation. These computers were required to stay on constantly, to never restart and if they were disconnected, they had to turn back on automatically. All energy saving features and automatic updates had to be disabled, because these features encourage periodic restarts. Firewalls had to be configured to allow remote access and access to specific ports for the ZigBee communication. It was discovered during a power outage, that once AC power was lost and battery power was drained, there was no way for us to remotely revive the computer to restart monitoring when AC power was resumed. This setting had to be adjusted in the computer's BIOS, and the fix could not be performed remotely. The computers were configured to "wake" on AC power, so that once power was restored, the computer would automatically boot up.

Remote interaction with the project laptops was achieved using the free web application called *LogMeIn*, which allows for remote desktop control of computers.

3.3 Organization and Planning of End-Use Monitoring

Each project home presented its own challenges in terms of data collection and load monitoring decisions. Approaching each home, we were faced with a wide variety of loads, system types and electrical circuit and panel configurations. In order to plan our monitoring in each home, a number of actions were required.

During our initial site visit to the project homes, all electrical panels were located and extensively photographed, including main panels, sub-panels, PV shut-offs and whole house shut-offs. Additionally, a suitable location for our meter enclosure had to be identified, which was no more than three feet from the panel itself. All gas appliances were also located. Gas appliance info plates were photographed and installation manuals and performance data were retrieved at a later date. Locations were identified for gas submeters and enclosures.

All circuits in the home were assigned a number and were then sorted into energy categories based on their labels—HVAC, hot water, lighting, appliances, plug loads, PV production, whole house or sub panel. Where possible, loads were isolated and monitored individually, and they were otherwise combined by their energy category and/or location. This was often complicated by panel layout/organization and circuits with multiple end-use types (combined plugs and lights circuit, for example). We typically made some effort to discuss energy use with the occupants, so that we could better understand which loads would be most useful to monitor closely. Trade-offs were required in every project, so we attempted to make these trade-offs in light of the occupant's preferences and estimated energy usage patterns. When this process of sorting and joining was complete, the circuit or groups of circuits were assigned to a specific channel on the ECM-1240.

End-use monitoring in existing homes poses numerous constraints and limitations. First, the layout of the electrical panels and the distribution of circuits was often a limiting factor. We typically placed only one seven channel meter at each panel, and this had to serve those panels with 30+ circuits and those panels with only 6 circuits. As a result, more circuits had to be combined onto single data channels at the larger panels, and more circuits are monitored individually at the smaller panels. Second, the labeling of the panels was often incomplete or complete but wholly inaccurate. Whenever this was encountered, we attempted to identify the loads actually on a given circuit by turning circuits off one-by-one and searching the home for the disabled equipment, plugs, lights, etc. In some cases, relabeling of the entire panel was necessary. Unfortunately, this process was undertaken in several homes on the day of the installation, which necessitated full revision of the ordering and pairing of circuits described previously. Third, it was not always clear what energy category a given circuit should fall in. This issue was exacerbated in those cases where mixed energy categories were found on the same circuit, such as a circuit with both lighting and plugs, or with the refrigerator and exhaust ventilation fan paired together. As stated earlier, in this situation, every effort was made to determine which part of the energy load would be most important or substantial for that specific home, and the circuit was categorized accordingly. Fourth, all circuits could not always be logically grouped onto a single meter, and these “leftovers” were calculated by subtracting the sum of monitored loads from the whole house usage. This worked nominally well, but by the last project we began monitoring every load on the panel as opposed to relying on the subtraction method. As a necessary result of this complexity, the end-use disaggregation presented in this research is unavoidably imperfect; we attempt to clearly indicate any mixed channels.

3.4 Data Acquisition and Lessons Learned

The data collection process was not always easy. Once the challenging planning and installation process was complete, each project computer had to be checked several times in order to confirm that data was in fact being recorded, and that the data actually made sense. The reliability of consumer laptops in this application seemed to vary inexplicably from house-to-house. Data losses resulted from:

- Computer crashes (one computer was replaced, but usually the homeowner would just re-boot the computer for us and it resolved the problem)
- Computer was un-plugged
- Internet service was lost in the home
- ZigBee wireless signals obstructed

There were also instances when either the electrician changed the layout of the circuits so our settings were wrong, or a CT was incorrectly wired, leading to faulty data. These issues were corrected prior to commencing the monitoring period. Other changes occurred mid-monitoring, such as the installation of an electric car charging station or the installation of solar PV.

Another challenge encountered in the gas end-use monitoring was the use of combisystems. A combisystem supplies both DHW and space heating using a single appliance. Four of the eleven homes had these systems, and with the selected monitoring equipment, it was not possible to disaggregate these two loads. Furthermore, three of these used solar combisystems. For these systems, we are only monitoring the gas use of the boiler, which supplies both DHW and space heating, not the energy required to meet the load (which would include solar contribution).

Utility bills were extremely challenging to receive in some cases. They were being collected three different ways. 1) The homeowner would send us electronic copies or spreadsheets of their monthly bills. 2) The homeowner would give us their login information to view their bills online. 3) A third party authorization form was signed by the homeowner, allowing the utility company to send us a copy of their monthly utility bills. We allowed the homeowner to decide which method they preferred and therefore ended up with some of each option.

3.5 Qualitative Data Collection

In order to learn what works and what does not in DERs, we must thoroughly understand the goals of the client, the design intent, the construction process, and the materials and construction methods used. We use qualitative project descriptions to achieve these ends. Qualitative project descriptions also provide a basis for understanding the monitored energy results. Descriptions were developed from a combination of firsthand observation, semi-structured interviews, un-structured interviews, email correspondence, phone and in-person conversations, and project web pages. Some of the data was hard to come by for various reasons. Pre-retrofit conditions were sometimes difficult to get data on as substantial time had passed since they were retrofitted, and sufficient information was not recorded regarding their pre-existing condition.

These results are reported in the "Project Description" section of the findings. Each project, P1 through P10, is introduced with a detailed narrative description and retrofit measure summary table. Elements covered include: building enclosure, heating ventilation and air-conditioning (HVAC), domestic hot water (DHW), appliances, plug loads, lighting and renewable energy systems.

Building Diagnostics

In each deep retrofit project home, diagnostic tests of building enclosure air leakage, duct leakage and ventilation flows were carried out. Infrared thermography was carried out in a subset of homes. Ideally, these tests would be carried out both before and after the retrofit process in order to assess changes in envelope airtightness and duct leakage. Unfortunately, this pre/post comparison was not always possible. Most of the project homes were already retrofitted when the study began, and as a result, pre-retrofit diagnostics were not possible. Diagnostic testing pre-retrofit by performance contractors was very rare, occurring in only three of eleven homes. Most projects did not pursue such testing due to the nature and extent of the changes that were being made to the home. Examples include, ducts being eliminated where they had previously existed, or previously separate structures being joined together as part of the retrofit. The added value of diagnostic testing was not perceived by occupants in these situations. If available, we used pre-retrofit results for comparison. Time and other restrictions existed in every project installation and diagnostics visit, and in order to avoid frustrating the occupants, some diagnostics were not performed in all post-retrofit settings, such as testing ventilation flows, for example.

Whole Building Airtightness and Duct Leakage

Air leakage through the building enclosure to outside was measured in one of two ways: multi-point blower door depressurization, using ('ASTM E779', 2010), which is the Standard Test Method of Determining Air Leakage Rate by Fan Pressurization, or Delta-Q, based on ('ASTM E1554', 2007), which is the Standard Test Method for Determining External Air Leakage of Air Distribution Systems by Fan Pressurization. The airtightness test results are combined with house characteristics, such as floor area, surface area or volume, to generate the following metrics:

- Airflow of cubic feet per minute at 50 Pa [7](Q_{50})
- Air changes per hour at 50 Pa (ACH_{50})
- Airflow per square foot of conditioned volume surface area (Q/ft^2_{SA})
- Airflow per square foot of floor area (Q/ft^2_{FA})
- Square inches of effective leakage area (ELA)
- Natural air changes per hour (nACH)

[7] "50 Pa" refers to a pressure difference between inside and outside the home of 50 pascals.

In homes that had ducted forced air conditioning systems, the Delta-Q test was used to measure both envelope leakage and duct leakage to outside. The computer-controlled test performs numerous building pressurization and depressurization tests with the air-handling fan off and then on. The difference in envelope flows between the air handler off and on at these multiple different pressures is used to generate duct leakage under actual operating conditions (Dickerhoff *et al.*, 2004, p. 1). Delta-Q tests were not performed in some homes due to wind conditions, which can adversely affect duct leakage results. Those homes with very large envelope leakages could also not be accurately tested by Delta-Q method. Duct leakage by Delta-Q is different than single-point tests at 25 Pa, and results are not directly comparable.

Where Delta-Q was not possible, total duct leakage was measured in some homes by the research team or by performance contractors working on the project. Duct registers were sealed and the duct system was pressurized to 25 Pa with respect to the house. These are reported as $Q_{ducts,25}$.

Ventilation Airflow Measurements

Mechanical ventilation airflows were measured wherever possible using either the Energy Conservatory Exhaust Fan Flow Meter or a custom powered flow hood using an Energy Conservatory Duct Blaster® fan. Multi-speed fans were tested at all speeds that were within the range of the flow meter. Bathroom and kitchen fans are required to meet certain minimum airflow requirements under ASHRAE Standard 62.2—50 cubic feet per minute (CFM) for bathroom exhaust and 100 CFM for kitchen range hoods. Where applicable, airflows are compared with these requirements.

Infrared Thermography

IR camera thermography was used to assess thermal leakage through the building enclosure in some, but not all DER homes. In this research it was used to check quality and continuity of insulation installation as well as identify moisture and air leakage locations. An IR camera measures the superficial temperature of a surface. There has been a relatively limited amount of research on specific testing methodologies for IR thermography. It is known that there are many limitations to the technology, mostly due to differing results from the effects of environmental conditions. Temperature, relative humidity, emissivity, color and moisture will all affect the thermography to varying degrees (Barreira & de Freitas, 2007). However, by keeping this in mind, it can easily be used as a qualitative assessment of insulation continuity, thermal bridges, as well as air and moisture leaks.

The case studies were thermographed using a Fluke TiR32 infrared thermal imager. All attempts were made to take the images on a dry, cool, fall morning in order to minimize the effects of solar gains and moisture on the surfaces, moisture in the air, as well as maximize the temperature differential between inside and outside for greater color variation in the images.

3.6 Quantitative Data Analysis

Energy Performance Metrics

As mentioned in the literature review, there has been a poor track record of building energy reporting using consistent metrics. In addition to the complexity of site energy, source energy and CO_2e, there are multiple other metrics that can be used for reporting whole house energy consumption (Deru & Torcellini, 2005). In DER performance assessment, the metric used will drive the results obtained. For example, if site energy is the chosen metric that is used in project design and planning, then source energy usage and CO_2e emissions may increase, despite 'efficiency' improvements. The energy use intensity (EUI) is a very popular metric normalizing energy use by floor area, but it is biased in favor of larger buildings. For example, a large house could have more energy use than a smaller house, but have a better EUI. Energy use per occupant is a very interesting metric as it reflects user behavior. However, it may be harder to use due to occupancy changes over time. One option would be to use the "number of bedrooms plus one" as default for number of occupants. This is the default method used to account of occupants in ASHRAE 62.2 for indoor air quality, as well as HERS scoring and CA Title 24 (2008). Some of the other metrics being used are energy cost and energy savings (% or absolute). In response to this confusion and the biases metrics can introduce, the Building Science Corporation created something called the "Mileage Box" (Ueno, 2010b), which provides all the data required to calculate these various metrics for any given project. We follow a similar path, providing project performance data across all of these metrics, with the exception of energy cost, which was not tracked.

It is important to bear in mind that there is no "correct" metric. They all provide valuable information about a project. The appropriate metric depends on what you are trying to demonstrate and who the audience or user is. It is possible to justify any metric, as long as there is an awareness of what story you are telling, and what you are not.

Unit Conversions

We used the following unit conversions in our report:
1,023 Btu's per ft^3 of natural gas ('EIA Energy Units', 2012).
100,000 Btu's per therm of natural gas ('EIA Energy Units', 2012).
3,412 Btu's per kWh ('EIA Energy Units', 2012).
1,450 Btu's per ft^3 of propane gas (not liquid) (Alternate Energy Systems, Inc., 2012).
8,000 – 8,500 Btu's per pound of non-resinous wood ('CEC Consumer Energy Center', 2012).

Site Energy

Site energy is determined using a combination of measured energy usage and utility billing data. Total electricity is measured using the electrical meters. Gas is measured either by submetering or using utility billing data, with units of ft^3 and therms, respectively. Gas and propane energy consumptions are calculated as follows:

$$Energy_{gas,\ submeter} = Gas_{ft^3} \times (1{,}023 / 3{,}412)$$
$$Energy_{gas,\ utility\ bill} = Gas_{therms} \times (100{,}000 / 3{,}412)$$

$Energy_{propane} = Propane_{ft^3} \times (1{,}450 / 3{,}412)$

Net-site electricity is measured by combining the total electricity and any PV electricity production. Over any given time period, the net-electricity is calculated as the difference between total consumption and total production:

$Electricity_{net} = Electricity_{consumption} - Electricity_{generation}$

Any wood used for auxiliary heating is weighed in a scale by the occupants. Wood site energy is calculated as:
$Energy_{wood} = Pounds_{wood} \times (8{,}250 / 3{,}412)$

Source Energy
From a societal point of view, a conversion to source energy is valuable in assessing the energy performance of buildings. Source energy is representative of the primary energy requirements of supplying household services. The US DOE Building America program has adopted source energy as its primary metric.

Numerous inefficiencies exist in the current electric grid. When power plant efficiency and distribution losses are accounted for, total system efficiency can be as low as 33% (Deru & Torcellini, 2007). Correspondingly, most source energy conversions heavily penalize electricity usage. All source energy values in this research were calculated in accordance with the Building America Performance Analysis Procedures for Existing Homes, (Robert Hendron, 2006) using national site-to-source conversion factors of 3.16 for electricity and 1.02 for natural gas. Calculation was performed as follows:

$Energy_{net\text{-}source} = (Electricity_{net\text{-}site} \times 3.16)+(Gas_{site} \times 1.02)$

A high efficiency wood stove was used in P10. No method exists for accounting for the source energy impacts of wood burning. For these purposes, we have used published average values for the Canadian softwood industry. Assuming the density of pine to be 23 pounds/ft^3, 1,000 board feet to contain 83.33 ft^3, there are an average 1,544 MJ/1000 board feet in Canadian surfaced green lumber, and 0.2778 kWh/MJ. The following equation is used to calculate source energy of wood burning:

$Energy_{source,\ wood} = Pounds_{wood} \times (8250/3412)+ (Pounds_{wood} / (23*83.33)) \times 1544 \times 0.2778$

This value is added to $Energy_{net\text{-}source}$ for P10 wherever it is reported.

Carbon Dioxide Equivalent (CO_2e)
CO_2e is the conversion of gas and electricity site energy use into carbon dioxide equivalent emissions, using the Global Warming Potentials (GWP) of individual greenhouse gases (Deru & Torcellini, 2007). Home energy use actually results in emissions of a variety of climate altering gases, but their equivalency in CO_2 is used for comparison and simplicity. CO_2e values are

suggestive of a home's contribution to global climate change. All CO_2e values were calculated using 2009 conversion factors from PG&E, the predominant local electric and gas utility, which serves nearly all 11 DER homes. Conversion factors of 0.399 pounds/kWh for natural gas and 0.57537 pounds/kWh for electricity (PG&E, 2012) were used. This California-Bay Area value is notably less than the national 2009 value of 1.302 pounds per kWh[8] (US EPA, 2012). Calculation was performed as follows:

$$CO_2e = (\text{Electricity}_{\text{net-site}} \text{ x } 0.57537)+(\text{Gas}_{\text{site}} \text{ x } 0.399)$$

One home (P10) used a high efficiency wood stove for supplemental heating. There is no clear existing methodology for accounting for the carbon impact of burning wood in buildings. Wood combustion can be considered essentially carbon neutral, as the tree very recently participated in the ongoing global carbon cycle. If not harvested and burned, the tree would have fallen and decomposed, also releasing its carbon content. This differentiates it from natural gas or other fossil fuels, which were essentially permanently sequestered until human intervention. If wood is burned or harvested and then replanted and biomass is consistently regenerated, then emissions could be considered neutral. Wood combustion contributes 211.38 pounds/MMBtu (0.7213 pounds/kWh) of CO_2e. If the CO_2 portion is deducted from this (considering it neutral), the remaining emissions of CH_4 and N_20 are reduced to 4.45 pounds/MMBtu (0.0152 pounds/kWh) of CO_2e (Goldmark, 2010). We present the latter value that assumes carbon neutrality for wood combustion CO_2 emissions. Total carbon values are presented in the project comparison section, and wood energy is not individually listed, rather it is added to the carbon total for this home alone. These values do not include the embodied carbon from the resource extraction. It is worth noting that the vast majority of wood burned during the measurement year came from the home's original framing, which itself had been salvaged from San Francisco buildings. Needless to say, reasonable accounting is not possible.

Weather Normalization

Energy use varies with outdoor weather conditions. Weather normalization is often performed in energy efficiency programs, in order to avoid attributing changes in energy use to efficiency measures, when they are actually the result of weather differences. Weather normalization is applied to pre-retrofit data, where available, for the purposes of quantifying energy savings. Monthly pre-retrofit data are also adjusted using a base 65 heating degree day (hdd_{65}) regression[9] method. A simple linear regression equation was developed using pre-retrofit monthly energy data and historical weather data. The monthly hdd_{65} values for the post-retrofit period were then plugged into the regression equation to generate the monthly adjusted pre-retrofit values.

Whole House Energy Use

[8] Assumes national average grid losses of 6.5%.

[9] A linear regression of pre-retrofit energy use on hdd_{65} allows us to predict how much energy would have been used by the pre-retrofit home, given the weather conditions of the post-retrofit year. Monthly heating degree days were calculated as the sum of the differences between the average daily outside temperatures and 65 degrees.

All annual energy data are presented in either kWh or CO_2e. Per the discussion of metrics above, energy data are reported in multiple formats in order to enable a variety of assessments:

- Net-site energy (pre- and post-retrofit, if both available)
- Net-source energy (pre- and post-retrofit, if both available)
- Net-carbon dioxide equivalent emissions (pre- and post-retrofit, if both available)

These are normalized by:

- per house
- per person
- per square foot

These nine values are then used to generate:

- Percentage reductions
- Absolute energy reductions

Energy End-Uses

End-use energy data are presented in site kWh in several formats in this report. These contrast with the whole house data, because they are consumption and not net-energy values. Uses are divided into the following seven categories:

- Heating
- Cooling
- Hot Water
- Ventilation fan power
- Central air handler or pumps
- Appliances
- Lights
- Plug Loads

These uses are summarized by monthly and annual consumptions for each end-use. Monthly end-uses are summarized in line graphs showing month-by-month progression, and annual uses are summarized using both pie charts and data tables.

Due to issues with imperfect end-use disaggregation, end-uses do not always align perfectly between homes. For example, P2, P3, P8 and P10 used combisystems, systems that provide both space and domestic water heating. These end-uses could not be disaggregated using the monitoring equipment employed in this research, and are reported as “heating” in the data tables. Other examples include home wiring and monitoring equipment issues, which led to dissimilar loads being combined onto a single data channel. This usually meant some combination of two of the following—plugs, lights and appliances. In such cases, data are still reported, but we indicate if some load mixing occurs, and we have attempted to classify them by the most representative end-use. In order to maintain the ability to make comparisons in these cases, heating, cooling, hot water, central air handler or pumps, and ventilation are summed and presented as “HVAC-hot water”. Appliances, lights and plug loads are summed and reported as “plugs-lights-appliances”.

Comparison of Modeled and Actual Energy Usage

Each DER was modeled in EnergyGauge USA using a combination of home inspection data, diagnostic testing results and project drawings and specifications. HERS (2006) ratings were generated from the models, as were annual energy reports, including annual end-use breakdowns of modeled consumption. Results of energy models are compared side-by-side with the monitored annual total and end-use consumptions. We identify drawbacks of the model itself that fail to adequately represent strategies and technologies used in DERs, and we also highlight modeling successes.

User Behavior

Analysis of user behavior in DERs is challenging. Some of the DER case studies actively use energy conservation alongside energy efficiency measures in order to achieve their reduction targets. We consider these to be “low energy user behavior” homes. Other homes use such impressive efficiency measures, that their energy use is low despite more average behavior patterns. Assessing this user behavior is essential to understanding project performance. Unfortunately, user behavior is not an end-use that can be easily measured, summed and reported. As a result, we provide a variety of indicators of behavior in an attempt to explore this feature of DERs. The following are used:

- Discretionary energy use
- Electrical baseload
- Indoor temperature profiles
- Energy models
- Discussion of casual observations about conservation efforts

Typically, discretionary energy use includes all plug loads, small appliances, and everything that does not fit into the categories of space conditioning, DHW, major appliances or lighting end-use categories. However, this definition is fraught with issues. For example, lighting is very much under user control in a home, and turning lights off when not in use represents an easy, cheap and painless way to save energy. Patterns of hot water consumption are “discretionary”, as are heating and cooling behaviors. Indeed, all energy use could be considered “discretionary” (think a zero-net energy home). Nevertheless, we consider the lights and plug loads of the home to be representative of the idea “discretionary use”, and we use this for comparisons.

Electrical baseload is the electricity being consumed when no one is home or actively “using” the home. This measurement provides insight into how the building occupants manage their energy consumption. If all plug loads, lights and pumps for example, are turned off and/or disconnected when not in use; they can significantly reduce the baseload and help reduce total energy consumption. Baseloads are calculated using one-hour whole house electricity data, and each home’s baseload is calculated as the average of its monthly minimum hourly wattages. Obvious outlier months are excluded, so as to not include vacation periods in the baseload

estimate. For homes with solar PV, the whole house consumption values are used, rather than net-electricity. These wattage values are converted to annual kWh estimates by dividing by 1,000 and multiplying by 8,760 hours per year. Annual kWh estimates are compared against total net-usage and heating energy usage.
As heating and cooling behavior can be key elements to reducing energy use, the temperature profiles are compared between homes. Of course, home temperature depends on insulation levels and other factors. Nevertheless, we use average indoor temperatures to assess if occupants are maintaining lower or higher temperatures, if they are changing average temperature by season, and if they are using a set-back thermostat. Average monthly temperatures are presented in each home, as are temperature profiles by time of day and by season.

Energy models control for occupant behavioral effects by applying the same operational profiles to every home. This way all homes are assessed with the same temperature set-points, same appliance patterns, etc. These patterns are based upon profile analyses in a large number of homes and they represent average patterns. If an energy model grossly under- or over-predicts an energy end-use, then this may provide an indication of user behavior that deviates from "average" in either direction.

Finally, casual observations from site-visits and verbal and email exchanges with occupants will be used to illustrate user behavior. These include occupants describing their efforts to reduce plug loads or eliminate energy "vampire loads". They also include observations of significant audio-visual equipment in homes and other such technologies.

Missing Data
Occasionally, missing data occurred in our time-series due to communication failures. These values were estimated using the monthly average value for that channel. For example, if 24 hours of data were lost in the month of February, the hourly average value for the load during February was multiplied by the number of missing values. This was used to generate the total monthly consumption and to be sure that one year meant 8,760 hours of energy use data in each home.

3.7 Indoor Environmental Quality

We characterize the indoor environment in deep retrofits using temperature, relative humidity and assessment of the installed ventilation equipment, in the context of ASHRAE 62.2 and Title 24 (2008) requirements.

Temperature
The temperature data are presented in a variety of formats, which will hopefully help facilitate interpreting the results. First, the data are summarized in a table by calculating monthly averages and standard deviations. A variety of other means are used to summarize temperature data, including the following. Monthly boxplots are used to show the distribution of temperature values during each month. This shows seasonal trends and temperature ranges experienced each month. Monthly or seasonal temperature profiles are created, showing the average temperature at a given time of day over the given period (e.g., all 3pm temperatures averaged during a given month). Finally, an illustration of the temperature consistency within the DERs is provided by

calculating the temperature difference between multiple sensors in a home at the same time period.

Relative Humidity

Due to the complexity of interpreting RH levels in homes (see literature review), a variety of methods are used to summarize the data. First, the data are summarized in a table by calculating monthly averages and standard deviations. A variety of other means are used to summarize temperature data, including the following. The data are summarized by monthly boxplots, showing the distribution of RH values during each month. This shows seasonal trends and RH ranges within the homes. The data are also summarized by a histogram of all RH values. The 30% to 60% range is highlighted, in order to show the amount of time spent in the 'acceptable' range. The total proportion of time spent in the acceptable range is also calculated for each month and for the entire measurement period. Finally, the counts of consecutive hours that the RH exceeded some critical values are tabulated, which for our purposes will be 60%, 70% and 80% RH. These are reported as number of days in excess of 60% RH, for example. When combined, these results provide a rich illustration of RH levels in these DER project homes.

Ventilation Systems

The ventilation installations in each project, if there were any, will be assessed using ASHRAE Standard 62.2 (ASHRAE, 2007) as a guide in determining the ventilation requirements for acceptable indoor air quality in homes. Minimum whole house ventilation rates are calculated for each home, and these are compared with measured whole house ventilation airflows or estimates of natural air exchange using blower door data (nACH). The measured airflows of intermittent bathroom and kitchen exhaust fans are compared with the respective 50 and 100 CFM requirements found in 62.2. We use these assessments to make judgments on the provision of acceptable IAQ in DERs and to generate suggestions for standard ventilation practice in DERs.

4 FINDINGS

Each deep energy retrofit is unique, varying significantly from one another. It can be difficult to make direct comparisons between projects. The goal of this research and analysis is to describe and evaluate each case study for its individual approach to saving energy, and the lessons learned from the particular techniques chosen. Each case study is presented according to its title: P1 – P10. The qualitative project descriptions include photographs, pre-retrofit descriptions, and a synopsis of all retrofit techniques implemented. Following the project descriptions, the results of the building diagnostics and the monitored energy data show a variety of possible solutions to achieve deep energy savings.

4.1 P1

4.1.1 P1 Project Description

Image 1 P1 Pre- and Post-Retrofit

P1	Pre-Retrofit	Post-Retrofit
ENVELOPE		
Wall Insulation	None	1st floor: 5.5" dense pack (dp) cellulose – R19 2nd floor: 3.5" dp cellulose, 2" PolyIso – R23
Attic/Roof Insulation	Some fiberglass	10" dp cellulose in attic floor- R38
Foundation Insulation	None	1" XPS slab perimeter – R5 3" Polyiso over slab with thermally broken wooden sleepers – R21
Windows	Single pane wood frame, double hung replacements	2 pane, low E, Argon, wood frame – U-0.3, SHGC-0.35, VT- 0.54
Air Leakage		271 CFM_{50}, 1.1 ACH_{50}
MECHANICAL		
Cooling	None	None
Heating	Gas Floor Furnace, 60% efficient, on second floor, no distribution	Electric resistance baseboard heaters in each room
DHW	40 gal gas tank in garage	Gas Tankless, 0.84EF. 11-199kBtu/hr
Ventilation	Natural	ERV – ECM motor, humidistat controlled, fully ducted bath & kitchen exhausts, bedrooms and living room supply. SRE 81-83, TRE 44-53
Distribution	None	R6, foil faced flex duct
LIGHTS/APPLIANCES/MEL	All incandescent lights, old appliances	100% CFL lights, new energy star appliances, small home office
RENEWABLES		None

Table 1 - P1 Retrofit Summary Table

General Information

P1 is located in Berkeley, CA just a few blocks from the UC Berkeley Campus and downtown. The original structure was built in 1904; it had two levels with a brick foundation. The home was uninsulated, except for sparse attic insulation, and with only one natural gas floor furnace on the 2nd level, it was very uncomfortable. The first level was only 7 feet high and did not qualify as livable space according to the local building code, but had always been fully utilized. The owner originally purchased and occupied the home while studying architecture at UC Berkeley, and then used it as a rental property while he and his family lived in Austria and Ireland for 13 years. In 2005, the family decided to move back to Berkeley; but the foundation had settled and was leaking water, and they decided that a remodel was necessary to transform the rental property into their ideal family home. The homeowner would not be satisfied by a typical, code-compliant remodel. He hoped to bring the principles of Passive House construction that he had learned in Austria back to the U.S., and to apply them to the first retrofit project attempted in the U.S. that would strive to attain those high standards.

The Passive House standard is a very demanding building energy planning and construction tool first popularized in Germany, then other parts of Europe, and more recently in the U.S. There are three required elements of Passive House construction. These were described in detail in the literature review and include (1) Space heating annual site energy not to exceed 15 kWh/m^2-yr, (2) Whole house annual source energy not to exceed 120 kWh/m^2-yr, and (3) Building airtightness tested below 0.6 ACH_{50}, measured with a blower door test. The planning of any Passive House project is demanding and requires detailed energy modeling using the Passive House Planning Package (PHPP) and extremely careful architectural detailing. Typical strategies used in Passive House construction include superinsulation, high-performance windows, high efficiency water and space heating, careful air sealing and mechanical ventilation with heat recovery.

Two primary goals were identified for P1: (1) the house should be as energy efficient as possible, and (2) the design should allow for the future construction of an additional backyard unit. The homeowner assembled a team of trusted local experts, which included himself as architect, a general contractor he had gone to architecture school with, and a local environmental design-build company. At the time of project planning and construction, not many people knew about the Passive House standard in the United States. The homeowner was able to consult with Eco-lab in Urbana, IL, who had experience with the PHPP. Through this collaboration, he identified the building envelope and energy system specifications required to achieve the Passive House standard.

The upper level of P1 was lifted approximately three feet, and the existing first level was demolished and rebuilt to a legal height of eight feet. The first level was reduced in width along the length of the home, in order to allow for driveway access to the rear, where the owner hopes to install a rental unit. This shrinkage/narrowing of the first level resulted in a ten-foot cantilever of the 2nd floor. It is supported by a series of large wooden structural beams that extend across the ceiling of the entire first floor. The homeowner reports lower temperatures in the rooms that the beams pass through. The IR images below show the effects of these thermal bridges. The existing foundation was demolished and new footings, stem walls, and concrete slab were poured, which allowed for foundation perimeter and under-slab insulation.

Building Enclosure

Many deep energy retrofits contain a variety of mixed envelope assemblies, which are the result of compromises made between design goals, existing structure, exterior finishes, etc. P1 is no exception, with different finishes, insulation and water management strategies on the 1st and 2nd levels, mixed placement of insulation in the slab and the attic, and insulation in all interior partition walls and framed floors.

The downstairs walls were rebuilt with 2X6 framing 24” on center, and filled with blown cellulose insulation. Back-ventilated, synthetic stucco serves as the exterior finish. The existing 2X4 exterior framing on the 2nd level was preserved and filled with cellulose insulation. Two inches of polyisocyanurate insulation was then installed to the outside with reused redwood siding installed over ¾” furring strips. The stem walls were insulated with 2” of XPS on the exterior, and the ground floor was insulated with 3” of polyisocyanurate rigid foam on top of the new slab, a floating wood floor was installed over that. The existing 2X4 attic floor joists were reinforced with 2X10’s and filled with cellulose insulation. This was then covered with a ¾” T&G plywood sub-flooring that was carefully air-sealed. The homeowner had originally intended to include the attic space within the thermal and air boundaries of the home, but ultimately decided to insulate and air seal the attic floor instead. Still, 3” of polyisocyanurate with reflective barrier was installed in the space between the sloped attic rafters. Additionally, all interior partition walls and framed floors were filled with cellulose insulation, in order to reduce sound transmission and thermally isolate the rooms.

The homeowner tried to figure out a way to import the triple pane, insulated windows that he had used in Austria, but the costs of shipping were prohibitive. After considering a lot of options, given the mild climate and cost advantage, all windows were replaced with wood framed, aluminum clad exterior, wood clad interior, double pane low E, with U-Value of 0.35, SHGC of 0.32, and VT of 0.54. P1 has only two small windows with Southern orientation, which limits its ability to use passive solar energy for space heating, but ample glazing areas were installed on the East and West facades.

Air Leakage
The homeowner was a Passive House pioneer in the Bay Area, and stated that no one understood how important airtightness is during the time of the retrofit. Due to his determination and skill, aggressive air sealing was implemented by caulking the exterior wall sheathing joints, sill plates, top plates and attic floor.

Ventilation
The kitchen range hood in P1 is a recirculating unit with grease screen and charcoal filter. Air is exhausted from the kitchen via an ERV return vent in the ceiling located adjacent to the cook top. This is a commonly used kitchen ventilation technique in Passive Houses, as there is a significant amount of heat produced in the kitchen that can easily be recovered, and extreme airtightness does not allow for unbalanced kitchen exhaust flows. In such setups, ASHRAE 62.2 requires that the continuous kitchen ventilation system provide five kitchen air changes per hour, as opposed to the 100 CFM requirement of intermittent range hood exhausts. The lack of a range hood vented to outside and the low airflow rate of the ERV mean that this system does not meet the ASHRAE 62.2 requirements for kitchen venting.

Heating
Space heating energy demands in homes retrofitted to the Passive House standard are typically lower than the minimum output of traditional heating equipment, so the designer is faced with the challenge of providing robust, well distributed and energy-efficient heating by another

method with smaller capacity. In P1, the homeowner chose the least expensive (first-cost) and most reliable system possible. After all, large amounts of time and money had already been allocated to improving the home's thermal performance, with the hope that an expensive, traditional heating system would not be necessary. So, simple adjustable 500 Watt electric resistance baseboard heaters were installed in each room. This resulted in a reliable system with low first costs, as well as detailed zone control, no thermal distribution losses and easy replacement of failed equipment. The interview identified this as one of the challenges of the project as the PHPP model results did not require very much heating, but the California residential building energy code (Title-24) requirements made it necessary to install a certain amount of heating capacity, whether or not it was needed. The Title-24 consultant was only used to pass the permitting process and was not interested or knowledgeable in the Passive House or energy efficient approaches to design, so at the end of the day, the heating system was a compromise.

The upside of this system is that each heater was only $25, and has an integrated thermostat. Although the thermostats are not very accurate, it is an extremely affordable and robust heating system. He has to manually adjust the levels of each heater based on comfort, which does not trouble the owner, because his office is at home and he enjoys being directly involved with the heating energy use in the home. The downside is that this strategy uses more source energy and produces more carbon emissions than other viable technologies. The resulting source energy penalty counted against the primary energy requirement of the Passive House standard, and the heating system is one of the reasons the home did not achieve Passive House certification.

If given another opportunity, the architect stated that he would have installed a combisystem with solar thermal domestic hot water and a heating coil for the ERV. At the time of the retrofit, it was hard to find any water-to-air heating coil product that would work for 70 CFM airflows; the smallest one available at the time was for 300CFM, and the manufacturer suggested that one be scratch built. Today, the same company makes a fan coil unit that attaches directly to the ERV. A lot has changed in the past 5 years.

Domestic Hot Water (DHW)
A tankless on-demand hot water heater replaced an old natural gas tank heater (see Image 2 below). These hot water heaters pull a maximum of 255,000 Btu/h, and require a ¾" gas line. In the future, the homeowner hopes to install a pre-heat solar thermal system to reduce the DHW energy use, which would also be fed through a coil on the supply side of the ERV to add additional space heating when needed and/or available (See P3 project description for additional information about this application).

Image 2 - P1 Tankless Gas Water Heater in Attic with Gas Submeter

Appliances
All appliances are new and Energy Star labeled, including a gas cooktop, an electric oven, refrigerator and dishwasher; they have a clothes washer but no dryer, relying instead on the sun and wind to dry their clothes.

Plug loads
No significantly large plug loads exist in the home, a true sign of low energy user behavior. The kitchen has an espresso machine, a hot water pot, and a toaster; in the living room there is one 24" television, a DVD player and a small radio/CD player with speakers. The home office has two laptops, plus the one we are using for monitoring, one printer, one modem and a wireless router.

Lighting
All lights in the home use compact fluorescent light bulbs and are controlled by wall switches.

Additional Information
The architect reported some of the challenges of the retrofit, "The rain screen was challenging in terms of finding the right products behind the cladding. In Europe they have dealers who specialize in a variety of different screens and membranes. I couldn't find hardly any information or products that met my needs." Similarly, in discussing the general lack of experience of DERs in the local industry, he noted that, "it would have been easier to do as part of an experienced team. The idea of these houses is to figure it all out, you have to challenge how things are done and figure out better ways to build. This is much more challenging if you are doing it alone. If I were to do it again, I would probably do a similar design if doing a DER. If I were doing a Passive House, I would spend more time on the PHPP and energy modeling to really understand the energy implications." However, "I am not convinced that reaching the Passive House standard is what is necessary in this climate. If you can get zero-net energy without meeting the Passive House standard, it's hard to do better than zero-net."

All deep energy retrofit projects are ultimately the result of compromises between design intentions, existing site conditions and other limiting factors, such as cost, material availability, and in this case, even challenges with the local building codes. Even with the carefully determined and precise specifications of the PHPP, P1 was constructed having to face real world challenges, and did not ultimately meet the Passive House standards in their entirety.

P1 has been occupied since the retrofit was completed in December of 2007. There are two adults and two teenage occupants. The home has received a fair bit of publicity, and the homeowner has actively used the project as a means of educating the design and construction community about Passive House design and advocating for its expanded adoption in the U.S. The home is not a certified Passive House, but has served as a powerful example to those pursuing deep energy reductions through home retrofits.

4.1.2 Building Diagnostic Results

Blower Door

P1 is the second tightest house of this research, and although it did not achieve the Passive House standard, it is far tighter than the average American home.

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH	SLA (ELA/ft^2_{FA})
P1	271	1.10	0.06	0.17	10.32	0.05	0.00004

Table 2 - P1 Blower Door Results

Ventilation Airflows

The 62.2 whole house mechanical ventilation requirement for P1 is 53.8 CFM, which is 0.219 ACH, and estimated annual nACH is only 0.049. The airflows of the ERV system were measured on the return grills in the two bathrooms and the kitchen. Total airflow on high was 152.8 CFM. The unit is typically operated on a medium-low level, and long-term monitoring of the ERV suggests a median ventilation airflow of 83 CFM. Detailed monitoring of this unit suggests a total recovery efficiency over the course of the year of 71.4%, with apparent sensible and humidity effectiveness of 90.6% and 71.6%, respectively. The leakage of the ERV duct system was not tested. On high, the two bathroom exhausts just barely meet 62.2 intermittent requirement of 50 CFM, but the kitchen exhaust does not. As P1 does not use a range hood exhausted to outside, it would be required to provide 5 kitchen ACH of continuous exhaust, which in this home would mean 241.5 CFM.

ERV Exhaust Location	Airflow (CFM) on High
Kitchen	48.1
2nd Floor Bathroom	51.7
1st Floor Bathroom/Laundry	53
Total	152.8

Table 3 - P1 Ventilation Airflow Measurements

IR Thermography

The IR photos show a moderate amount of thermal bridging (thermal leakage through high conductance materials connecting the exterior to the interior) at the structural beams, especially at the metal support brackets in Figure 4. Other structural systems, such as the steel "strong wall" in Figure 5 and Figure 6 used on both levels, were visible, as was the steel bracket that holds the cable used to support the deck in Figure 7. Most surprising was that the thermal bridges of the upstairs 2X4 studs were still visible from the interior, even though there is 2" of exterior XPS insulation, visible in Figure 8.

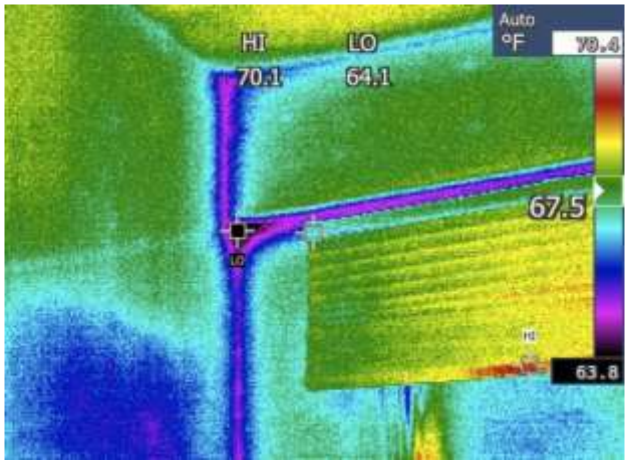


Figure 3 - P1 thermal bridge at structural beam

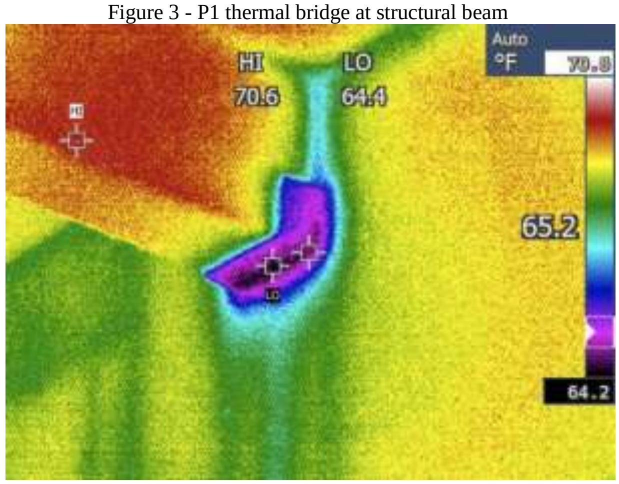


Figure 4 - P1 thermal bridge at structural beam

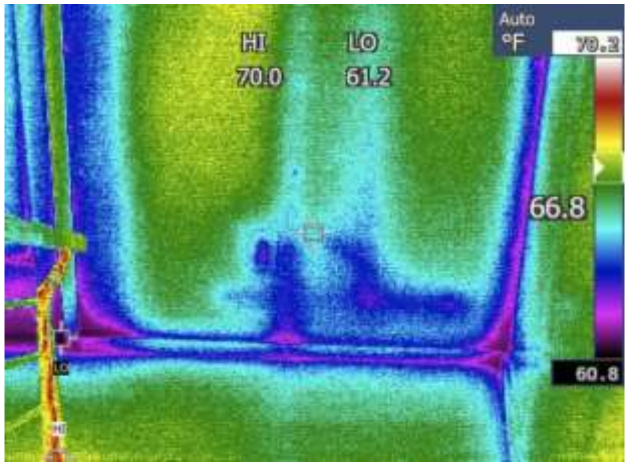


Figure 5 - P1 thermal bridge at “strong wall” downstairs

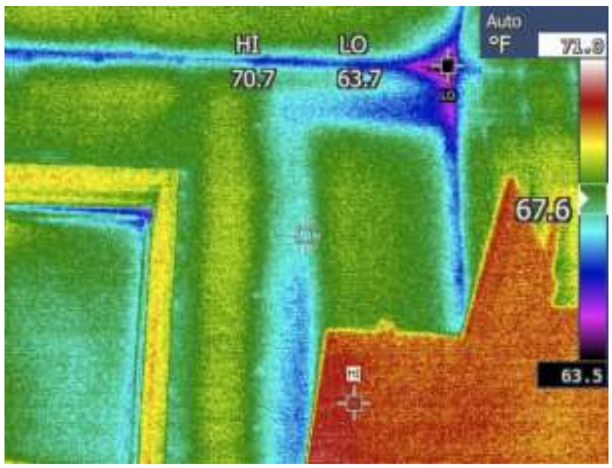


Figure 6 - P1 thermal bridge at “strong wall” downstairs

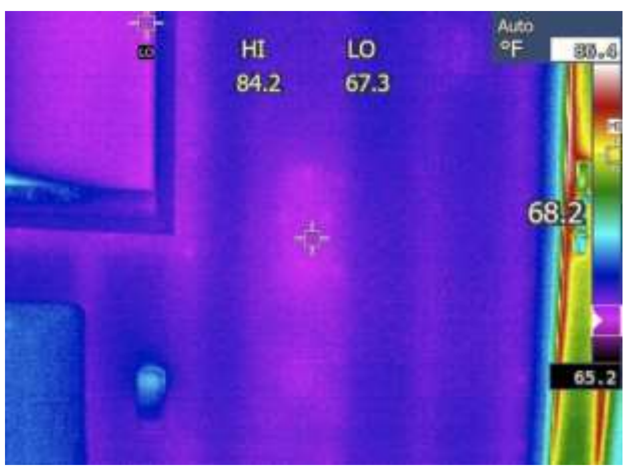


Figure 7 - P1 thermal bridge at deck support bracket

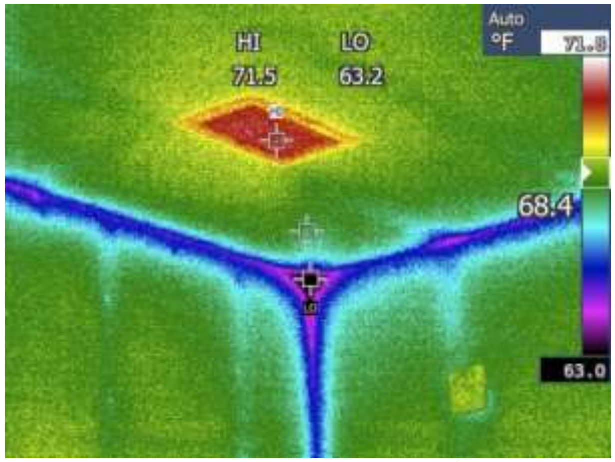


Figure 8 - P1 ERV supply register, leakage from attic

4.1.3 Monitored Data Results

Whole House Energy Use

P1 (Pre) - WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e
18,942 kWh	13,552 kWh	5,829 lbs
Occupants	Area	HERS Rating
2	960 ft^2	-

P1 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e
21,218 kWh	9,414 kWh	4,714 lbs
Occupants	Area	HERS Rating
4	1,630 ft^2	73

Table 4 - P1 Pre- and Post-Retrofit Mileage Boxes

Annually, P1 used 9,414 kWh in net-site energy, a reduction of 31% from its pre-retrofit net-site consumption of 13,552 kWh. Unfortunately, when converted to source energy, P1 actually consumed more post-retrofit, for an increase of 12%, from 18,942 to 21,218 kWh. The CO_2e emissions were reduced 19%, from 5,829 to 4,714 pounds. The average CA single family home uses 20,061 kWh net-site energy, 36,737 kWh net-source energy and 9,346 pounds of CO_2e. The HERS score for P1 was 73, suggesting that it would use 27% less energy than the HERS reference home.

Monthly electrical and gas energy consumptions are shown in Figure 9. Despite being a highly insulated, very airtight home, P1 still shows a distinct seasonal pattern with higher usage in winter. Some of this might be due to the home’s low usage during non-heating months of approximately 500 kWh (for comparison average monthly hot water gas energy in CA single family homes is 476 kWh).

The source energy increase of P1 is largely the result of electric resistance baseboard heating. The reasons for installation of this system were explored above. The decision was not made with source energy or carbon in mind, so these results were not anticipated. While increases in comfort, floor area and occupancy were achieved, an increase in source energy consumption is incompatible with the goals and intentions of a whole house DER. Future DERs must avoid this pitfall. It is possible that electrical heating equipment with a high COP, such as a mini-split heat pump, could avoid this issue. In addition, the source energy penalty may not be of concern in regions with clean electricity production.

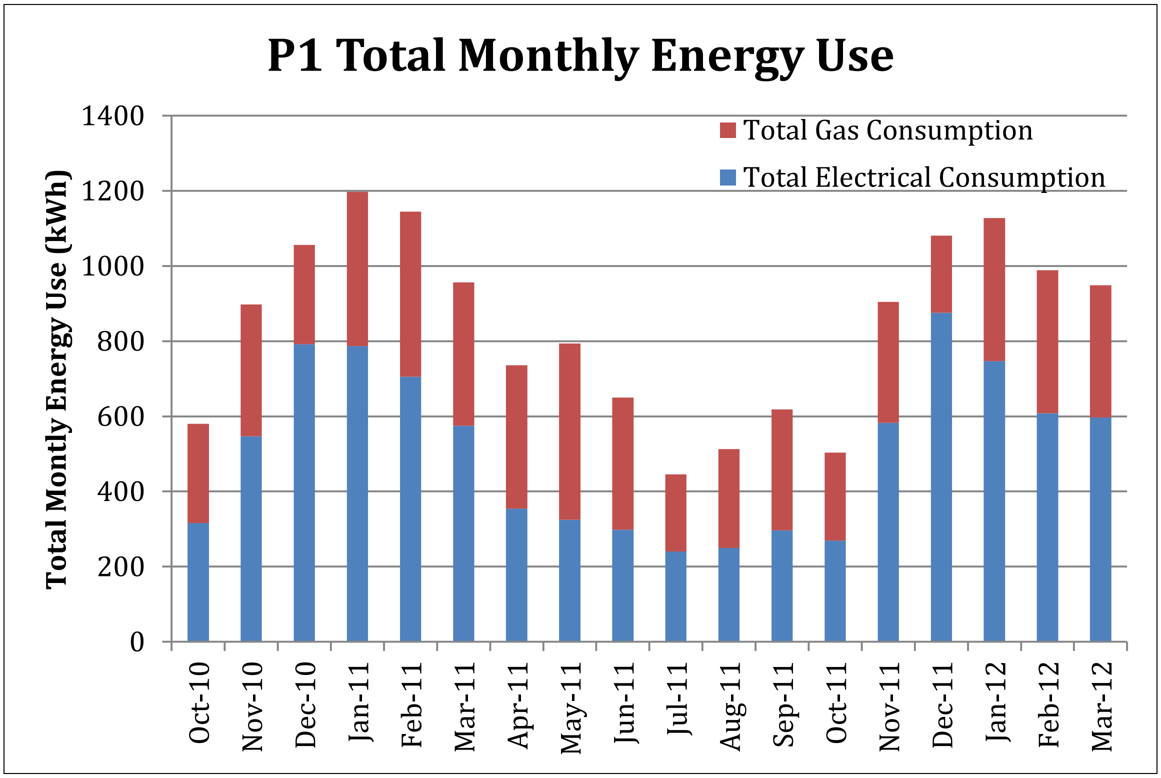


Figure 9 - P1 Total Monthly Energy Use

Monthly pre and post-retrofit total net-site energy is compared in Figure 10 below. Most reductions in usage occurred during heating months, with the other months having similar consumptions pre and post. This does not mean that efficiency gains were non-existent, rather the home double its occupied floor area and double its occupancy rate and is now completely heated. For example, the home went from using an inefficient tank gas water heater to a high efficiency tankless unit, but the number of hot water users doubled as well, likely wiping out this efficiency gain. In addition, P1 was a low energy use home prior to the renovation, with annual usage 33% less than an average CA single family home.

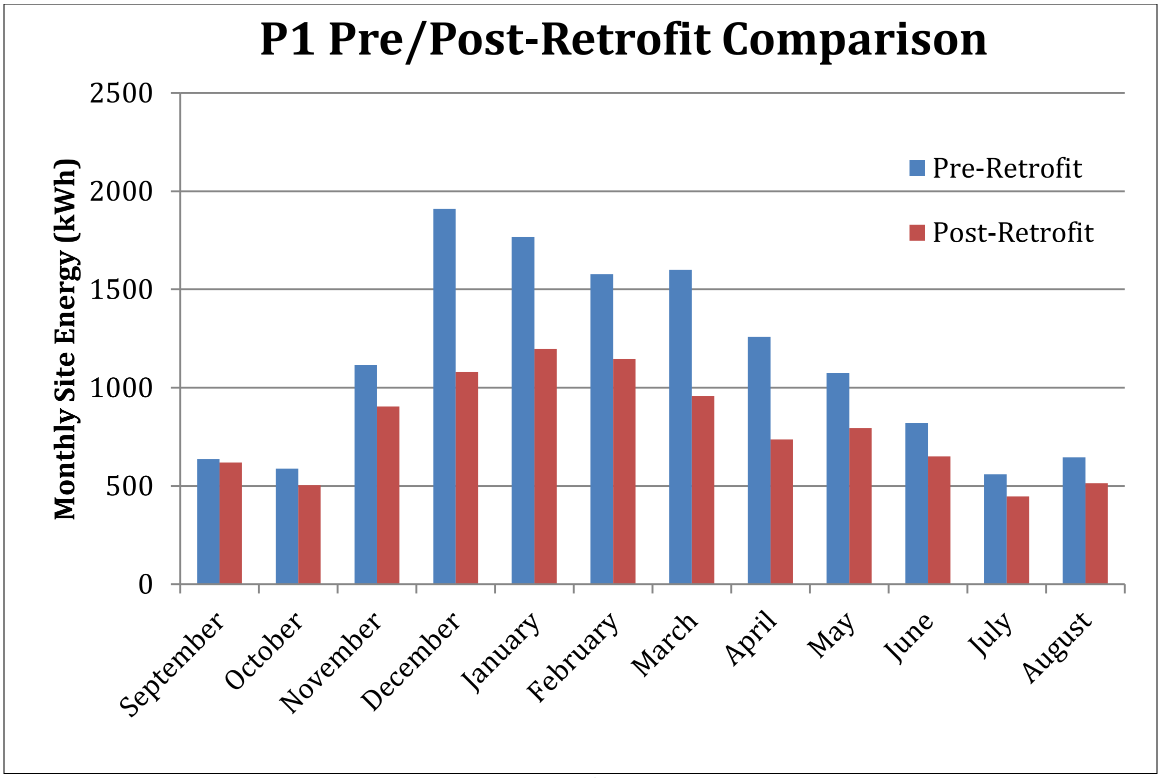


Figure 10 - P1 Pre/Post Retrofit Site Energy Comparison

The hourly whole house electricity demand profile is pictured in Figure 11 below. The demand is greatly increased during the heating months of December and March, due to electric heating. The June and September profiles are representative of non-heating electricity demand in the home. Two clear peaks occur across seasons, one at 6 or 7am and another at 6 to 8pm. This pattern is typical of a home where the majority of occupants leave during the day and use less energy at night. It is noteworthy that P1 has an adult who works from home, so the house is occupied for most hours of the day.

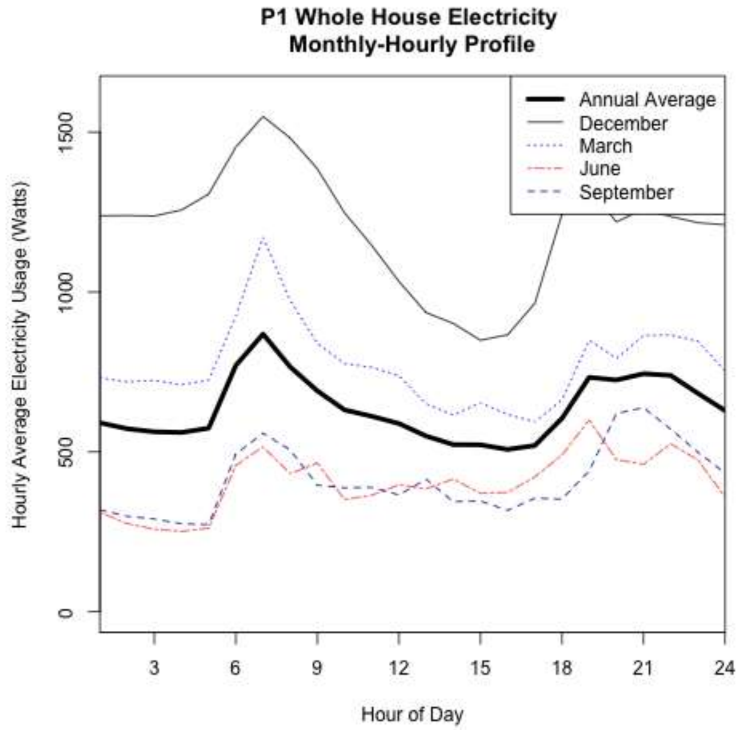


Figure 11 - P1 Whole House Electricity, Monthly Hourly Profiles

End-Uses

Annual end-uses are summarized and compared with modeled results in Table 5 and Figure 12 below, and monthly end-uses are summarized in Figure 13. Hot water was the largest annual end-use, with heating occasionally exceeding hot water during certain months. On an annual basis, P1 actually used more energy for plug load energy than heating. The whole house plugs increased in August 2011; the occupant could not identify what caused this increase. Lighting energy was low (153 kWh less than predicted by the model) which resulted from efficient lighting and behavioral patterns. The electric resistance heating system was used more than one might imagine for a Passive House. The high-resolution data revealed that the heaters were on for long periods of time throughout the heating season, albeit at low levels (<1,000 watts). The office and bedrooms downstairs were heated more than the upstairs, which is consistent with the daily use of the downstairs home office. Also of note, is the energy consumed by the ERV, which used 850 kWh annually, or 8.5% of tot net-site energy. ERV energy usage was comparable to that of all household appliances and was significantly higher than lighting energy.

	P1 Actual	P1 Modeled
Floor Area	*1630*	1630
# of Occupants	*4*	4
Heating	*2182*	1834
Cooling	*0*	0
Central Air Handler(s)	*0*	0
Hot Water	*3405*	3634
Ventilation	*850*	579
Combined HVAC and Domestic Hot Water	**6437**	***6047***
Appliances	*1036*	1704
Lights	*325*	478
Plug Loads	*1617*	1795
Combined Appliances, Lights and Plugs	***2977***	***3977***
Annual Total	***9414***	***10025***
PV Production	*0*	0
Annual Net	***9414***	***10025***

Table 5 - P1 Site Energy End-Use Summary

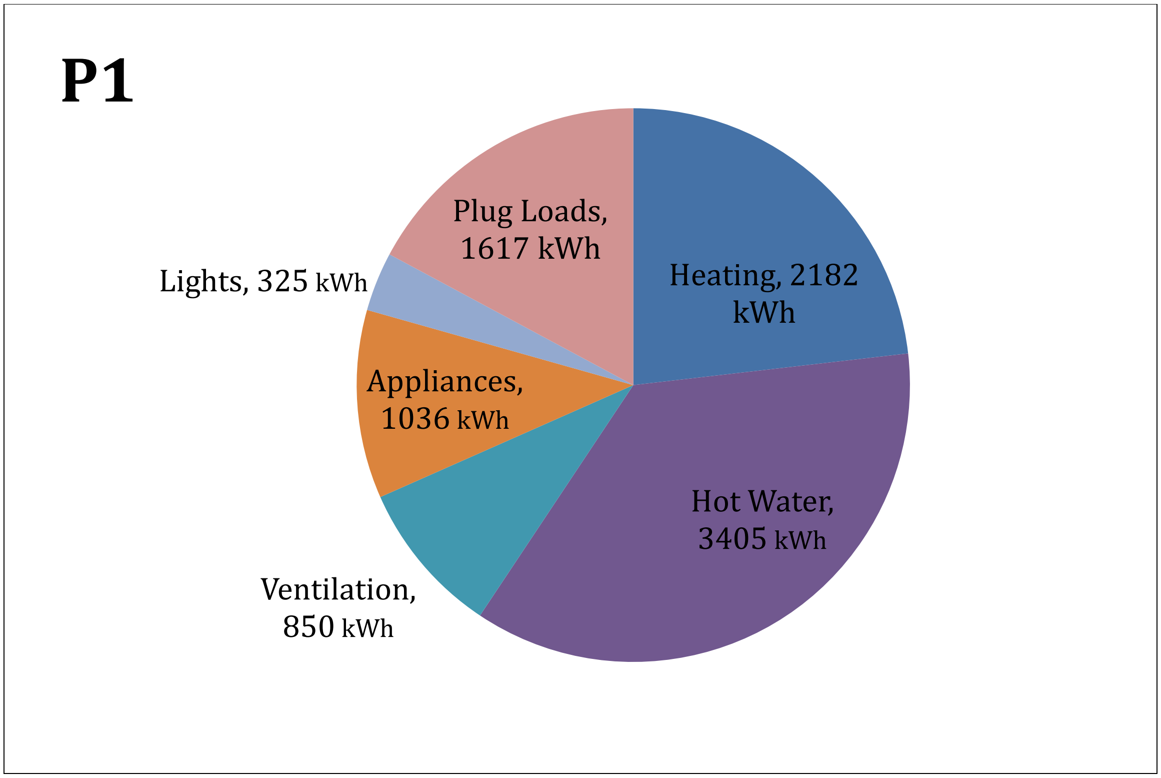


Figure 12 - P1 Annual Energy End Uses

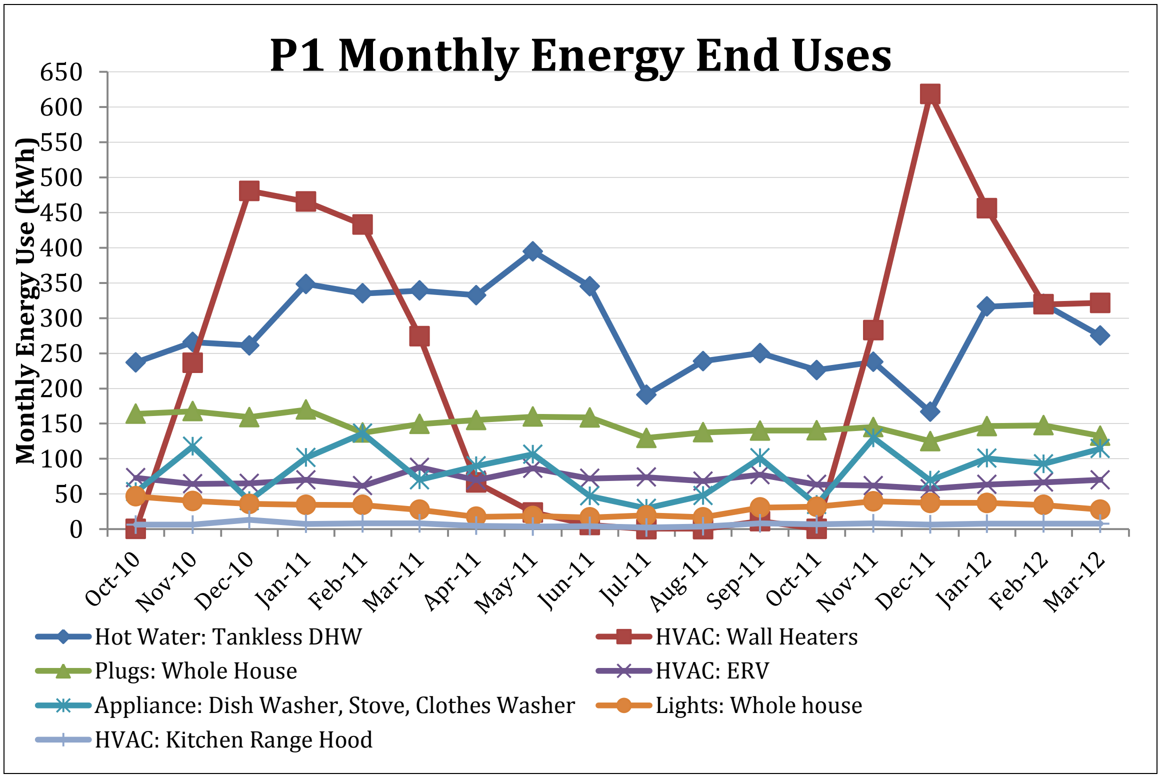


Figure 13 - P1 Monthly Energy End-uses

User Behavior
The baseload in P1 is 191.5 Watts, which is approximately 1,678 kWh annually. Subtracting the electricity used by our monitoring of 15 Watts, gives a baseload of 177 Watts which is 1,546 kWh. This is 16.4% of annual net-site energy use in the home.

Temperature and Relative Humidity
The monthly first and second floor temperature and relative humidity means and standard deviations are presented in Table 6 below. Monthly mean temperatures in P1 varied between approximately 68 and 71 degrees F. A slight average temperature increase is notable in the summer months, but the change is very minor. Monthly mean relative humidity varied from 50% to 60%. The relative humidity is somewhat higher than desired, with some months averaging at the top of the acceptable 30-60% range.

The temperature differences between the 1st and 2nd floors are presented below in Figure 14. The Air Conditioning Contractors of America (ACCA) provide industry guidelines for the provision of thermal comfort in single and multi-zone residences. Between floors, ACCA stipulates a maximum heating season temperature difference of four degrees, and six degrees (for single-zone) and four degrees (for multi-zone) during cooling (ACCA, 2005). P1 spent only 1.4% of the year with temperature differences between floors in excess of the four degree maximum recommended by ACCA. Very consistent temperatures were maintained in this Passive House-inspired project.

P1 Summary of Temperature and Relative Humidity by Month								
	Temperature				Relative Humidity			
	1st Floor		2nd Floor		1st Floor		2nd Floor	
Month	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
January	69.2	0.8	70.1	1.4	58.2	6.0	58.0	5.9
February	69.2	1.1	70.8	1.9	54.4	4.5	52.8	5.7
March	69.5	0.9	70.7	1.7	60.1	3.3	59.5	4.3
April	69.9	0.9	71.7	1.4	55.2	4.8	53.5	4.4
May	70.0	1.3	72.0	1.5	54.0	2.8	51.5	2.7
June	70.8	1.3	72.3	1.5	57.7	2.8	55.3	2.0
July	69.8	2.3	71.1	2.0	55.6	2.2	53.5	2.6
August	68.9	3.3	70.3	3.3	53.7	3.4	52.8	4.4
September	71.7	2.0	73.0	2.1	51.4	4.4	50.3	5.5
October	69.7	2.0	70.9	2.3	52.9	5.5	52.6	6.5
November	68.8	1.5	70.0	2.1	53.4	4.3	53.7	5.4
December	68.4	1.3	68.8	1.4	57.4	4.5	60.0	5.8

Table 6 - P1 Summary of Temperature and Relative Humidity by Month

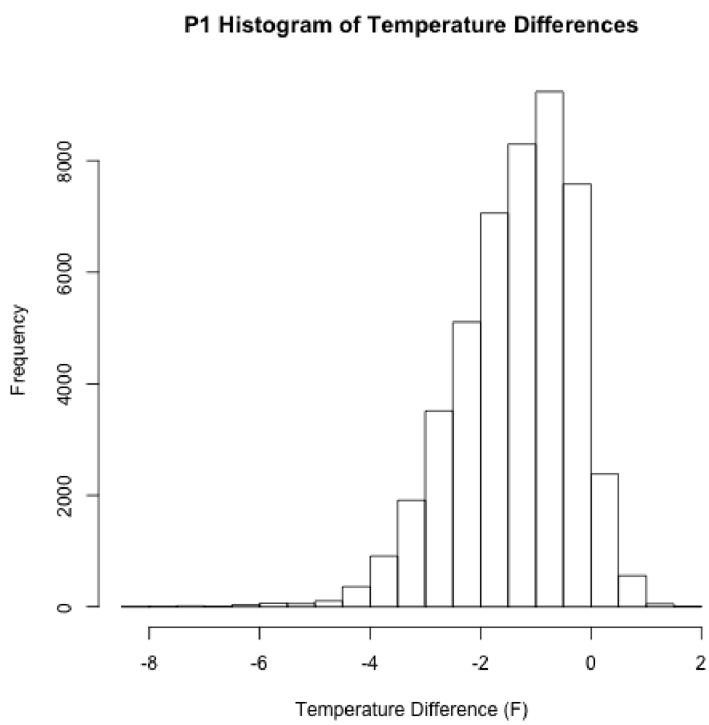


Figure 14 - P1 Histogram of Temperature Differences Between Floors

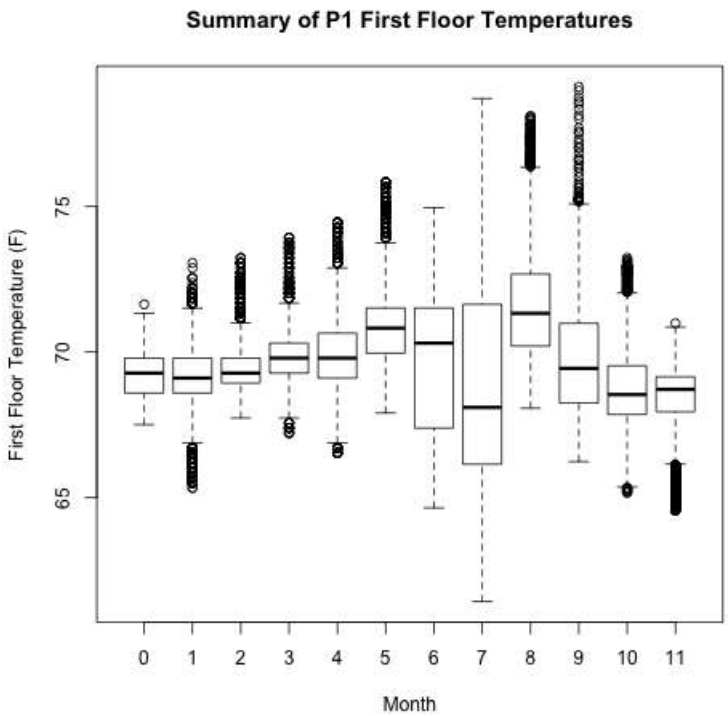


Figure 15 - P1 Boxplots of First Floor Temperatures by Month

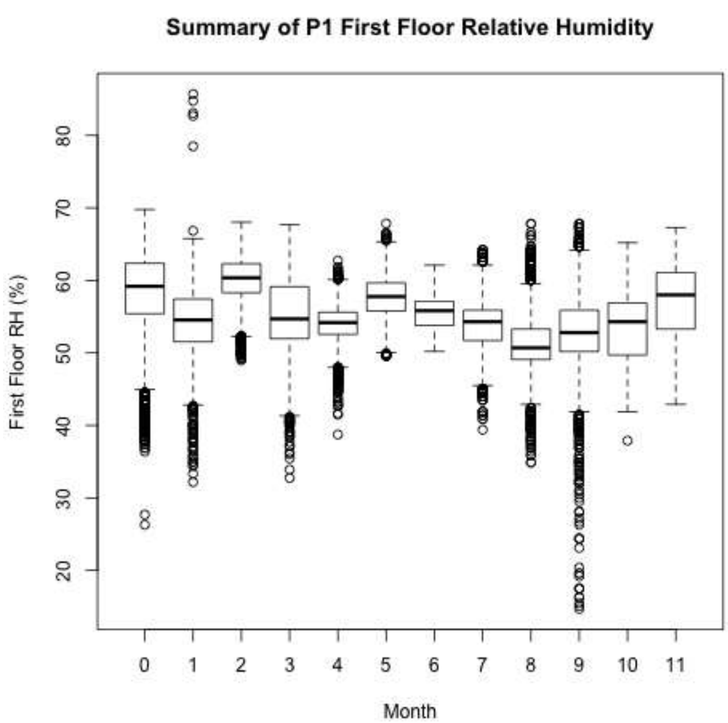


Figure 16 - P1 Boxplots of First Floor Relative Humidity by Month

Indoor relative humidity is recommended to be maintained within a range of 30-60%. The percentage of time that P1 spent below, within and above that range is summarized in Table 7 below. Just less than 1/5th of the year was spent with RH in excess of the recommended range. But as can be seen in Figure 17 and Figure 18, the indoor RH almost never exceeded 70% for even 15 minutes. So, while indoor RH in P1 did exceed recommended limits for a substantial portion of the year, it just barely exceeded and no moisture issues observed in the home.

Proportion of Time Relative Humidity was Below, Within and Above the Recommended Range			
Location	**Below 30%**	**30% to 60%**	**Above 60%**
First Floor	0.0508%	81.9%	18.0%
Second Floor	0.0486%	83.5%	16.5%

Table 7 - P1 Proportion of Time Relative Humidity Was Below, Within and Above the Recommended Range

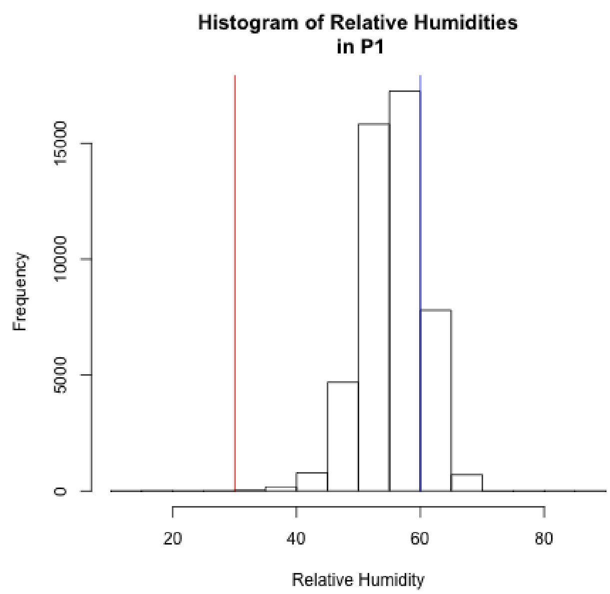


Figure 17 - P1 Histogram of First Floor Relative Humidity

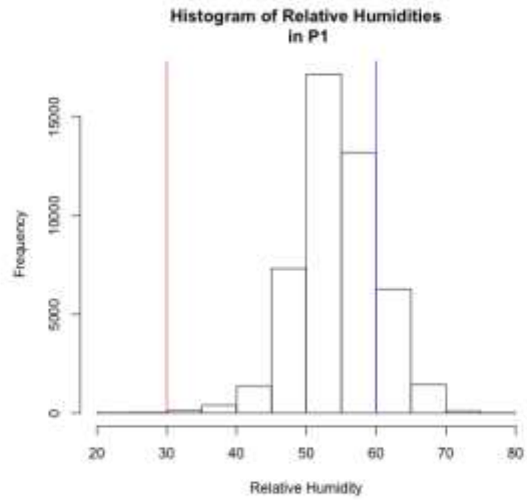


Figure 18 - P1 Histogram of Second Floor Relative Humidity

4.1.4 P1 Overview

The final results of 31% net-site and 19% carbon savings in P1 are slightly disappointing at first glance. However, when all aspects of the project are considered, including doubling of the occupancy and the conditioned floor area, as well as greatly improving both the durability and aesthetics of the home, then the overall evaluation of the project must consider more than just carbon and energy savings, and incorporate the associated non-energy benefits as well.

The choice of performance metric has pronounced effects in P1. This results from changes in fuel mix, occupancy and floor area. At 31%, the pre- vs. post-retrofit whole house site energy savings are decent but not great, compared to the goal of 50% or greater, or the THC goal of 70% or greater. The CO_2e savings were only 19% and net-source energy increased 12%. However, if evaluated on per person or per square foot bases (See Table 65), then reductions improved to acceptable DER levels. For example, per person net-site, net-source and CO_2e reductions were 65%, 44% and 60% respectively.

The online energy dashboard at P1 revealed that the ERV is operated on its highest setting at seemingly random intervals. The issue is presumed to be a problem with the humidistat controls but is unresolved to date. These sensors should function properly, and it raises the question of system simplicity for lowest energy consumption. If there were only a timer, and not a humidistat, then this issue would not arise. Operation would then need to account for sufficient ventilation through frequency and duration, in order to meet the health and safety requirements, which is a standard mode of operation to meet ASHRAE 62.2 (Walker & Sherman, 2008).

The belief that homes built to the Passive House standard do not need a conventional heating system drove the original idea in P1 to provide all space heating with electric resistance baseboard heaters. They were also chosen because of their affordability, and due to the improved building enclosure and the PHPP calculations, it was believed that they would be seldom used; many were only installed to accommodate building code compliance. While the temperature data

(See Table 6 above) shows that the building enclosure improvements did help achieve a very stable and comfortable environment, it was not without significant heating energy from November through March. This result shows that even Passive Houses need a well-distributed heating system in the Bay Area climate, and they should not employ electric resistance heating if saving energy and reducing GHG emissions is the goal.

In addition to the important lessons learned from the energy and CO_{2e} results of this study, P1 has helped raise awareness of DERs and the Passive House standard in the Bay Area. The homeowner has also been extremely accommodating and interested in our research, allowing us to perform multiple diagnostic tests and additional monitoring research such as the ERV performance monitoring that is currently taking place.

4.2 P2

4.2.1 P2 Project Description

Image 3 - P2 Post-Retrofit Exterior and Insulated Attic

P2	Pre-Retrofit	Post-Retrofit
ENVELOPE		
Wall Insulation	None	3.5" cellulose – R13
Attic/Roof Insulation	None	6.5" open cell spray foam – R23
Foundation Insulation	None	6.5" open cell spray foam in basement ceiling – R23
Windows	Single pane, steel frame	2 pane, low E, Argon – Interior storm windows, values unknown
Air Leakage		2144 CFM_{50}, 5.7 ACH_{50}
MECHANICAL		
Heating, Cooling & DHW	Natural gas furnace, 40 gal gas tank DHW heater	3 ton air to water heat pump, EER 9-12, Variable speed compressor
Ventilation	Natural	2 Air Handlers, integrated HRV's – continuous ventilation, bath exhaust fans
Distribution	None	R6, foil faced flex duct in sealed and conditioned attic and basement
LIGHTS/APPLIANCES/MEL	All incandescent lights, old appliances	CFL, Halogen and LED lights, new energy star appliances, very high MEL loads
RENEWABLES	None	4.3 kW PV

Table 8 - P2 Retrofit Summary Table

General Information
This home was built in 1936 in the English Tudor revival style near downtown Palo Alto. The original home was timber framed with stucco finish on the exterior. The home had a strong local historical and cultural presence, with a cedar-shingled roof, exposed beams on the interior, wood paneling, and locally made decorative iron frame windows and ceramic tile. When a renovation of the home was undertaken in 2009, five primary project goals drove the decision-making processes: (1) energy efficiency, (2) comfort, (3) health, (4) water efficiency and (5) historic preservation. Initially, the renovation was designed and marketed as a zero-net energy project, and all gas consumption was switched to electricity, with the intent to offset all site energy usage with site-generated energy from PV. No square footage was added to P2 during its renovation, which preserved its historical character, limited increases in energy use, and reduced the amount of new material that was required in construction. Yet, the interior of the home was reorganized to some extent, in order to facilitate its transition to modern lifestyles. The kitchen and bathrooms were fully remodeled, and a family room and new half bathroom were created. The building enclosure, HVAC systems, appliances, lighting and plumbing were all upgraded to high-performance standards, while successfully maintaining the home's footprint, interior historical character and exterior appearance. It has five bedrooms, 3 baths and a home office. All five of the initial goals were achieved; however, the home is currently rented to a family with highly mixed patterns of occupancy from day-to-day and week-to-week. It is unknown why the homeowner decided to rent the home, but the result is that the tenants do not have the same goals and behavior patterns as the project intended.

Building Enclosure
The design of the P2 retrofit was guided by integrative design strategies, which included ongoing dialogue between designers, energy professionals and the contractor. This discussion was enhanced by the use of building energy simulation and a detailed home energy audit at the start of the project, which identified numerous energy wasting features, including lack of insulation, excessive air leakage, incandescent lighting, and outdated appliances.

The first goal of the project was the reduction of the existing heating and cooling loads, to be achieved through insulating and air sealing the structure. These upgrades proved to be quite challenging due to the post and beam structure and construction detailing of the home. Projects that are dedicated to historical preservation often encounter this trade-off between achievement of exceptional envelope performance and preservationist goals, which typically limit insulation and air barrier levels, placement, continuity, etc. Numerous examples of this tension exist in P2. For example, the exterior walls in the sunroom were not insulated, due to decorative paneling, which could not be drilled and filled with cellulose insulation, as the rest of the exterior walls were. Despite these challenges, nearly all of the exterior 2X4 structure was insulated with blown cellulose, and 6.5" of low-density spray polyurethane foam (SPF) was placed in the crawlspace/basement ceiling and against the roof deck in the attic (see Image 4 below).


Image 4 - P2 Spray Polyurethane Foam in Sealed Attic

In order to preserve the historic single pane windows, the owner devised a plan to install interior double pane, fiberglass-framed storm windows. These were fixed to the existing window frame by magnets in order to facilitate removal for cleaning and opening of existing windows when desired. As this was a custom application, the whole window U values and SHGC are unknown.

Air Leakage

The design team reduced air leakage by fixing a fireplace damper that did not close, a kitchen exhaust vent that was always open, and a bathroom exhaust fan that was venting to the attic. The insulation of the floor and ceiling with spray foam, and the walls with cellulose also improved airtightness. However, due to the goal of minimal impact to existing finishes, eliminating air leakage altogether was not possible.

Ventilation

A healthy indoor environment was also an integral goal of the project, and was achieved using both mechanical ventilation, filtration of air, and avoidance of unhealthy building materials. Fresh air is provided using Heat Recovery Ventilators (HRVs) with pleated filters that are integrated into both air handler units, which provide fresh air during fan operation (see Image 5 below). These air handlers use electronically commutated motors (ECM), which can continuously vary airflow and are designed in P2 to operate at very low power 24 hours a day, providing continual, distributed fresh air. Mechanical exhaust fans are also used in all bathrooms and the kitchen for point-source pollutant removal.


Image 5 - P2 Passive HRV Core Integrated with Attic Air Handler

Heating, Cooling and DHW

Energy consultants on the project entirely redesigned and replaced the HVAC system as part of the retrofit effort. The original 80% efficient gas furnace and 55% efficient atmospherically drafted water heater were replaced with an electric heat pump hydronic system, providing heating, cooling and DHW to the entire home. It consisted of an air-to-water heat pump to create hot and cold water/glycol fluid for space conditioning using air handlers with a hydronic coil in the basement and attic, as well as two radiant floor zones. The water/glycol mix serves space heating directly, and it is then passed through a submerged heat exchanger in the 80-gallon domestic hot water storage tank. The chilled water-glycol solution is passed through a heat exchanger in the cold-water storage tank, which then circulates chilled water to the air handlers for space cooling (see Image 6 below). This system required very complicated controls to manage the diverse loads, and it also used significant pumping power. The result was a complex system, unfortunately prone to malfunction.

The complexity of the space conditioning systems in P2 was increased by the inclusion of two radiant floor heated zones in the home, the uninsulated sunroom and the master bedroom. These areas could not be served by the two forced air hydronic furnaces/air conditioners, which resulted in the placement of hydronic tubing for under-floor heating and cooling. This feature added complexity to an already complex HVAC system, requiring a further level of sophistication in controls and increased pumping energy. All of this results in a system that can only reliably be serviced by the designer/installer, and which can result in increased liability for the contractor.


Image 6 - P2 Heated and Chilled Water Storage Tanks in Basement

The original heat pump unit encountered numerous problems during our monitoring, including very high energy use and failure to meet the domestic hot water loads. It eventually had to be replaced in January of 2011, when the cold water storage tank and two circulation pumps were also removed. Since the heat pump was replaced it has been functioning far better, meeting heating and DHW loads, as well as the cooling loads, and using significantly less energy than the previous model (see Image 7 below).


Image 7 - P2 Replacement Heat Pump Outdoor Unit

Appliances
The Kitchen was upgraded to the most efficient Energy Star appliances including an induction electric cook top, electric oven, double door refrigerator, front-loading washer and dryer.

Plug Loads
As the original intent of this home was to be a mid-sized office for the homeowners company, there are an extremely large number of plug loads. The basement has a large server rack (see Image 8 below), and the living room is outfitted with state-of-the-art audio and video equipment, including a built in projector. These loads have significantly affected P2 energy use, increasing its baseload electrical usage to the highest of any project home. These loads are unfortunately not easily controlled or turned-off by the occupants. Additionally, the kitchen has a toaster oven, and a coffee machine, and the office has two computers and a printer.

Image 8 - P2 AV and Data Equipment in Basement Cabinet

Lighting
The home has an assortment of lights, mostly CFLs, with a few LED and halogen fixtures. All lights are controlled by wall switches.

Renewables
A PV system of 4.3 kW was installed, which serves to offset some of the home's electrical usage. All other power is purchased through PaloAltoGreen, the city's Department of Utilities' 100% renewable energy rate program.

4.2.2 Building Diagnostic Results

Blower Door
P2 is not the leakiest home of the study, but is tied for 3rd in the group of homes that are still very leaky. A lot of space conditioning energy could be saved through a tighter building enclosure. However, the interior finishes prohibited the contractor from performing more extensive air sealing measures.

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH
P2	2260	5.67	0.32	0.59	124.60	0.27

Table 9 P2 Blower Door Results

Duct Leakage
The basement and attic air handlers were tested using the Delta Q test, and the passive ERV inlets and outlets were sealed. Results for duct leakage were so low that they were indistinguishable from 0 for this test method. Nearly all ducts are in conditioned space, so this result is not surprising.

Ventilation Airflows
The 62.2 whole house mechanical ventilation requirement for P2 is 57.8 CFM, but passive ERV airflows were not measured, as the inlets and outlets were not accessible. The bathroom exhaust fans were tested for airflow during commissioning. The current Title 24 2008 building code requires that bathroom fans deliver a minimum of 50 CFM. None of these four fans achieved the required airflow, with the downstairs full bathroom performing significantly below the standard. A kitchen range hood fan was also installed, but it was not tested during diagnostics.

Location	Airflow (CFM)
Downstairs Full Bathroom	19
½ Bathroom First Floor	46
Upstairs Full Bathroom	40
Upstairs Master Bathroom	49

Table 10 - P2 Ventilation Airflow Measurements

IR Thermography
The IR images reveal that P2 is still very leaky and has missing insulation in various locations, visible from the exterior in Figure 19Figure 20, and from the interior in Figure 22Figure 30. In roughly half of the windows the occupants removed the interior storm units in order to have access to the operable windows; the difference in heat transfer is visible in Figure 21. The sunroom is the most problematic as the interior finishes prohibited the installation of insulation but is still conditioned with air and radiant floor heating, requiring the constant conditioning of outdoor air (see Figure 25 - Figure 27).

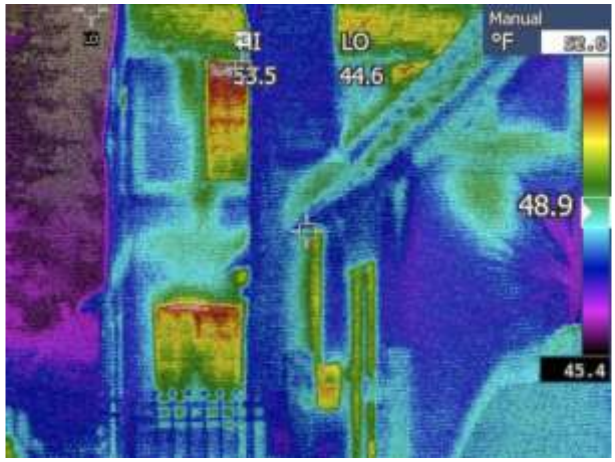


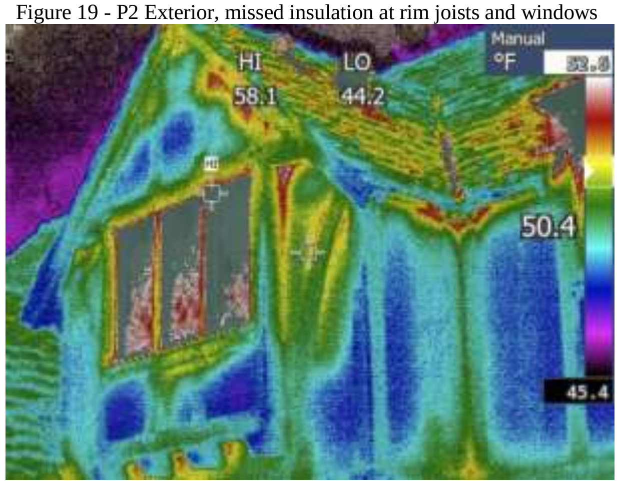
Figure 19 - P2 Exterior, missed insulation at rim joists and windows


Figure 20 - P2 Exterior thermal bridges and leakage at front of building

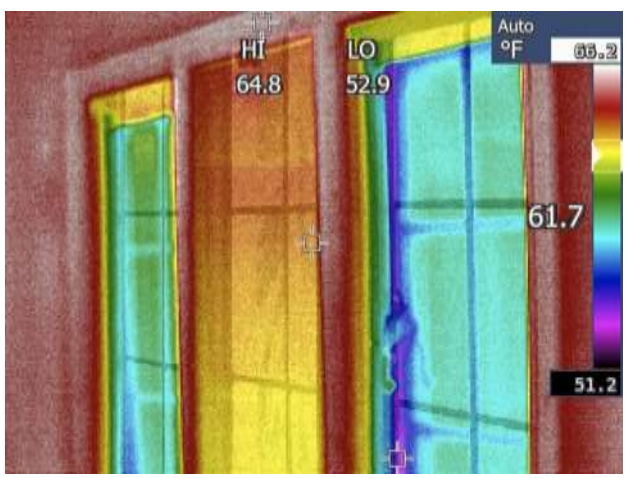


Figure 21 - P2 Tenants removed double pane interior storm windows

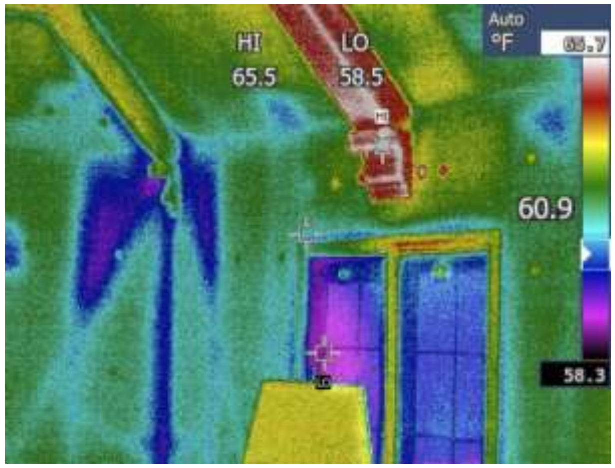


Figure 22 - P2 thermal and air leakage in living room

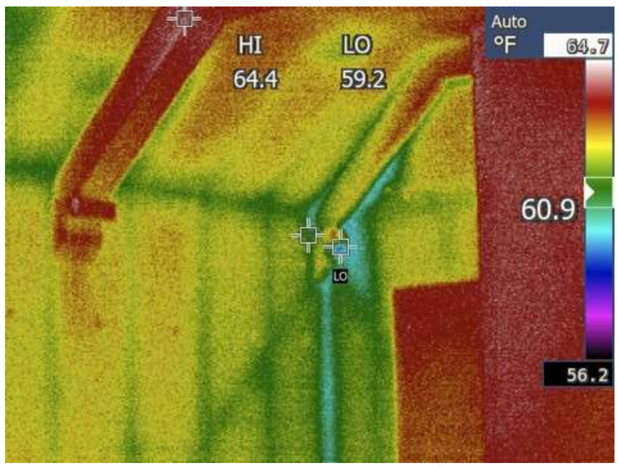


Figure 23 - P2 Thermal leakage at corner of living room

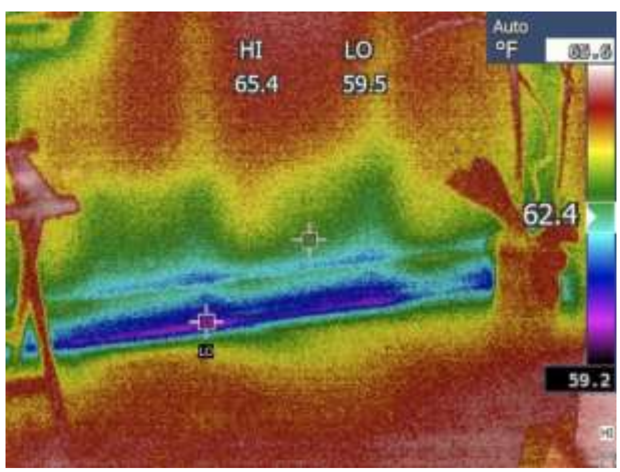


Figure 24 - P2 Air leakage under baseboard in bedroom

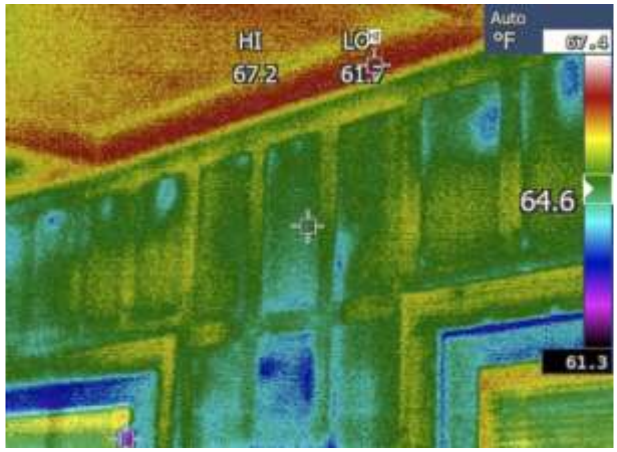


Figure 25 - P2 Uninsulated sunroom

Figure 26 - P2 sunroom radiant floor and register next to leaky door

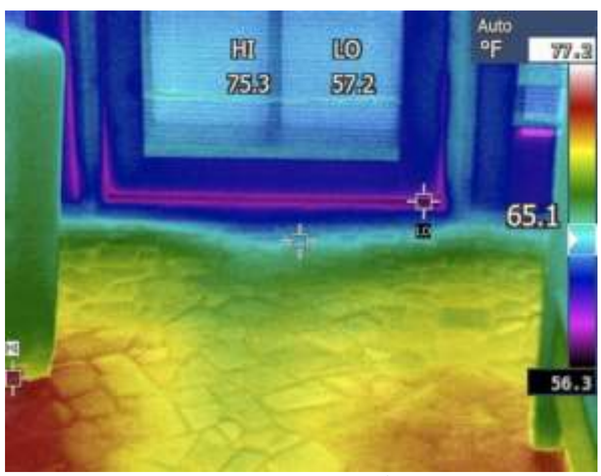


Figure 27 - P2 leaky door at radiant floor in sunroom

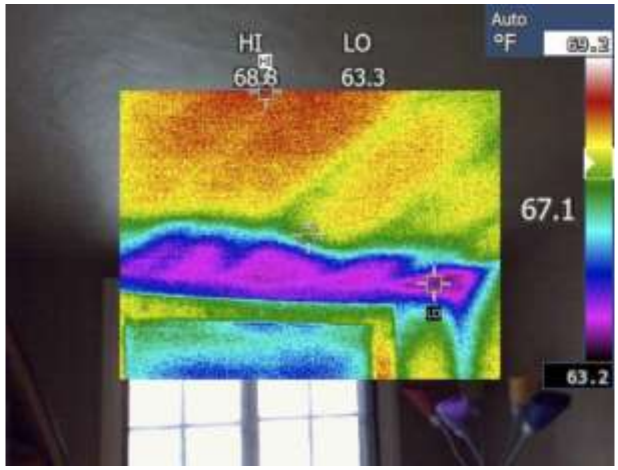


Figure 28 - P2 missing insulation and/or air leakage at bedroom window

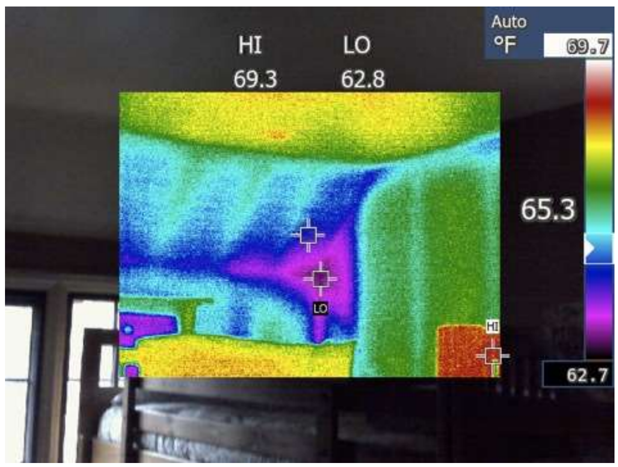


Figure 29 - P2 missing insulation and/or air leakage at bedroom

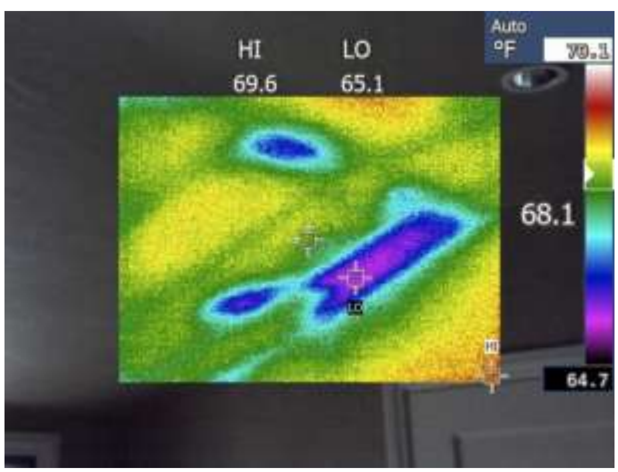


Figure 30 - P2 missing insulation and/or air leakage at bedroom

4.2.3 Monitored Data Results

Whole House Energy Use

P2 (Pre) - WHOLE HOUSE ENERGY USE			P2 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e	Net-Source Energy	Net-Site Energy	Total CO_2e
53,474 kWh	40,284 kWh	17,094 lbs	49,901 kWh	15,791 kWh	9,086 lbs
Occupants	Area	HERS Rating	Occupants	Area	HERS Rating
2	2,780 ft^2	-	2+	2,780 ft^2	55

Figure 31 - P2 Pre- and Post-Retrofit Mileage Boxes

Annually, P2 used 15,791 kWh in net-site energy, a reduction of 61% from its pre-retrofit net-site consumption of 40,284 kWh. Unfortunately, when converted to source energy, P2 only reduced net-energy consumption 7%, from 53,474 to 49,901 kWh. The CO_2e emissions were reduced 47%, from 17,094 to 9,086 pounds. The average CA single family home uses 20,061 kWh net-site energy, 36,737 kWh net-source energy and 9,346 pounds of CO_2e. P2 consumed almost exactly the CA average site energy, and its PV production reduced its net-site to 79% of the average. P2 is another example of a home that transitioned from gas to electric for space and water heating, and just as in P1, the source energy savings are very poor. Clearly, this issue also plagues homes with impressive site energy reductions.

Monthly electrical and gas energy consumptions are shown in Figure 32. A high winter peak usage is seen in 2010 due to the heat pump malfunction (see above), which is greatly reduced in the winter of 2011/12. With the new heat pump, much less of a seasonal trend is observed in P2. This is likely due to the persistent high energy use of the heat pump across seasons, as well as the large miscellaneous uses in the home. The PV production is pictured in blue in the figure, and production from this 4.3 kW system is always dwarfed by consumption.

The monthly site energy reductions are pictured below in Figure 33, shown on both a consumption and net-energy basis. Dramatic heating energy decreases are evident from the monthly data, and cooling energy increases are evident during the summer months. No mechanical cooling existed pre-retrofit. Designers were able to add cooling to this home with essentially no net-energy penalty. Of course, these values are all site energy, whereas source savings were only 7% annually.

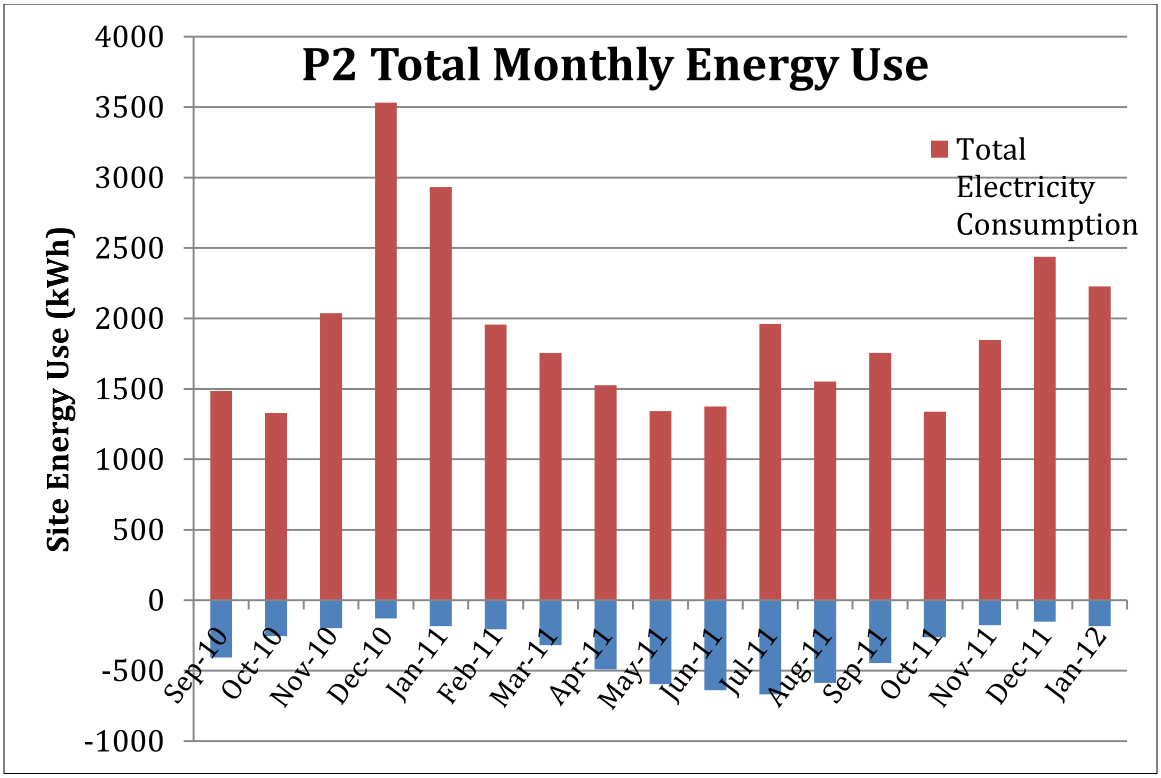


Figure 32 - P2 Total Monthly Energy Use

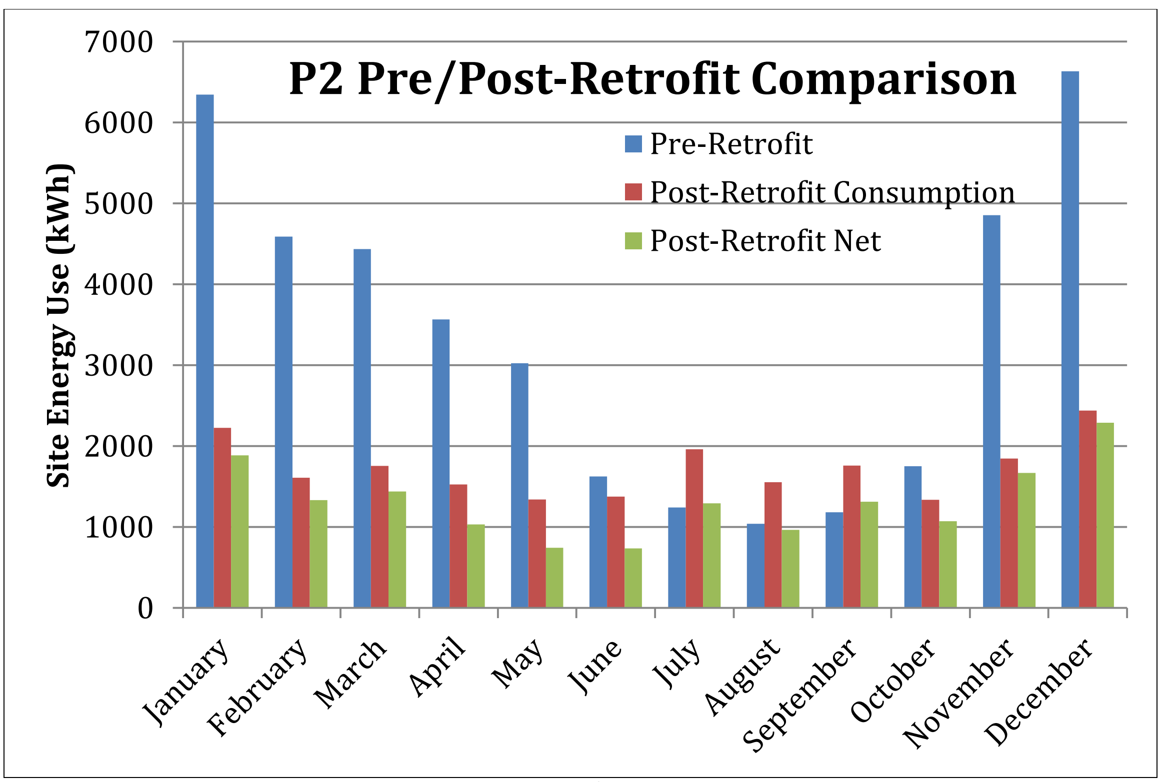


Figure 33 - P2 Pre/Post -Retrofit Site Energy Comparison

In the retrofit, P2 switched fuels from natural gas and is now an all-electric home. The original design intent was for the PV to offset all of the electric use, which would make this a ZNE and carbon neutral home; however, this is not being achieved. Additionally, the design intent was for the homeowner to use this as his home office, and closely manage the energy use in the home; instead, it is now a rental property and the user behavior of the current tenant was not considered in the retrofit. The saving grace is that the purchased electricity is from "Palo Alto Green." The Palo Alto Utility fuel mixture for 2010 was 44.5% large hydro, 35% unspecified (which is poorly defined, but claimed to be a mixture of wind, land fill gas (LFG) and natural gas), 11.9% wind, 7% LFG, 0.9% small hydro, 0.1% natural gas ('PaloAltoGreen Program', 2012). This fuel mixture is estimated to produce 0.325 lbs of CO_{2e} per kWh. This is less than half of the CO_{2e} of the average California fuel mixture for electricity (Deru & Torcellini, 2007). The Palo Alto Green program then purchases Renewable Energy Credits (RECs) for the customers who opt in to the program, which costs an additional $0.015 per kWh, and is claimed to offset all CO_2e emissions. Reported CO_2e values for P2 reflect PG&E conversions as discussed in the methods section, and do not include this purchased offset or the fuel mix of the Palo Alto electrical utility. The 47% CO_2e reduction achieved by P2 can be interpreted in the context of these purchased carbon offsets. The question of the role of purchased carbon offsets in DERs has not been explored.

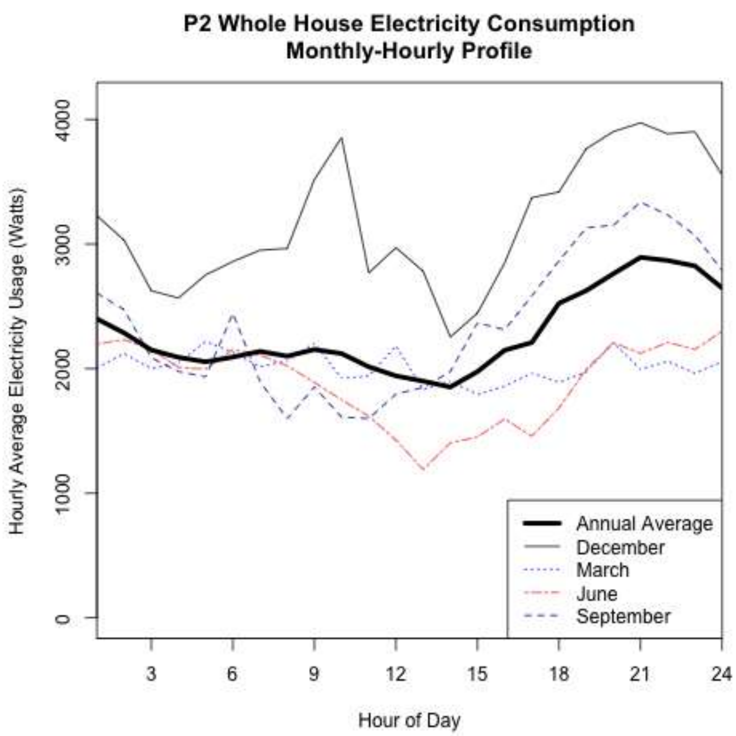


Figure 34 - P2 Whole House Electricity, Annual Hourly Profile

Hourly average profiles for whole house electricity and PV production are pictured in Figure 34 and Figure 35. Average electricity demand in P2 is quite high, rarely dipping below 1,000 watts for any hour of any month. A peak in whole house electricity is evident in the afternoon and evening, particularly during December and September, which is probably space conditioning related. The home shows no signs of retreating into an "off" mode when occupants are gone. The PV profile is typical, with higher system outputs during the summer months. Peak summer output is around 3,000 W.

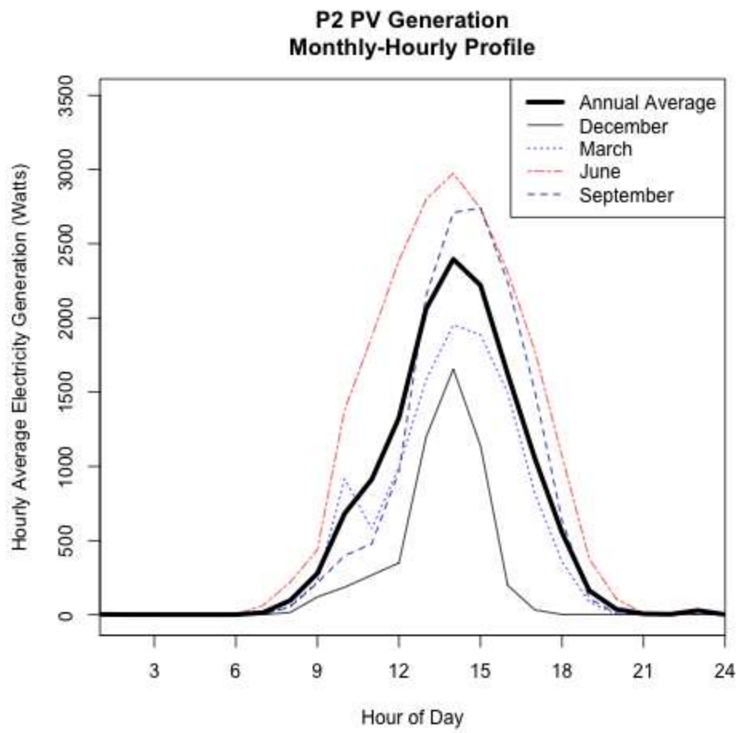


Figure 35 - P2 PV Generation, Monthly Hourly Profiles

End-Uses

Annual energy end-use summaries are provided in Table 11 and Figure 36 below, and Figure 37 provides monthly end-use trends. Due to monitoring limitations, the "Heating" use of P2 includes cooling, heating and hot water from the combined heat pump appliance. This combined load is by far the largest in the home, and the second largest is plug loads, which were also large, exceeding those of any other project home by a factor of 2.8. The heating energy usage in this home exceeded the total net-site usage of five other project homes (P1, P3, P4, P5 and P7). The modeled energy use of P2 can be compared with actual by looking at the combined HVAC and DHW energy, where the model under predicted by 60%. The high plug loads were driven by a large home audiovisual and data/communications system in the basement.

	P2 Actual	P2 Modeled
Floor Area	2780	2780
# of Occupants	2	2
Heating, Cooling and Hot Water	9867	3197
Cooling	0	764
Central Air Handler(s)	1854	483
Hot Water		2458
Ventilation		181
Combined HVAC and Domestic Hot Water	***11720***	*7083*
Appliances	1673	2187
Lights	2105	1514
Plug Loads	5097	4201
Combined Appliances, Lights and Plugs	***8875***	***7902***
Annual Total	***20596***	***14985***
PV Production	4804	6226
Annual Net	***15791***	***8759***

Table 11 - P2 Site Energy End Use Summary

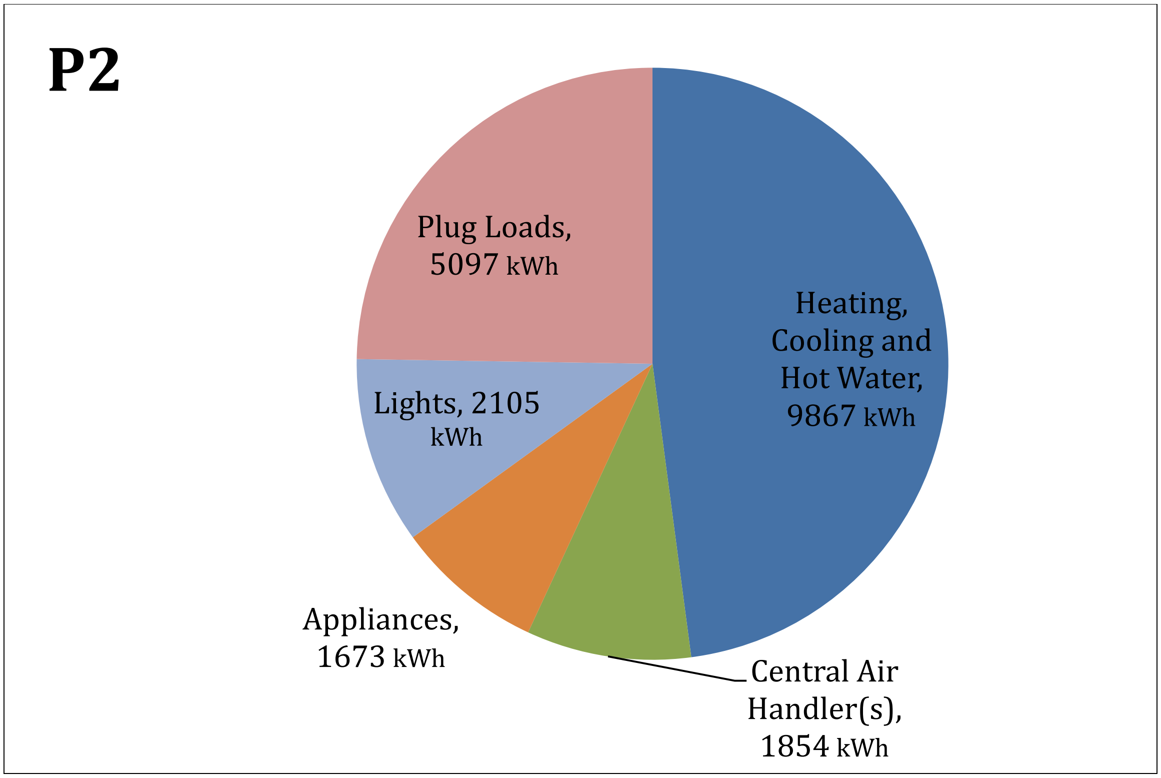


Figure 36 - P2 Annual End Uses Summary

Two notable peaks occurred in the monthly end-use data in December and January of 2010/11. These are the result of the malfunctioning heat pump. The "HVAC and DHW" peak in December and January is when the heat pump itself failed and used more energy to provide the same service, and the "Plugs" peak in January is from an electric resistance DHW heater that was installed while the heat pump was being replaced. Also of note is where you can see the significant drop in the "Plugs: A/V, Server" channel in February 2011, this is actually the pumps and controls from the original heat pump system, where two hydronic pumps were removed in February. The new unit has one integrated pump for hydronic distribution. The original system was using around 300kWh per month of additional pumping energy than that what was being monitored on the heat pump channel alone. These mixed issues with the end-uses also illustrate the difficulty of monitoring in existing homes, where loads are combined on the circuits, unbeknownst to the installer.

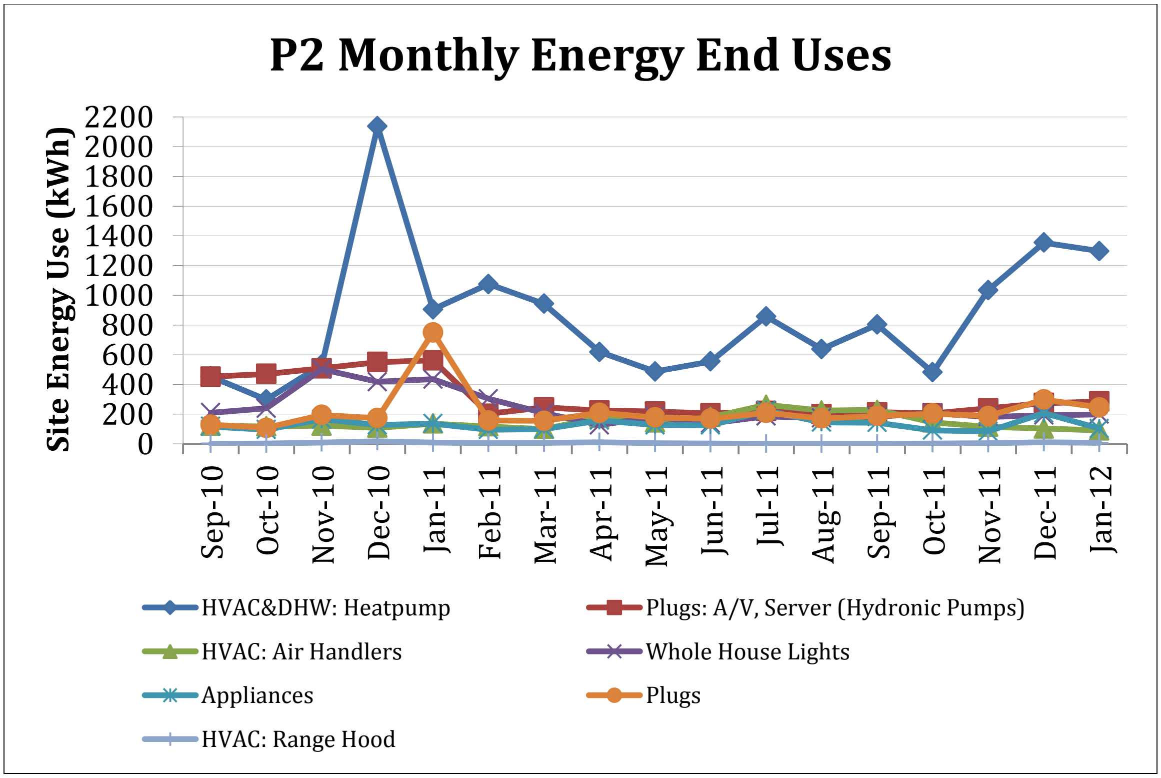


Figure 37 - P2 Monthly Energy End-uses

User Behavior

This home is an important case study to show how user behavior and MELs can impact overall performance. Even though the total energy savings of pre- vs. post-retrofit are impressive, the potential to save far more is great. The baseline in P2 is 562 Watts, which is approximately 4,926 kWh per year. This accounts for 31.2% of total net-site energy consumption. This is the highest baseload of all the project homes. As mentioned above, the server rack and A/V equipment is what is really driving the baseline and MEL use, and it is unclear whether or not the current occupants have any need for such equipment. The problem is that the house alarm system, the projector and audio system, and the server are all on the same rack, and powered together, so decoupling the server is not a simple task, but would require the original installer to fix.

IEQ Summary

The monthly first and second floor temperature and relative humidity means and standard deviations are presented in Table 12 below. Monthly mean temperatures in P2 varied between approximately 67 and 73 degrees F. An average temperature increase is notable in the summer months on the first floor and no increase is noted on the 2nd floor. Monthly mean relative humidity varied from 38% to 68%. The relative humidity is higher than desired, particularly on the 2nd Floor, with five consecutive months averaging greater than 60% RH.

These floor-by-floor results are surprising, because only the basement air handler was used to provide mechanical cooling during summer months. Yet, average temperature increases were noted on the level receiving cooling, whereas the non-cooled floor remained relatively stable. Relative humidity on the 2nd floor was higher than on the 1st, which could be the result of cooler average temperatures on floor two or moisture removal by the system on floor one. A spot check of absolute humidity during summer months confirms that levels were lower on the 1st floor, suggesting the presence of mechanical cooling. We cannot currently explain this phenomenon.

P2 Summary of Temperature and Relative Humidity by Month								
	Temperature				Relative Humidity			
	1st Floor		2nd Floor		1st Floor		2nd Floor	
Month	Mean	SD	Mean	SD	Mean	SD	Mean	SD
January	69.5	2.8	67.7	2.3	39.6	5.2	45.0	4.7
February	68.9	3.6	67.4	3.2	41.4	3.3	46.7	2.6
March	73.2	1.7	70.9	2.2	43.0	3.7	48.8	3.8
April	70.5	2.2	68.7	4.0	45.6	5.0	51.6	6.4
May	69.8	2.6	68.0	2.9	47.1	2.3	53.9	3.5
June	72.0	2.6	69.1	3.2	52.5	3.0	61.0	4.4
July	73.1	2.5	68.4	3.6	56.0	3.2	67.5	5.7
August	73.2	2.4	69.8	4.2	57.0	2.6	66.6	5.5
September	72.2	2.5	67.4	3.1	57.6	3.1	68.3	4.2
October	71.0	2.4	67.5	2.8	56.5	4.3	66.1	5.2
November	68.9	3.4	69.5	2.9	47.5	4.3	50.3	4.5
December	69.6	2.7	68.9	2.4	38.1	3.9	44.5	5.0

Table 12 - P2 Summary of Indoor Temperature and Relative Humidity by Month

Temperature differences between the 1st and 2nd floors are pictured in Figure 38 below. An annual average temperature difference of 2.4 degrees was measured, and as the figure shows, significant periods of time were spent with temperature differences in the five to ten degree range. P2 spent 27.1% of the year with temperature differences in excess of the +/- four degrees recommended by ACCA.

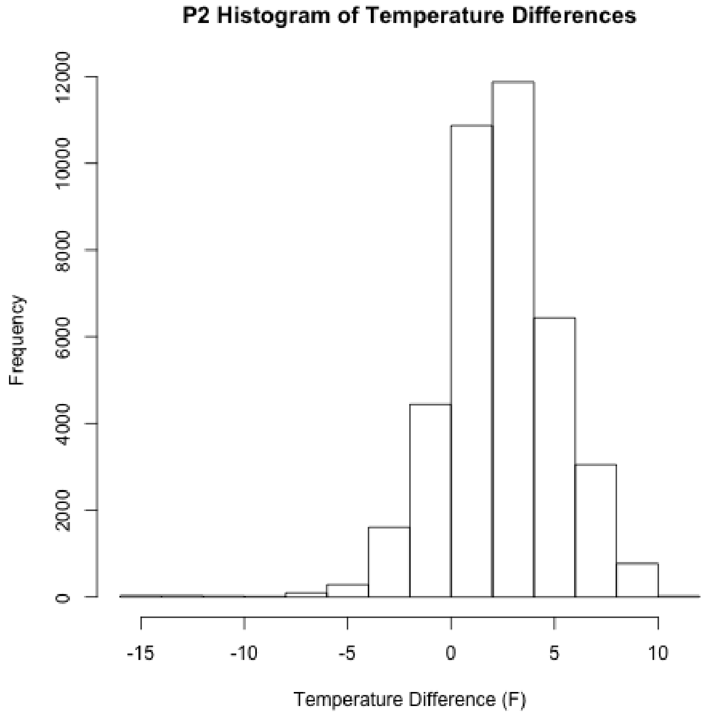


Figure 38 - P2 Histogram of Temperature Differences (1st to 2nd Floor)

Monthly distributions of 1st and 2nd floor temperature and relative humidity are pictured in Figure 39, Figure 40, Figure 41 and Figure 42 below. These figures show the variability in temperature and RH around the monthly values presented above. Monthly temperature ranges were commonly on the order of 10 to 15 degrees.

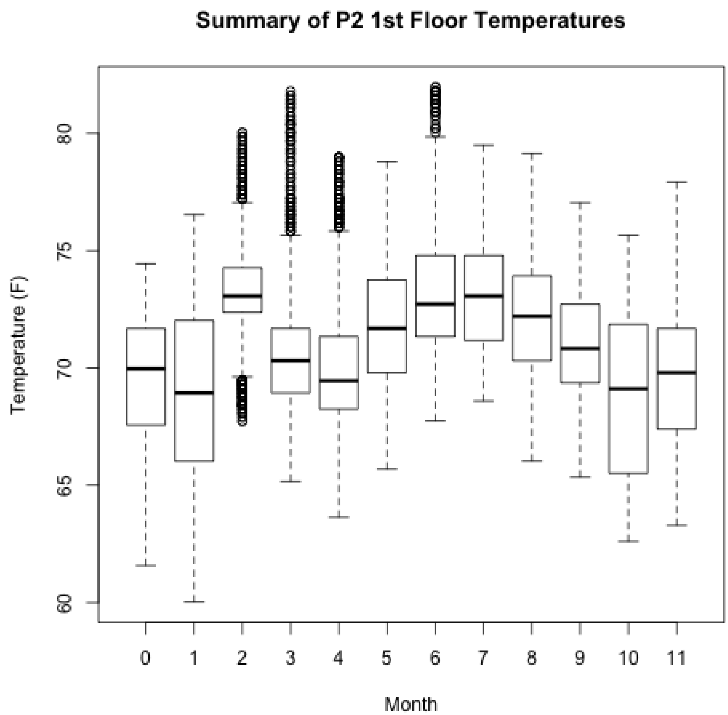


Figure 39 - P2 Summary of 1st Floor Temperatures

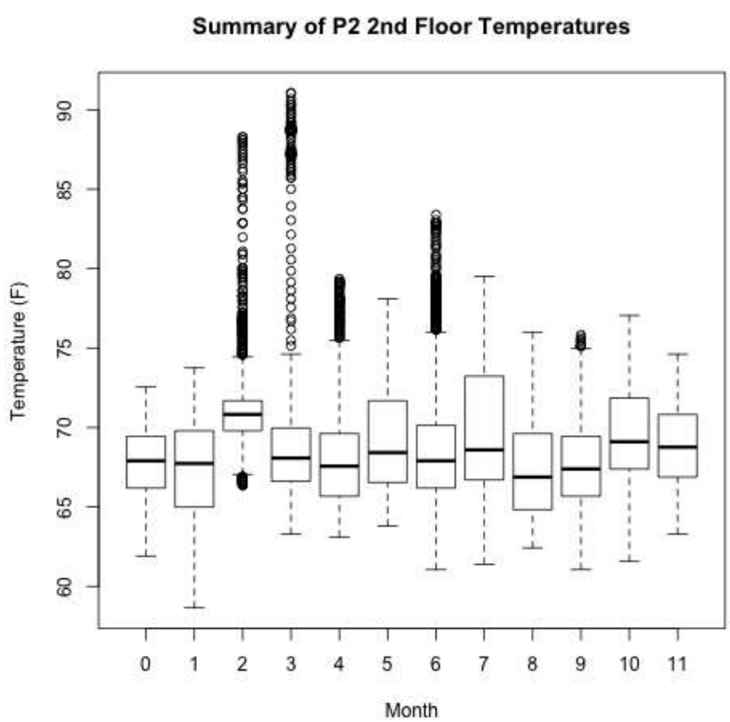


Figure 40 - P2 Summary of 2nd Floor Temperatures

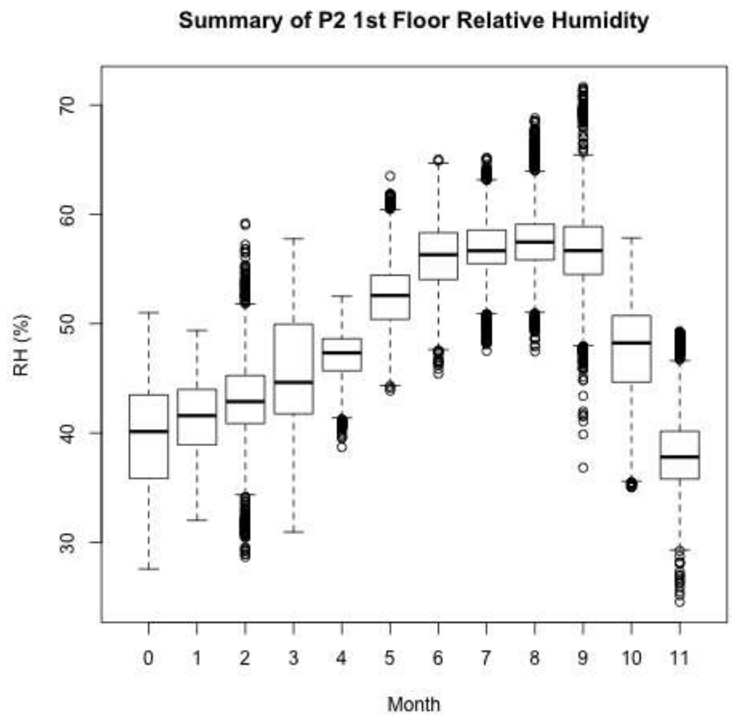


Figure 41 - P2 Summary of 1st Floor RH

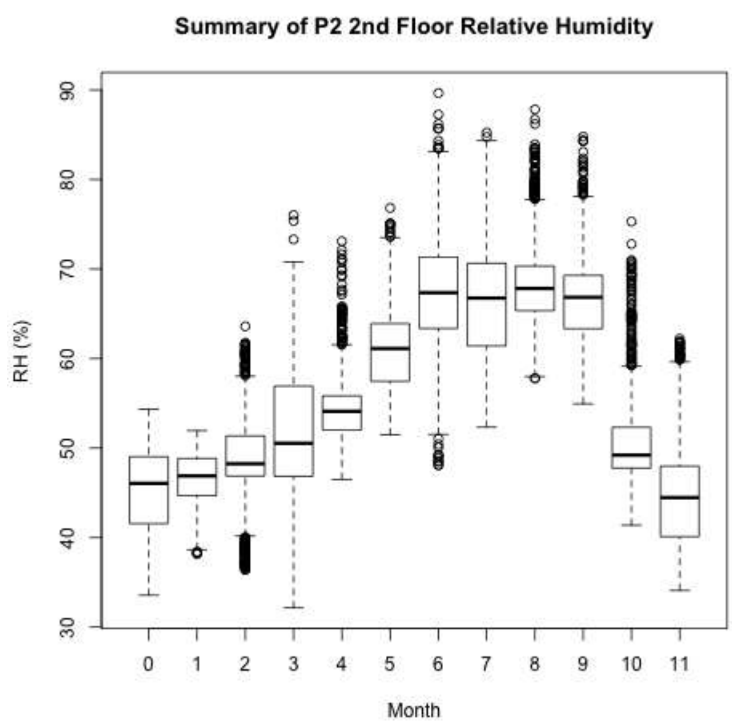


Figure 42 - P2 Summary of 2nd Floor RH

Table 13, Figure 43 and Figure 44 below show the proportion of time that the RH on the 1st floor and 2nd floor were below the recommended 30-60% range, within it and above it. Clearly moisture control was much more effective on the 1st floor, with 95% of the time spent in the recommended range. On the other hand, the 2nd floor spent a significant proportion of the time in excess of the recommended levels. This issue was investigated further in a more time-resolved fashion using 15-minute data, in order to determine how long the RH remained elevated in the home consecutively without dropping into the acceptable range. On the 2nd floor, one instance occurred in the monitoring year when the RH was above 80% for 130 minutes, and one instance occurred when it was above 70% for 1700 minutes (1.2 days). The 2nd floor was consecutively above 60% for one period of 16.3 days, and during three independent instances the RH remained above 60% for 10 consecutive days. In contrast, the longest duration during which RH on the 1st floor remained in excess of 60% was 1.75 days. These results represent both a comfort and possible human health issue, as outlined in the literature review on health effects of indoor RH.

Proportion of Time Relative Humidity was Below, Within and Above the Recommended Range			
Location	**Below 30%**	**30% to 60%**	**Above 60%**
1st Floor	1%	95%	4%
2nd Floor	0%	63%	37%

Table 13 - P2 Proportion of Time Indoor Relative Humidity was Below, Within and Above the Recommended Range

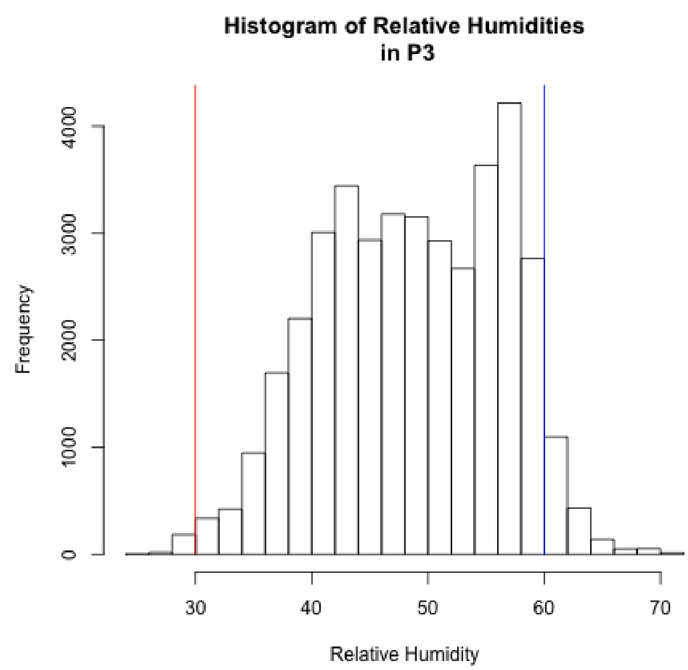


Figure 43 - P2 Histogram of 1st Floor RH

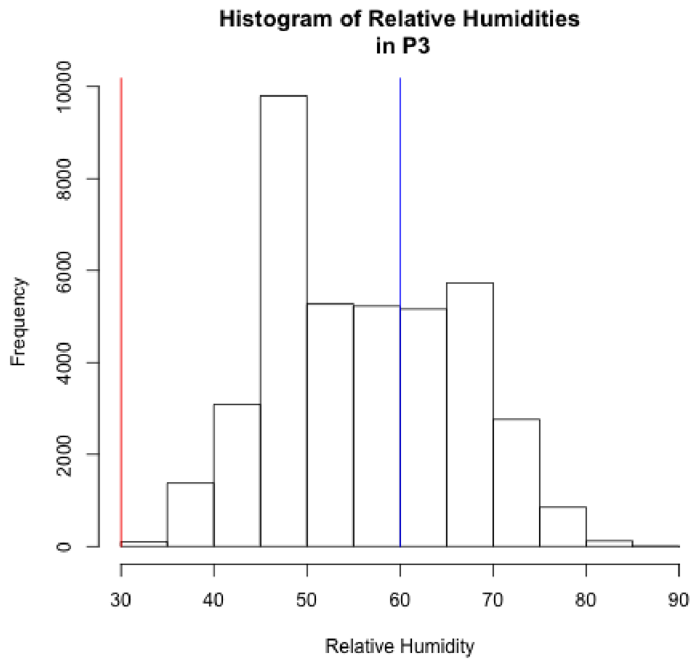


Figure 44 - P2 Histogram of 2nd Floor RH

4.2.4 P2 Overview

The site energy savings for P2 are commendable, and show that insulating, air sealing, HVAC and appliance upgrades, with the addition of PVs can save over 60% of site energy, regardless of user behavior and original project goals. However, it also shows that complex HVAC/DHW and ventilation systems, combined with very high MEL loads, and a lack of low energy user behavior, results in far greater energy consumption than expected. P2 has an MEL load of 32% of all site energy used, compared to the California average of 10-15% (CPUC, 2008). As discussed above, P2 is barely performing better than the typical California single-family home (KEMA, Inc., 2010). The CO_2e results however, show a 47% decrease in GHG emissions. Carbon emissions from P2 are almost identical to the CA single family average. Pre- retrofit, this home was a serious energy hog, post-retrofit it is performing relatively similar to a modern code-compliant home. P2 achieved deep energy savings, even though the end result is not a low energy home.

P2 is the 2nd highest energy consumer of the study. One factor is the high baseload of 562 Watts, which is in large part due to the computer/server system and A/V equipment that continuously uses over 200 Watts, larger than the entire baseload of the majority of other homes in this research. It is unclear as to whether or not the current resident uses the server as the design was originally intended for a home business. Simply disconnecting the server and A/V rack when not in use would save an estimated 2,400 kWh/year, resulting in 13% annual energy savings. Although the site energy savings and CO_2e reductions are commendable, the overall consumption in P2 is a great example of the need for both energy efficiency and energy conservation if we are to meet the goals of AB 32 and California's Long Term Energy Efficiency

Strategic Plan (CPUC, 2008). The plan calls for 25% of existing homes in California to decrease purchased energy 70% from 2008 levels by 2020. P2 has not achieved this goal however, with only slight behavior adjustments, this could easily be achieved.

Notably, the basement air handler ERV inlets and outlets were very close to grade level, and others have noted the tendency of such inlets to clog with yard waste/debris (see P3), which degrades ventilation airflow, ERV performance and quality of ventilation air. In addition the operation of the air handlers providing ventilation in P2 was erratic and unpredictable over the measurement period. The air handlers provided no consistent ventilation for large portions of the year, and at other times, never once stopped providing continuous ventilation. The reliability of the controls and performance of these systems is questionable.

4.3 P3

4.3.1 P3 Project Description

Image 9 - P3 Post-Retrofit Front (left) and Rear of Home (right)

P3	**Pre-Retrofit**	**Post-Retrofit**
ENVELOPE		
Wall Insulation	None	1: 3.5" dense-packed fiberglass, 5" EPS – R38 2: 5.5" dense-packed fiberglass, 2.5" EPS – R33
Attic/Roof Insulation	Vented Attic, R19 batt insulation	15" blown fiberglass, 2.5" EPS – R68
Foundation Insulation	None	Slab edge: 3.75" Rockwool – R16 1: 4.5" EPS – R19 2: 1.5" EPS, .6" Aerogel – R12.5
Windows	U: 1.2, SHGC: 0.8	3 pane, wood frame , U: 0.125, SHGC: 0.53
Air Leakage		151 CFM_{50}, 0.48 ACH_{50}
MECHANICAL		
Heating and cooling	Gas boiler, air handler with hydronic coil	Mini Split Heat Pump, solar hydronic coil on ERV
DHW	Gas tank, 0.58EF	3-4'X6' Solar thermal panels, 80 gallon insulated storage tank, Gas tankless backup 0.82 EF
Ventilation	Kitchen and bath exhaust	ERV SER 81-83%, exhausts from bath and kitchen, supplies living room and bedrooms
Distribution	R4 ducts in attic	Ducted ERV, all within thermal envelope
LIGHTS/APPLIANCES/MEL	All incandescent lights, old appliances	CFL and LED lights, new energy star appliances, second refrigerator, home office, high MELs
RENEWABLES	None	2.15 kW PV, 3 solar thermal panels

Table 14 - P3 Retrofit Summary Table

General Information
P3 is a very exciting and influential project, because it is the first certified Passive House retrofit in the United States. It has taken building envelope efficiency further than any of our other deep retrofit project homes. Similar to a number of other deep retrofits, P3 has served as a regional model for DERs, having hosted numerous tours, publicity outreach efforts and conference presentations by the design and construction team. Two existing 1958 ranch homes in the town of Sonoma, totaling 1,933 square feet, were originally connected by a covered breeze way. In 2010, these two structures were combined into one U-shaped Passive House of 2,342 square feet. The homeowner wanted to make a sustainability statement for future generations, and found the design and construction team that would do all that they could to help achieve these goals. There is one occupant, three bedrooms, two baths and a home office.

The design of P3 as a Passive House retrofit was challenging for a number of reasons. Passive House design requires exceptional heating energy performance, which is typically achieved using superinsulation, extreme airtightness, mechanical ventilation with heat recovery, non-traditional heating/cooling equipment, and renewable energy technologies. These design constraints have often resulted in architecturally crude, "box"-like structures with very few windows, which are often uninviting. In contrast to this, P3 presents a homey and somewhat complex geometry, the result of the existing structural constraints, with nearly maximum envelope surface area to house volume ratio, and fairly large areas of fenestration. This required greater effort in design and construction to achieve Passive House performance than would be typical in the thermally forgiving climate of Sonoma County.

With these limitations and opportunities in hand, integrated design planning began to take place between the contractor, designer, homeowner and Passive House consultant. The energy modeling efforts undertaken in this project are noteworthy. In an attempt to find the best balance between buildability, cost and performance, 76 full iterations of the home's envelope details were simulated using the Passive House Planning Package (PHPP). This process gave the designers a very good sense of exactly what performance attributes they were trading with the decisions they were making.

Building Enclosure
P3 has achieved exceptional building envelope performance. A residential exterior membrane outside insulation technique, or REMOTE, wall system (Cold Climate Housing Research Center, 2002) was used throughout on the exterior, with a fully continuous exterior air and moisture barrier integrated between the walls and roof. Walls are a mix of 2X4 and 2X6 construction, all of which are filled with blown fiberglass insulation, with 2" of expanded polystyrene (EPS) foam board to the outside of the air/moisture barrier. The siding is then back ventilated using pressure treated wooden furring strips over the foam board. No mechanical, electrical or plumbing utilities (MEPs) were run in the exterior walls for purposes of insulation continuity and air sealing; instead a cavity was provided for them to the inside of the interior air barrier.

The two existing slabs were on slightly different levels, but they needed to be joined and continuous in the new structure. Insulation layers were built-up on each slab to thicknesses that would allow them to meet on the same plane with plywood sub-flooring. Floor #1 used 1.5" of

EPS with a 0.6” layer of Aerogel, and floor #2 used two 2” layers of EPS. These were then covered with two layers of plywood sub-flooring, with finished hardwood on top. All slab perimeters were insulated using 3.75” of mineral wool board insulation. The attic uses a similar system to the walls, with 15” of blown fiberglass against the underside of the roof deck, continuous air and moisture barrier on top of the roof sheathing, followed by 3.5” of EPS. The windows and doors are imported from Germany and are triple pane, highly insulating wood framed units with U-values between 0.095 and 0.125, and SHGC values of 0.52-0.53.

Air Leakage
As the Passive House standard requires a maximum air leakage requirement of 0.6 ACH_{50}, extreme care was taken in every detail of this home to eliminate air leakage. In addition to the REMOTE wall system, all penetrations through the building enclosure were minimized, and those that were unavoidable were carefully detailed for airtightness. Air infiltration was avoided at all costs, this included installation of a condensing, unvented dryer, and the use of an air admittance valve as opposed to an open pipe sewer vent, which eliminated the need for roof penetrations.

Ventilation, Heating, Cooling and DHW
P3’s mechanical systems are non-traditional, relying on a variety of heat and energy sources, as well as distribution methods. This makes describing them difficult, because their functions are mixed and intertwined with other building services, such as ventilation or domestic water heating. This same feature can sometimes make their controls quite complicated and challenging for the occupant to understand. Passive House design attempts to eliminate traditional comfort systems through very aggressive envelope measures, and as a result, there is no traditional, central furnace or air conditioner in P3. Yet, P3 pursued comfort through very different methods than P1, which was also designed to the Passive House standard. Whereas P1 used a very simple and inexpensive system of baseboard electric radiators, P3 has two primary space conditioning systems: a mini-split air source heat pump and an Energy Recovery Ventilator (ERV) with a solar-fed hydronic heating coil on the ventilation supply to the house.

The designer and contractor thought that the mini-split heat pump would serve as a rarely or never used back-up conditioning source, which would only be needed on the hottest or coldest days to supplement the home’s passive design and solar-assisted ERV. However, in the home’s first heating season, this did not prove to be the case, as the mini-split heat pump was needed on a daily basis to maintain the homeowners desired comfort levels in the home. Unfortunately, further complications were encountered due to the placement of the mini-split wall unit, or head.


Figure 45 - Wall unit of mini-split heat pump. Source: www.drenergysavervirginia.com

Many homeowners do not want the wall units to be visible, due to aesthetic concerns (see Figure 45 above). In addition, the project designers thought that this unit would never be used, so they placed it in a very constricted ½ bathroom with a typically closed door. This setup may have proved acceptable, but the thermostat placement further complicated the system. While the interface thermostat is in the central living area, the actual controlling temperature sensor is located on the heat pump head itself. So, short-cycling would occur, as the heat pump would heat the air to the set point in the very small ½ bath, while the rest of the home remained uncomfortably cool. This issue was further complicated with only one method provided for heat distribution, the ERV. An ERV air return was provided in the ½ bathroom, which designers hoped would help distribute the conditioned air to the rest of the home. Of course, this air had to first pass through an ERV, which would immediately discard 10% to 20% of the heat with the exhaust air stream. Needless to say, this strategy did not prove effective. Electric resistance space heaters were required for a few months during the first heating season, while the heat pump head was moved to a more central, open area in the home. This relocation appears to have solved the problems encountered during the first heating season. Additionally, an ethanol burning space heater was installed in the master bedroom.

P3 used a number of renewable energy systems in its design. As alluded to earlier, a solar thermal water heating system was installed, using three roof-mounted evacuated tube solar collectors. The solar heated water is stored in an 80 gallon insulated storage tank, with a back-up instantaneous natural gas boiler for domestic hot water. The solar heated water also serves as a pre-heat for the hydronic heating coil in the ducted ERV supply. The performance of this solar water heating system is being monitored separately by Davis Energy Group as part of the Building America program.

Appliances

There is a large double door refrigerator in the kitchen, as well as the owner’s old refrigerator in the garage. The second refrigerator is an unnecessary MEL. Refrigerator replacement programs have found that many homeowners do the same, simply put the old one in the garage, which is why most programs require pick up of your old refrigerator in order to qualify for the rebates on a new, more efficient one. Needless to say, we recommend against maintaining old refrigerators alongside new ones in DERs. There is a gas oven and range, a microwave, a dishwasher, a front-loading clothes washer and a condensing electric dryer. All new appliances are Energy Star labeled.

Plug Loads
The project is typical of the other high-end DER projects in this study, in that plug loads, particularly for A/V and networking equipment, remain a sizeable load in an otherwise exceptionally efficient home. The homeowner works from home and has a large A/V and server rack in the den, one large LCD flat screen and two other televisions. There are two computers in the office, a printer and a fax/scanner. The landscape and garden has an irrigation system, and a fountain pump is always on in the courtyard.

Lighting
This home has more lights than any other case study. They are a mix of LED and CFL. Part of the problem is that the living room lights are controlled by one switch but include over a dozen fixtures. So although they are highly efficient, the quantity results in a significant load.

Renewables
A 2.15 kW photovoltaic system was installed on top of the garage. PG&E made the connection after we began our monitoring, which required us to reconfigure our equipment, unfortunately resulting in some lost data.

Additional Information
The construction quality was most impressive in P3. The greatest level of attention to details and proper implementation was inherent in every aspect of the project. Additionally, it was a true collaborative design process where the contractor, architect and building scientist/Passive House consultant all worked together with the client from the beginning. Although costs of individual projects were not evaluated in this research, P3 was observably the most expensive.

4.3.2 Building Diagnostic Results

Blower Door
Not only did P3 achieve the challenging Passive House standard for air infiltration, but is also the tightest home of the study, and more than twice as tight as the other homes considered to have low air leakage. The construction quality and the REMOTE wall system implemented both prove to be very effective at reducing air leakage.

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH
P3	151	0.43	0.02	0.06	8.30	0.02

Table 15 - P3 Blower Door Results

Duct Leakage
Leakage of the fully ducted ERV system was tested by a HERS rater, and the total leakage was less than 6% of the rated airflow. We could not get an exact value from the rater.

Ventilation Airflows
The 62.2 whole house mechanical ventilation requirement for P3 is 46.1 CFM, which is 0.13 ACH. nACH predicted from the blower door test was 0.02. Davis Energy Group performed diagnostics and monitoring on the ERV unit, including airflow measurements of all supply and exhaust inlets and outlets, as well as the outside intake and outlet, with the unit on high. The register airflows sum to a total supply airflow of 181 CFM and total exhaust of 184 CFM. Measurements at the outside intake and outlet were different than summing the registers. Reasons could include leakage inside the unit, house pressurization by wind or intake duct leakage. With the unit on high, none of the bathroom or kitchen airflows meets the intermittent operation requirements of 62.2. P3 does not use a kitchen range hood exhaust to outside, so it would be required to provide continuous 5 kitchen ACH of exhaust, which would be 172 CFM. Bathroom exhausts may meet the 20 CFM continuous bathroom option in 62.2, but the airflows were not measured.

ERV Airflow	**Exhaust or Supply**	**Airflow (CFM)**
East Bathroom	Exhaust	30
Laundry Room	Exhaust	36
Kitchen	Exhaust	40
Powder Room	Exhaust	40
Master Bathroom	Exhaust	38
Total	*Exhaust*	*184*
Bedroom 1	Supply	28
Den	Supply	31
Living Room	Supply	35
Craft/Family Room	Supply	32
Master Bedroom	Supply	34
Master Bedroom Closet	Supply	21
Total	*Supply*	*181*
Outside outlet	***Exhaust***	***190***
Outside Intake	***Supply***	***173***

Table 16 - P3 Ventilation Airflow Measurements

4.3.3 Monitored data results

Whole House Energy Use

P3 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e
12,383 kWh	4,534 kWh	2,449 lbs
Occupants	Area	HERS Rating
1	2,357 ft^2	25

Figure 46 - P3 Mileage Box

Annually, P3 used 4,534 kWh in net-site energy and 12,383 kWh in source energy, with CO_2e emissions of 2,449 pounds. No pre-retrofit data were available for assessing reductions in energy use for P3. Instead, we compare the project to the CA average single family home, which uses 20,061 kWh net-site energy, 36,737 kWh net-source energy and 9,346 pounds of CO_2e. In comparison, P3 used 77% less net-site energy, 66% less source energy and 74% less CO_2e emissions. Another means to objectively assess its performance is by HERS score, which was 25. This suggests the home would use 75% less energy than the HERS reference home. P3 is a home that used electricity for space conditioning, but unlike P1 and P2, its loads were so low that the source energy penalty did not reduce overall net-energy performance.

Monthly electrical and gas energy consumptions are shown in Figure 47. Notably, the home never produced more energy on a monthly basis than it consumed. Very little seasonality is apparent in the data, which suggests that space conditioning energy is contributing very little to the overall consumption pattern. This is consistent with the goals of a Passive House. The lion’s share of the home’s energy use is electricity, as the only gas loads are the solar assisted hot water with one user and a gas dryer, also infrequently used. The monthly usage appears to have flat-lined in March through May of 2012, which could suggest a vacation period; the occupant has another home elsewhere in the state.

In addition to end-use monitoring as part of this project, P3 was also monitored by another Building America team—Davis Energy Group—who performed detailed assessments of building system performance, including solar hot water, hydronic coil in ERV supply duct and others. This report will be accessible from the Building America website in the future as “Sonoma Deep Retrofit Technical Report.”

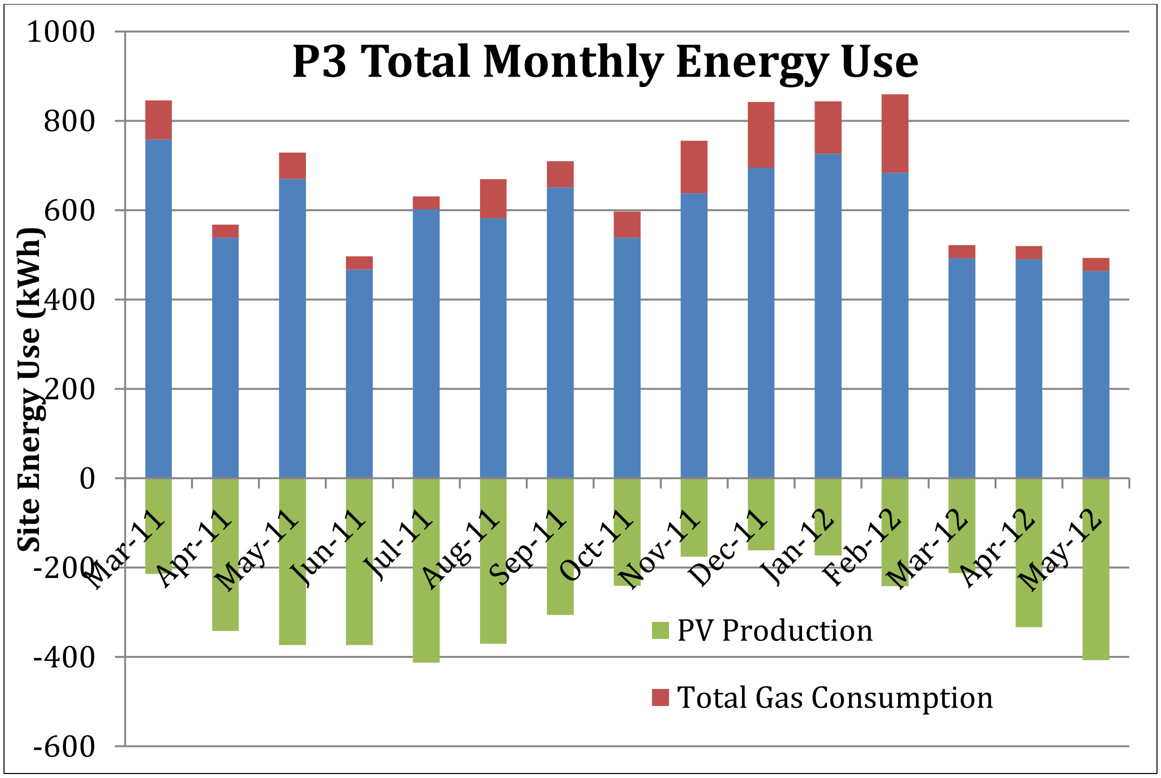


Figure 47 - P3 Total Monthly Energy Use

The P3 whole house electricity consumption, net-usage and PV production hourly profiles are pictured below in Figure 48, Figure 49 and Figure 50. Whole house electricity consumption rarely drops below 341 watts during any month of the year, which suggests a substantial baseload. Peaks are apparent during the awake hours, but with no obvious dip mid-day, which is consistent with our understanding that the home is occupied all day via the home office. The hourly net-electricity profile never drops below zero for any hour of the year. So, on average the household demand exceeds the production of the PV system even during peak system output. Peak PV output is 1,600 watts on average during June.

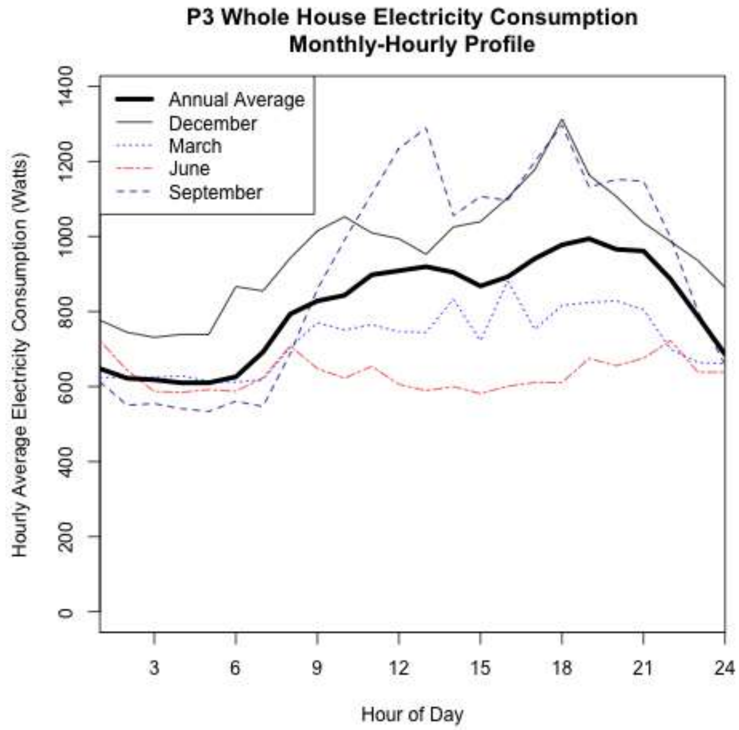


Figure 48 - P3 Whole House Electricity Consumption, Monthly-Hourly Profile

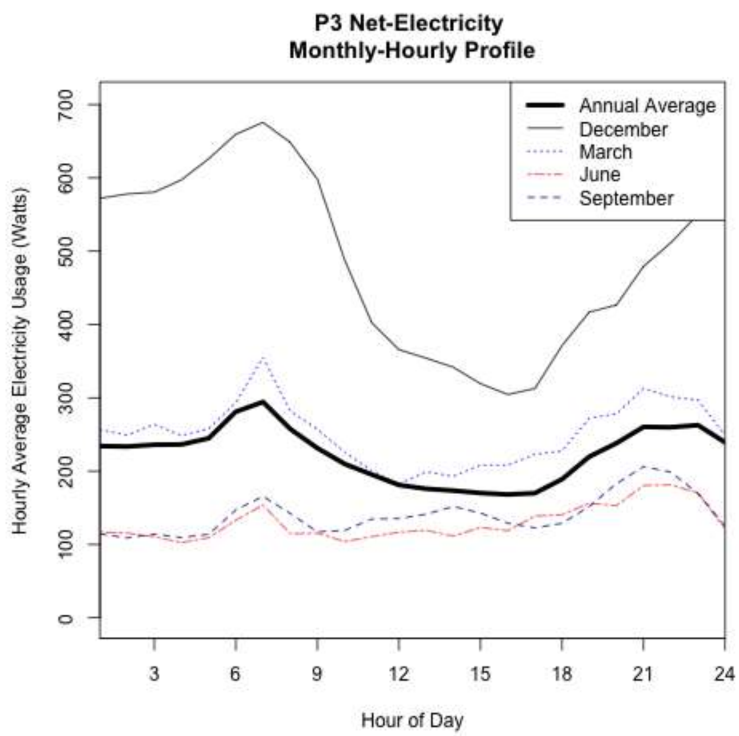


Figure 49 - P3 Whole House Net-Electricity, Monthly-Hourly Profile

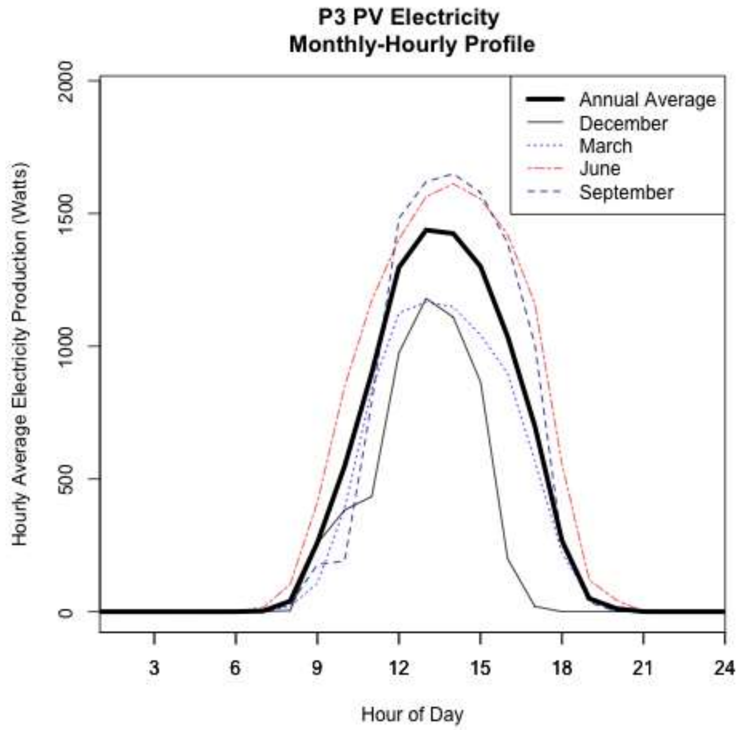


Figure 50 - P3 PV Electricity Production, Monthly-Hourly Profile

End-Uses

Annual energy end-uses summaries are provided in Table 17 and Figure 51 below, and monthly end-uses are pictured in Figure 52. In contrast to most other project homes, space heating (includes both heating and cooling from mini-split heat pump) is actually the single smallest energy end-use in P3. In fact, when heating, cooling, hot water and ventilation energies are combined, they are less than half of the combined usage of the plugs, lights and appliances. The energy model built of P3 actually under-predicts space conditioning, hot water and ventilation energy and it over-predicts other uses. Annual net-site usage is over-predicted by 22.2%. P3 is a good illustration of how end-uses can be distributed in very energy efficient homes, with miscellaneous uses accounting for just over 75% of total usage. But this is in the context of a home that uses a lot of energy for plugs, lights and appliances. If these uses were more like those in P1 or P4, the energy split would still be around 50/50.

	P3 Actual	P3 Modeled
Floor Area	2357	2357
# of Occupants	1	1
Heating and Cooling	576	144
Cooling	0	24
Central Air Handler(s)	0	0
Hot Water	751	825
Ventilation	841	275
Combined HVAC and Domestic Hot Water	***2168***	***1268***
Appliances	1786	3057
Lights	1903	632
Plug Loads	2081	3547
Combined Appliances, Lights and Plugs	***5375***	***7236***
Annual Total	***7543***	***8504***
PV Production	3405	3187
Annual Net	***4138***	***5317***

Table 17 - P3 Site Energy End Use Summary

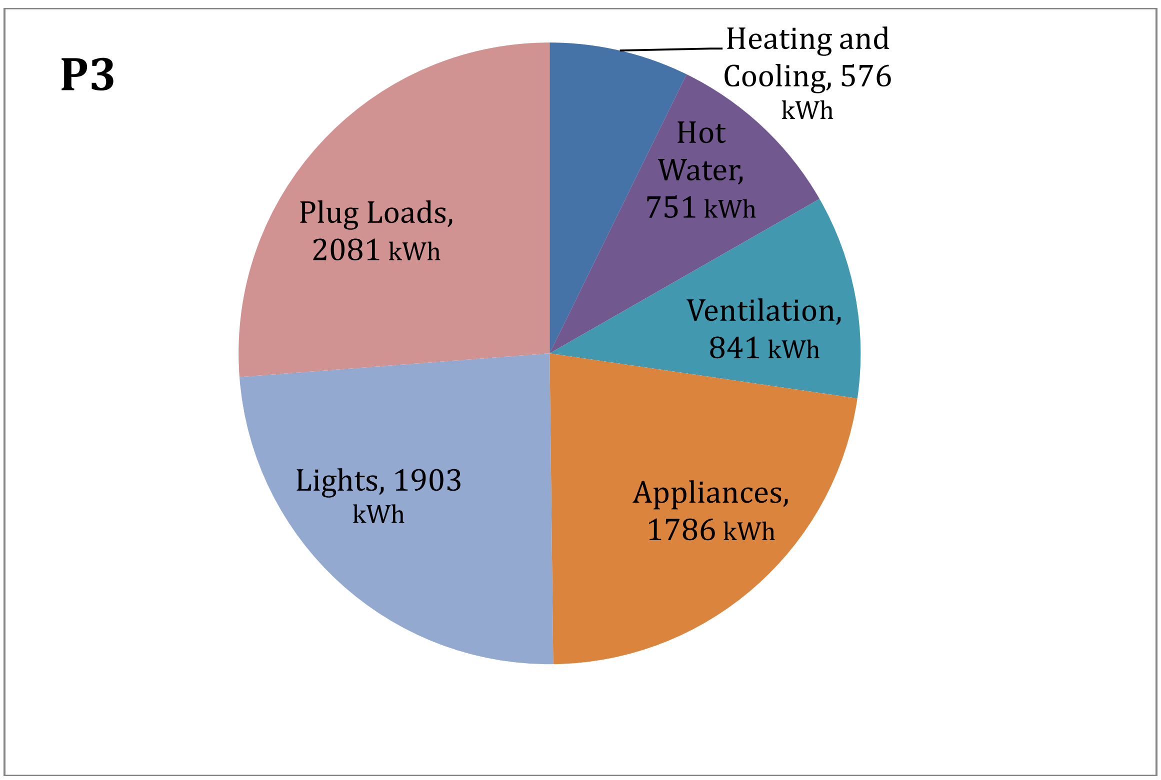


Figure 51 - P3 Annual Energy End-Uses

The monthly end-uses pictured in Figure 52 show almost no seasonal variation, with the exception of the hot water usage, whose months of low consumption corresponds with high solar fractions during spring, summer and early fall. The large peak in December and January of 2010/11 are when the mini-split heat pump was not meeting the load (see above) and plug in resistance space heaters were used. Plugs are consistently the highest energy use in the house, but it is noteworthy that these included our monitoring equipment as well as that of Davis Energy Group, which totaled 45 watts or approximately 32.5 kWh per month.

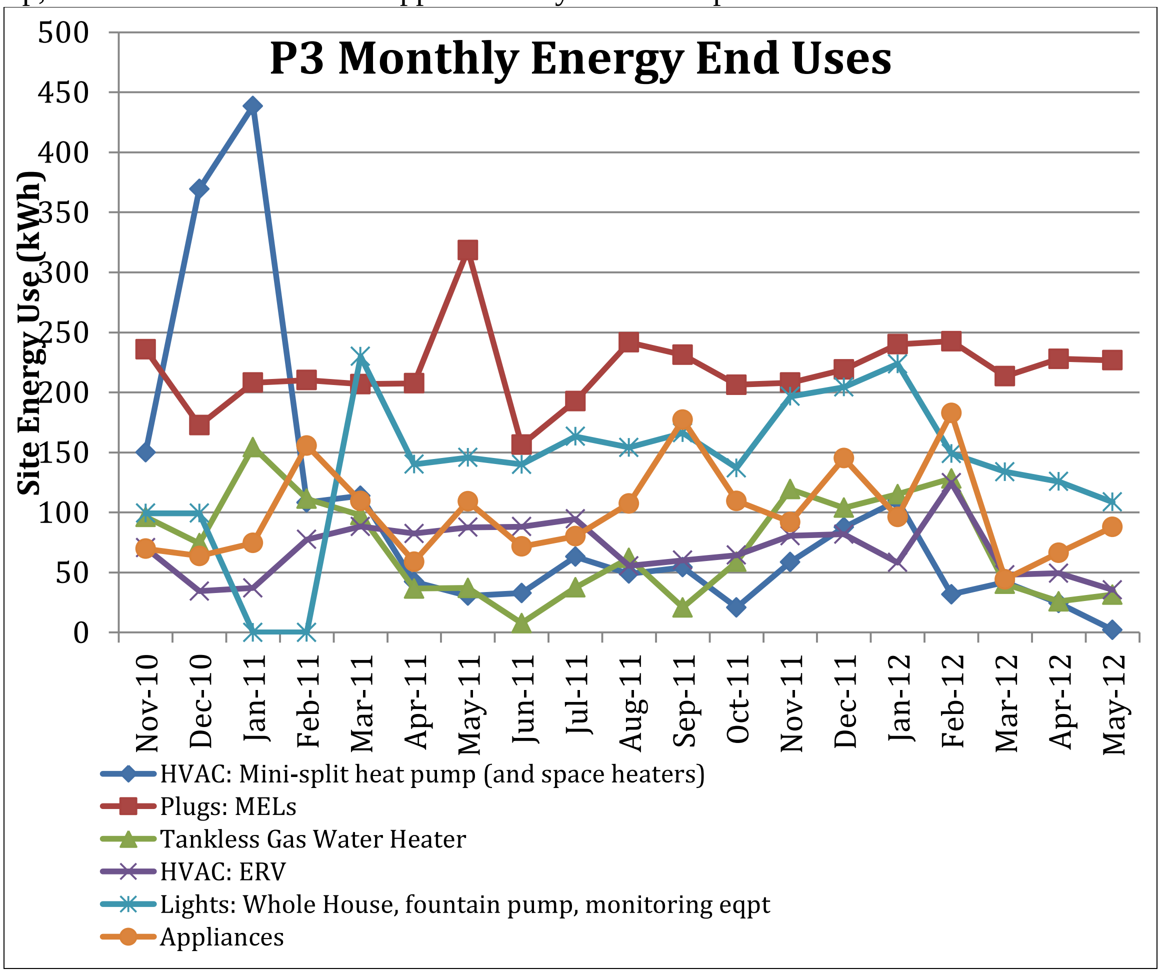


Figure 52 - P3 Monthly Energy End-uses

User Behavior

The baseload in P3 is the second highest of all the case studies, averaging 341 Watts, for an estimated annual total usage of 2,983 kWh. This is 66% of the total net-site energy usage for the year. In other words, almost ¾ of the total energy use of the home came from loads that essentially were never turned off. This is consistent with the very small peaks seen in the load profiles pictured above.

P3 combines an ultra-efficient building envelope with a substantial baseload, which means the home’s energy performance could be significantly improved with relatively simple solutions. The second refrigerator is a significant load that could be easily eliminated, especially with one occupant. Due to the fact that this home also serves as a home office, a significant portion of the MEL load is dedicated to the servers, computers etc. Nevertheless, these could be targeted for substantial reductions. Also contributing to the baseload is the continuously operating ERV, which uses an annual average 96 watts. If the baseload were similar to P1 (also with ERV and home office), then the annual energy use of P3 would be further reduced by 34.7%.

Temperature and Relative Humidity

The monthly Master and Guest Bedroom temperature and relative humidity means and standard deviations are presented in **Error! Reference source not found.** below. Monthly mean temperatures in P3 varied between approximately 69 and 78 degrees F. Significant increases in average temperature occurred from April to October, which reflects the modest cooling climate of Sonoma, CA. Monthly mean relative humidity varied from approximately 34% to 50%. The monthly mean relative humidity in P3 was solidly in the desirable 30-60% range.

The temperature differences between the master and guest bedrooms are pictured in Figure 53 below. They are approximately normally distributed around an average temperature difference of 1.1 degrees F. Consistent, comfortable interior temperatures are claimed as a benefit of Passive House construction. These results suggest that consistency was achieved, with only a few hours of the year having temperature differences greater than plus or minus 2 degrees. ACCA recommends temperature differences of less than +/- four degrees for single-zone systems in both heating and cooling, and P3 was within this requirement for 99.7% of the year. This is particularly commendable in a sprawling, u-shaped 2,357 ft^2 home with a single, point-source conditioning system. Superior comfort was unquestionably provided in this DER.

P3 Summary of Temperature and Relative Humidity by Month								
	Temperature				Relative Humidity			
	Guest Bedroom		Master Bedroom		Guest Bedroom		Master Bedroom	
Month	Mean	SD	Mean	SD	Mean	SD	Mean	SD
January	70.3	3.3	70.6	3.1	38.0	5.2	37.8	5.1
February	70.2	1.8	70.9	1.9	39.9	4.8	39.1	4.7
March	69.9	3.7	70.9	3.8	40.8	5.2	40.0	5.5
April	72.8	2.4	73.6	2.3	42.4	4.1	41.8	4.5
May	75.3	1.5	76.1	1.5	42.3	2.4	41.1	2.6
June	75.1	2.5	76.7	2.8	46.4	2.3	45.0	2.5
July	75.5	3.4	77.2	3.4	48.0	3.1	46.5	2.8
August	75.9	0.8	78.2	0.7	49.8	1.3	47.5	1.1
September	76.9	1.1	78.3	1.0	47.5	1.9	46.3	1.7
October	74.1	1.2	75.5	1.2	49.2	4.2	48.3	3.5
November	69.9	2.8	70.6	2.8	42.3	4.7	42.0	4.9
December	68.9	3.2	69.4	2.9	33.7	6.5	33.1	6.1

Table 18 - P3 Summary of Temperature and Relative Humidity by Month

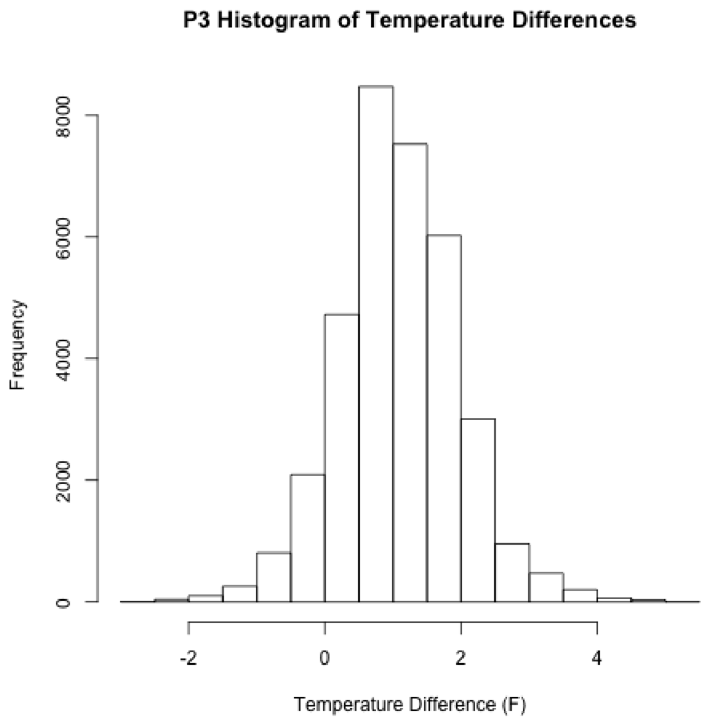


Figure 53 - P3 Histogram of Interior Temperature Differences

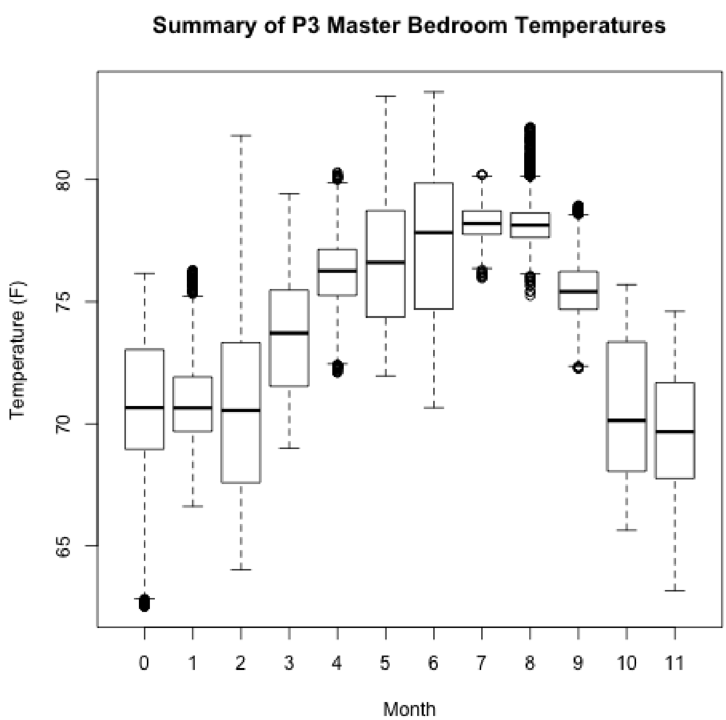


Figure 54 - P3 Summary of Master Bedroom Temperatures

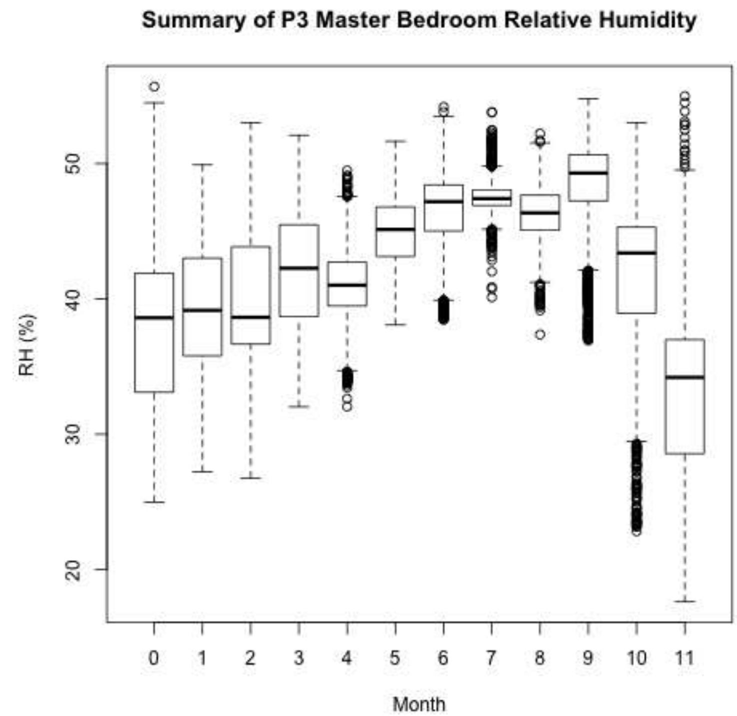


Figure 55 - P3 Summary of Master Bedroom Relative Humidity

Indoor temperature/relative humidity is recommended to be maintained within a range of 30-60%. The percentage of time that P3 spent below, within and above that range is summarized in Table 19 below. No time periods had RH in excess of the recommended range, and only ~3.5% of the time was spent below the range. As can be seen in Figure 56 and Figure 57, the indoor RH was within the recommended range for the vast majority of the year. This consistency is likely the result of continuous, humidity-controlled ventilation, as well as the home's low occupancy, with only one person generating moisture from showering, cooking, etc.

Proportion of Time Relative Humidity was Below, Within and Above the Recommended Range			
Location	**Below 30%**	**30% to 60%**	**Above 60%**
Master Bedroom	4%	96%	0%
Guest Bedroom	3%	97%	0%

Table 19 - P3 Proportion of Time Relative Humidity was Below, Within and Above the Recommended Range

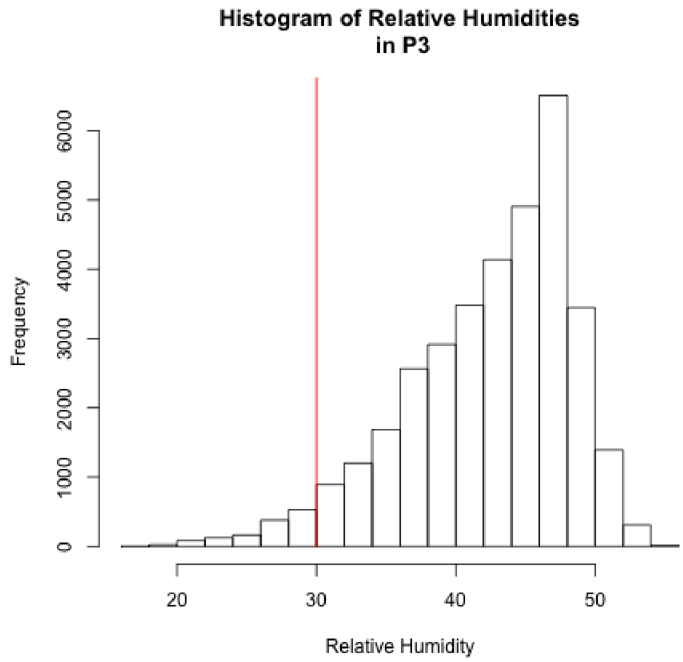


Figure 56 - P3 Histogram of Master Bedroom Relative Humidity

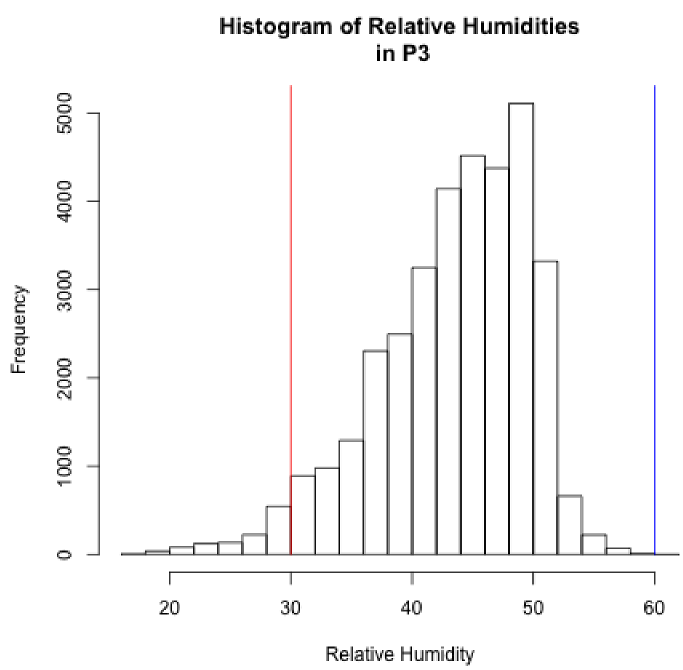


Figure 57 - P3 Histogram of Guest Bedroom Relative Humidity

4.3.4 P3 Overview

The P3 Passive House retrofit was wildly successful at creating a low space conditioning, hot water and ventilation energy home. Its interior temperatures were extremely consistent, providing continual comfort without periods of over-heating and cooling. This was done in a sprawling, single story home, with only a point-source for comfort and lots of surface area per volume. It was less successful at reducing miscellaneous energy uses, which ended up accounting for greater than ¾ of the total consumption. This project demonstrates the levels of efficiency that are required to produce a high performance home with an occupant who does not make behavioral modifications. We think that the two can meet somewhere in the middle, for a lower cost, less complex deep retrofit that still provides superb comfort.

Some equipment performance issues were observed that are troubling. The location and performance problems of the mini-split heat pump shows that even in a Passive House, mistakes are made, commissioning is essential and complex systems will likely require some coaxing to function properly. The clogging of the ERV supply air inlet was also troubling, particularly in a context where this unit almost exclusively provides air exchange, due to extreme airtightness. The reliability and long-term performance of ventilation systems is critical in Passive Houses and other extremely airtight homes. The clogging of the ERV inlet has become a perpetual maintenance issue, which may go unnoticed by future occupants, resulting in air quality problems.

The high MEL loads from the irrigation and fountains, as well as the excessive lighting fixtures, the second refrigerator, and the A/V and server rack again resulted in higher than expected energy consumption. P3, similar to P2, demonstrates that a focus only on efficiency leaves substantial GHG emission reductions from reduction of MELs off the table. These are the easiest and cheapest reductions to implement, and they should be the starting point in any deep reduction project.

P3 represents one extreme of the DERs in this case study; it is a very efficient luxury home, and sets a high bar for construction quality of DERs in the Bay Area. However, it still leaves something to be desired in regards to energy conservation. Despite this, the overall performance of P3 is very impressive, and is the only project that provides a solution to deep energy reductions independent of user behavior.

4.4 P4

4.4.1 P4 Project Description

Image 10 - P4 Pre- and Post-Retrofit

P4	Pre-Retrofit	Post-Retrofit
ENVELOPE		
Wall Insulation	None	1: 5.5" Dense pack cellulose – R19 2: 3.5" Dense pack cellulose – R13
Attic/Roof Insulation	None	12" loose fill cellulose – R43
Foundation Insulation	None	Stem wall: 1.5" XPS – R7 exterior
Windows	Single pane aluminum frame	2 pane, Low E, argon filled, fiberglass frame U: 0.32 SHGC: 0.3
Air Leakage		1,983 CFM_{50}, 5.4 ACH_{50}
MECHANICAL		
Heating and cooling	Gas furnace, 40% EF	Condensing Gas furnace, variable speed fan, 2 stage gas valve, 96.1 AFUE, 200ft^2 of SolarWall with 500CFM supply fan
DHW	Gas tank, 58%EF	Condensing gas tankless, 80% EF, demand recirc pump
Ventilation	Kitchen exhaust, vented to inside	Bath and kitchen exhaust, natural vent stack in stairwell, SolarWall 500CFM fresh air supply fan
Distribution	Sheet metal ducts	Manual central dampers added to ducts, supply leakage: 61CFM Return leakage: 99CFM
LIGHTS/APPLIANCES/MEL	All incandescent lights, old appliances	CFL and LED lights, top 10% energy star appliances, home office, very low MELs
RENEWABLES	None	2.5 kW PV

Table 20 - P4 Retrofit Summary Table

General Information
P4 is a bungalow-style home in Petaluma, CA, which has undergone a 3-stage DER that has unfolded over the past 10 years. The ultimate goal of the homeowners is for their home to be carbon neutral. The occupants chose to buy and retrofit an existing home in a walkable community with the intention of lowering their carbon footprint. This home was originally constructed in 1940; when the owners purchased it in 1998, they decided to do an energy retrofit prior to moving in.

The homeowner in P4 is an architect with a particular focus on energy efficiency, and he has used his own home as a test bed for strategies and technologies to reduce energy use. He also regularly gives presentations about his home, in order to instruct and inspire others who are pursuing deep energy reductions. P4 is a good example of a home where goals other than energy savings—such as health, sustainability, materials re-use, water efficiency and greywater re-use were also pursued. These multiple goals drove the retrofit process along with energy.

As part of the initial retrofit, the entirety of P4 was insulated and air sealed and the HVAC equipment and hot water heater were replaced. At that time, the basement was turned into a home office for the owner's design practice. Using Energy-10 to model, the retrofit was predicted to reduce energy usage by 75%. The occupants were not satisfied with the energy performance of the home after this initial retrofit effort.

During the second phase, the homeowner made efforts to further improve the home's performance. An entire new roof structure was installed, which also allowed for a new innovative ventilation system, installation of solar PV, and extended overhangs for shading in the summer. The new ventilation system has a heating and a cooling season strategy, with different equipment serving each purpose. A large passive stack vent in the center of the home facilitates nighttime summer cooling with a turbine ventilator at the roof outlet. During summer nights, this vent stack is opened, along with windows, so that built up heat in the home can be purged. The PV panels are installed upon a *SolarWall* ('SolarWall PV/T', 2011), which is an enclosed cavity behind the solar panels that allows them to be back-vented. It also connects to the passive stack vent with the intention of increasing heat and therefore buoyancy to assist in extracting air from the house. However, PV performance did not increase, because much higher airflows were required to back-cool them effectively. The *SolarWall* on the roof also assists with wintertime ventilation as a pre-heat to the fresh air supply to the basement office and family room. The homeowner mentioned that the *SolarWall* tech support was awful; "the material was delivered before I got any tech support, they wanted a 1600 CFM fan to cool the panels, which used far more energy than it would have saved, so the whole product was sort of a bust" (P4 Homeowner, 2011). Instead of installing the fan, he used a wind-powered turbine, the overall efficiency of this system is not being monitored in the research project, and so the actual effectiveness is not known. Ultimately, the homeowner concluded that this solar pre-heat of the air was not as effective as was hoped in offsetting furnace gas usage.

In the third, most recent phase of the remodel, the owner made seismic upgrades and additional energy improvements to the home. A hydronic coil was installed in the furnace to facilitate future integration of the unit with a solar thermal system. A station for electric car charging was also installed, and a new Nissan Leaf began to be charged in May 2011. All areas that were disturbed by the seismic retrofitting were further air sealed. Inconsistency and gaps in the wall insulation were identified and filled in, and the attic insulation level was increased from R-30 to R-40.

A fourth stage is currently in planning, where the homeowners hope to install solar thermal panels and a back-up biomass boiler to service their hot water and space heating needs, leading to a carbon neutral home.

Building Enclosure

The existing structure was entirely uninsulated, and was suffering from termite and water damage in various places. Cellulose insulation was dense-packed into the 2X6 wall cavities in the basement and 2X4's in the main living space upstairs, plus 12" or roughly R-40 in the attic. The exterior of the foundation stem wall was insulated with 1.5", R-7 of Extruded Polystyrene (XPS) foam.

The original single pane aluminum framed windows were replaced with fiberglass framed, low-e double pane units, with a U-value of 0.32 and an unknown SHGC. One large window in the family room was not replaced, as it was cost prohibitive. An interior 3-layer honeycomb shade is used to control heat flow as a compromise. According to the homeowner, the windows were the best available at that time, without having to go through extremes (like ordering from Germany) to get them.

Air Leakage

Air leakage reduction measures were taken wherever possible as the retrofit progressed, but they were not the clear focus of efforts nor were specific goals or targets used. It proved difficult to air seal the attic for example, after it was insulated. The homeowner stated that if he were to do it all over again, he would start by addressing air leakage better from the beginning.

Ventilation

The bathrooms have Energy star exhaust fans, and the kitchen has a custom variable speed range downdraft. There is a natural vent stack in the stairwell with heating/stack effect assist from the *SolarWall* array (see Image 11 below), and a whole house fan that pulls 100% outside air, pre-heated by the *SolarWall* in the winter.

Image 11 - P4 View of Large Natural Stack Vent Duct at Top of Stairwell

Heating

With the envelope improved, the contractor installed a 96% efficient forced air gas furnace with variable speed ECM fan motor and a two-stage gas valve. Manual dampers were installed throughout the duct system in order to facilitate zoning efforts. The *SolarWall* and fan assembly on the roof creates solar heated air behind the PV panels; the *SolarWall* literature says it has an output when installed behind PV panels of 20-30 Watts/SF, and without PV panels of 50-60 Watts/SF (‘SolarWall PV/T’, 2010). A fan brings the additional heat created from the *SolarWall* to the basement office and second floor den.

Domestic Hot Water (DHW)

In the first phase, the owner replaced the existing tanked gas water heater with an atmospherically drafted, tankless on demand water heater, 80% EF, connected to an on demand recirculation pump (see Image 12 below). It is pre-plumbed for a future solar thermal combisystem, and the owner plans to use a biomass auxiliary boiler and eliminate this unit.

Image 12 - P4 Tankless Gas Water Heater in Garage, Atmospherically Drafted

Appliances
All top 10% Energy Star labeled appliances were purchased and the occupants/homeowners use a clothes line, with the dryer serving as a rare back up.

Plug Loads
Even though there is a home office, there are very low plug loads in the home. There are two computers, which get switched off daily, a printer, a modem and a backup server for storage. Efforts by the homeowner to reduce plug load energy included unplugging our monitoring equipment.

Lighting
All lights are CFL and LED, and controlled by switches.

Renewables
A 2.5 kW PV array was installed in 2004.

Additional Information
A few things are notable about this project: First, the staged retrofit approach allowed the homeowner to make smaller investments and learn from each phase, ultimately resulting in a very high performance DER. The progression of annual net-site energy usage from 2002 to 2011 is pictured in Figure 58 below. Second, is the effort to wring multiple benefits out of a single investment, such as the new roof and all of the added features embedded within it. Third, is the dedication of the occupants in the home to understand and pro-actively reduce their energy use. Energy monitoring and feedback were greatly appreciated by the homeowners, and have been used to further reduce energy loads in the home. For example, the continuous wattage draw of the furnace was quickly identified after monitoring began, and the homeowner unplugged the unit, which is not in use for ~9 months of the year. In addition, air leakage testing inspired a new

fervor for finding the remaining air leakage and duct leakage pathways. Multiple efforts were made to engage natural energy flows and take advantage of electricity and gas-free heating and cooling energy; mechanical solutions were often avoided in favor of lower tech strategies that engaged the occupants in operating the home. It may be that such engagement is required if we are going to reliably see 70% to 90% reductions in household energy use. P4 did not pursue super-insulation or extreme airtightness, yet it is a zero-net electrical[10] home because of very conscientious occupants. It is also the first building in northern California to achieve the Thousand Home Challenge. These homeowners are especially interested in understanding their energy use and have the goal of actively reducing it through a combination of behavior modification and appropriate technology. Conservation and behavior was made easier through unique designed solutions, such as the simple grey water recycling scupper at the kitchen window that feeds outdoor planter beds (see Image 13 below)

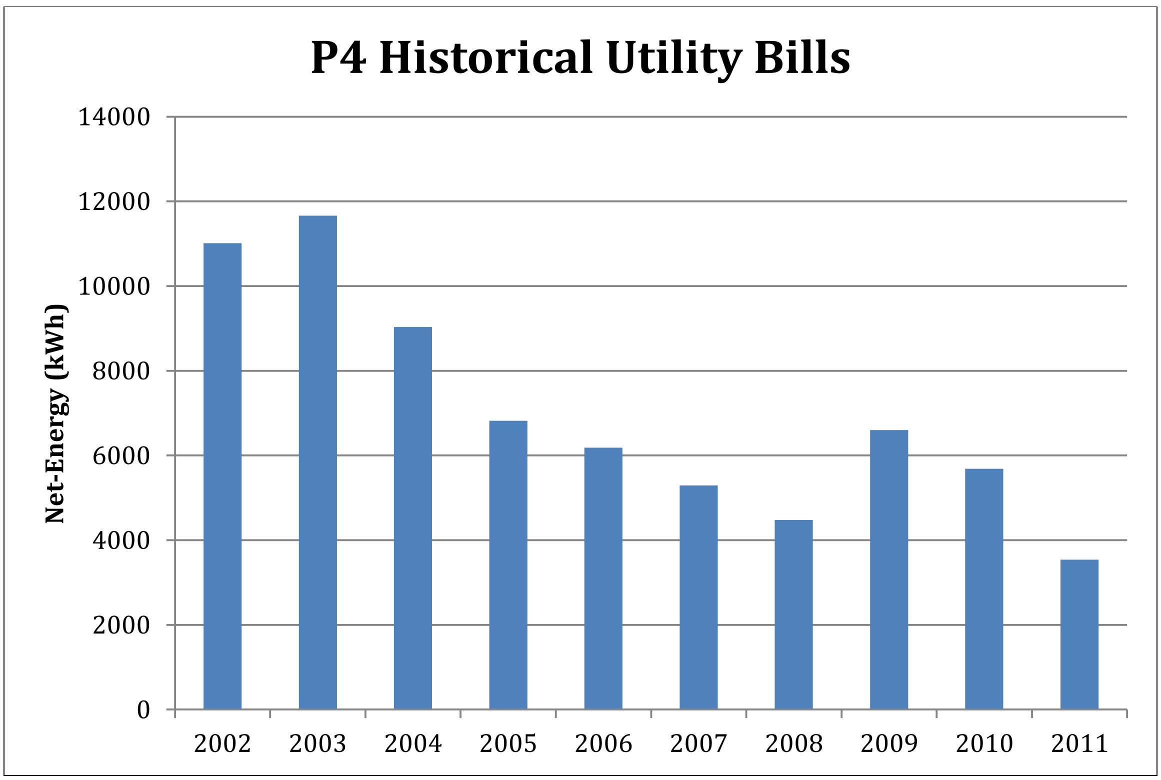


Figure 58 - P4 Historical Utility Bill Analysis

[10] A zero-net electrical home produces as much electricity annually as it consumes. Gas energy consumption is not considered.

Image 13 - P4 Simple Grey Water Collection System at Kitchen Window

P4 is an interesting project that has progressed at its own pace, the owner-occupants learning from its mistakes and growing in knowledge over time. In reflecting on the retrofit process, the homeowner noted: “Looking back it was done in a silly way, each phase I am making up for past mistakes, but there were also financial constraints. I didn’t start off with a master plan; I was doing the best I could do at the time” (P4 Homeowner, 2011). He also mentioned that it was a big challenge getting the contractors to understand the importance of high quality, energy efficient workmanship. This feedback reinforces the idea that a clear plan for achieving deep energy reductions is essential prior to beginning a project, and that experienced trades-people and contractors should be used wherever feasible.

4.4.2 Building Diagnostic Results

Blower Door

P4 is an interesting case study in regards to construction quality. Although the building enclosure is still very leaky, it is the lowest energy use home in our study.

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH
P4	1983	5.43	0.32	0.79	110.03	0.26

Table 21 - P4 Blower Door Results

Duct Leakage

Duct leakage testing could not be performed on P4, due to repeated wind issues. All ducts are located within conditioned space, so leakage to outside is expected to be low.

Ventilation Airflows

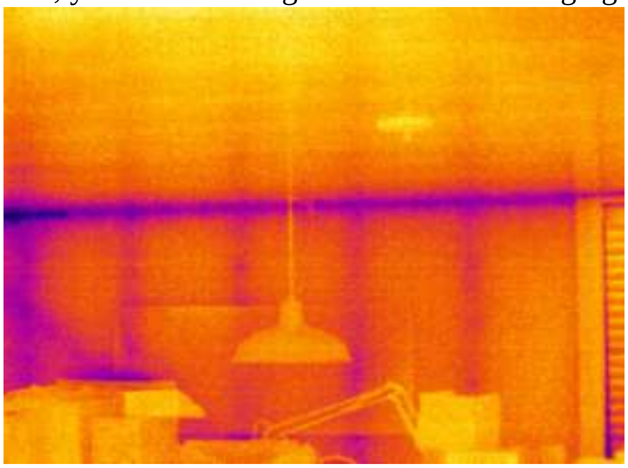
The 62.2 whole house mechanical ventilation requirement for P4 is 57.4 CFM. No continuous mechanical ventilation is provided. Airflows were measured in bathroom and kitchen exhaust fans. Both bathroom and kitchen exhaust fans meet 62.2 requirements at all speed settings. Additional supply air fans are used intermittently in the home, and these were not measured.

Fan Location	Fan Speed	Airflow (CFM)
Bathroom	Single	58
Kitchen	Low	244
Kitchen	Medium	333
Kitchen	High	385

Table 22 - P4 Ventilation Airflow Measurements

IR Thermography

The IR images below show a few of the issues encountered in the insulation installation and other thermal and air leakage locations at P4. Overall the building enclosure is what would be expected of a typical California home built to the Title 24 energy code. It is insulated relatively well, yet still shows significant thermal bridging and air leakage, visible in Figure 59-68.



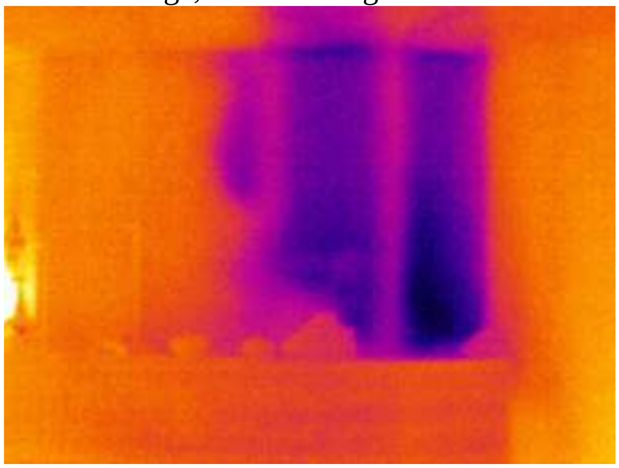


Figure 59 - P4 thermal bridges in office, and air leakage in corner Figure 60 - P4 missing insulation in chimney

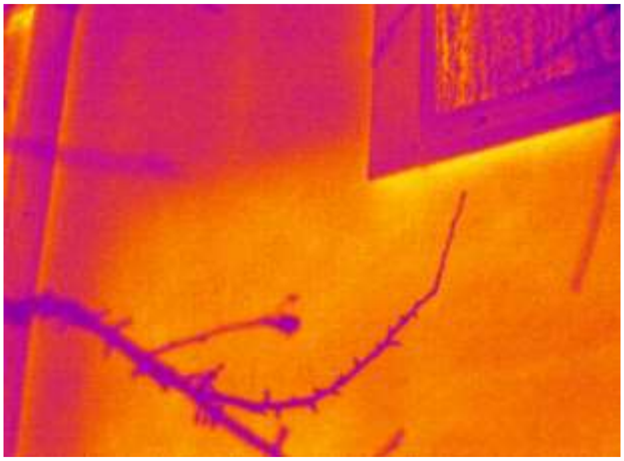


Figure 61 - P4 missed insulation in bathroom due to tiled wall

Figure 62 - P4 missed insulation around bathroom window

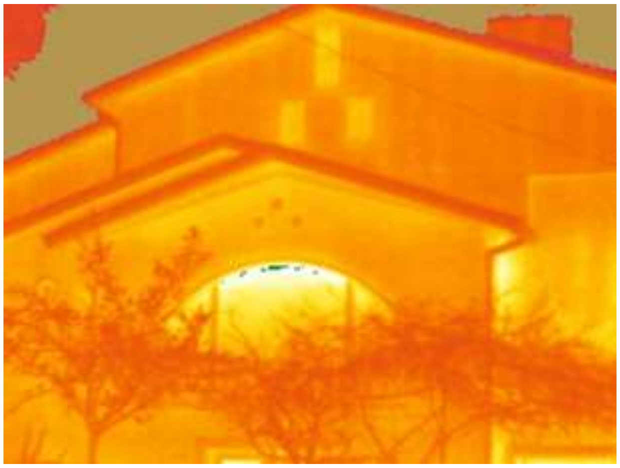


Figure 63 - P4 thermal leakage above honeycomb shade in living room

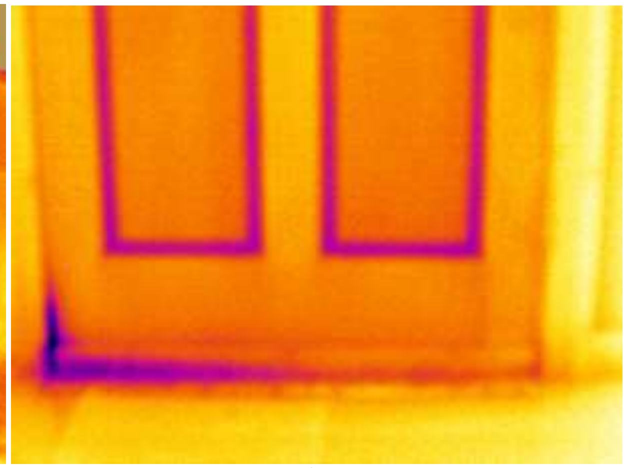


Figure 64 - P4 air leakage around front door

4.4.3 Monitored Data Results

Whole House Energy Use

P4 (Pre) - WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e
17,704 kWh	12,169 kWh	5,291 lbs
Occupants	Area	HERS Rating
2	1,540 ft²	-

P4 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e
685 kWh	3,214 kWh	1,069 lbs
Occupants	Area	HERS Rating
2	2,510 ft²	36

Figure 65 - P4 Pre- and Post-Retrofit Mileage Boxes

Pre-retrofit data were not available in P4, but we have used the annual energy usage after the Phase I retrofit to calculate reductions. Net-site energy was reduced from 12,169 to 3,214 kWh, for a reduction of 74%. Net-source energy was reduced from 17,704 to 685 kWh, for a 96% reduction[11]. CO_2e emissions were reduced 80%, from 5,291 to 1,069 pounds. For an additional comparison, the CA average single family home uses 20,061 kWh net-site energy, 36,737 kWh net-source energy and 9,346 pounds of CO_2e. In comparison, P4 used 84% less net-site energy, 98.1% less source energy and 88.6% less CO_2e emissions. Another means to objectively assess its performance is by HERS score, which was 36. P4 illustrates that with pre-retrofit homes that

[11] Post-retrofit net-source energy was actually less than net-site energy, which is counter-intuitive at first. P4 produced more electricity annually than it consumed, resulting in a negative net-site value for electricity, which when converted to net-source is approximately tripled. This increase in the negative electricity value exceeded the increase in net-source gas energy, resulting in an overall drop in usage during conversion from net-site to net-source. All other homes experienced net-increases when converting from net-site to net-source.

have fairly low energy use, installation of PV can be a key contributor to greater percentage reductions.

Monthly electrical and gas energy consumptions are shown in Figure 66. From May 2011 to October 2011, the home produced more energy on a monthly basis than it consumed. The monthly data is very seasonal, which shows the impact of heating energy on household consumption. Electrical usage is very consistent across the months, because heating loads are met with natural gas.

Monthly site energy consumption and net-site energy use are compared with the pre-retrofit (Phase I) data in Figure 67 below. Heating energy reductions from Phase I to Phase III are evident in the monthly total consumption data, whereas the PV clearly played the largest role in cutting electrical consumption. For example, without the PV energy, July through September are essentially identical from Phase I to Phase III. The net-production of PV electricity by P4 is what has allowed it to cut its source energy so drastically, as net-production is triple counted as a credit, just as net-usage is triple counted as a debit.

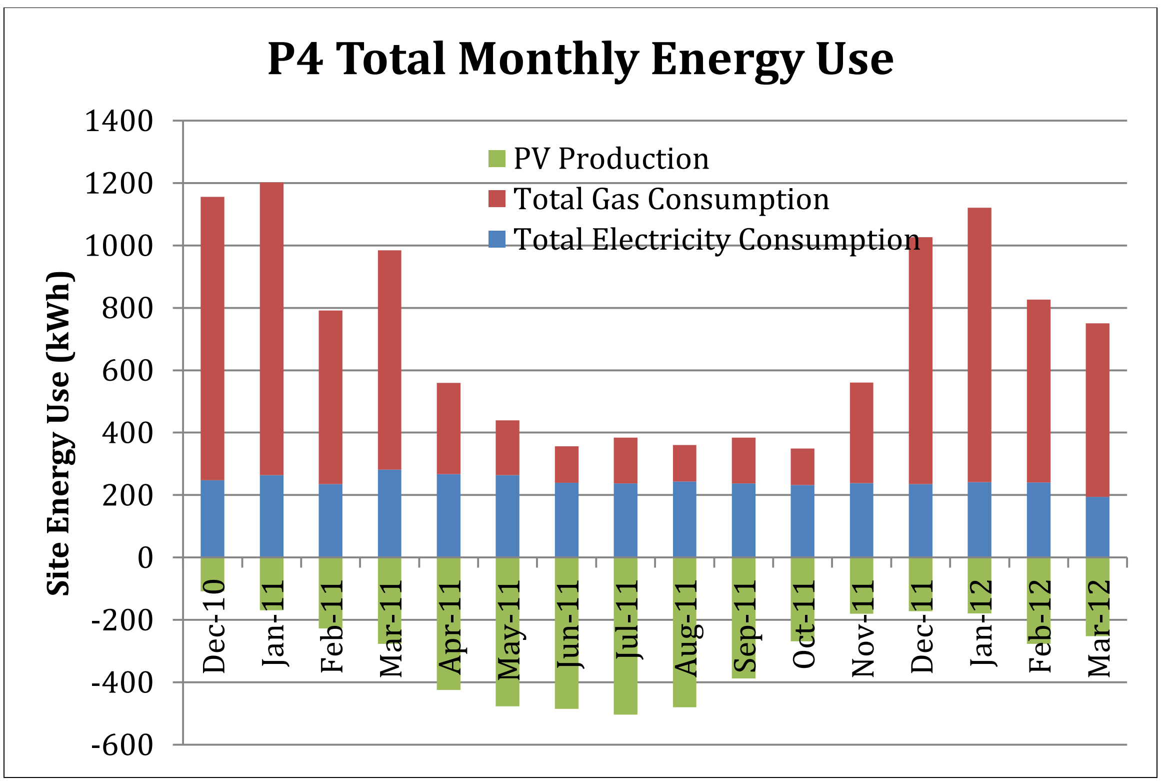


Figure 66 - P4 Total Monthly Energy Use

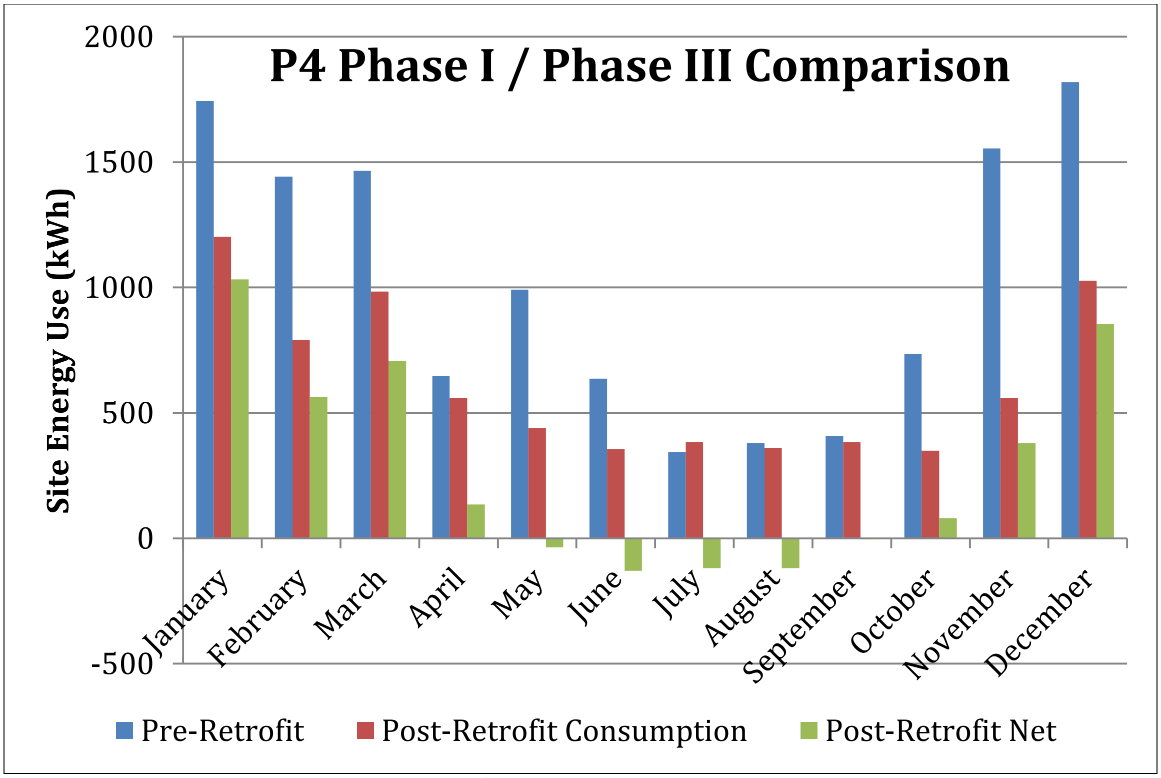


Figure 67 - Pre/Post-Retrofit Site Energy Comparison, Phase I and Phase III

Whole house hourly profiles of electricity consumption, net-consumption and PV production are pictured below in Figure 68, Figure 69 and Figure 70. The whole house hourly electricity profile does not change substantially from month-to-month, as all heating is done with gas. Two evident peaks occur at breakfast and dinner hours, suggesting typical usage patterns. The home seems to go into "off" mode overnight, with an average power consumption of ~200 watts. The net-electricity profile shows that the home exports energy on average during PV production hours every month of the year.

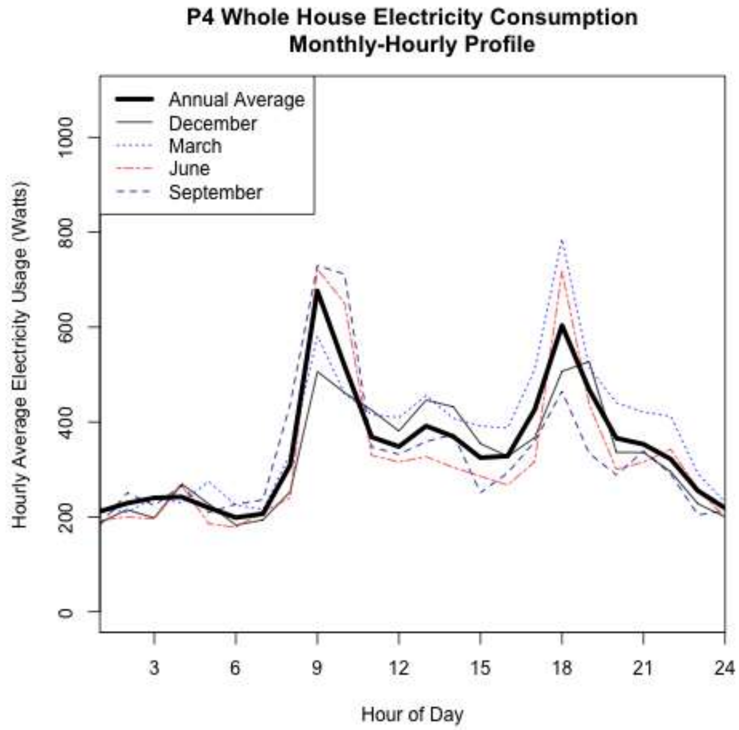


Figure 68 - P4 Whole House Electricity Consumption, Monthly-Hourly Profile

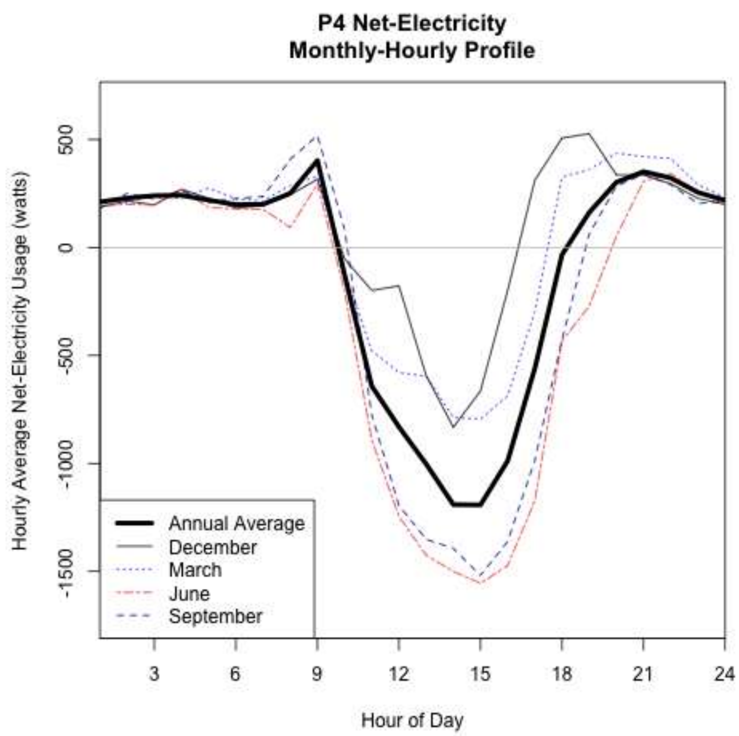


Figure 69 - P4 Whole House Net-Electricity Usage, Monthly-Hourly Profile

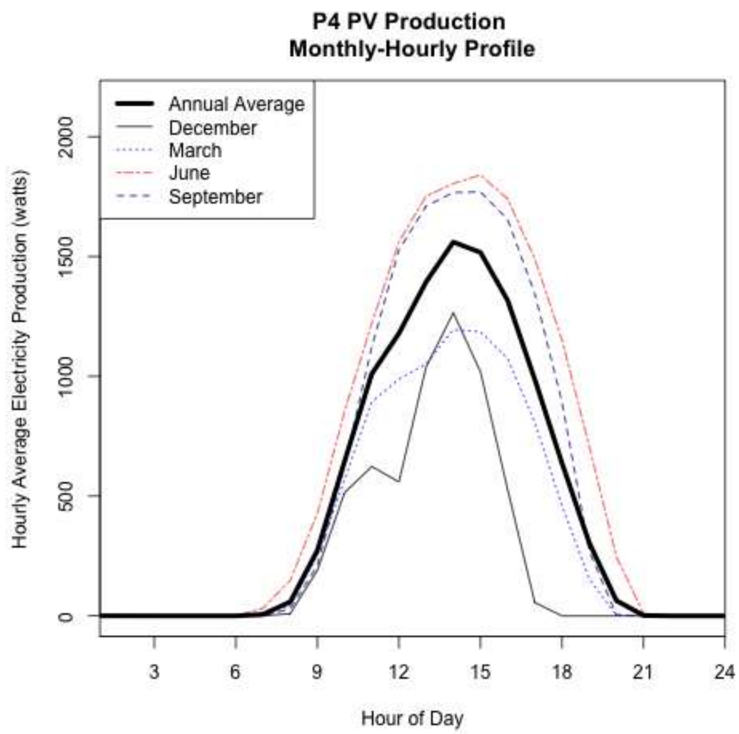


Figure 70 - P4 PV Electricity Generation, Monthly-Hourly Profile

End-Uses

Annual energy end-use summaries are provided in Table 23 and Figure 71 below, and monthly end-use data are pictured in Figure 72. Heating energy is the single largest end-use in the home, just barely greater than the combined plugs, lights and appliances usage. This is consistent with the home's code-level building envelope and the below average miscellaneous usage of P4. The electric car energy use is not included in these totals in order to be consistent across all case studies. The monthly end-uses are very consistent, with the exception of the highly seasonal furnace energy. The electric car is pictured in the monthly end-uses, with usage beginning in April of 2011. The usage for the electric car charging is similar to that for appliances, plugs or hot water.

	P4 Actual	P4 Modeled
Floor Area	2510	2510
# of Occupants	2	2
Heating	2751	5481
Cooling	0	0
Central Air Handler(s)	83	174
Hot Water	1720	1758
Ventilation	0	0
Combined HVAC and Domestic Hot Water	***4554***	***7413***
Appliances	1142	1411
Lights	399	715
Plug Loads	1217	4639
Combined Appliances, Lights and Plugs	***2714***	***6765***
Annual Total	***7268***	***14178***
PV Production	4054	3750
Annual Net	***3214***	***10428***

Table 23 - P4 Site Energy End Use Summary

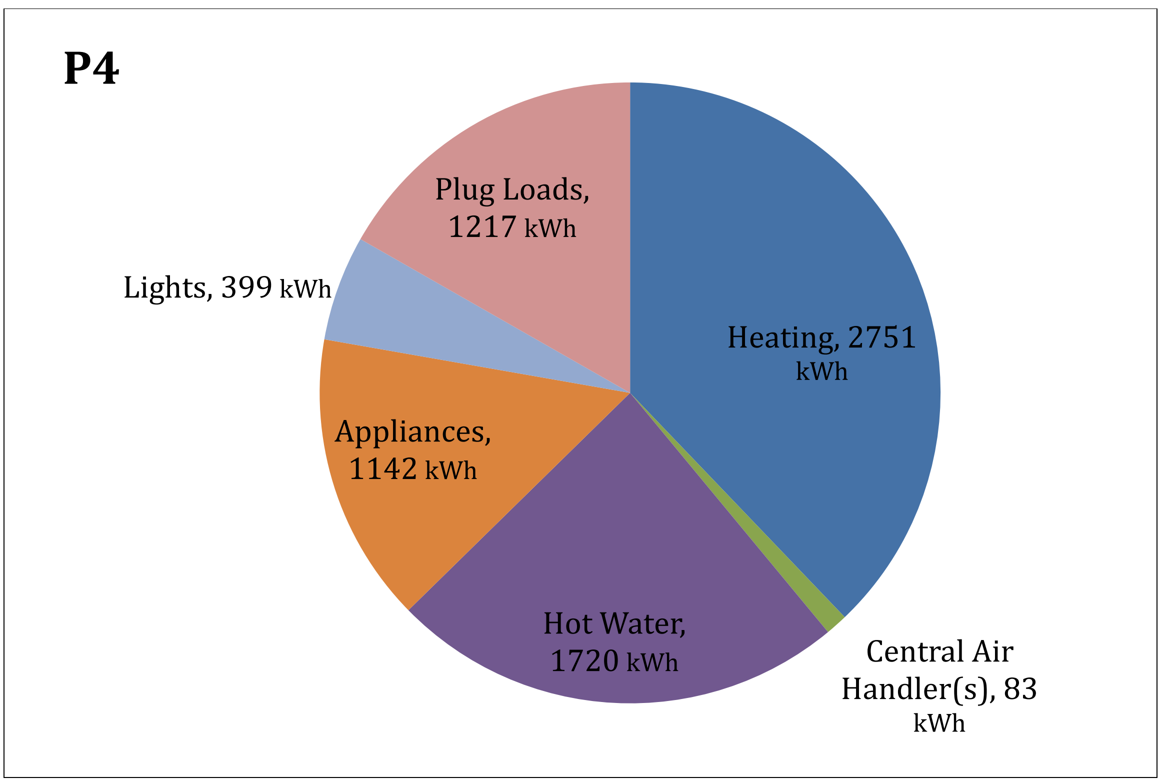


Figure 71 - P4 Annual Energy End-Uses

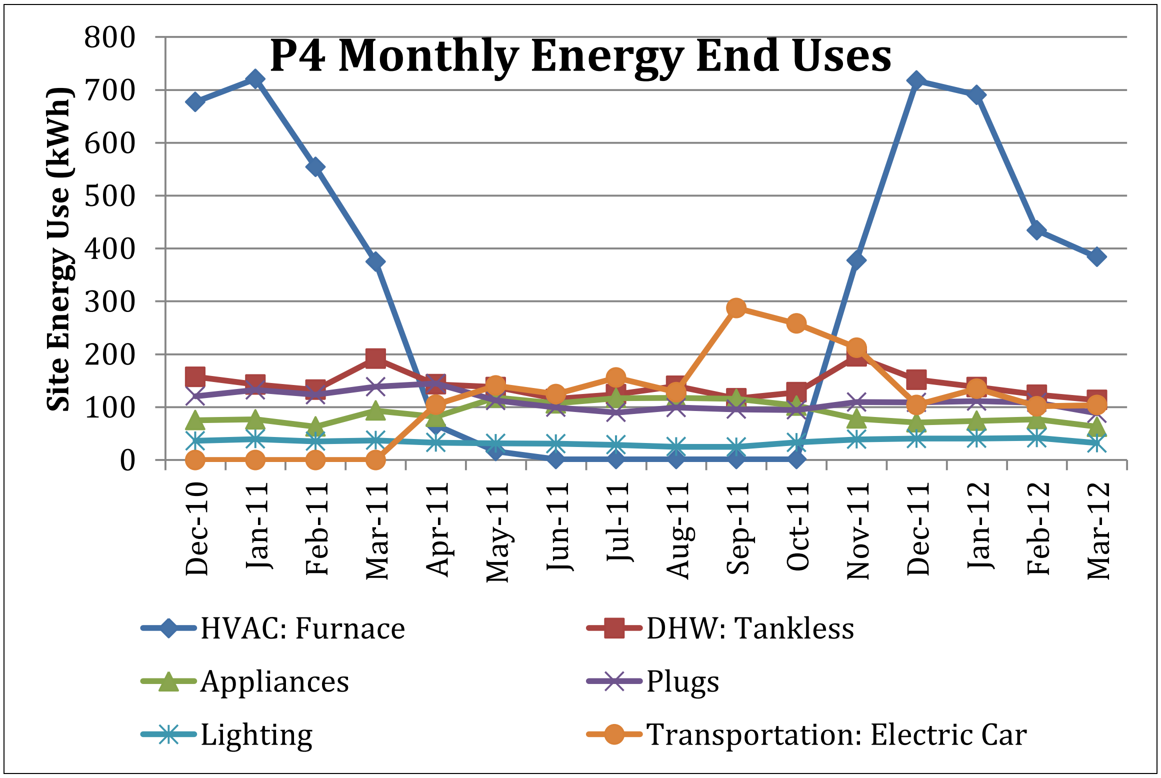


Figure 72 - P4 Monthly Energy End-uses

User Behavior

The consistently low MELs and baseload energy use is most impressive in P4. The average continuous baseload was 95 Watts, which translates to an estimated 835 kWh per year. This is 26% of the annual net-site usage. The low energy user behavior in P4 is further substantiated when actual usage for combined plugs, lights and appliances is compared with the predicted usage. Actual usage was only 40% of predicted.

Temperature and Relative Humidity

The monthly downstairs office, den and hall temperature and relative humidity means and standard deviations are presented in Table 24 below. Monthly mean temperatures in P4 varied between approximately 64 and 74 degrees F. Significant increases in average temperature occurred from July to October, which reflects the lack of mechanical cooling in P4 (pictured for the Den in Figure 73 below). Temperature and relative humidity varied between the ground floor office, which is minimally conditioned, and the upstairs den and hall, which are more fully heated. The temperatures maintained in P4 were quite a bit lower than in the other project homes, with winter averages of 66 degrees F. This was intended to conserve heating energy, and while temperatures were lower than other project homes, they were not exceptionally low. In addition, heating energy was reduced using nighttime temperature setbacks during winter, as pictured in Figure 74 below. Pre-dawn hourly temperatures were allowed to drop as low as 62 degrees F. Monthly mean relative humidity varied from approximately 47% to 65%. The monthly mean relative humidity in P4 was in the desirable 30-60% range for the upstairs den and hall, but the ground floor office had elevated relative humidity, most likely due to its cooler temperatures.

Summary of Temperature and Relative Humidity by Month												
	Temperature						Relative Humidity					
	Office		Den		Hallway		Office		Den		Hallway	
Month	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
January	64.0	1.7	66.0	2.3	64.9	1.7	61.2	3.5	52.9	4.4	55.8	3.5
February	64.4	1.9	66.4	2.8	65.4	2.1	58.1	4.9	50.9	4.1	52.7	3.4
March	64.0	1.1	66.5	2.2	65.6	1.7	65.4	5.6	56.0	4.8	57.2	4.3
April	65.7	1.4	68.8	2.5	67.9	1.9	63.5	4.6	54.9	4.4	56.9	4.9
May	66.6	1.7	69.7	2.5	68.8	2.1	61.7	4.1	53.3	3.8	55.7	4.3
June	68.1	1.9	71.7	3.0	70.5	2.5	64.3	3.9	52.3	5.7	55.2	5.8
July	70.1	1.2	73.3	2.0	72.1	1.5	63.4	4.0	50.7	3.6	53.6	3.8
August	70.7	0.7	72.9	1.6	71.9	1.0	63.1	3.1	52.9	3.2	54.8	3.2
September	71.3	0.9	73.9	2.0	72.8	1.5	61.6	2.1	53.1	3.2	54.9	3.1
October	70.6	1.1	72.7	2.4	72.0	1.9	63.5	1.5	56.7	2.7	57.6	2.7
November	64.7	0.5	66.1	2.1	64.8	0.9	52.9	1.0	46.7	1.4	48.8	2.5
December	64.3	1.0	66.2	2.3	65.1	1.4	64.6	4.3	56.1	3.8	57.6	3.7

Table 24 - P4 Summary of Indoor Temperature and Relative Humidity by Month

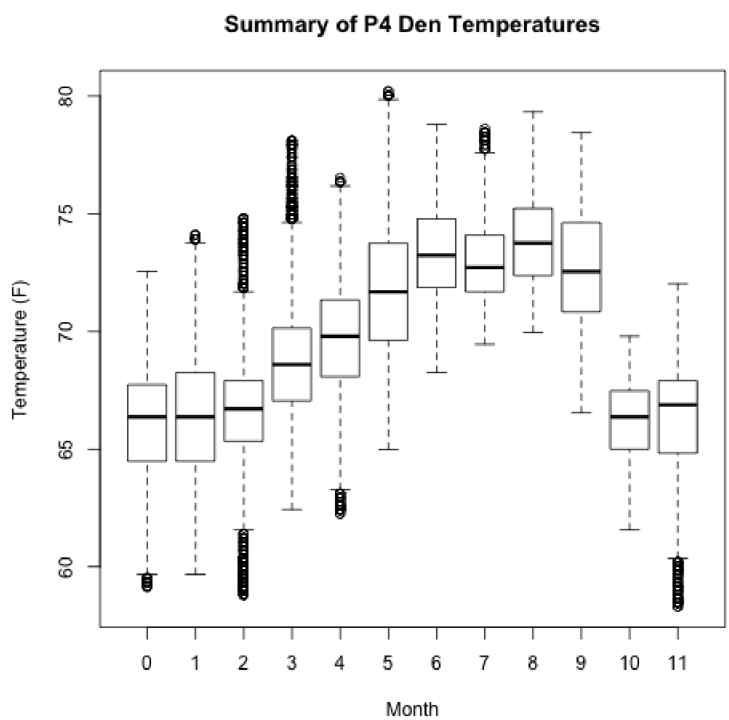


Figure 73 - P4 Summary of Den Temperatures

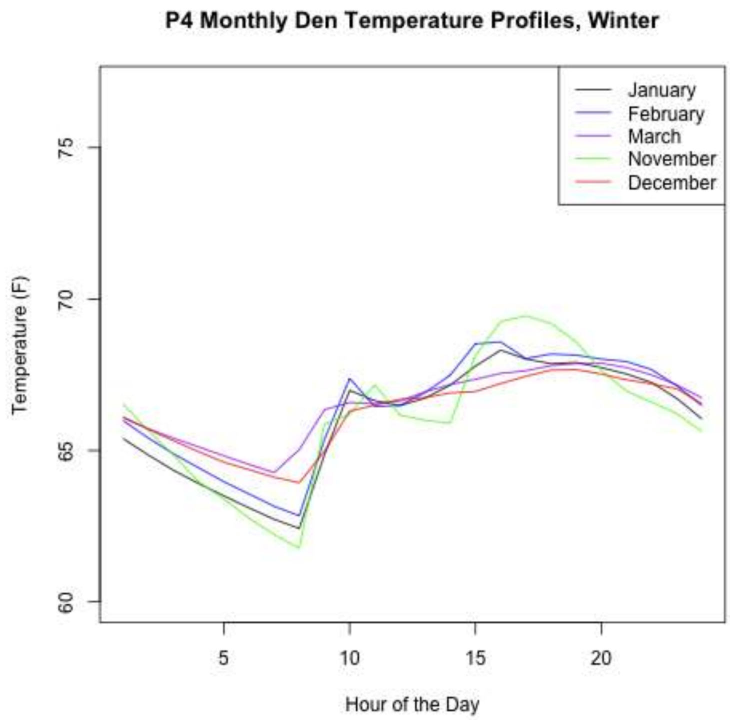


Figure 74 - P4 Monthly Den Temperature Profiles, Winter

The temperature differences between the den and ground floor office are pictured in Figure 75, and between the den and hall in Figure 76 below. Temperature differences between floors were clearly greater than between sensors on the same floor, with average differences of 2.7 degrees F between floors and 1 degree F within. ACCA recommends temperature differences of less than +/- four degrees for single-zone systems in both heating and cooling. P4 was within this requirement for 98.1% of the year between the den and hall, but was outside the recommended range 20.2% of the year between floors—this was a purposeful energy conservation effort and should not be viewed as a design flaw. Comfort was provided in this DER in a manner acceptable to the occupants, but other occupants may not accept such austerity measures.

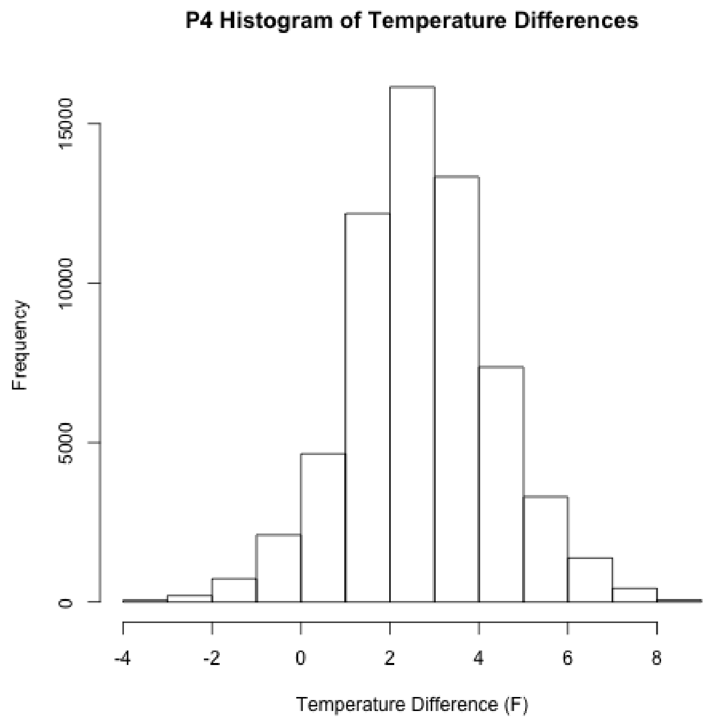


Figure 75 - P4 Histogram of Temperature Differences, Den to Basement Office

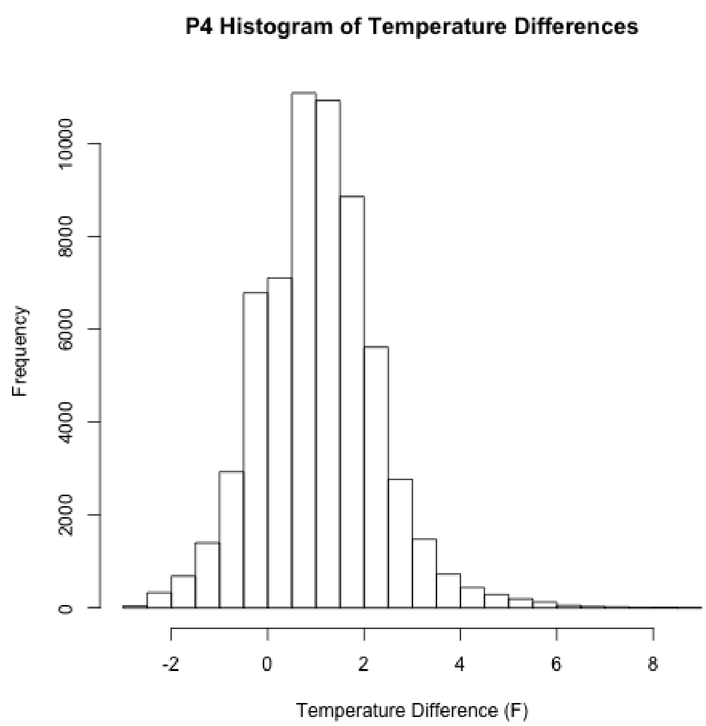


Figure 76 - P4 Histogram of Temperature Differences, Den to Hall

The proportion of time that indoor relative humidity was below, within, and above the recommended 30% to 60% range are pictured in Table 25 below. The ground floor office did not manage RH well due to its lower average temperatures, with the 60% limit being exceeded 79.2% of the year. Yet, no 15-minute period during the entire year exceeded 75% relative humidity in the office. The upstairs spaces did much better. The hall was above the recommended range 16.2% of the year, which was most likely due to its closer proximity to the bathroom used for showering. The relative humidity levels in P4 are not troubling. The office was not fully conditioned and as a ground-coupled space, experienced naturally high relative humidity. The upstairs spaces were well controlled without any mechanical dehumidification, and while the hall was above 60% for a significant period of time, it never exceeded 75%.

Proportion of Time Relative Humidity was Below, Within and Above the Recommended Range			
Location	**Below 30%**	**30% to 60%**	**Above 60%**
Office	0%	21%	79%
Upstairs Den	0%	93%	7%
Upstairs Hall	0%	84%	16%

Table 25 - P4 Proportion of Time the Relative Humidity was Below, Within and Above the Recommended Range

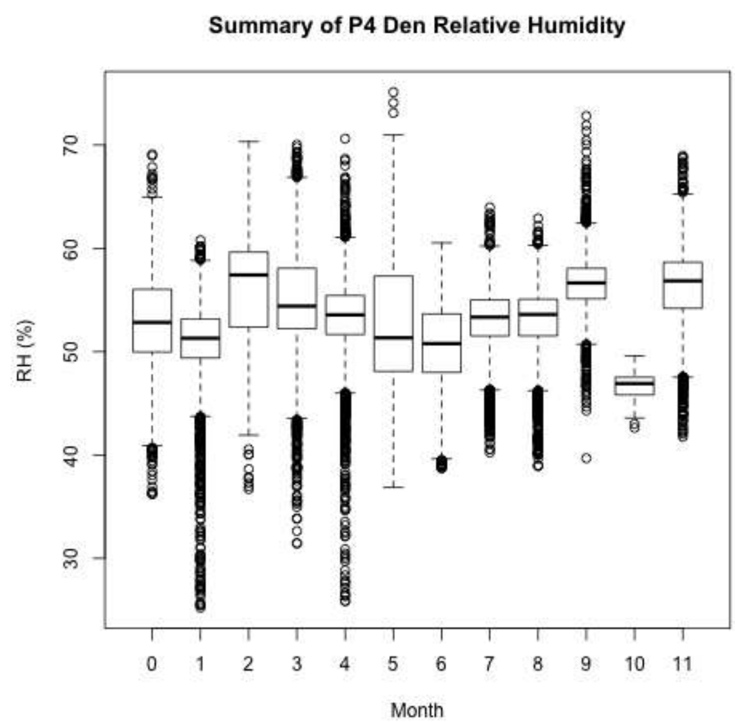


Figure 77 - P4 Summary of Den Relative Humidity

4.4.4 P4 Overview

P4 is overall the most exemplary DER to date. What is most notable is that net-site and net-source energy reductions of 74% and 96% were achieved by implementing measures in a home that was already insulated, with a high efficiency furnace, ECM air handler and tankless water heater. Actual energy usage prior to the Phase I retrofit is unknown, but the designer's Energy-10 model suggested a 75% reduction from the Phase I efforts.

The formula for success has been the combination of optimized energy efficiency and energy conservation. The homeowners of P4 are models of low energy user behavior. In addition to minimizing plug loads and eliminating vampire loads, minor temperature reductions were used in the winter to reduce heating energy. The advantages that the homeowner has over other projects are that he is an experienced architect with a focus on energy efficiency, and he was able to carry out the retrofit in stages, learning from the results of each subsequent retrofit and adjusting the building accordingly. Heating fuels were kept the same, which entirely avoided any source energy penalty for the retrofit activities, and the solar PV system was used to net-produce electricity on an annual basis, which also provides a substantial source energy boost.

The energy monitoring has helped the homeowner further reduce the MELs and phantom loads of the home, including unplugging the furnace when not in use, and changing out the server for his business. The project verifies that it is possible to have a home office in the Bay Area and still reduce your energy use more than 75%. The other major takeaway is that if you are able to minimize energy consumption, then superinsulation and extensive building enclosure improvements are unnecessary in this climate. Low energy user behavior combined with insulating the existing enclosure to code, minimizing air leakage wherever possible, and updating the equipment to Energy Star levels, can result in a successful DER.

4.5 P5

4.5.1 P5 Project Description


Image 14 - P5 Pre- and Post-Retrofit

P5	Pre-Retrofit	Post-Retrofit
ENVELOPE		
Wall Insulation	2X4 fiberglass batts	3.5” cellulose, 1” XPS – R18
Attic/Roof Insulation	Some fiberglass batts	16” loose fill cellulose – R57
Foundation Insulation	R-19 fiberglass batts	Sealed crawlspace, 11.5” blown cellulose – R41
Windows	Single pane aluminum frame	2 pane, Low E, argon filled, fiberglass frame. Unknown values
Air Leakage		292 CFM_{50}, 2.4 ACH_{50}
MECHANICAL		
Heating	Wood fireplace	Electric wall radiators
DHW		40 gal. electric tank EF 0.88
Ventilation		Bath and kitchen exhaust, point source ERV
LIGHTS/APPLIANCES/MEL		Mostly CFL, fairly inefficient appliances, very low MELs
RENEWABLES		None

Table 26 - P5 Retrofit Summary Table

General Information
P5 is a small, single-story, 900ft^2 affordable housing project located in Point Reyes Station, CA. The project is owned and managed by the Community Land Trust Association of Marin (CLAM), a local nonprofit. Their mission is to provide stable, permanently affordable and environmentally responsible housing in the communities surrounding Tomales Bay, CA. The project was an attempt to "put into practice the growing consciousness and goals of our community and the nation to reduce carbon emissions" ('Community Land-Trust Association of West Marin', 2010). The original 1920's structure was remodeled using Passive House design principles, with the hope that it would provide the lowest operating costs for the future tenants.

This very small, compact ranch-style home has a simple layout, which makes it a good candidate for super insulation and airtightness. In its original condition, the home was 795 square feet; and just over 100 square feet were added to the home, to accommodate an utility/laundry room to the rear. Small front and rear porches were also added to the home during the retrofit process. The existing structure was sparsely insulated with sagging, poorly installed crawlspace insulation, mixed insulation and debris in the attic, and sparsely insulated walls with single-pane windows. The pre-retrofit home was heated with a wood-burning fireplace, with a self-reported use of around 3 cords of hardwood per year. The pre-retrofit utility bills were reportedly shared with another structure on the property, and as a result, are not very useful for comparison.

This case study differs most from the others in purpose, scale and cost. A local contractor was the expert behind the project and volunteers did a portion of the labor. The house was lifted, a new foundation was built, extensive air sealing and insulation was performed, and the most cost effective low energy solutions were implemented. It is an all-electric home except for a small propane tank used for cooking. There are two bedrooms, one bath and three occupants.

Building Enclosure
The house was lifted off the existing foundation, and a new stem wall and footings were put in place. The above grade walls were retrofitted from the outside, which minimized the damage and rework necessary on the interior, and allowed for replacement of the old siding and placement of exterior foam insulation. This strategy eliminated thermal bridging and provided easy integration of window flashing with the wall moisture barrier. The 2x4 walls were filled with blown cellulose insulation from the outside and were then covered in a 1" layer of continuous XPS foam board in a rain screen application. The 2X12 floor joists were filled with Blown Cellulose and 16" of cellulose was blown into the attic floor, reaching R50. All windows were replaced with new vinyl framed, double pane, low-E windows.


Image 15 - P5 Sealed Crawlspace

The new foundation allowed for the creation of an ideal crawlspace environment (see Image 15 above). The underside of the floor framing was skinned with oriented strand board (OSB), the joints and perimeter were taped and sealed, and then the cavities were filled with blown cellulose insulation. A durable vapor barrier ground cover was placed over a protective layer of sand and all seams were taped, as were connections to the stem wall and piers.

Air Leakage
New air barriers were installed on all six sides of the home. The plywood sheathing on the walls, roof and crawlspace ceiling was taped and sealed. Extreme care was taken to seal every penetration, outlet, joint and crevice in the home.

Ventilation
Ventilation is provided in the home by a point source ERV located in the living room. In addition, a kitchen exhaust fan (see Image 16 below) and a bathroom exhaust fan were installed. Monitoring and site-visits to the home have revealed that the ERV is rarely operated. But, one site visit also found the ERV running, the bathroom exhaust running and the bathroom window open – an operating condition that eliminates most benefits achieved by using an ERV.

Image 16 - P5 Kitchen Range Hood Exhaust

Heating

All of the existing mechanical, electrical and plumbing equipment were removed from the original structure and were replaced with energy efficiency and health in mind. The wood burning fireplace and its chimney were demolished, and a new heating system, consisting of thermostatically controlled, electric resistance wall radiators in each room were installed (see Image 17 below). This is a very low-cost, robust heating system that provides lots of zoning and control for personal comfort preferences. The source energy implications of such a system are justified by the project team because of the extremely low heating load of the home, limited project budget, and ease of operation. This is similar to the system and justifications outlined for P1.

Image 17 - P5 Electric Resistance Wall Heater

DHW
Hot water is provided in the home by a 40 gallon, 4.5 kW electric resistance storage tank with an EF of 0.88, located in the utility/laundry room (see Image 18 below).

Image 18 - P5 Electric Resistance Water Heater in Laundry Room

Appliances
The appliances are standard affordable units, it is unknown if they are Energy Star or not. The stove/oven uses propane.

Plug Loads
The home has all the basic MELs of any home - computer and peripherals, television, microwave, etc. - yet it has far less MELs than some of the other project homes. There is only one computer, one television, and no dishwasher.

Lighting
All lighting is CFL and wall switch controlled.

Additional Information
As an affordable housing, deep energy retrofit, P5 is notable for its use of low-cost, very simple strategies. Technologies were selected that require little maintenance and are not prone to malfunction, and whose performance does not degrade quickly under sub-optimal conditions. P5 relies on high insulation values, a tight building envelope and a small, compact shape to achieve its high performance levels. Unlike some other case studies presented here, the energy performance of P5 is likely not the result of highly energy conservative occupants, but is instead a great example of compact, energy efficient, affordable housing.

4.5.2 Building Diagnostic Results

Blower Door

Since P5 is such a small building, it demonstrates the importance of different air leakage metrics in understanding the building enclosure performance. At 292 CFM, the Q_{50} number is very small, but then looking at ACH_{50}, it falls significantly short of its Passive House design target. Overall, it is the third tightest house of the case studies.

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH
P5	292	2.42	0.10	0.32	13.97	0.10

Table 27 - P5 Blower Door Results

Ventilation Airflows

The 62.2 whole house mechanical ventilation requirement for P5 is 31.6 CFM. A point-source ERV provides continuous mechanical ventilation. We were not able to measure its airflow, but manufacturer's specification suggests exhaust airflow of 40 CFM on high and 20 on low, with supply airflow of 30 CFM on high and 20 on low. ERV was observed to be either off or on low during site visits. The bathroom exhaust fan was measured and it delivered 55 CFM, which exceeds the 62.2 requirement. A kitchen range hood was also installed, but not measured.

4.5.3 Monitored Data Results

Whole House Energy Use

P5 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e
20,255 kWh	6,602 kWh	3,749 lbs
Occupants	Area	HERS Rating
3	905 ft^2	86

Figure 78 - P5 Mileage Box

The annual net-site energy use of P5 was 6,602 kWh, net-source energy usage was 20,255 kWh and CO2e emissions were 3,749 pounds. Unfortunately, pre-retrofit utility bills are not available for P5. For comparison, we compare P5 to the average single family CA home, which uses 20,061 kWh, 36,737 kWh and 9,346 pounds of net-site, net-source and CO_2e annually. When compared with this average home, P5 used 67.1% less net-site energy, 44.9% less net-source energy and produced 59.9 % less CO_2e emissions. Notably, P5 is much smaller than the average CA single family home, which is 1,579 ft^2. The HERS score for the home, which is compared with a reference home of the same size, was 86.

The home is quite small, which will make it look like a high energy user when any metric that normalizes to house size is used. When energy per square foot is used, P5 becomes the single worst performing of the eleven project homes in this research. When compared with the CA average, net-site energy use for P5 is 43% less, but net-source energy and CO_2e emissions are very similar to the average home. However, on a whole house or a per person basis, P5 has significantly better performance compared to some of the other projects.

Monthly net-site energy consumption is shown for P5 in Figure 79 below. The home uses propane for cooking, but is otherwise all-electric. Monthly energy usage shows almost no seasonal variation, which suggests that the home's usage is not dominated by space conditioning.

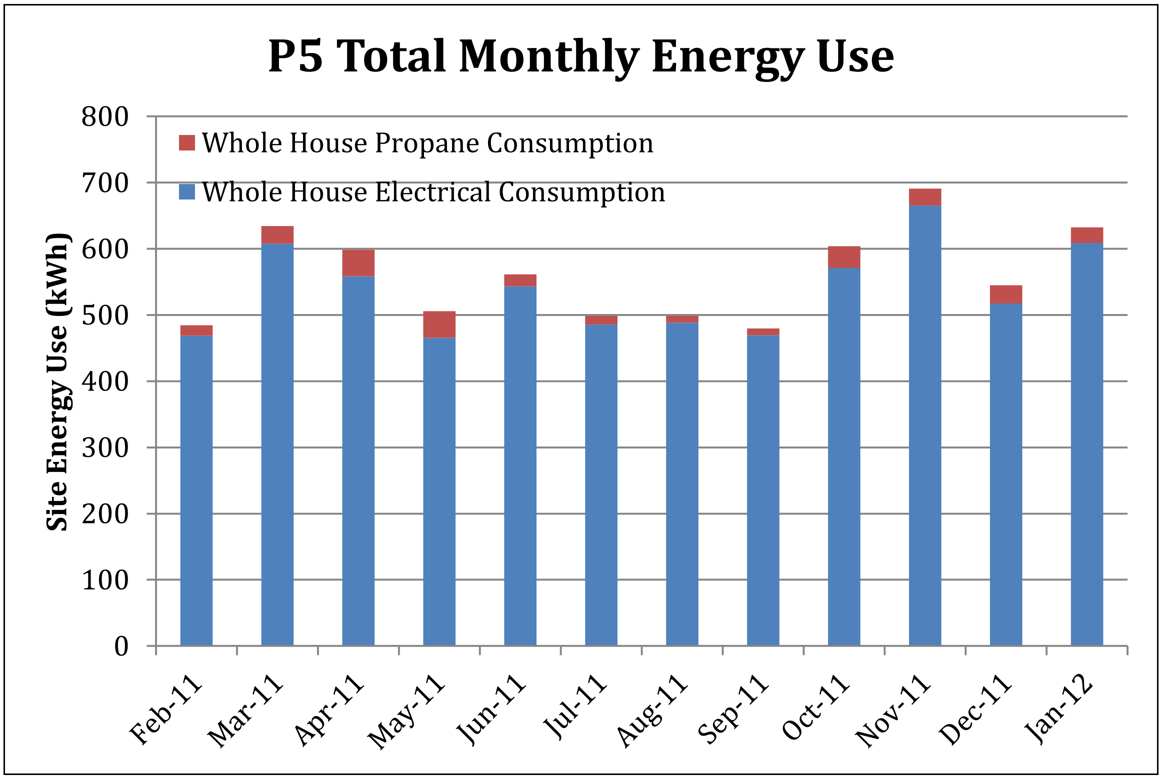


Figure 79 - P5 Total Monthly Energy Use

End-Uses

Annual energy end-uses are summarized in Table 28 and Figure 80 below, and monthly end-uses are pictured in Figure 81. Water heating is the single largest end-use in P4, which is not surprising, given the occupant density, low heating energy and low miscellaneous electric usage. The usage of a heat pump water heater would likely provide substantial energy reductions in P5. Heating energy is the lowest of all project homes, a combination of its size and envelope. Peak monthly heating energy in P5 was less than 100 kWh—quite an impressive achievement. The energy model actually predicted the usage of P5 very accurately, for an annual total within 210 kWh. Lighting usage was much higher than expected, which could suggest use of some incandescent lamps in plug-in fixtures.

	P5 Actual	P5 Modeled
Floor Area	905	905
# of Occupants	3	3
Heating	415	544
Cooling	0	0
Central Air Handler(s)	0	0
Hot Water	2632	2802
Ventilation	103	133
Combined HVAC and Domestic Hot Water	***3150***	***3479***
Appliances	1826	2282
Lights	1034	319
Plug Loads	593	732
Combined Appliances, Lights and Plugs	***3452***	***3333***
Annual Total	***6602***	***6812***
PV Production	0	0
Annual Net	***6602***	***6812***

Table 28 - P5 Site Energy End Use Summary

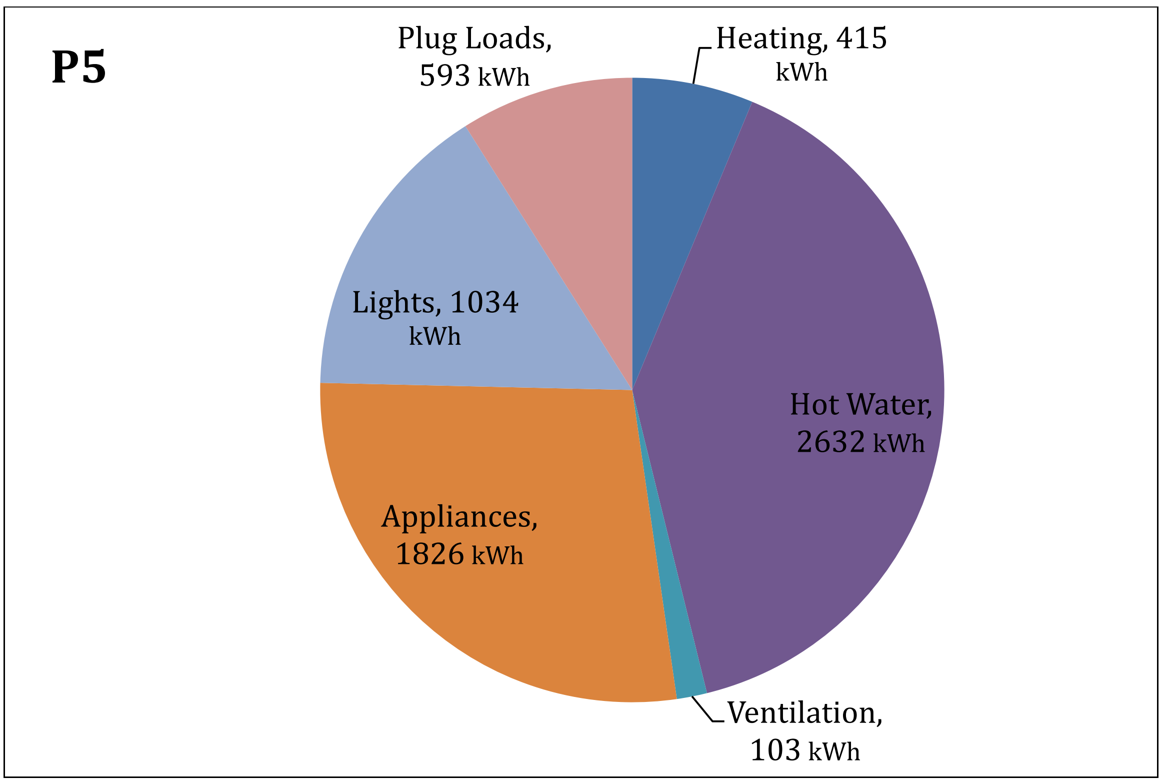


Figure 80 - P5 Annual Energy End-Uses

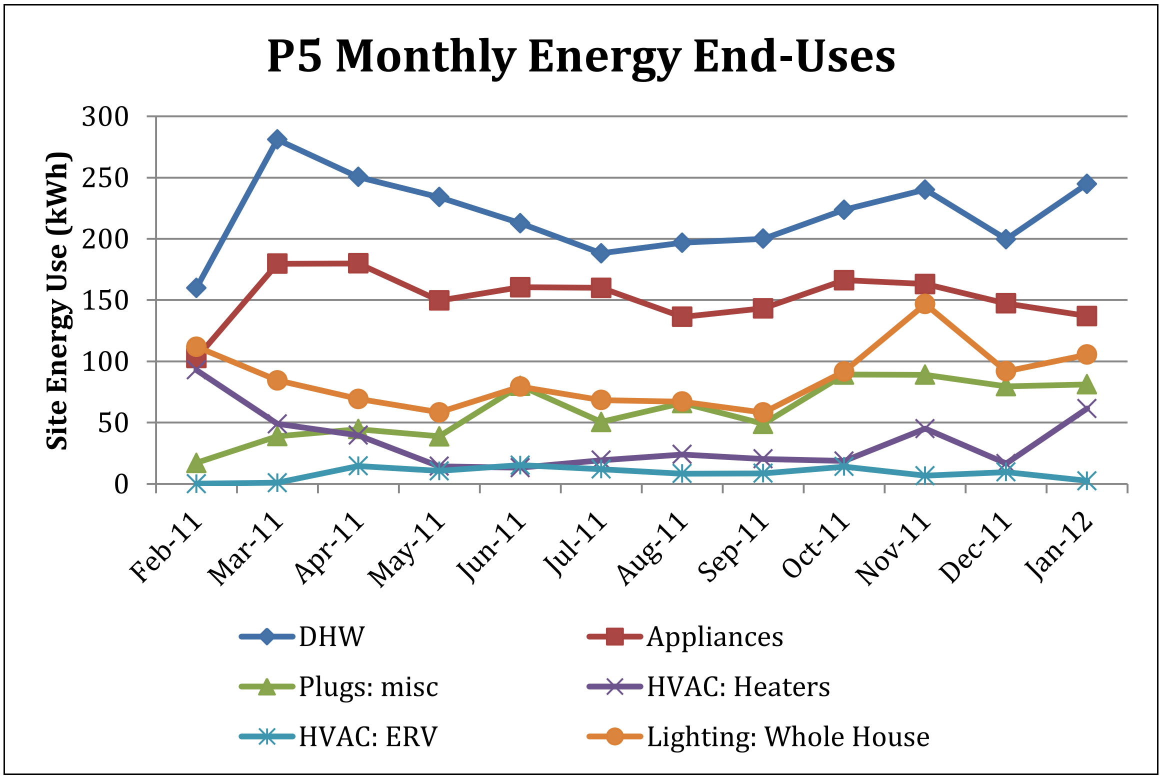


Figure 81 - P5 Monthly Energy End-uses

User Behavior

As mentioned above, the occupants have all of the standard MELs, but just fewer of them, and as a result, P5 plug loads are lowest of any project home. At the same time, the baseload is the fourth smallest, at 124 Watts, which is an estimated 1,087 kWh per year. This accounts for 16% of the annual net-site energy usage, and it is 2.6 times the total annual space heating energy use. The occupants do not appear to be actively engaged in understanding or reducing their energy use, rather they simply live their lives normally, as if they were in any home.

IEQ Summary

Indoor temperature and relative humidity means and standard deviations are presented on a monthly basis in Table 29 below. Average winter temperatures were slightly cool (66 to 67 degrees F), with the exception of December, which averaged 62.6 degrees F. It is possible that the home was not occupied during the month of December, as no other explanation is available for this effect. Average summer temperatures varied between 70 and 73 degrees F. No mechanical cooling was needed to maintain these temperatures in the Marin County coastal climate, which is dominated by the nearby Pacific Ocean. Monthly mean relative humidity was on the high end of the acceptable range of 30% to 60% for 10 of 12 months, with means just barely exceeding 60% in January and March. RH was quite consistent; the operation of the ERV ventilation system might have contributed to this.

Summary of Indoor Temperature and Relative Humidity by Month				
	Temperature		Relative Humidity	
Month	**Mean**	**SD**	**Mean**	**SD**
January	66.4	3.6	62.2	6.0
February	66.9	3.4	57.8	7.0
March	67.1	3.1	62.4	6.4
April	67.7	2.8	56.3	6.1
May	69.8	3.2	55.9	5.2
June	72.0	3.4	54.2	5.0
July	73.7	2.6	53.5	4.5
August	72.5	2.5	54.7	3.8
September	73.3	2.9	53.2	4.7
October	71.2	3.6	56.1	6.1
November	67.6	3.3	52.9	6.1
December	62.6	4.0	55.5	9.4

Table 29 P5 Summary of Indoor Temperature and Relative Humidity by Month

Hourly temperature profiles for winter and summer months are pictured in Figure 82. Hourly temperatures followed a diurnal pattern throughout the year, with consistent results in summer and winter, with the exception of December. Nighttime temperatures dropped to approximately 65 degrees F during the winter, and they were ramped back to approximately 68 degrees F during the day and evening. Boxplots of all temperatures by month are pictured in Figure 83, and wide temperature ranges were experienced within months. For example, average maximum to minimum temperature ranges were 25 degrees F during November through February, which suggests a very wide range of indoor temperatures during heating months. It is possible that the prevalence of high-end outlier data points in Figure 83 resulted from overheating during major cooking events, and was not representative of heating patterns. It is not clear from this data how temperature was managed during the winter months. Heating energy was exceptionally low, though it was just 129 kWh less than predicted by the EnergyGauge USA model.

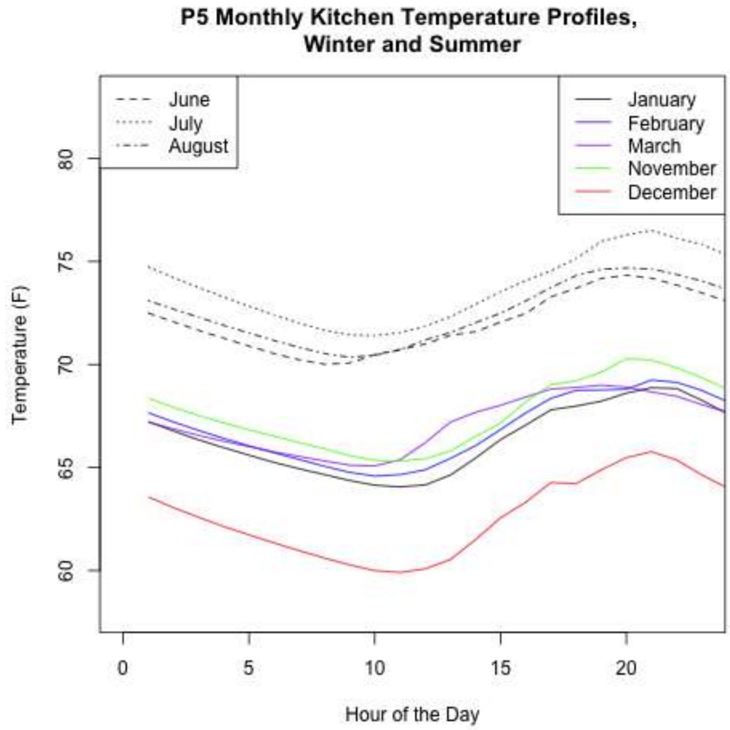


Figure 82 - P5 Monthly Kitchen Temperature Profiles, Winter and Summer

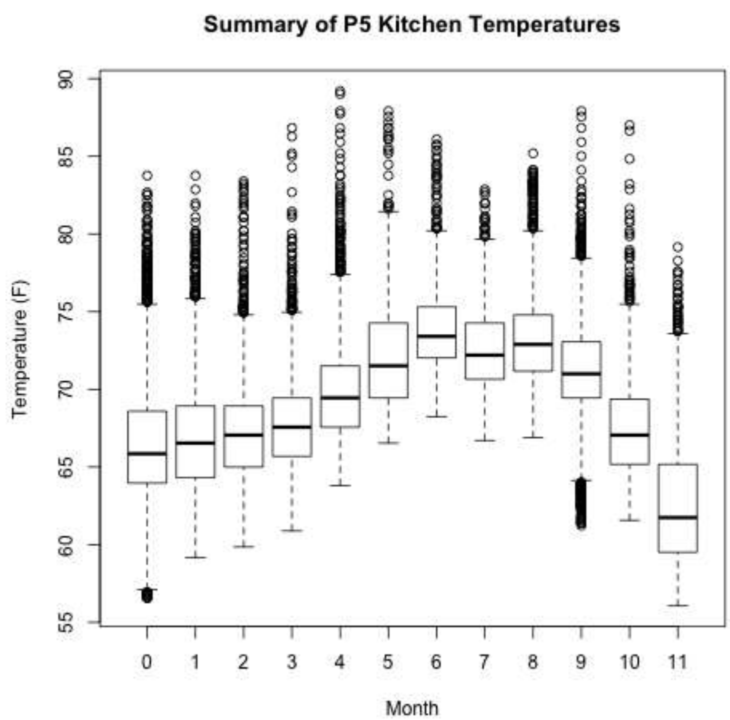


Figure 83 - P5 Summary of Kitchen Temperatures

The proportion of time that indoor RH was below, within and above the recommended 30% to 60% range is summarized in Table 30, and all RH data are pictured in Figure 84. P5 spent 34% of the monitoring year with indoor humidity in excess of 60%. As seen in the histogram, the vast majority of these exceedences were in the range of 60% to 70% RH. The longest period continually above 60% RH was 6.8 days, and RH was elevated continuously for a whole day on 26 separate instances. Only a single instance occurred of an entire day over 70% RH, and the longest single period in excess of 80% was two hours.

Proportion of Time RH Was Below, Within and Above the Recommended Range			
Location	**Below 30%**	**30% to 60%**	**Above 60%**
Kitchen	0%	66%	34%

Table 30 P5 Proportion of Time RH Was Below, Within and Above the Recommended Range

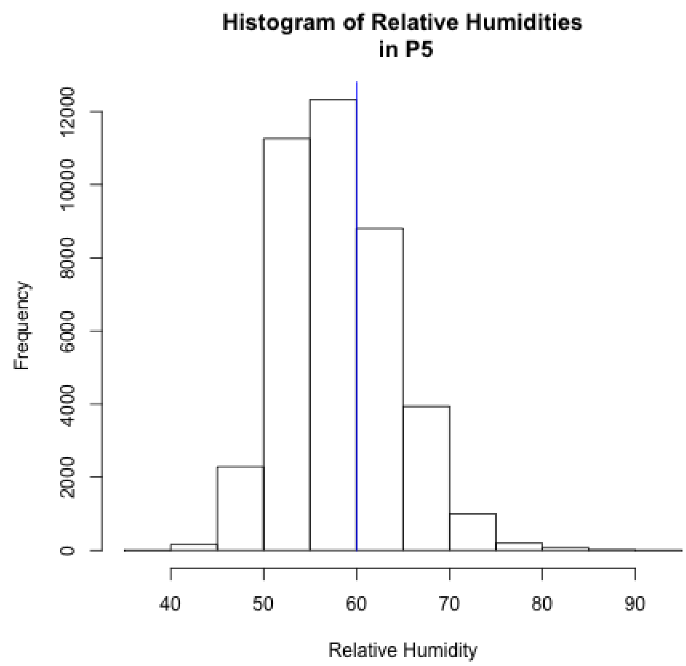


Figure 84 - P5 Histogram of Kitchen RH

4.5.4 P5 Overview

P5 illustrates the impressive results that can be achieved in an affordable DER project that is designed for high levels of efficiency. All means and methods were fully off the shelf, with no custom designed systems. Where P5 excelled was in its exceptionally low heating energy use. The electric resistance space and water heating negatively impacted the home's source energy consumption, but it still consumed 45% less than an average CA single family home. With relatively little additional investment, a heat pump water heater is the obvious finishing touch for this retrofit; a PV system would have the same effect.

The combined plugs, lights and appliances energy use in P5 was comparable to the other low-users in this research (P1, P4, P6N and P10). P5 is a low-income home, and it does not have lots of plug loads nor extra appliances and gadgets that were found in some of the other project homes (P2 and P3). They do have a television, computer, printer and radio, but are modest in their consumption. One explanation could be related to the fact that the 2010 California RASS (KEMA, Inc., 2010) shows a parallel relationship between income level and energy consumption (see Figure 85 below).

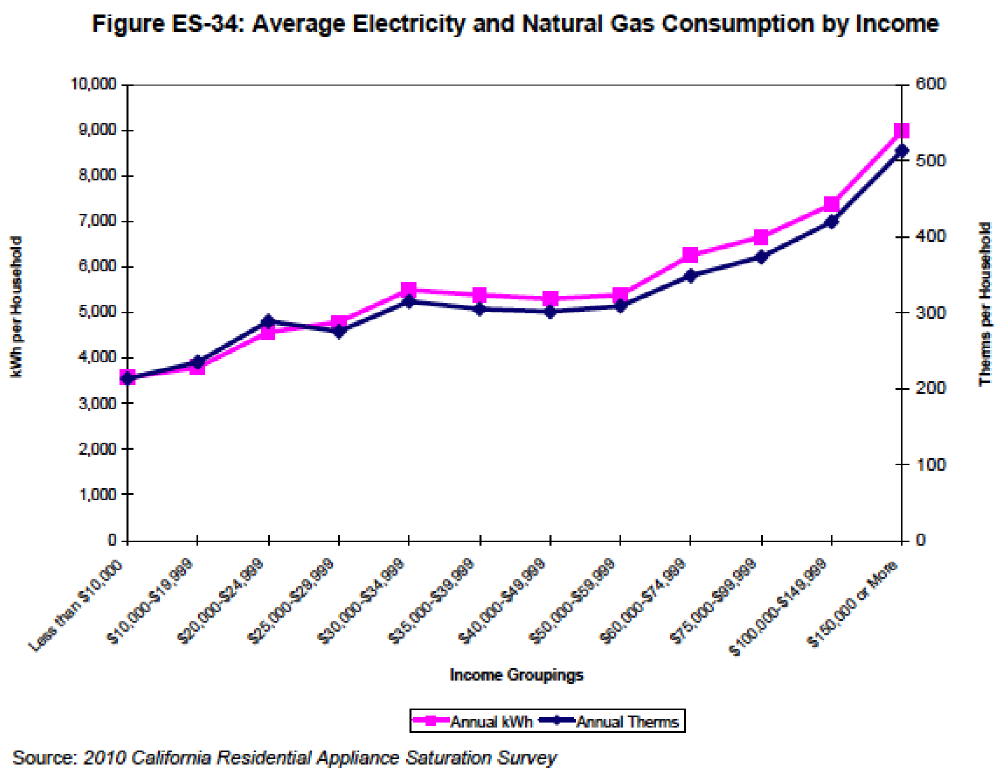


Figure 85 - Average Electricity and Gas Consumption by Income Level (KEMA Inc. 2010)

4.6 P6

4.6.1 P6 Project Description

Image 19 - House Move (left and right) and Proposed Design (center)

P6	**Pre-Retrofit**	**Post-Retrofit**
ENVELOPE		
Wall Insulation	None	7” cellulose – R25
Attic/Roof Insulation	Some fiberglass batts	12” loose fill cellulose – R44
Foundation Insulation	None	Sealed crawlspace, 2” XPS on interior of stem walls, 6” SPF at rim joist – R12
Windows	Single pane aluminum frame	1) 2 pane, Low E, argon filled, fiberglass frame U: .33, SHGC: .18, VT: .41 2) Retrofit original double hung units with additional pane, weather strips and air seals
Air Leakage	NA	1) 991 CFM_{50}, 2) 1,114 CFM_{50}
MECHANICAL		
Heating and cooling	Forced air gas furnace	Point source natural gas fireplace
DHW	Tank gas	2 – 4X10 Solar thermal panels, 80 gal. storage, condensing natural gas tankless backup
Ventilation	Natural	Bath and kitchen exhaust, Whole house fan
Distribution	Ducts in crawlspace	None
LIGHTS/APPLIANCES/MEL	NA	100% CFL, Energy Star ref, very low MELs
RENEWABLES	None	N-2.4 kW PV S-2.0 kW PV

Table 31 - P6 Retrofit Summary Table

General Information
P6 is located in Davis, CA It is the only case study that is not a single-family home, but consists of two single-family homes that the Solar Community Housing Association (SCHA) retrofitted and joined together to turn into a demonstration of low-energy cooperative housing for eight occupants. SCHA is a Davis-based non-profit that has been providing environmentally conscious and affordable cooperative housing since 1979 ('Solar Community Housing Association', 2009). They have two additional units in Davis and this project was seen as an opportunity to demonstrate the latest and greatest in cost effective solutions to reducing energy while increasing the comfort, health and safety of the occupants. The original homes were built in 1932 and 1934. They were lifted off their original foundations and moved across town to their current location. Community volunteers, including the current occupants, provided a portion of the labor for both the design and construction of the project. In kind donations also played a key role. The project is applying for LEED for homes certification and has created a lot of excitement around DERs in Davis. The homes are identified by their location on the site, as P6-North and P6-South.

Building Enclosure
The original buildings were uninsulated with single pane windows, lath and plaster interior and stucco exterior. New foundations and stem walls were poured to create unvented crawlspaces, without any means of conditioning. Two inches of XPS foam was placed on the inside of the stem walls, and 6" of low density SPF was sprayed around the rim joist. A thick polypropylene moisture barrier was laid over the ground, taped and sealed at all joints, as well as around each pier and at the attachments to the stem walls. The original goal was to maintain the exterior stucco so a decision was made to demolish the interior walls and build a double framed 2X4 wall, resulting in a 7.5" wall cavity (see Image 20 below). These were filled with dense packed cellulose insulation and the attics were filled with 12" of loose fill cellulose. The exterior stucco ultimately had to be demolished due to too many unavoidable penetrations and the lack of a consistent moisture barrier (see Image 21 below).

Image 20 - P6 Double Stud Wall Framing with New Wall Built to Inside of Existing

In the north house all of the existing windows were replaced with double pane, low-E fiberglass framed units with a U value of 0.33 and an SHGC of 0.18. In the south house a window refurbishment team added a second pane and weather sealed all of the existing double hung windows in an attempt to save resources and cost (see Image 22 below). The result was a vast improvement on the original windows but still left air gaps between the two sashes in various locations.

Image 21- P6 North, New Tar Paper WRB and Windows, with Plaster Lathe

Image 22 - P6 South, Existing Wood Frame Windows Rehabbed with Second Pane of Glass

Air Leakage

The entire home was re-sheetrocked, which acts as the interior air barrier. Additionally, the sealed and conditioned crawlspace helps reduce air leakage through the floor. The south house did not have all of the windows replaced and is likely the reason for higher air leakage. Air leakage was addressed in both homes through the use of volunteer labor and cans of spray foam crack sealant.

Ventilation

Each home has a whole house exhaust fan located in the attic (see Image 23 below). The fans provide fresh air and exhaust heat during the summer. They move 1,150 CFM using only 78 watts, and are manually controlled by a wall controller. Additionally, each bathroom has a bathroom exhaust fan and each kitchen has a range hood (see Image 24 below).

Image 23- P6 Whole House Fan Without Trim

Image 24 - P6 North, Kitchen Range Hood Airflow Measurement

Heating

Each building is heated using a point source natural gas fireplace in the living room (see Image 25 and Image 26 below). Both heaters are direct vented units with sealed combustion chambers. This system is far smaller, and less expensive than any other case study.


Image 25 - P6 North, Gas Point Source Heater, Direct Vent, Sealed Combustion


Image 26 - P6 South, Gas Point Source Heater, Direct Vent, Sealed Combustion

DHW

Both homes have solar thermal systems, with condensing, direct-vent tankless gas water heaters. P6-North uses an 80 gallon solar storage tank in the attic, which serves as pre-heat for the tankless 0.96 EF water heater. P6-South uses collector integrated storage, which serves as pre-heat for a tankless 0.96 EF water heater.

Image 27 - P6 South, Gas Tankless Water Heater with Solar Thermal Pre-Heat

Appliances
As there are two homes, there are also two kitchens. However, the residents use only one of the kitchens, and they eliminated the second refrigerator. Therefore there is now one old gas oven/range, one energy star refrigerator, one electric range that is seldom used, two energy star dishwashers, one gas dryer, and one washing machine – both are Energy Star rated.

Plug Loads
There are very few plug loads at P6. There is a toaster in the kitchen, each resident has a laptop, and there are several radios.

Lighting
All lights at P6 are CFLs, the bathroom lights have occupancy sensors and timers, but wall switches control all others.

Renewables
A PV system was installed on each home in May 2012, in the middle of our monitoring period. Systems installed on P6-North and P6-South were 2.4 kW and 2 kW (DC), respectively.

4.6.2 Building Diagnostic Results

Blower Door
As stated above, the two homes were treated identically, except for the windows. The North house had all windows replaced, and the South house had all the windows refurbished; the difference in airtightness is likely due to this.

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH
P6 N	991	5.08	0.2219	0.6781	49.4	0.176
P6 S	1114	5.59	0.2469	0.7447	55.9	0.195

Table 32 - P6 Blower Door Results

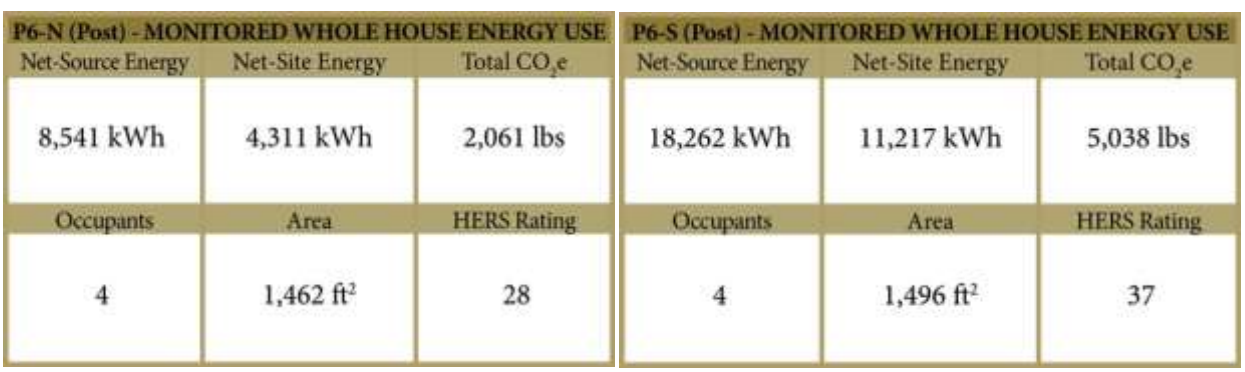
Ventilation Airflows

The 62.2 whole house mechanical ventilation requirement for P6N and P6S are 52.1 and 52.5, respectively. Neither home provides continuous mechanical ventilation, but occupants actively operate windows. Kitchen range hoods were installed and measured in each home on both high and low. The low speed in the South house did not meet 62.2 requirements, but all others did. Bathroom fans were also measured in each home, and the fan in the North house exceeded the requirement and South house fell below.

Fan Location	Fan Speed	Airflow (CFM)
P6 North		
Kitchen	Low	156
Kitchen	High	230
Bathroom	Single	87
Whole House Fan	Single	685
P6 South		
Kitchen	Low	80
Kitchen	High	202
Bathroom	Single	41

Table 33 - P6 Ventilation Airflow Measurements

4.6.3 Monitored data results



P6-N (Post) - MONITORED WHOLE HOUSE ENERGY USE			P6-S (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e	Net-Source Energy	Net-Site Energy	Total CO_2e
8,541 kWh	4,311 kWh	2,061 lbs	18,262 kWh	11,217 kWh	5,038 lbs
Occupants	Area	HERS Rating	Occupants	Area	HERS Rating
4	1,462 ft^2	28	4	1,496 ft^2	37

Figure 86 - P6 Post Retrofit Mileage Boxes

Whole House Energy Use

A full year of detailed monitoring could not be carried out on P6-North and South within the required time period. As a result, utility billing data have been used to generate the annual results presented here. Furthermore, solar PV systems were installed on each home in mid-May 2012 and net-metered billing data was unavailable. The sum of the monitored loads has been used to generate total monthly electricity in place of the utility data for these months (May-July 2012).

P6-North and South are a co-housing group, where some elements are shared by residents across the structures, for example cooking and laundry. All data for P6 should be interpreted in this context.

The annual net-site energy use of P6-North was 4,311 kWh, net-source energy usage was 8,541 kWh and CO_2e emissions were 2,061 pounds. P6-South used 11,217 kWh net-site, 18,262 kWh net-source and 5,038 pounds of CO_2e. When considered as a single home, their net-site usage was 15,528 kWh, net-source energy was 26,803 kWh and CO_2e was 7,099 pounds. Unfortunately, pre-retrofit utility bills are not available for either home. For comparison, we compare these homes to the average single family CA home, which uses 20,061 kWh, 36,737 kWh and 9,346 pounds of net-site, net-source and CO_2e annually. When compared with this average home, P6-North used 78.5% less net-site energy, 77% less net-source energy and produced 78 % less CO_2e emissions. P6-South used 44.1%, 50.3% and 46% less respectively. Both homes are approximately 100 ft^2 smaller than the average CA single family home, which is 1,579 ft^2. As a combined home, P6 reduced energy use by 23%, 27% and 24%, respectively, relative to the CA average. Notably, there were four residents in each structure, for a total of eight, which makes it the most populated project home, with 2.7 times the number of occupants in the average CA home. The HERS (2006) scores for the North and South houses with PV systems included were 28 and 37, respectively.

The energy generated by the PV systems was not included in this assessment, as discussed above. In future years, these systems are estimated to generate 3,492 kWh to 4,366 kWh for the North house, and 2,910 kWh to 3,638 kWh for the South house[12]. In a good year, this would result in P6-North performing at zero-net site energy. As a combined home, net-site usage would be offset 41% and 52% in low and high-output years, respectively. Given the two-to-one ratio of gas-to-electricity usage in P6, net-source energy reductions would be significantly larger.

[12] Assumes a Southern orientation panel mounted on a 7:12 roof in Sacramento, CA. Low and high output estimates per kW installed PV are 1,455 and 1,819 kWh/year.

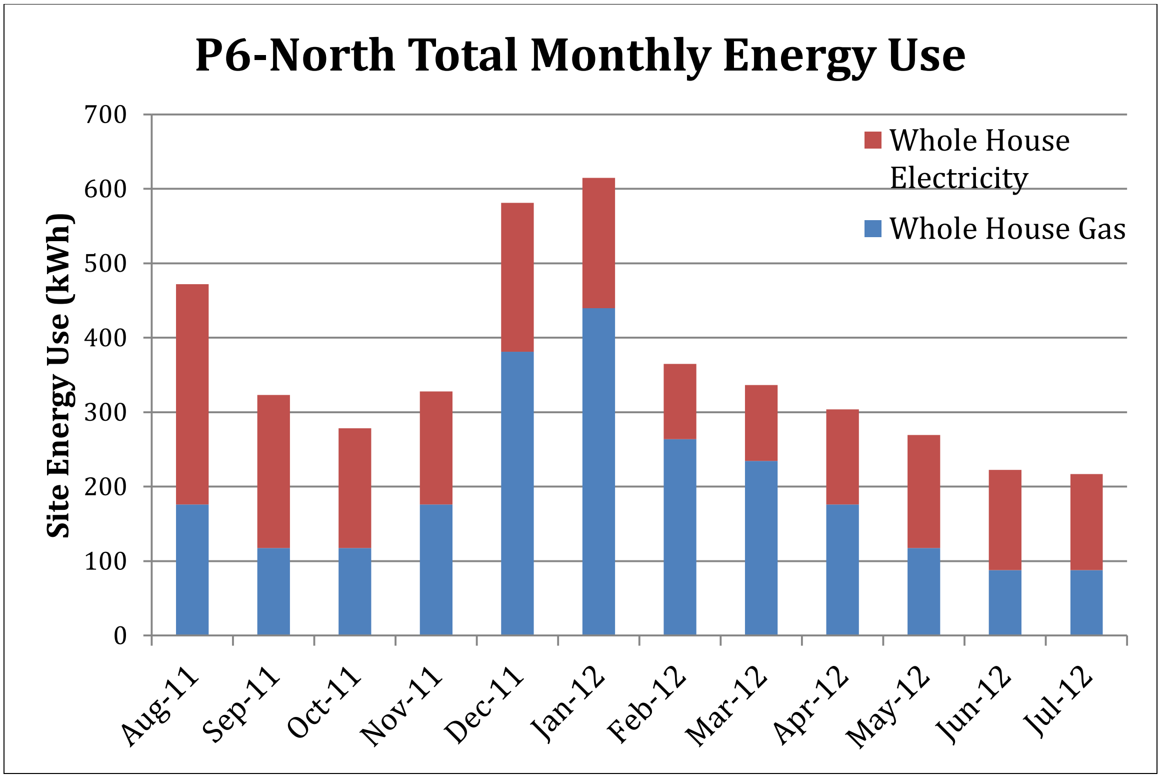


Figure 87 - P6 North Total Monthly Energy Use

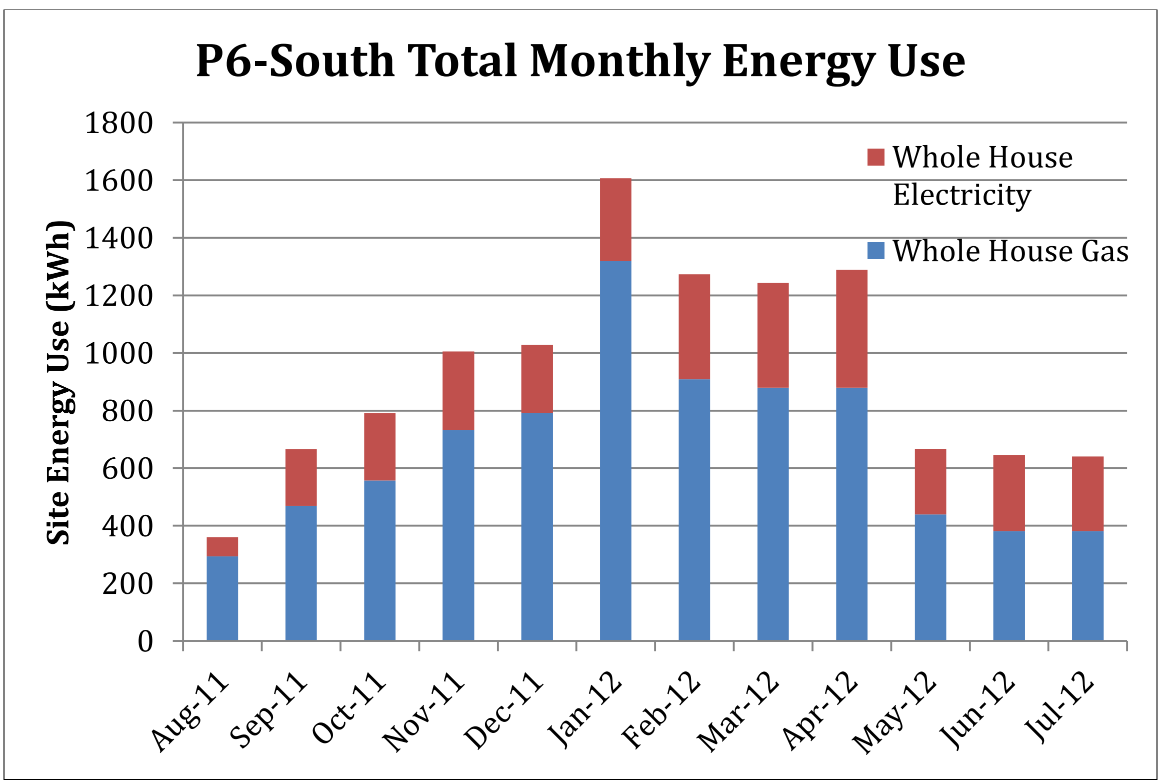


Figure 88 - P6-South Total Monthly Energy Use

Total annual energy use varies significantly between the two homes despite being of similar construction quality, location, orientation, etc. The South house used 1.6 times as much electricity and 3.4 times as much gas on an annual basis. As for the electricity, two main elements likely contribute to the difference. First, the North house does not have a refrigerator. Essentially all cooking and food preparation for the combined eight occupants occurs in the South house. Second, a relatively large fish tank is located in the South house, which has lights, heaters, pumps, etc. In terms of gas usage, the two likely contributors are the historic gas range, which is used to cook for eight adults, and slightly increased heating energy demand due to rehabbed versus new windows. The bulk of the increase is due to the gas cooking. The historic range uses multiple pilot lights, so in addition to actual cooking activity, the pilots contribute on a 24/7 basis to the 8,030 kWh gas energy each year.

Monthly site energy consumption is shown for P6-North and South in Figure 87 and Figure 88 above. Both homes show a weather-dependent gas consumption pattern, with increases in the wintertime, due both to heating loads and decreased solar thermal input to hot water.

End-uses

Part-year end-use summaries for P6-North and South are pictured below in Figure 90 and Figure 91. Their combined part-year end-uses are summarized in Figure 89. As a combined home, P6 is dominated by appliance energy usage (43.5%), specifically the gas range in the South house. Heating and DHW are similar, making up 17% and 21% of the total respectively. Domestic hot water is the dominant end-use in the North house, where no cooking occurs and heating energy is kept very low with cold winter indoor temperatures. The gas range clearly dominates the total usage of the South house, but plugs, heating and lighting are all higher than in the North house as well.

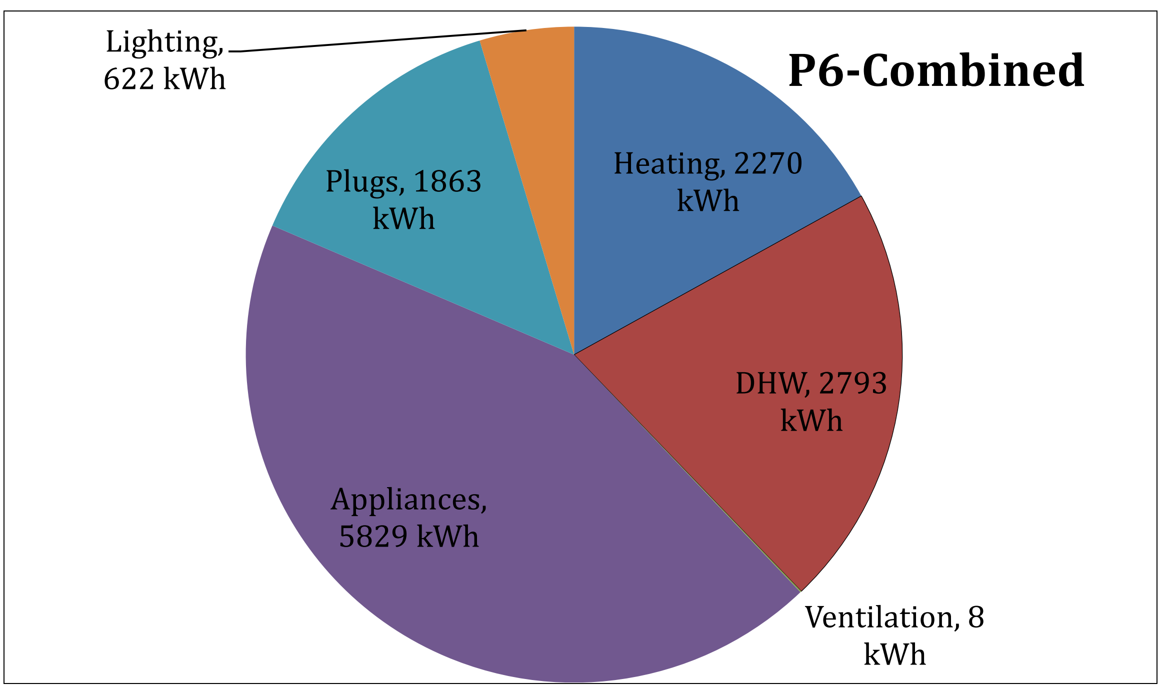


Figure 89 - P6 Combined Annual End-Uses (only 10 months)

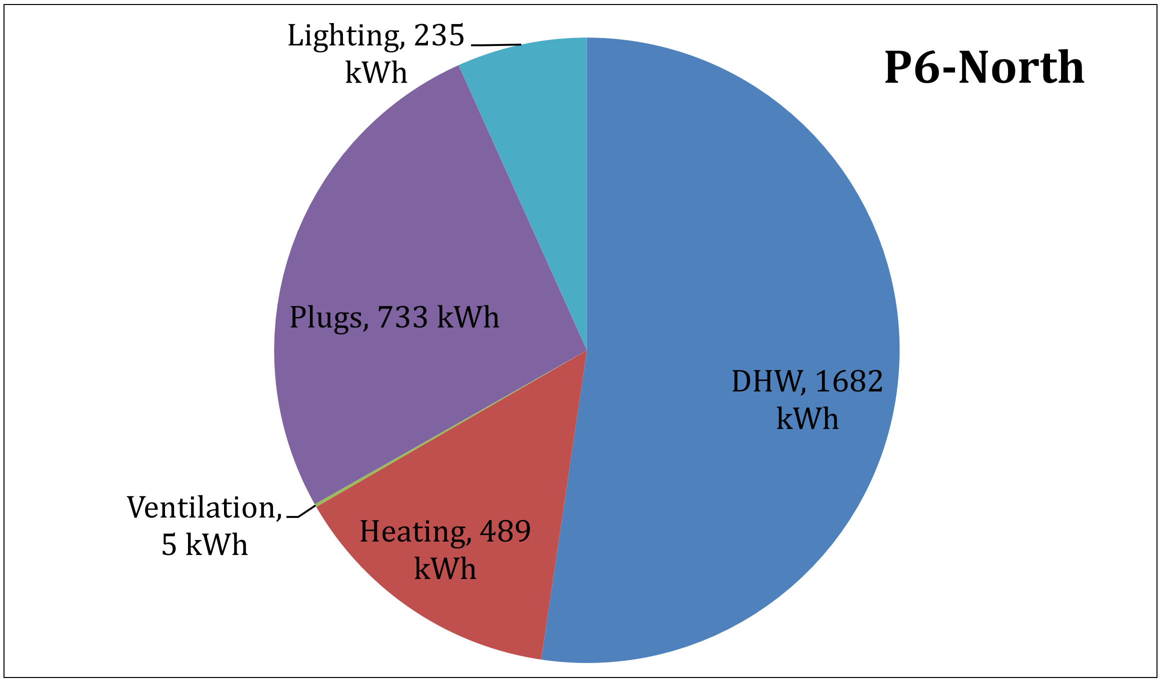


Figure 90 - P6-North Annual Energy End-Uses (only 10 months)

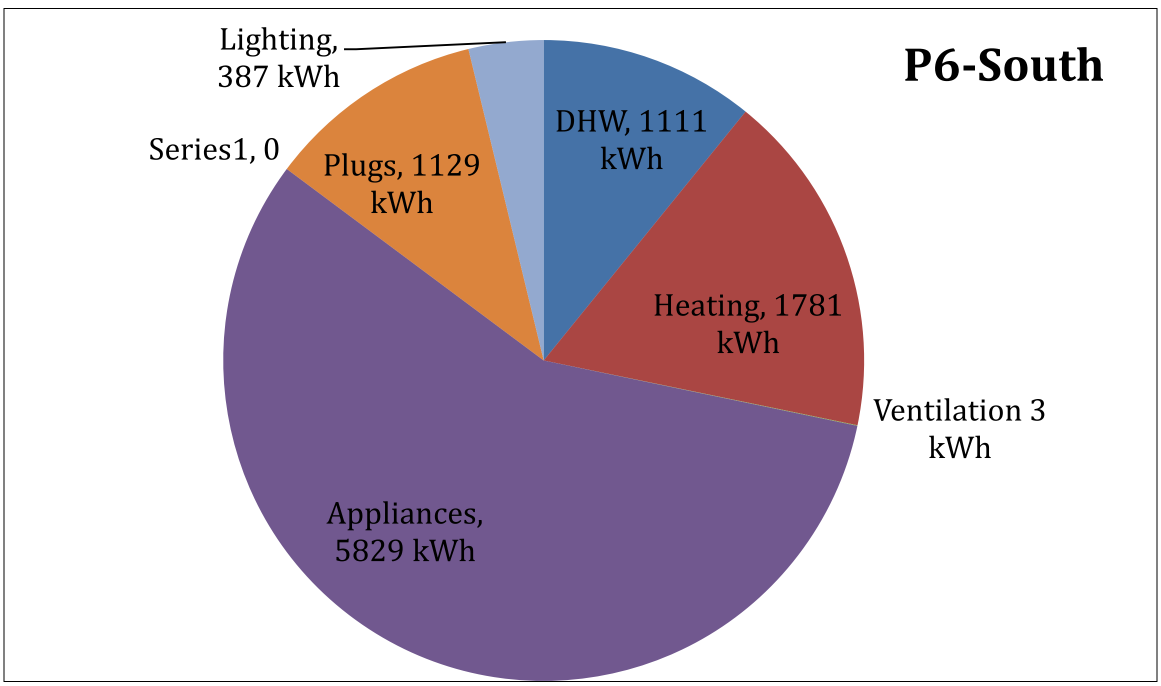


Figure 91 - P6-South Annual Energy End-Uses (only 10 months)

Monthly energy end-uses for P6-North and South are summarized in Figure 92 and Figure 93 below. Consumptions between the homes are similar with the exceptions of the gas range in P6-South and heating energy consumptions. Peak heating month energy used in the South house was 661 kWh versus 258 kWh in the North House. This is likely the result of the temperatures maintained in the projects. The South house averaged around 61 degrees F from December through March, whereas the North house averaged 67 degrees F during the same time period. In addition, substantial heating energy was used in the South house from December through April, whereas the North house went from December to February.

The dominant end-use in the South house was the historic gas range, which averaged 445 kWh per month, which is equivalent to a 24/7 baseload of 618 watts. This is an estimated 5,339 kWh per year, which is 1,000 kWh more than the total annual net-site consumption of the North house. As noted above, the North and South houses are a co-housing facility, which means that some facilities are shared—cooking is one of them. Essentially all cooking for the eight residents was done in the South house; the electric range in the North house remained unused.

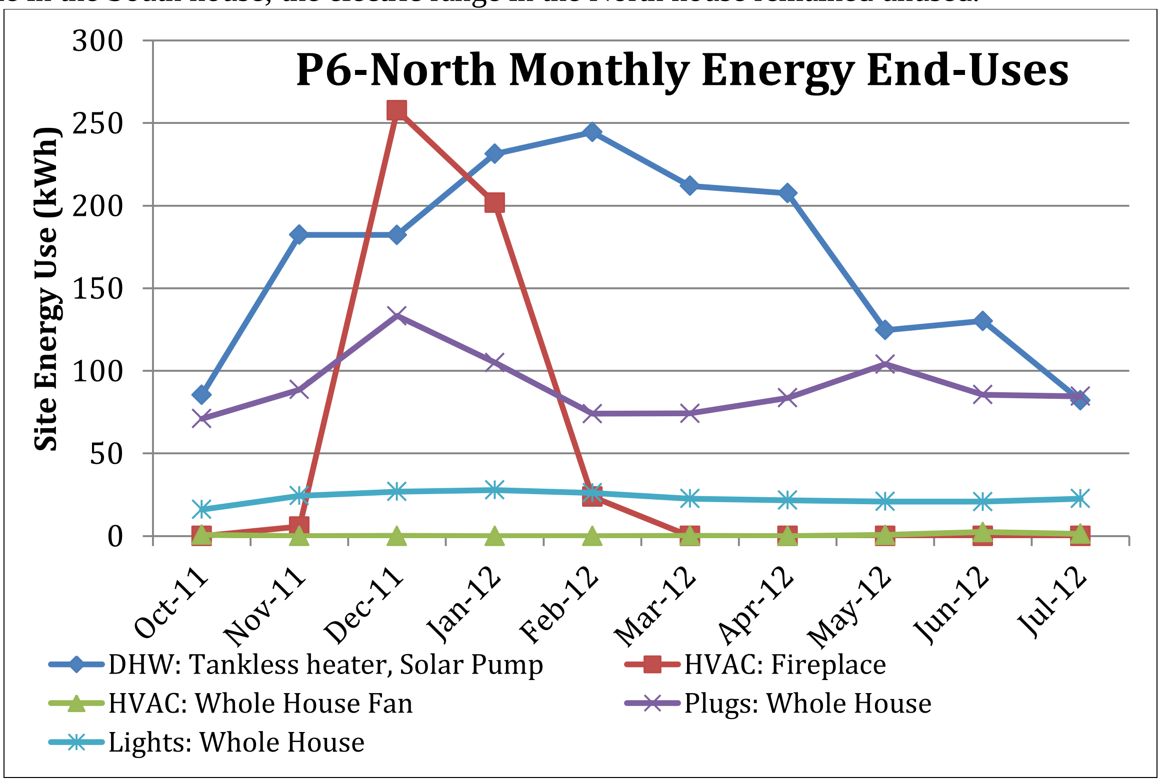


Figure 92 - P6-North Monthly Energy End-uses

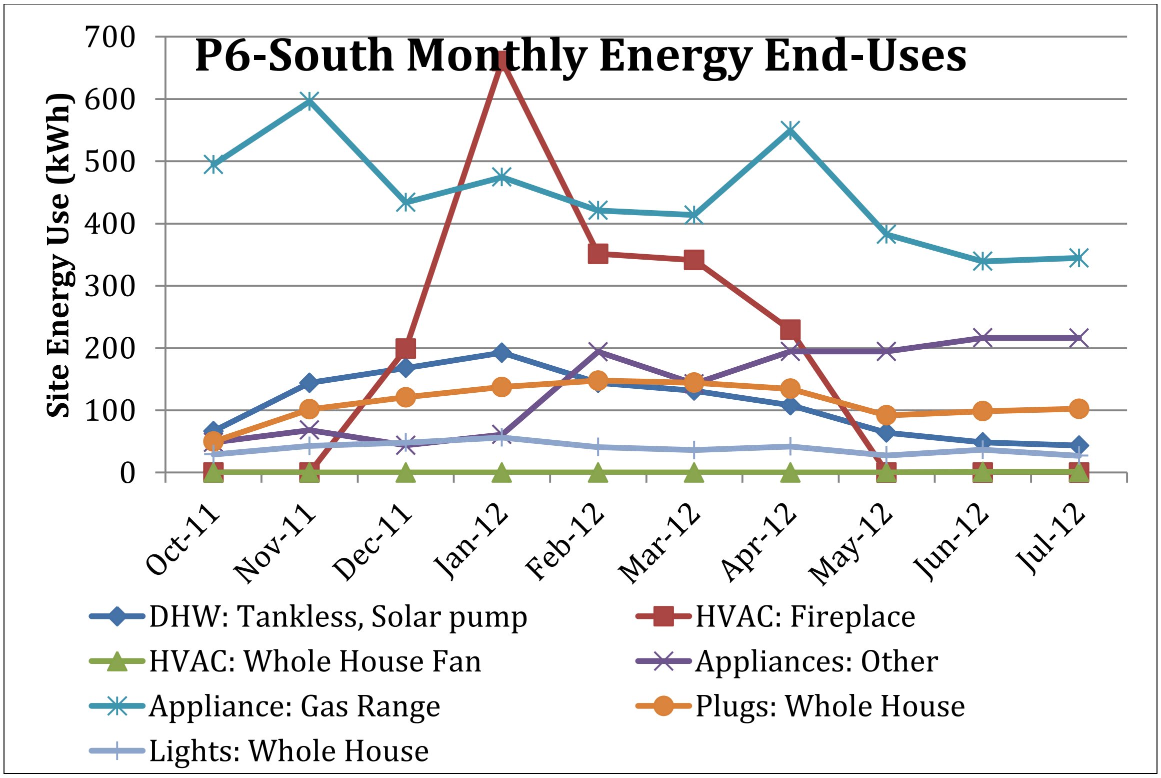


Figure 93 - P6-South Monthly Energy End-Uses

User Behavior

The occupants of P6 were very committed to a low-energy lifestyle. The North home had a baseload of 43 Watts, which led to an estimated 380 kWh of annual baseload consumption. This baseload value accounted for 8.8% the total annual net-site energy consumption. The South house had an electric baseload of 111 Watts, which led to an estimated 974 kWh annual baseload consumption. The baseload value of the South house accounted for 8.7% of the annual net-site energy consumption. Heating energy in both homes was greater than the baseload consumption.

IEQ Summary

Monthly temperature and relative humidity means and standard deviations for P6-North and P6 – South are presented in Table 34 and Table 35 below. The temperatures maintained in the two side-by-side project homes were quite different, with much higher winter temperatures in the South house. Monthly averages varied from 61 to 75 degrees F in the North house and from 63 to 79 degrees F in the South house. The monthly indoor temperatures are compared in Figure 94 below. Monthly averages were about six degrees cooler in the North house from January through August, and then became much more similar to one another from September through December. This odd pattern was likely the result of thermostat settings in each home, as both houses were super-insulated and of similar airtightness. Oddly enough, P6-North had all new efficient windows, where as the South house rehabbed the existing wood framed units. Nevertheless, in both homes, the living room and bedroom temperature averages tracked each other very closely, which is impressive, as each house was heated solely by one central gas-burning fireplace. Regression slopes were 1.2 in both homes, with R^2 >0.99. The bedrooms were selected as the ones furthest from the heat source, and the living room sensor was in the room with the heater. This temperature consistency supports the use of point-source heaters in super-insulated homes in California and other similar climates. These results suggest that both homes were capable of delivering superior, consistent comfort levels.

Relative humidity was reasonably well-controlled in both homes, despite the low winter temperatures in the North house, which could have led to elevated RH.

P6-North Summary of Temperature and Relative Humidity by Month								
	Temperature				**Relative Humidity**			
	Living Room		**Bedroom**		**Living Room**		**Bedroom**	
Month	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
January	60.9	1.9	60.6	1.6	53.6	5.5	59.5	5.6
February	60.6	1.9	61.5	1.7	53.1	9.7	60.4	7.8
March	61.0	2.2	61.8	1.9	55.2	9.2	59.1	7.0
April	65.8	5.0	66.6	4.9	53.9	7.6	61.6	4.1
May	69.8	3.5	71.8	2.9	46.1	7.2	51.8	5.2
June	72.6	4.2	75.3	3.3	45.0	7.3	47.8	4.3
July	72.8	3.7	76.5	2.6	54.2	4.4	52.0	3.5
August	73.4	3.7	76.6	2.7	53.8	4.4	51.6	2.9
September	75.4	4.4	78.0	2.9	49.3	7.0	48.4	4.6
October	69.9	3.7	71.1	3.5	53.4	9.2	53.6	6.6
November	63.1	2.1	63.8	2.3	52.4	8.5	55.6	7.6
December	61.0	2.3	60.3	1.6	47.3	5.7	54.6	5.8

Table 34 - P6-North Summary of Temperature and Relative Humidity by Month

P6-South Summary of Temperature and Relative Humidity by Month								
	Temperature				Relative Humidity			
	Living Room		Bedroom		Living Room		Bedroom	
Month	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
January	67.1	2.5	66.1	2.3	55.8	3.2	57.9	5.1
February	67.3	1.7	67.4	1.5	52.3	5.2	54.7	7.6
March	68.7	1.8	68.8	1.7	49.9	4.2	54.7	6.8
April	71.7	4.1	72.4	4.3	49.5	3.0	52.3	5.4
May	74.8	3.3	76.3	3.7	41.7	3.7	40.5	6.5
June	78.3	4.0	79.4	4.4	40.0	3.4	38.2	5.1
July	78.4	3.2	79.6	3.6	46.1	3.0	45.3	4.4
August	78.9	2.7	79.9	2.6	46.8	3.1	45.2	3.8
September	78.2	2.9	80.2	2.7	47.2	3.8	46.3	4.8
October	72.2	2.8	73.4	3.0	52.4	4.9	52.9	6.3
November	66.8	1.7	66.3	2.5	53.6	6.5	55.2	5.8
December	63.2	2.6	62.0	2.5	55.7	3.0	55.0	5.1

Table 35 - P6-South Summary of Temperature and Relative Humidity by Month

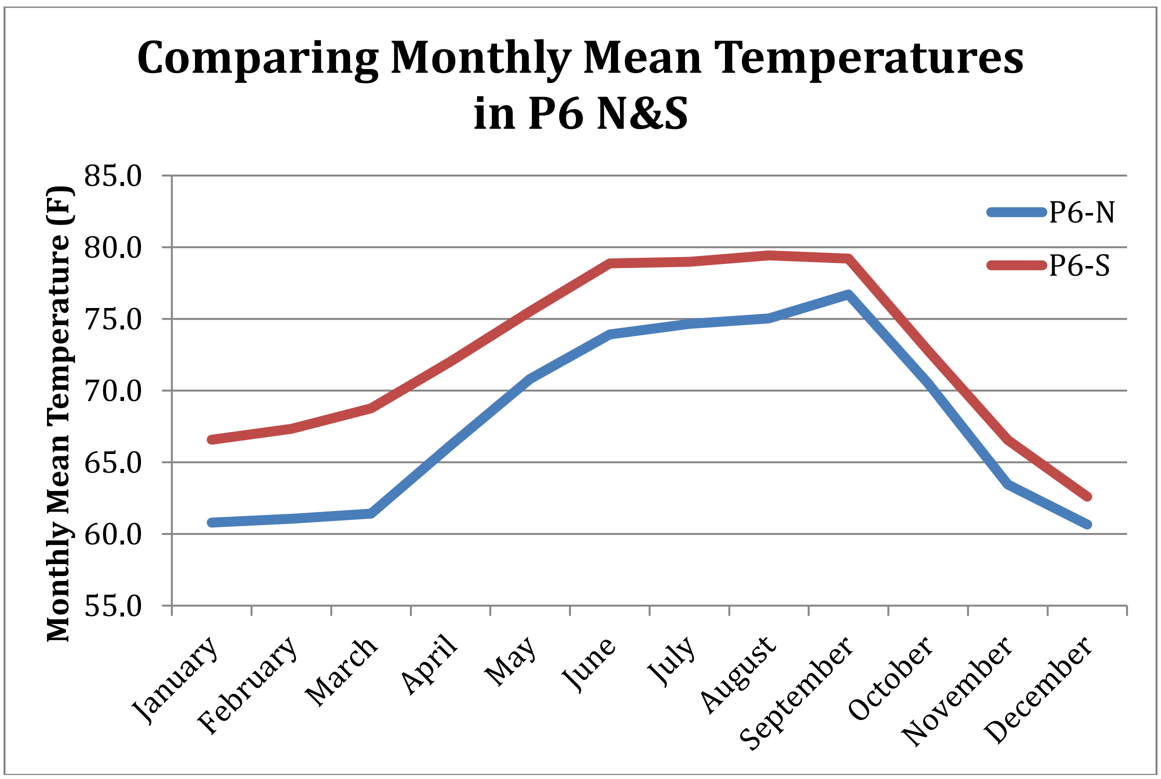


Figure 94 - P6 North and South, Comparing Monthly Mean Living Room Temperatures

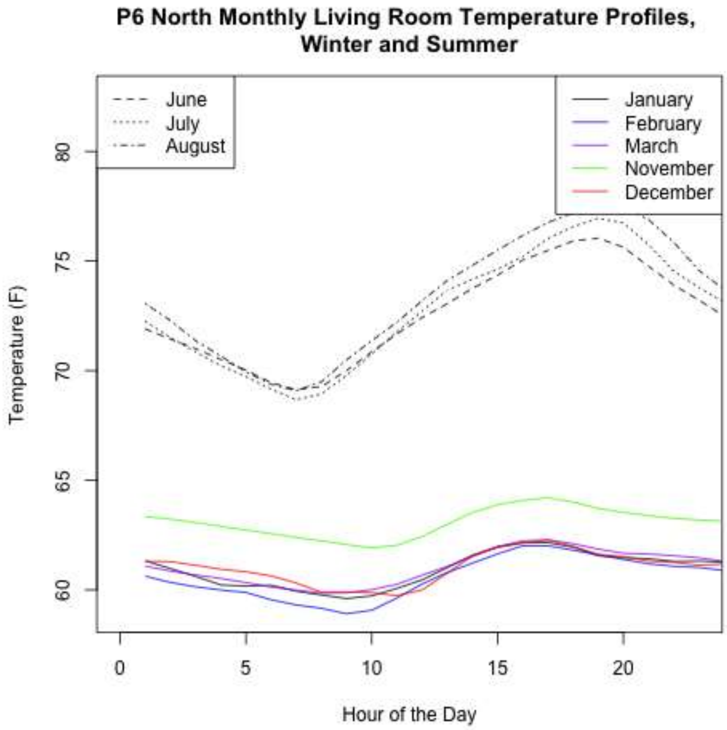


Figure 95 - P6 North, Monthly Living Room Temperature Profiles, Winter and Summer

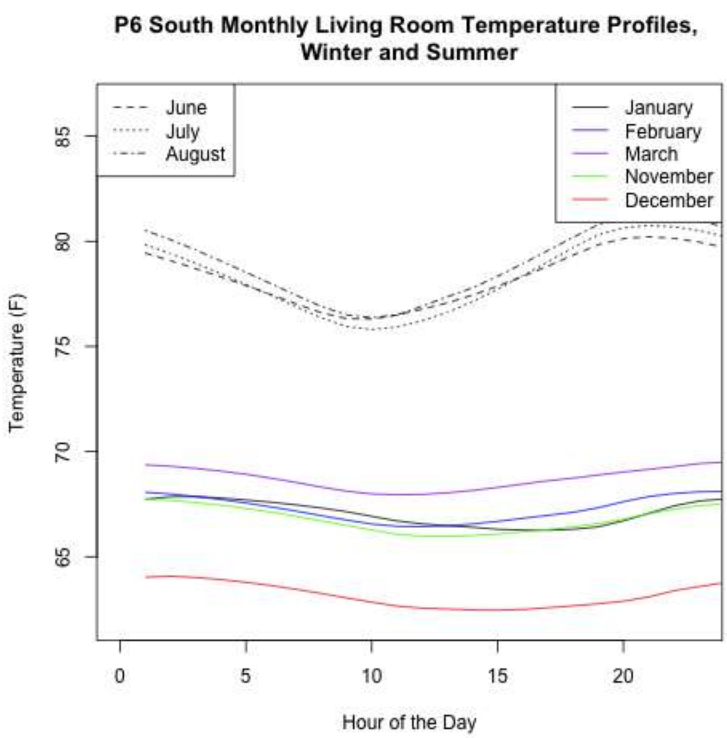


Figure 96 - P6 South, Monthly Living Room Temperature Profiles, Winter and Summer

15-minute temperature differences between the bedroom and living room in P6-N and P6-S are pictured in Figure 97 and Figure 98 below. Annual average temperature differences were 1.4 degrees F in P6-North and 0.5 degrees F in P6-South. P6-North spent 17.8% of the year outside of the ACCA recommended range of +/- four degrees, and P6-South was outside the range only 1.8% of the year. This is consistent with the reduced space heating temperatures that were maintained in the North house, despite its enhanced envelope (more airtight and new windows).

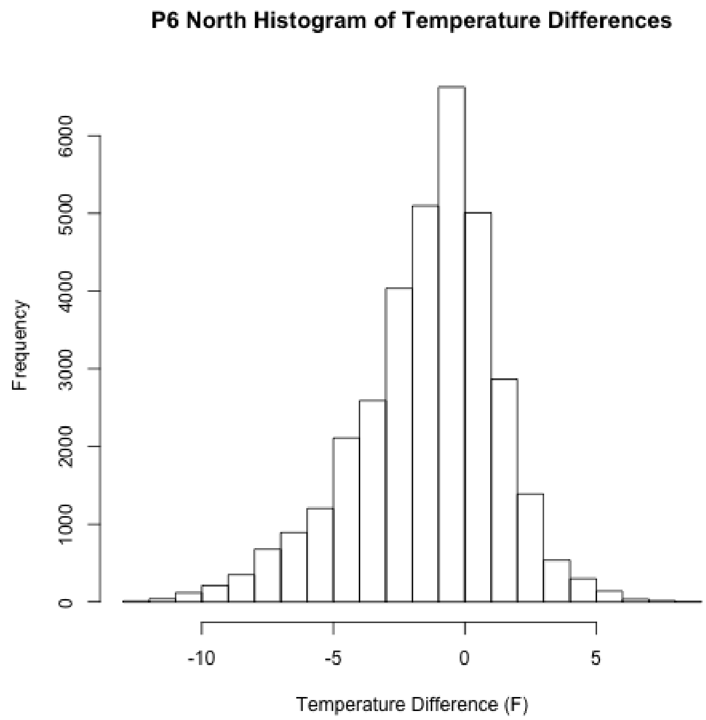


Figure 97 - P6-N Histogram of Temperature Differences

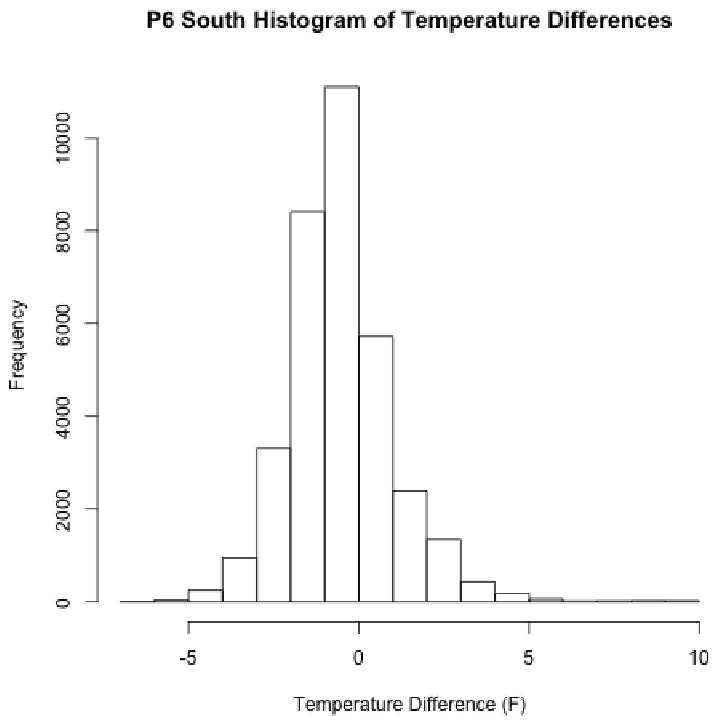


Figure 98 - P6-S Histogram of Temperature Differences

The proportion of time that relative humidity was below, within and above the recommended range of 30 to 60% in P6-North and South is presented in Table 36 below. Both homes were rarely below 30%, and both spent a significant portion of time above the recommended range, with the North house more than doubling the time of the South house. As indicated in Figure 99 and Figure 100 below, while the bedrooms in both homes experienced RH above the recommended range, neither spent significant periods above 70%.

Proportion of Time Relative Humidity Was Below, Within and Above the Recommended Range			
Location	**Below 30%**	**30% to 60%**	**Above 60%**
P6-North			
Living Room	1%	85%	14%
Bedroom	0%	75%	25%
P6-South			
Living Room	0%	97%	3%
Bedroom	1%	89%	10%

Table 36 - P6 N and S Proportion of Time Relative Humidity Was Below, Within and Above the Recommended Range

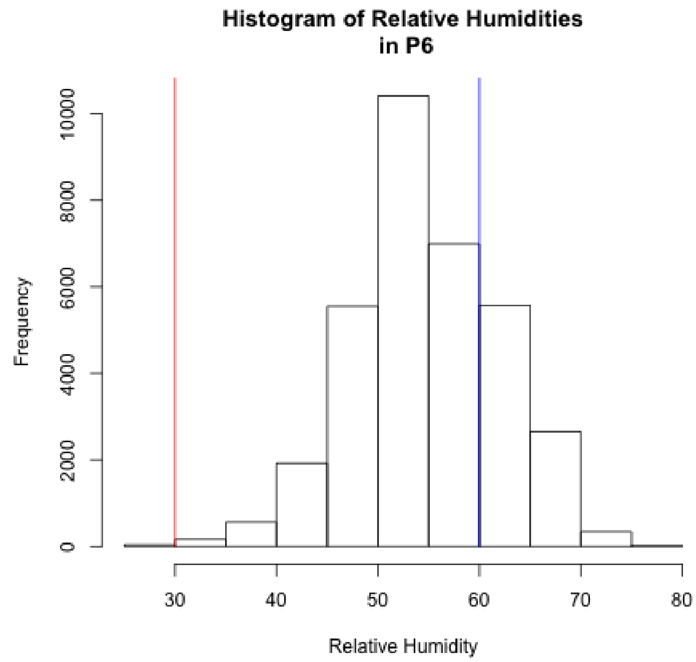


Figure 99 - P6 North Histogram of Bedroom Relative Humidity

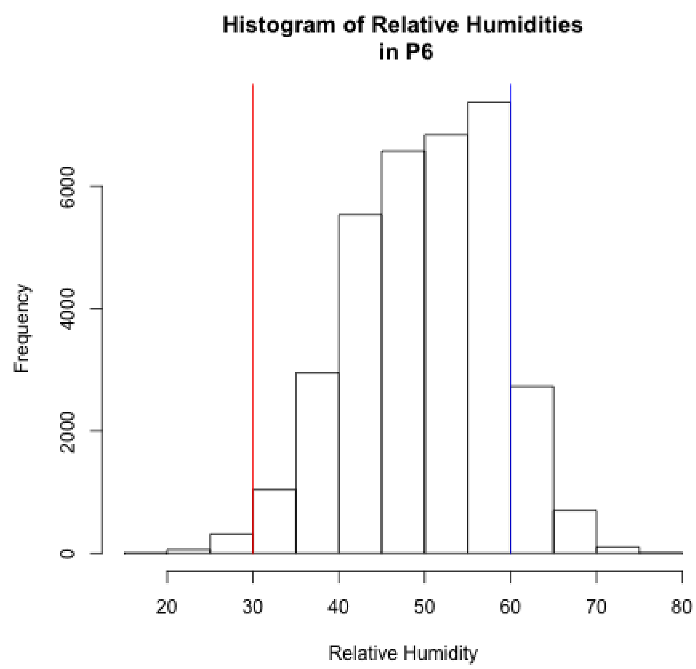


Figure 100 - P6 South Histogram of Bedroom Relative Humidity

4.6.4 P6 Overview

P6 North and South are a co-housing project that has taken a unique approach to deep energy reductions. In addition to renovating two aged structures into super-insulated, passively cooled and point-source heated homes with solar thermal and PV systems, the occupants have chosen a lifestyle where they share resources in an effort to further reduce their footprint. They leverage the investments made in an energy efficient home by living more densely and co-operatively. Due to its co-housing nature and use of two independent structures, interpretation of the performance of P6 is challenging and difficult to compare against the other DER project homes. We have elected to consider the two structures as separate homes, but they could also be considered a single home, as was done in the energy sections above.

An obvious performance issue in P6 was the historic gas range in the South house, which used more energy than P3, P4 and P6-North did as whole homes. Partly this resulted from cooking for eight occupants, but the pilot lights surely also contributed greatly to this total, with four cook top pilots and two oven pilots. Elimination of these pilots would save substantial energy and reduce exposures to combustion pollutants.

The temperatures in the two structures were quite different, with much lower temperatures being maintained throughout the winter in the North house. It is not clear why such a great difference was maintained between the structures, as both have four bedrooms with similar occupancy patterns. Clearly the residents were willing to engage in conservation at the expense of comfort on some levels. Despite the lower temperatures, relative humidity indoors was kept consistently below the 60% recommended RH threshold.

Miscellaneous electricity uses in both homes were very low, particularly given the high occupancy of adults with personal computers, entertainment devices, etc. When the PV production is included in the assessment of these homes, this low electricity use will lead to exceptional net-source energy performance.

While unique and not easy to compare with other project homes, P6 provides a different vision of how deep energy reductions can be pursued alongside lifestyle changes. This combination can be especially powerful at reducing the ecological footprint of the occupants. While co-housing may not be an acceptable model for many Americans, the example of high-density living applies across lifestyle choices, and can lead to lower cost DERs, reduced energy usage from heating, as well as reduced plug loads and lighting energy.

4.7 P7

4.7.1 P7 Project Description

Image 28 - P7 Front of Home and House-Within-A-House Insulating

P7	Pre-Retrofit	Post-Retrofit
ENVELOPE		
Wall Insulation	None	Rear zone: 5.5" BIB, 1" polyiso – R23 Upstairs: 3.5" blown fiberglass – R13 Downstairs: None
Attic/Roof Insulation	Some fiberglass batts	5.5" BIB, 2" polyiso – R36 Rear zone ceiling: 7.5" BIB – R30
Foundation Insulation	None	Sealed crawlspace and basement, 2" polyiso under floor joists – R12.9
Windows	Single pane aluminum frame	Rear zone: 2 pane, Low E, argon filled, fiberglass frame - U: 0.28 SHGC: 0.27 Rest of house: Old, leaky double hung wood frame, single pane
Air Leakage	8,432 CFM_{50}	5,336 CFM_{50}, 10.8 ACH_{50}
MECHANICAL		
Heating and cooling	119kBtu/hr gas furnace AFUE 75-80%	(2) 26-40 kBtu/hr gas furnaces, three stage variable speed blower, 95% AFUE
DHW	Tankless gas heater & 40 gal gas tank heater	Condensing gas tankless with 2 gallon integrated storage tank
Ventilation	Bath exhaust	Bath exhaust fans and 1400CFM kitchen exhaust
Distribution	Sheet metal, supply leakage 115CFM, return 123CFM	R6 foil faced flex duct, 86 CFM total supply leakage and 67 CFM total return leakage
LIGHTS/APPLIANCES/MEL	6 burner commercial gas range, 6 pilots	All CFL, Very high gas use from range, disabled all but 1 pilot
RENEWABLES		None

Table 37 - P7 Retrofit Summary Table

General Information

P7 is located in San Mateo, CA. The occupants have used an intriguing zoned heating strategy to achieve low levels of energy use in a relatively large home, while maintaining the historical character. The home was originally constructed between 1910 and 1912, and it is resplendent with historical detailing throughout, from the decorative plaster (see Image 29 below) and three large fire places, to the ubiquitous wood paneling and original wood frame, tilt out/double hung, wavy glass windows. The occupants of P7 are extremely dedicated to pursuing energy reductions in their home, and they have been undergoing a ten-year long process of identifying and eliminating energy waste. More recently, P7 has entered into the Thousand Home Challenge (THC), which has focused the occupants on a 70% to 90% whole house energy reduction.

Image 29 - P7 Example of Decorative Plaster on 1st Level

As part of the THC planning process, the homeowners, designers, contractor and consultants underwent a careful process of energy budgeting, in order to identify energy retrofit measures that would have the greatest impact, given the specific lifestyle of the occupants. Utility bills for the home have been collected since 1997, and the three highest consumption years were used to generate a weather adjusted pre-retrofit usage of 31,248 kWh/year site energy. In addition to careful tracking and charting of utility billing data, the occupants of P7 also underwent an extensive energy use data collection and budgeting process, in preparation for their deep energy retrofit. The homeowner created a spreadsheet containing every energy-using device in the home, and measured the power draws of these devices with a plug-through power meter. Estimated usage times were then used to apportion daily and annual energy use to these devices. All of this was used to focus the efforts of the retrofit so that specific loads could be targeted and reduced purposefully.

The occupants of P7 had already achieved impressive energy reductions in their home prior to starting the retrofit, but the majority of these savings were the result of "austerity measures" or comfort experiments. These measures included infrequent use of the existing forced air furnace, and a reliance on using the rear zone of the home, with doors closed and oven pilot lights firing, as a concentrated zone of relative comfort. The occupants performed some temperature data logging in their home during the winter of 2009, and from September 22nd to January 13th, the temperature in this zone was below 60 degrees F for 902 out of 2,714 hours. With this heating energy reduction effort and other energy reduction strategies, P7 reduced its annual energy use from a high of 34,933 kWh in 1999 to a low of 17,325 kWh in 2009—a 50.4% reduction.

Needless to say, the goal of the deep energy retrofit was to achieve similar or greater energy reductions, while providing higher levels of comfort and convenience in the home.

The primary constraints in P7 are the large size of the home at 3,288ft^2, its historical details and the sheer magnitude of costs and time associated with a full envelope retrofit. With only 2 occupants, the 3,288 ft^2 of conditioned space in P7 cannot be fully utilized. As a result, the occupants see it as a waste to condition the entire home. The historical detailing on the first floor made it difficult or impossible to insulate or properly air seal without highly destructive means, which would go against the desire to preserve the historic nature of the home. Ultimately the solution to these issues is what the project designers call a “house within a house”, where an L-shaped portion of the 1st floor is fully insulated and air sealed, with respect to both the exterior and the rest of the home. This “house within a house” forms a single HVAC zone, which can be conditioned separately in the heating season, without fully heating the rest of the home. In addition, wherever the historical detail constraints were absent, the rest of the structure was insulated and brought up to a high performance standard.

Building Enclosure

Despite the constraints, the enclosure retrofit of P7 was substantial and wide-ranging, and it provided for increases in efficiency, comfort and seismic security. The basement/crawlspace was left unconditioned and moisture is controlled through extensive exterior drainage and an under slab moisture barrier. The underside of the floor framing is insulated with 2” of continuous foil-faced polyisocyanurate foam board, taped and sealed at all joints and edges (see Image 30 below). Above grade 2x4 walls were drilled and filled with blown fiberglass insulation in all portions of the home where decorative wood paneling and large windows were not prohibitive. The rear-L of the home, which is the “house within a house” zone, had the exterior structural framing replaced, facilitating new window flashing and waterproofing details (see Image 32 below). The 2X4 framing in this area is insulated with blown fiberglass and then an additional layer of 1” foil-faced polyisocyanurate foam board. The foam board was placed on the exterior for most of the rear-L, but one wall had the foam board installed on the inside of the framing in order to match the thickness of the existing adjacent wall (see Image 31 below). The attic framing was reinforced to facilitate future installation of PV or solar thermal collectors, and the previously vented attic was insulated at the sloped roof deck and vents were removed. The attic rafters were filled with blown fiberglass insulation, and then 2” of continuous foil-faced polyisocyanurate foam board was installed and sealed to the underside of the roof framing. This brought the attic furnace and ducting into conditioned space.

Windows in the rear-L were replaced with wood framed, double pane, low-e windows, with U-values ranging from 0.28 to 0.3 and SHGC values ranging from 0.23 to 0.3. All other windows in the home were not replaced, but may receive weather stripping in the future.


Image 30 - P7 Crawlspace with New Slab, Foam Board Insulation, Structural Reinforcement, Air Sealing and Water Proofing


Image 31 - P7 Rear-L New Windows, Interior Continuous Foam Board and Sheetrock

Image 32 - P7 Installation of New Window Flashing on Rear-L

Air Leakage

The majority of the home remains very leaky. However, the "house within a house" zone effectively acts as if it were a multi-family building, with very little surface area exposed to outside, as it is shielded by a partly conditioned buffer zone to the top and along approximately 50% of its perimeter. As this area was completely re-built and isolated from the rest of the home, they were able to minimize air infiltration through the proper use of drywall as an air barrier. This zone may suffer from a lack of continuous ventilation, but the occupants are active in opening windows during fair weather.

Ventilation

No continuous mechanical ventilation was provided in P7. New exhaust fans were installed in the upstairs and downstairs bathrooms, as well as a variable speed kitchen exhaust fan. The home is fairly leaky with respect to infiltration, with the obvious exception being the newly tightened "house within a house".

Heating

The mechanical equipment in the home was replaced as part of the retrofit, and it was designed to facilitate the "house within a house" design concept. The pre-retrofit heating system was a 25-year-old natural gas, forced air 119 kBtu/hr furnace with powered atmospheric combustion exhaust located in the unconditioned crawlspace. This unit, with estimated efficiency of 75% to 80%, was replaced with two high-efficiency natural gas furnaces, one in the crawlspace and another in the conditioned attic. The new units are sealed combustion, 3-stage, 24-40 kBtu output burners with 95% AFUE and variable speed ECM fan motors. The new furnaces are connected to all new R-6 foil faced flex ductwork, and sealed with mastic (see Image 33 below). The new duct systems are zoned to provide on-demand space conditioning, with two zones on the first floor and three zones on the second floor. The attic duct system and air handler is entirely located in conditioned space, while the crawlspace ducts and air handler are located partially in the unconditioned crawlspace/basement and partially in conditioned space.


Image 33 - P7 New Furnace and Ductwork in Sealed Attic

DHW

Hot water has been a troubling issue in P7, and as of this writing, no hot water system has provided truly acceptable service to the occupants. The hot water system prior to the 2010 retrofit consisted of a tankless 20-185 kBtu/hr modulating gas water heater, and a 40-gallon gas tank water heater. This latter unit was used as a buffer tank to eliminate the common "cold water sandwich" problem associated with short, fast water draws on a tankless gas heater. This is a problem that arises when the hot water remains in the pipe from the previous use, then when a faucet gets turned on again it takes a few seconds for the instant hot water heater to actually get the water up to temperature, the water that flowed through the heater up until then remains cold and is surrounded by hot water on both sides. The occupants alternated use between the two units, and they were not integrated with one another. In an effort to get the best of both worlds, a hybrid natural gas water heater was installed during the retrofit. This new unit, which was mounted on the exterior of the home, has an instantaneous gas boiler with a small 2-gallon storage tank and a rated energy factor of 0.96. The intention of such “hybrid” units is to buffer the typical “cold water sandwich”, but it is not working very well at P7. The occupants are very judicious with their hot water draws, and this results in a quick drawdown of the 2-gallon tank, while never firing the gas burner, and then the cold water sandwich resumes. Current considerations are the installation of an optional 7-gallon buffer storage tank, which is typically reserved for commercial applications. The occupants are nervous about the regular gas draw that is required to heat the current 2-gallon buffer, and are even more concerned about a 7-gallon tank. They currently turn the water heater off manually when not in use, in order to avoid the heat penalty of keeping the buffer tank warm, but this does require a period of waiting for hot water in the morning.

Appliances

Cooking is very important to the occupants of P7, which is reflected by their calculation that cooking made up greater than 20% of their total annual household energy use pre-retrofit. They were determined to keep their large 6-burner gas range in operation. Experiments with their utility meter revealed that pilot light usage on this stove was approximately 1 Therm every 3 days. The occupants were experimenting with using the waste heat from cooking and from these pilot lights to heat the "house within a house" prior to the insulation and HVAC retrofit. But once other provisions for zoned comfort had been made, this did not seem ideal. The large amount of energy use attributed to the wasteful pilot lights and their likely contribution to poor air quality (Logue *et al.*, 2011) in the "house within a house" began to concern the occupants once monitoring began. With a gas submeter in place, the occupants were informed that their stove used a cubic foot of gas every 40 minutes when not being actively cooked upon (estimated 3,951 kWh per year). They then extinguished the stovetop pilots, but left the oven pilot burning, as that one is not easy to relight when cooking. This reduced the pilot light gas usage to 1 cubic foot every hour and 40 minutes (estimated 1,580 kWh per year). While a large improvement, the energy used by the pilot lights is still disconcertingly high. The homeowner has taken it upon herself to learn about and experiment with some alternative cooking methods, which she hopes will further reduce the gas used for cooking. Cooking is not typically an energy end-use that is considered for energy reductions (aside from fuel switching), but P7 is an example where ignoring this load can in a way sabotage deep energy reduction efforts. Also, by not targeting this highly wasteful pilot light energy more aggressively, more expensive investments must be made in efficiency elsewhere, in order to achieve the same household energy performance.

There is no dishwasher or clothes dryer, and the rest of the appliances are Energy Star rated.

Plug Loads

There are very few plug loads in the home. The office has our small netbook for energy monitoring that is always on, as well as the wireless modem. Additionally there are two computers and a printer in the home. Apart from this, most of the plug loads are cooking related.

Lighting

All lights are CFL and controlled with wall switches.

Additional Information

The retrofit strategies used in P7 are uncommon and innovative, and some of the energy use patterns are not altogether typical. First, the highly detailed energy budgeting and load inventorying efforts are notable. Aside from detailed energy submetering, such efforts are a great way for deep energy retrofit planners to understand how energy is actually used in their project homes. Without this knowledge, they cannot hope to most effectively target their retrofit strategies, and they will be less likely to meet their real-life energy reduction goals. Second, the "house within a house" strategy is a unique solution to the problem of large, historic homes, which can be too large for the occupants and too difficult or expensive to effectively thermally retrofit. This solution provides for thermal comfort, a flexible space and a creative approach to a DER. Third, P7 is notable for the problem it is experiencing with pilot light energy use, as it will likely make up a sizable portion of the home's annual energy usage, and is serving no occupant or building need. Apart from this, P7 is exemplary for the dedication its occupants have shown for understanding energy use in their home, and their continued effort to understand and reduce usage before and after the retrofit was complete.

4.7.2 Building Diagnostic Results

Blower Door

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH
P7	5336	10.82	0.79	1.62	300.62	0.72

Table 38 - P7 Blower Door Results

The pre-retrofit structure was uninsulated throughout, and a pre-retrofit blower door test measured 8,432 CFM_{50}. How effective is the house-within-a-house strategy? Post-retrofit blower door diagnostics revealed a remaining 5,336 CFM_{50} of air leakage to outside and total ELA of 300.62 in^2. But special efforts were paid to carefully seal the "house within a house" rear-L portion, where leakage-to-outside was separately measured at 448 CFM_{50} (ELA of 21.1 in^2). The total leakage of the rear-L, which includes both leakage to outside and leakage to the other house zones, was measured as 978 CFM_{50} (ELA of 59.6 in^2). When these ELA are normalized by floor area, the post-retrofit total ELA/ft^2 in the rear-L was 0.1 and ELA/ft^2 in the whole house was 0.091. Proportionally, the ELA to outside of the rear-L made up 7% of the total, but occupied 18.1% of the floor area. These numbers are not straightforward to interpret. In terms of total leakage area per unit floor area, the rear-L is no more airtight than the rest of the home. This could be the result of the kitchen range hood, whose damper may not achieve proper seal. Other efforts in the rear-L were quite substantial and thorough.

Duct Leakage

Duct leakage to outside was measured using the Delta Q test prior to the retrofit activities. Supply leakage to outside was 115 CFM and return duct leakage to outside was 124 CFM. Post-retrofit Delta Q testing found combined leakage to outside for both systems to be 86 CFM supply and 67 CFM return. The mechanical contractor measured total duct leakage at 25 Pa, getting 84 CFM and 81 CFM for the attic and basement units, respectively.

Ventilation Airflows

The 62.2 whole house mechanical ventilation requirement in P7 is 63 CFM. No continuous mechanical ventilation is provided. We measured two bathroom exhausts and the manufacturer's representative measured the kitchen range hood. One bathroom and the kitchen meet the 62.2 requirements, but the large upstairs bathroom fan failed.

Location	Airflow (CFM)
Small Upstairs Bathroom	58
Large Upstairs Bathroom	43
Kitchen	1305

Table 39 - P7 Ventilation Airflow Measurements

IR Thermography

The homeowner of P7 had the contractor take IR photos prior to the retrofit, so it was possible to compare pre- and post-retrofit thermal leakage. Overall, the rear L portion is vastly improved but still has more air and thermal leakage than expected; this is visible in figures Figure 101 -108. The rest of the house is very leaky, and it is hard to discern what is thermal leakage and what is air leakage. Certain areas were improved, such as the attic access door in Figure 109 and 114; others remain problematic, as shown in Figure 105 - Figure 109.

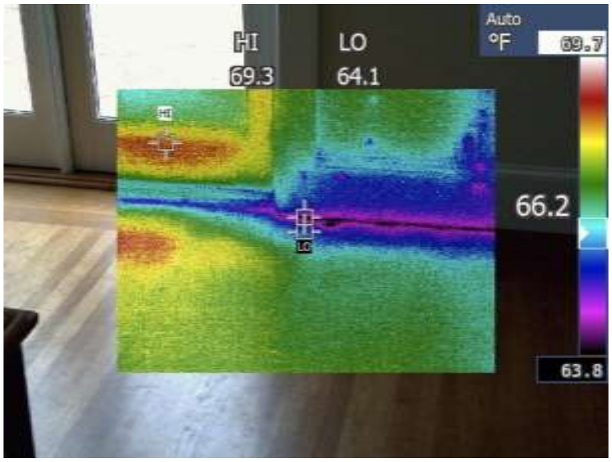


Figure 101 - P7 thermal leakage in rear L, likely concrete stem wall

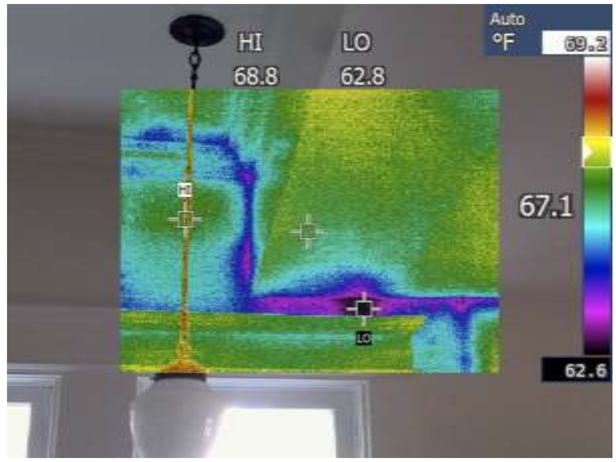


Figure 102 - P7 thermal/air leakage above kitchen sink

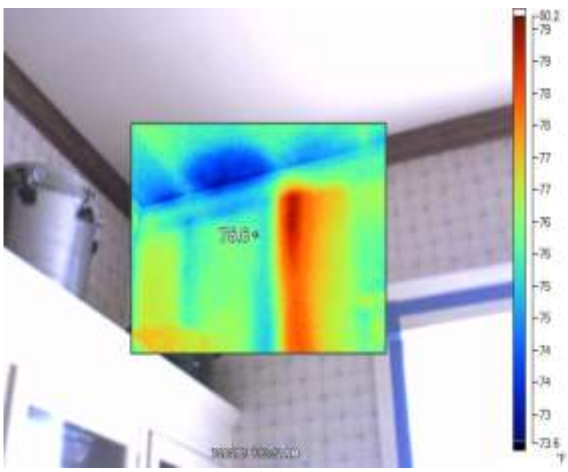


Figure 103 - P7 Pre-retrofit thermal bridges/air leakage in kitchen

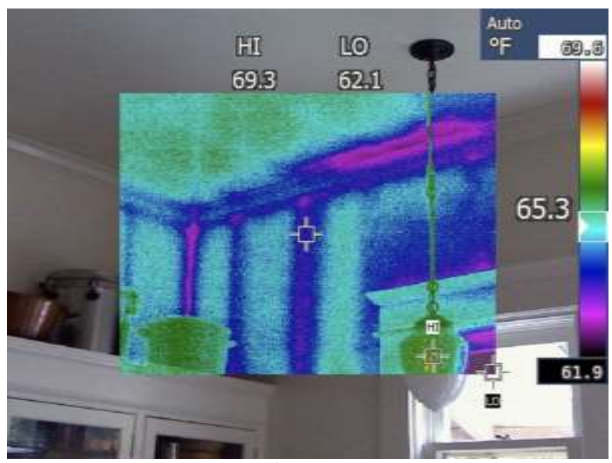
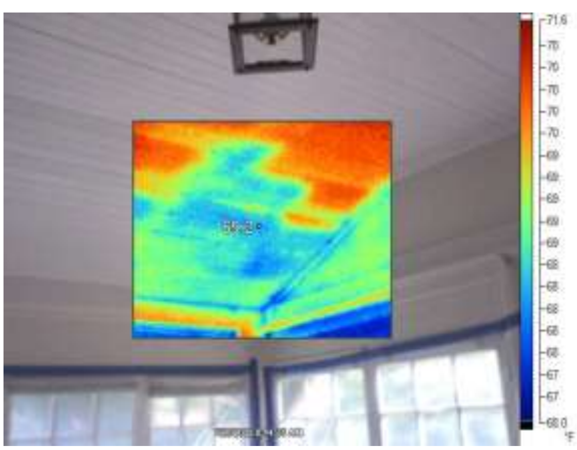


Figure 104 - P7 Post-retrofit problems persist in same location



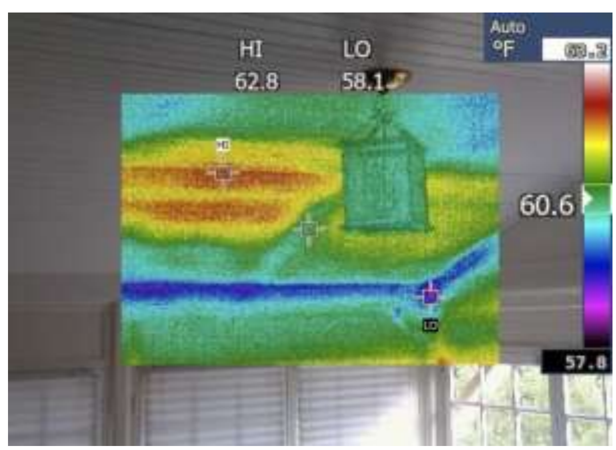


Figure 105 - P7 Pre-retrofit thermal leakage in guestroom ceiling

Figure 106 - Post-retrofit thermal leakage persists in same location

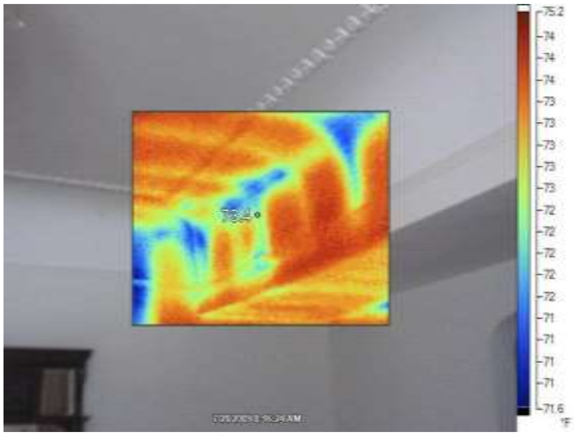


Figure 107 - P7 Pre-retrofit thermal leakage in master bedroom

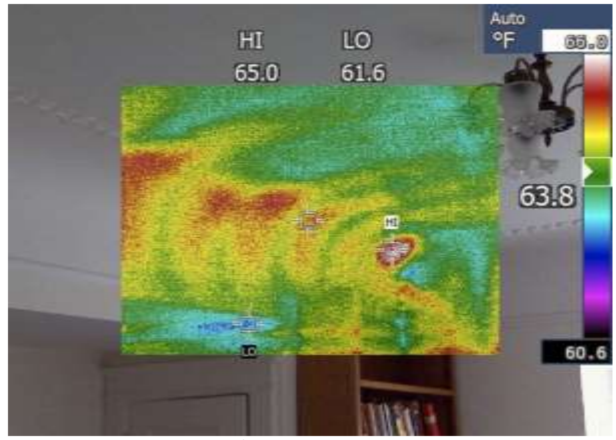


Figure 108 - P7 Post-retrofit thermal leakage persists in master bedroom

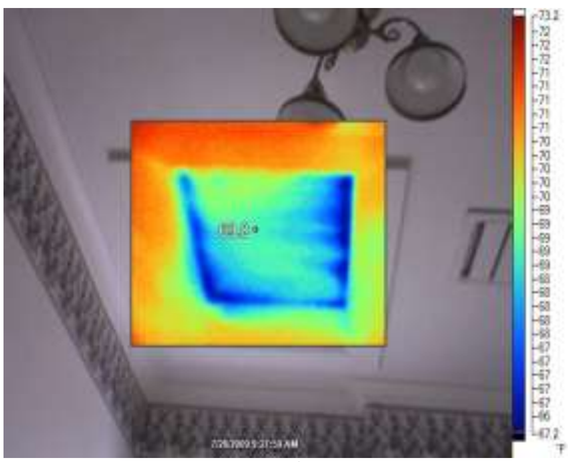


Figure 109 - P7 Pre-retrofit attic access door, very leaky

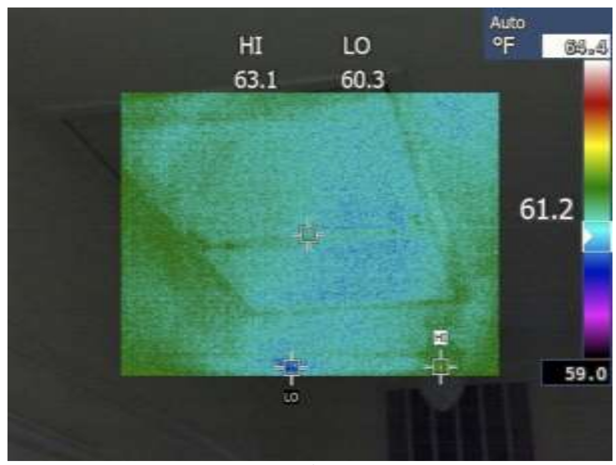


Figure 110 - P7 Post retrofit new attic door, well sealed

4.7.3 Monitored data results

Whole House Energy Use

P7 (Pre) - WHOLE HOUSE ENERGY USE			P7 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e	Net-Source Energy	Net-Site Energy	Total CO_2e
45,244 kWh	31,248 kWh	13,570 lbs	15,187 kWh	8,596 kWh	3,959 lbs
Occupants	Area	HERS Rating	Occupants	Area	HERS Rating
2	3,136 ft^2	-	2	3,288 ft^2	70

Figure 111 - P7 Pre- and Post-Retrofit Mileage Boxes

Annually, P7 used 8,596 kWh in net-site energy, a reduction of 72% from its pre-retrofit net-site consumption of 31,248 kWh. When converted to source energy, P7 saved 66%, from 45,244 to 15,187 kWh. The CO_2e emissions were reduced 71%, from 13,570 to 3,959 pounds. The average CA single family home uses 20,061 kWh net-site energy, 36,737 kWh net-source energy and 9,346 pounds of CO_2e. P7 is more than double the size of the average CA home, and on a per square foot basis, it uses 78% less net-site energy than an average home. Performance is much poorer on a per person basis, with only a 37% net-site reduction. The HERS score for P7 is 70. Overall, energy use in P7 is quite low, and with natural gas making up the majority of its usage, the project does not suffer a major source energy or carbon penalty.

Figure 112 below shows total site electricity and gas usage on a monthly basis. The electricity load is very small and consistent throughout the year, showing careful management of plug loads. However, the gas use is high and relatively consistent due to the extremely inefficient commercial gas oven and range that is used very regularly. The home is conditioned only during extreme weather events, or when there are visitors who prefer higher indoor temperatures for comfort, as happened during November and December of 2011.

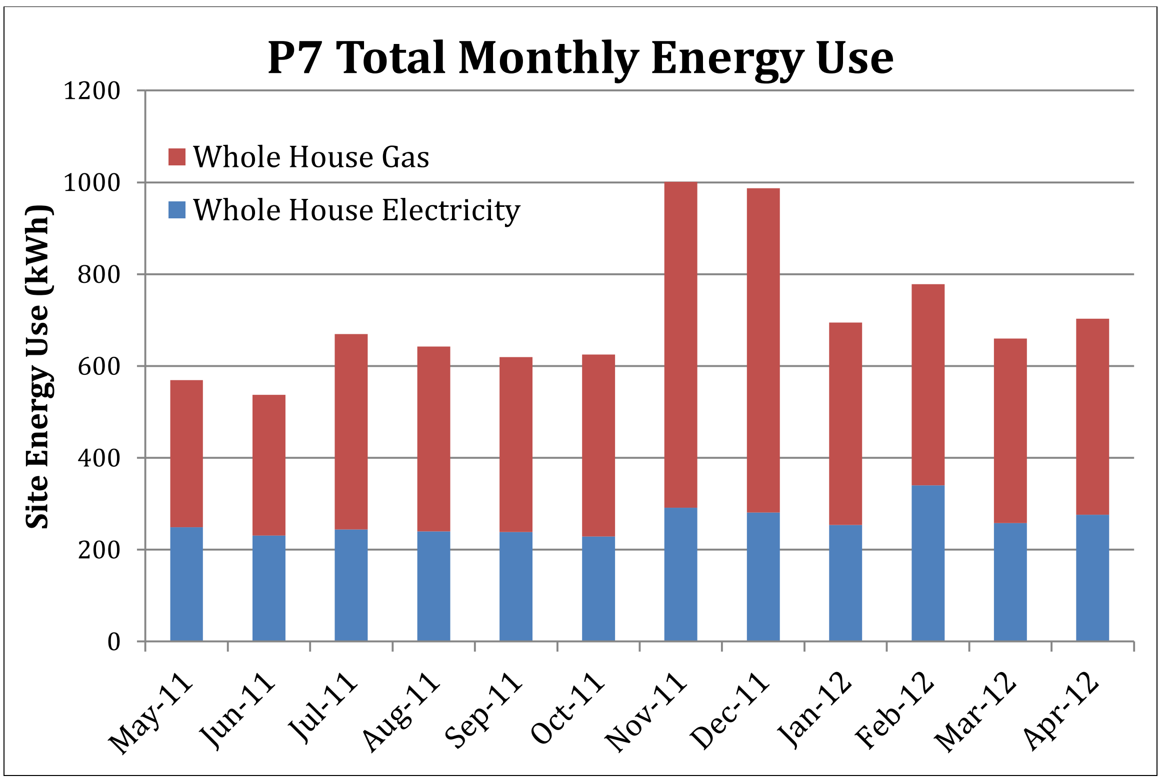


Figure 112 - P7 Total Monthly Energy Use

In Figure 113 below, the pre vs. post-retrofit energy use shows that space conditioning of the large interior volume of P7 was the dominant load prior to the retrofit, and the increased insulation and lack of space conditioning post retrofit resulted in significant savings. In addition, significant monthly energy reductions are evident during the spring and summer, which suggests major improvements in miscellaneous electricity use and hot water.

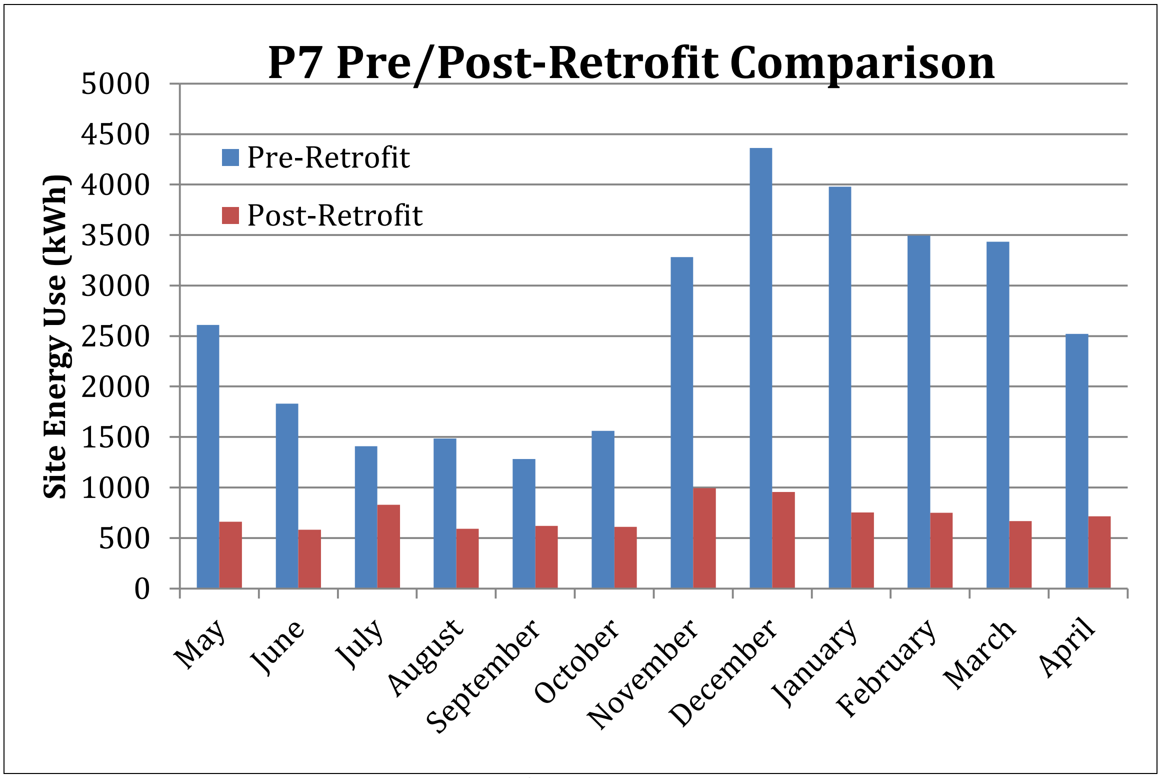


Figure 113 - P7 Pre/Post-Retrofit Comparison, with Weather Normalization

Figure 114 shows the hourly profile of whole house electricity use in P7. Hourly profiles of a representative month for each season provide a quick representation of average electricity use in the home. The evening spike is likely due in most part to lighting and potentially to the use of the kitchen exhaust fan. The morning spike in December is mysterious; it could be from a space heater, or a similar large load that was used briefly during that month alone.

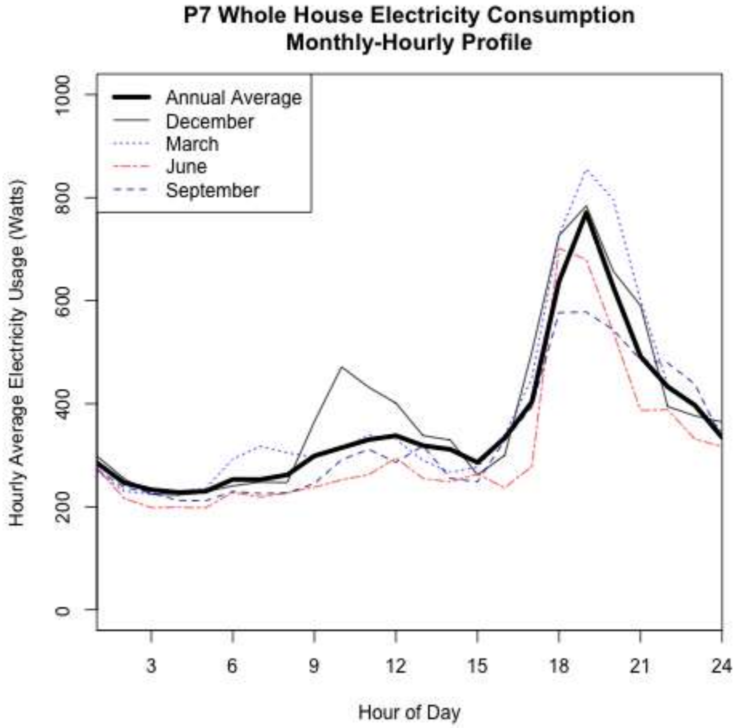


Figure 114 - P7 Whole House Electricity Consumption, Monthly-Hourly Profiles

End-Uses

The annual energy end uses are presented in Table 40 and
Figure 115 below, and monthly end-uses are pictured in Figure 116. The gas range is by far the outlier, driving the appliances usage to very high levels. The appliance usage in P7 was higher than the heating energy used in five project homes (P1, P3, P4, P5 and P7). The heating and hot water energy uses in this home are very low. P5 is the only project to have lower heating consumption, and of those homes with disaggregated hot water energy, only P3 used less, with solar thermal and a single occupant. These results are due to a combination of retrofit measures and austerity by the occupants. In fact, the EnergyGauge USA model over predicted heating energy usage in P7 by 16,211 kWh; the furnaces were barely used and the occupants accepted low winter temperatures (see IEQ Results below). Hot water usage was similarly over predicted, because very little hot water was used (cold water for hand washing, for example) and the water heater was switched off during periods of non-use.

	P7 Actual	P7 Modeled
Floor Area	3288	3288
# of Occupants	2	2
Heating	553	16764
Cooling	0	0
Central Air Handler(s)	135	474
Hot Water	778	1583
Ventilation	0	0
Combined HVAC and Domestic Hot Water	***1466***	***18821***
Appliances	5524	3033
Lights	290	834
Plug Loads	1316	4396
Combined Appliances, Lights and Plugs	***7084***	***8263***
Annual Total	***8596***	***27084***
PV Production	0	0
Annual Net	***8596***	***27084***

Table 40 - P7 Site Energy End Use Summary

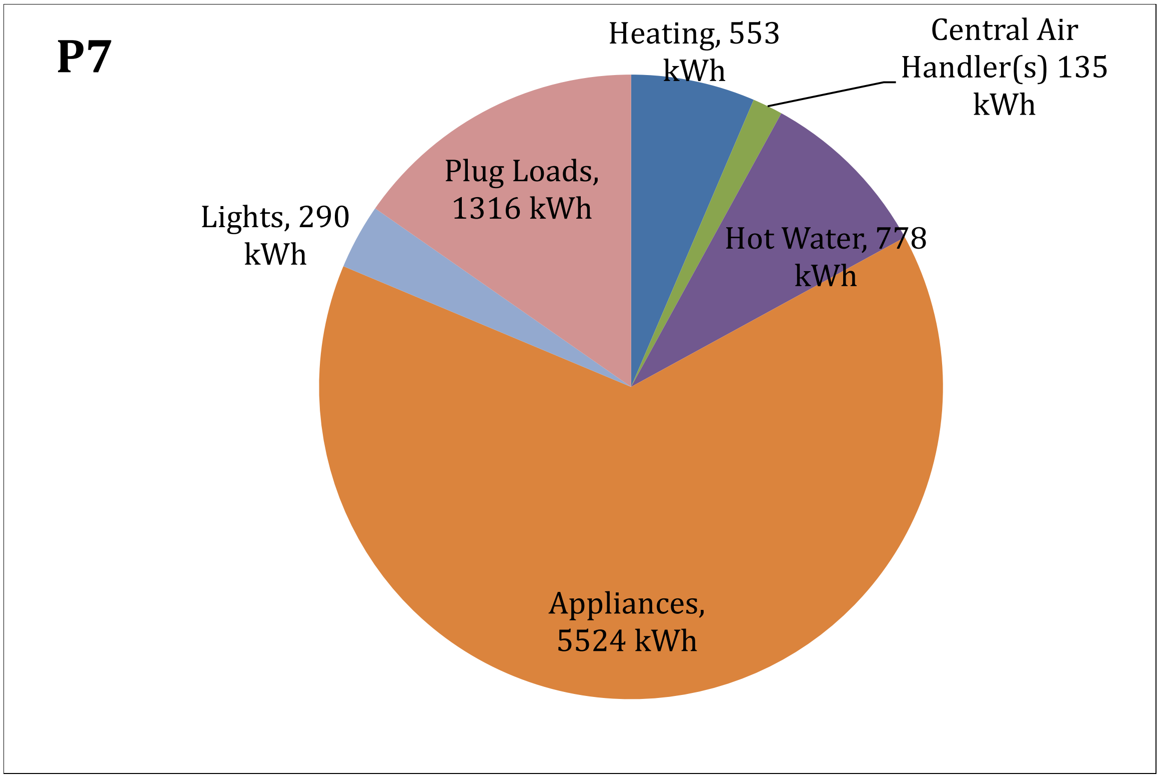


Figure 115 - P7 Annual Energy End-Uses

The dominance of the gas range in whole house energy use is clear in the monthly end-use data below. In addition, the relatives of the homeowners were visiting during November and December so they heated the entire home and had higher DHW usage during these months, which is visible in Figure 116. Apart from that, the furnaces were barely used at all. Also, one of the homeowners was ill for several weeks in February, and used a space heater for personal comfort, which is visible in the plug loads spike in the graph below. As mentioned above in the project description, the homeowners understand that the cooking energy is extremely high and are looking at alternative cooking methods to help reduce this end use.

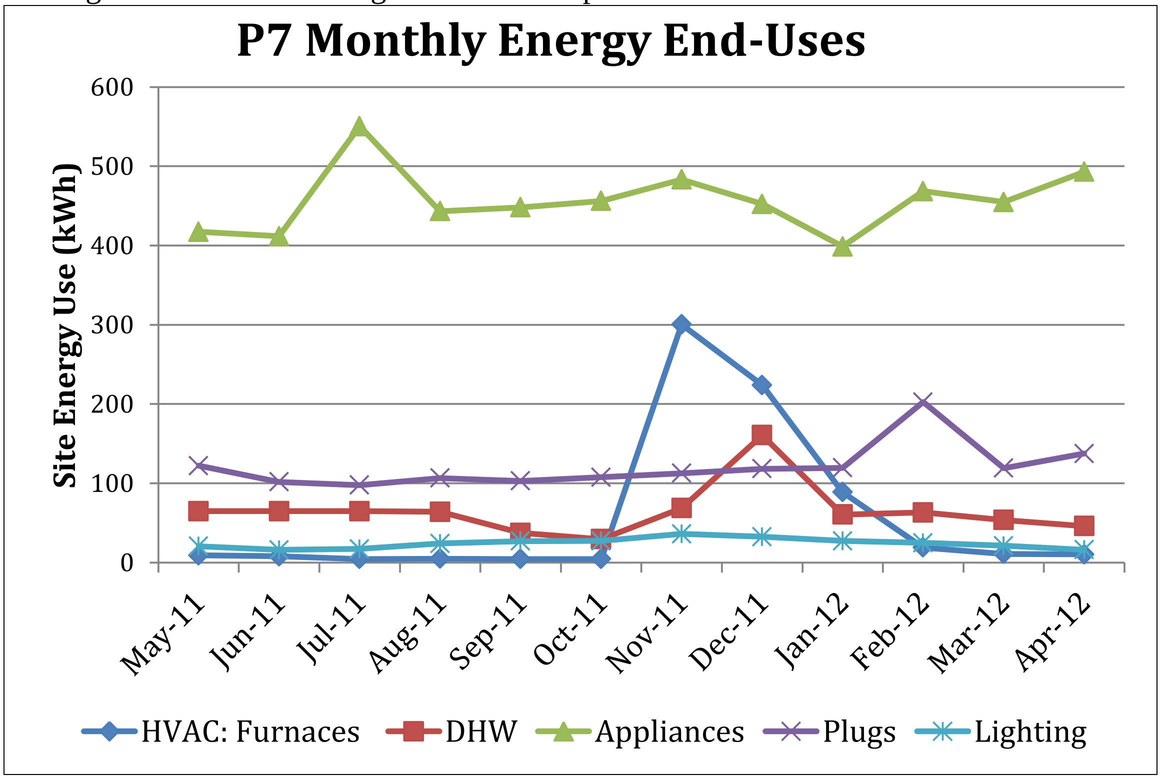


Figure 116 - P7 Monthly Energy End-Uses

User Behavior

P7 is a great demonstration of user behavior. One of the most notable aspects of user behavior in this project is shown through a simple analysis of their utility bills over the past ten years. Figure 117 shows just over a 50% reduction in energy use through austerity measures from 1999 to 2009. All of this was prior to beginning the retrofit in 2010.

On the other hand, the extremely high cooking energy is a great example of how user behavior can inhibit far greater savings than could be realized. If, for example, the homeowners were willing to give up the oven/range for a far more efficient unit, they could easily half their gas use and ultimately result in an extremely energy efficient home. Or they could maintain similar overall energy performance levels, but they could provide greatly increased levels of comfort through increased furnace usage. Despite this, the energy savings at P7 are exemplary.

The baseload at P7 is 151 Watts, resulting in 1,325 kWh per year, or 15.4% of the total annual energy consumption. However, since the gas range has such a large baseload as well, due to the pilot light using 0.6 cubic feet of gas per hour, the gas baseload should also be considered for this project. This is equivalent to 1,580.5 kWh per year, in addition to the electric baseload above; resulting in a total of 2,905.5 kWh of energy, or 33.8% of the total annual energy consumption. This combined baseload would make it the third highest user in the study.

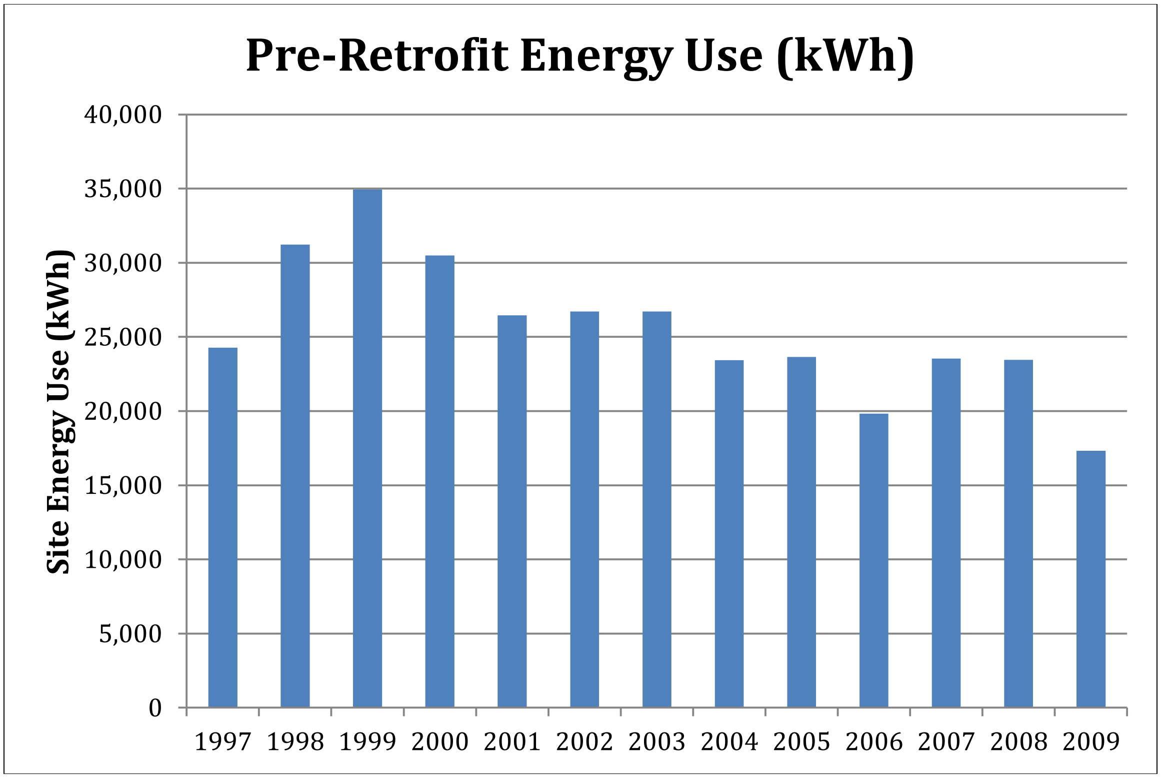


Figure 117 - P7 Pre-Retrofit Energy Use

The T/RH data analysis in IEQ Results below, shows that the home is kept at lower temperatures than what is normally considered "comfortable." This is an austerity measure that clearly resulted in significant energy and cost savings in P7.

IEQ Summary

Indoor temperature and relative humidity means and standard deviations are presented on a monthly basis in Table 41 for the kitchen, living room and master bedroom locations. The kitchen location is in the "house within a house" portion of the home, which was fully air sealed and insulated with respect to both inside and outside, and it was intended to act as a zone of relative comfort. Consistent with this zoned approach, average winter temperatures in the kitchen were approximately six to ten degrees warmer than either of the other zones. In fact, temperatures were warmer on average in the kitchen than in the other two zones every month of the year. During non-heating months, this likely resulted from higher occupant densities and significant internal heat gains from the gas range. Average winter temperatures in the kitchen were cool, but not excessively so, with averages between 65 and 69 degrees F. The other zones experienced very cold average temperatures during winter. The master bedroom was heated more than the living room, and its winter temperatures varied from 59 to 65 degrees F. The living room varied from 54 to 60 degrees F. Despite these low temperatures, monthly average relative humidity in the living room and master bedroom just barely exceeded the recommended upper limit of 60% RH during four months. Absolute humidity must have been low, which likely resulted from a combination of high air exchange rates (due to the leaky envelope), and low occupant densities with low internal moisture sources.

Summary of Indoor Temperature and Relative Humidity by Month												
	Temperature						Relative Humidity					
	Kitchen (1st Flr)		Living Room (1st Flr)		Master Bed (2nd Flr)		Kitchen (1st Flr)		Living Room (1st Flr)		Master Bed (2nd Flr)	
Month	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
January	65.9	2.0	55.5	3.0	59.9	2.5	65.2	5.5	63.1	5.0	57.1	6.7
February	68.0	2.4	59.1	2.6	61.9	2.3	63.6	4.5	60.8	4.9	57.4	4.5
March	69.2	2.4	59.8	2.6	62.0	2.4	62.6	4.3	59.0	6.3	56.2	5.5
April	70.8	2.9	62.6	3.0	66.6	4.3	56.8	5.1	53.0	5.2	56.8	3.7
May	68.1	2.8	64.0	3.1	67.4	3.4	54.8	5.2	50.5	4.3	52.1	4.3
June	70.9	3.3	67.1	3.6	69.9	3.5	55.7	5.6	53.1	5.1	55.4	5.2
July	73.5	2.5	70.4	2.9	71.9	2.9	54.4	3.6	51.3	4.6	55.4	4.7
August	72.6	2.4	71.7	2.1	72.3	2.2	56.0	3.1	50.8	5.8	56.2	3.2
September	74.1	2.2	72.2	2.5	72.9	2.6	53.7	2.6	55.7	2.4	54.7	3.9
October	71.2	3.2	69.2	3.4	70.8	3.2	55.8	3.5	58.5	3.6	54.8	4.8
November	67.3	2.3	60.1	2.5	65.1	2.0	60.9	5.7	63.1	6.9	52.7	3.8
December	65.1	3.0	54.2	3.1	59.4	3.2	61.1	5.0	60.9	4.7	51.8	4.5

Table 41 P7 Summary of Indoor Temperature and Relative Humidity by Month

One-hour temperature differences are plotted between the kitchen-living room and the kitchen-master bedroom in Figure 118 and Figure 119 below, respectively. The kitchen and living room are on the same floor, and the kitchen and master bedroom are on different levels. Average temperature differences were 6.1 and 3.1 degrees F, respectively. Temperature differences were quite large at times, with maximum deviations of 15 to 20 degrees F between zones. ACCA recommends that zones be kept at ±4 degrees F. The kitchen-living room temperature difference was outside this range for 64% of the year, and the kitchen-master bedroom difference was outside the range for 37% of the year. While these results are consistent with the “house within a house” strategy chosen by the occupants for pursuing deep energy savings, the results would not be acceptable for the vast majority of occupants.

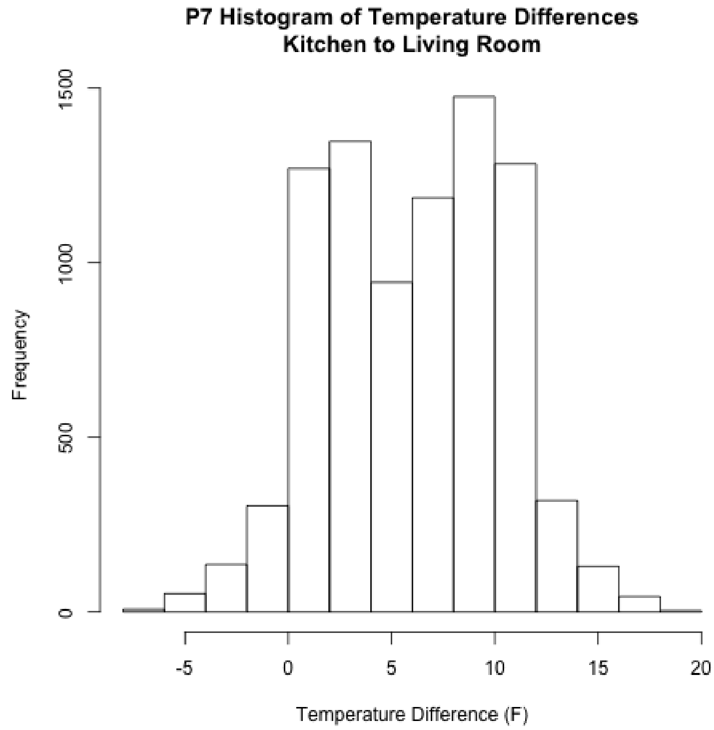


Figure 118 - P7 Histogram of Temperature Differences, Kitchen to Living Room

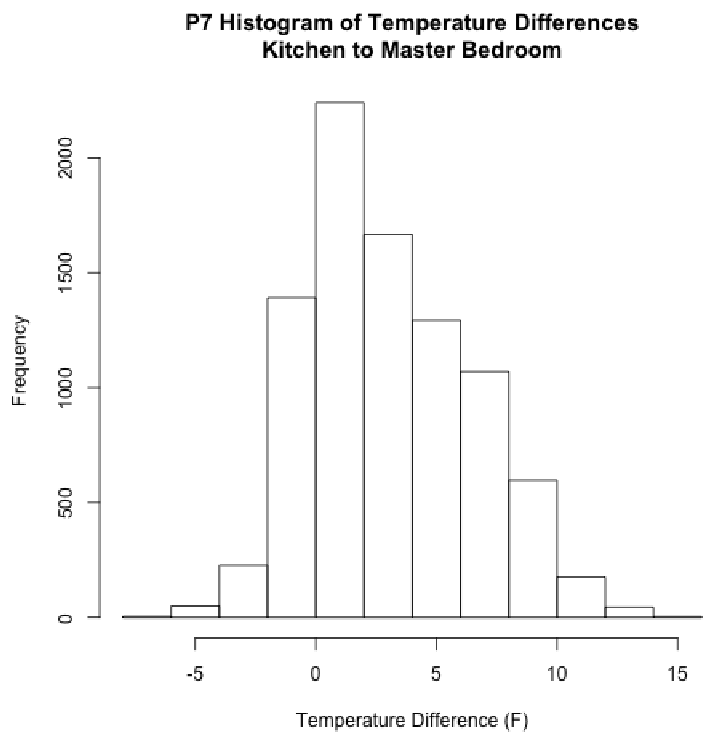


Figure 119 - P7 Histogram of Temperature Differences, Kitchen to Master Bedroom

Hourly temperature profiles are pictured by month for the kitchen zone in P7 in Figure 120 below. The home followed a consistent pattern each month of the year, with the minimum temperature occurring between 8 and 10 am, followed by temperature increases until 10 pm to 12 am, and temperatures decay from there until morning. It is not clear why the winter average temperatures do not overlap, but rather are separated by about one degree F across the day. This suggests varying monthly thermostat set points. Temperatures were several degrees higher during November, but were then reduced in January and December, which could be the result of the occupants attempting to drive down heating energy use after seeing the November furnace gas usage results.

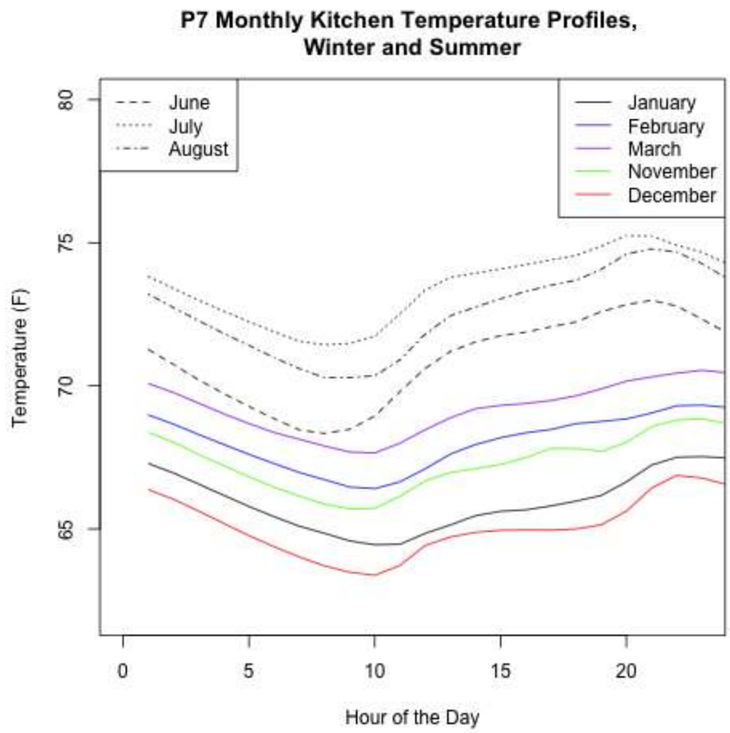


Figure 120 - P7 Monthly Kitchen Temperature Profiles, Winter and Summer

The proportion of time that indoor relative humidity was below, within and above the recommended 30% to 60% range is summarized in Table 42. While monthly average RH values were within acceptable limits (see above), significant portions of the year were spent above the recommended range in all three indoor locations. The kitchen experienced the most time above 60% humidity, just over one-third of the year, which likely resulted from cooking and occupant density in an airtightened space. The durations of high humidity events were also assessed. The longest period in excess of 60% in the kitchen was 6.4 days, but on 30 instances, RH was above 60% consecutively for a whole day. Kitchen RH was above 70% for only half of a day consecutively. The living room spent 11.5 consecutive days above 60% RH, and was in excess of 70% for just over one day only one time. As can be seen in the histograms of kitchen and master bedroom relative humidity in Figure 121 and Figure 122, the vast majority of RH values above 60% were in the 60-70% range; instances above 70% were rare.

Proportion of Time Relative Humidity Was Below, Within and Above the Recommend Range			
Location	**Below 30%**	**30% to 60%**	**Above 60%**
Kitchen	0%	65%	35%
Living Room	0%	72%	28%
Master Bedroom	0%	84%	16%

Table 42 P7 Proportion of Time Relative Humidity Was Below, Within and Above the Recommended Range

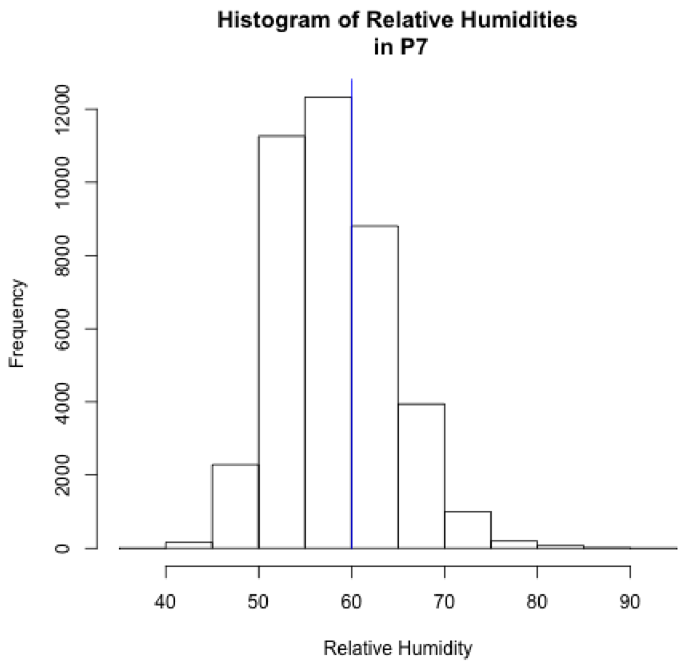


Figure 121 - P7 Histogram of Kitchen Relative Humidity

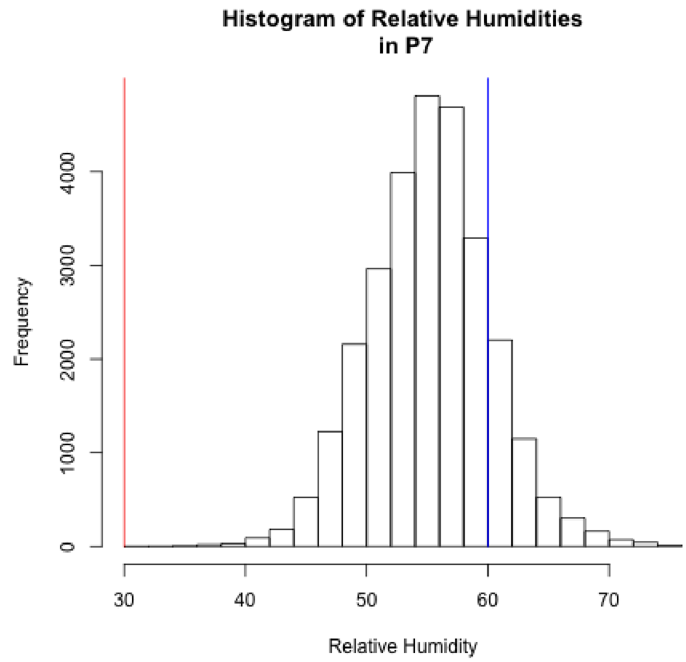


Figure 122 - P7 Histogram of Master Bedroom Relative Humidity

4.7.4 P7 Overview

The energy and carbon savings measured at P7 prove it to be an exemplary DER. As discussed in the literature review, the cost of DERs is beyond the scope of the research. However there is an obvious need to find cost effective solutions to DERs; the greatest example of this is shown in Figure 117, the pre-retrofit energy analysis of P7. The fact that 50% of their site energy could be saved through austerity measures prior to the retrofit is an extremely important finding. It is a unique case of user behavior, but the fact that they were able to achieve this level of savings shows how much user behavior can influence energy use.

P7 shows unique user behavior, with low electricity use combined with very high gas use for cooking. A monitoring study done by PG&E in which 199 range and range/ovens were monitored from 1985-1986, found total cooking energy use averaged 656 kWh/yr (Parker *et al.*, 2010). P7 used 4,219 kWh. During the first few months of monitoring, our data helped discover the extremely high amount of gas used for the stove pilot lights, which were then reduced by extinguishing all of the range pilots, but the oven pilot light remains. Alternative solutions for reducing the cooking energy are being explored with the homeowner, although aside from replacing the stove (which the homeowner does not want to do) are so far inconclusive. This end-use alone accounts for 49% of the energy used in the home.

While the energy performance is commendable, P7 must also be identified as a potential problematic home in terms of IEQ. Tremendous amounts of natural gas are being burned and large amounts of cooking are occurring in a relatively small, isolated zone that has been air sealed. The combustion and cooking pollutants are likely to build up to unhealthy levels in this space. A kitchen exhaust fan is provided with capacity ~1,300 CFM, but the frequency of usage is unknown. Such concerns are very important, as we attempt to drastically cut energy use in homes, without decreasing occupant health. In addition, P7 is almost an unconditioned home, with low winter temperatures that would be unacceptable across most of the population. This inverts the typical scenario where a DER improves IEQ parameters, such as comfort and health.

4.8 P8

4.8.1 P8 Project Description

Image 34 - P8 Pre- and Post-Retrofit

P8	Pre-Retrofit	Post-Retrofit
ENVELOPE		
Wall Insulation	None	3.5” blown cellulose – R13
Attic/Roof Insulation	Some fiberglass batts	4” closed cell spray foam – R28
Foundation Insulation	None	Fiberglass batts – R19
Windows	Single pane wood frame	Most windows replaced with 2 Pane, Low E, Argon, fiberglass frame – U: 0.33 SHGC: 0.3
Air Leakage		2,397 CFM_{50}, 9.3 ACH_{50}
MECHANICAL		
Heating and DHW	Old gas furnace with 2 floor grills, gas tank DHW	3 panel solar thermal combisystem with 96% efficient condensing gas boiler, 120 gal storage tank, hydronic baseboard radiators, zone controlled
Ventilation	None	Bath and kitchen exhaust
Distribution	Sheet metal	Insulated Pex
LIGHTS/APPLIANCES/MEL	Old, inefficient	New, highest efficiency, CFL & LED lighting, 2nd Refrigerator in garage, high MELs
RENEWABLES	None	2.7 kW PV

Table 43 - P8 Retrofit Summary Table

General Information

This 1,588 ft^2 craftsman bungalow is located in the Rockridge neighborhood of Oakland, CA. P8 is a deep green remodel first and a deep energy retrofit second. The project pursued sustainability from multiple angles including: greywater and rainwater harvesting (see Image 35 below), water efficiency, health, recycling, local materials, etc. It received the highest LEED for Homes score in the country at the time of certification and was also the highest-ever *Build It Green* Green Point Rated project at the time of completion. As with a number of other projects, maintaining the historical character was a priority in P8, but the homeowners also desired a modern living space, and high levels of thermal comfort and energy performance. P8 project goals included a 70% improvement in energy efficiency and zero-net electrical energy performance. As part of its broader sustainability goals, P8 implemented energy efficient retrofit measures to the extent that they aligned with other project goals, met code requirements and would create a comfortable and convenient home. Similar to a number of other project homes, P8 was intended by the homeowner to serve as a model for practitioners and to teach the public about green renovations.

Image 35 - P8 Rainwater Collection Storage

P8 is a relatively small home for a family of four, and it was about 60% the size of the owners' previous residence. Their first step was to redesign the interior of the home, removing a number of partition walls that split the dining room and kitchen apart, as well as eliminating all interior hallways. These space-maximizing steps were used to increase the usable floor area. In addition, the front porch was integrated into the conditioned volume as a mudroom. These changes resulted in a net increase in the home's square footage from 1,440 to 1,588 ft^2. A small 120 ft^2 office pod was also constructed in the back yard, which serves as a home office space for the homeowner. It was built out of a prefabricated panel system of metal studs and shear walls. The interior was insulated with blown cellulose insulation and XPS on top of the roof sheathing and under the slab. The pod construction was one of the features filmed for the television show "Renovation Nation" that dedicated an entire episode to P8.

Building Enclosure
The entire building enclosure was retrofitted from its previously poorly insulated and drafty state. The only existing insulation in the home was a layer of 3.5” fiberglass batt insulation in the attic. All other building cavities were uninsulated and all windows were single-pane, wood frame, double hung units. The previously vented attic assembly was sealed with 4” of high-density polyurethane spray foam insulation installed at the attic rafters and gable end walls. The above grade walls were drilled and filled with dense packed cellulose insulation, except in the sunroom where there was very little wall area to insulate. R-19 fiberglass batt insulation was placed between the floor joists, and the crawlspace remained vented.

Most windows in the home were replaced with low-e, fiberglass framed, double hung tilt-pac units, with a U-value of 0.33 and a SHGC of 0.3. Several original windows remain, as their replacement was cost prohibitive. During the initial site visit to P8, significant levels of condensation were visible on the interior glass panes of some of the original windows, which were located in the sunroom, an area without significant interior moisture generation.

Air Leakage
Similar to P2 and P7, the historical character of this building did not allow for significant air leakage improvements. Furthermore, air leakage reduction was not a primary goal of the project, and specific targets were not used. Although the closed cell spray foam under the roof deck and at the gable end walls helped, there is still a significant amount of air leakage in the building.

Ventilation
No continuous mechanical ventilation is provided in P8, though Energy Star exhaust fans were installed in both bathrooms, and a variable speed, downdraft range hood exhaust was installed in the kitchen. Image 36 shows the downdraft hood being tested for airflow.

Image 36 - P8 Measuring Airflow of Downdraft Kitchen Exhaust Fan

Heating and DHW

All of the plumbing, electrical and comfort systems were replaced in P8 as part of the retrofit, and these were selected on the basis of efficiency, zoning control and renewable energy integration. The existing home had an old (pre-1970) natural gas furnace located in the unconditioned crawlspace, with only 2 supply air registers in the living space. An atmospherically drafted natural gas tank water heater was used for hot water, and infiltration was the source of fresh air.

Space conditioning and hot water are now achieved in P8 using a solar thermal combined space and water heating system, there is no cooling needed in this climate. Three roof-mounted solar thermal collectors are plumbed to an insulated, 120-gallon storage tank in the detached garage, with a tank-mounted back-up natural gas condensing boiler (see Image 37 below). The natural gas boiler manufacturer claims up to 96% thermal efficiency, and the tank is insulated with 2" of foam. This tank serves domestic hot water directly, and space heating is delivered using new baseboard radiators in the living space and office pod, with 6 thermostatically controlled zones. All space heating water distribution piping is run through the crawlspace, and all pipes are wrapped with pipe insulation (see Image 38 below). Numerous pumps are required to distribute heat and hot water in this system, and additional pumps were installed to operate a grey water recycling system. These pumps add significantly to P8's electrical load. In addition, placement of the hot water storage tank in the garage means that the tank is exposed to the harshest possible conditions during the heating season, and there is a significant distance to the end-uses. Both of these factors appear to be driving down the performance of the system.

Image 37- P8 Solar Combisystem Storage Tank in Garage

Image 38 - P8 Crawlspace, with Fiberglass Batts in Ceiling and Insulated Hot Water Distribution System

Appliances
All natural gas appliances were removed from the living space and connected zones, with electric appliances replacing gas ones inside the home. All appliances are Energy Star rated, and include an induction electric cook top. The homeowners placed the old refrigerator in the garage for additional food storage.

Plug Loads
There were three televisions with apple TV in the home while the first family occupied the home, which used a significant amount of energy. The new occupants have one television, and a gaming box. The first occupants had two laptops and a desktop, the new occupants have two laptops, a modem, a printer and standard small kitchen appliances.

Lighting
The incandescent lighting in the structure was replaced with a mix of LED and Energy Star certified fluorescent lighting. The bathrooms have lights on fans with timers but all other lights are controlled with wall switches.

Renewable Energy
As part of the zero-net electrical goal of P8, a 2.72 kW solar PV system was installed on the roof. This grid-tied system is net-metered, and a live web-feed of the system's performance was published to the Internet as part of outreach and publicity efforts for the project.

Additional Information
P8 is notable for the homeowner's dedication to energy efficiency, as well as other important aspects of sustainable building design and renovation. A number of design and construction decisions were made, which have impacted the home's energy performance. These include the use of the old refrigerator in the garage, the placement of the solar storage tank in the uninsulated garage, not replacing all windows, the lack of airtightness and the use of a high pumping energy grey water and rain water system, as well as space conditioning and DHW system. P8 is a project that attempted to take deep sustainability seriously, and while energy performance was part of its

goals, efforts were not aggressive enough. In light of the owner's achievement of record breaking numbers of points in green certification, had airtightness and energy conservation been aggressively targeted, it is likely that these too also would have been achieved.

4.8.2 Building Diagnostic Results

Blower Door

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH
P8	2397	9.3	0.48	1.5	131	0.63

Table 44 - P8 Blower Door Results

Ventilation Airflows

The 62.2 whole house mechanical ventilation requirement for P8 is 46 CFM. No continuous mechanical ventilation is provided. A downdraft kitchen exhaust and two bathroom fans were measured during diagnostics. Only the full bathroom exhaust failed to meet 62.2 requirements.

Location	Speed	Airflow (CFM)
Kitchen Downdraft	Low	141
Kitchen Downdraft	Medium	185
Kitchen Downdraft	High	247
Half Bathroom	Single	92
Full Bathroom	Single	27

Table 45 - P7 Ventilation Airflow Measurements

4.8.3 Monitored data results

Whole House Energy Use

P8 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e
23,304 kWh	17,086 kWh	7,302 lbs
Occupants	Area	HERS Rating
4/2	1,627 ft^2	33

Figure 123 – P8 Post Retrofit Mileage Box

Annually, P8 used 17,086 kWh in net-site energy, 23,304 kWh in net-source energy and produced 7,302 pounds of CO_2e emissions. No pre-retrofit data are available for P8. When compared with the average CA home, P8 uses 14.8% less net-site energy, 37% less net-source energy and produces 22% less CO_2e emissions. The home's HERS score was a 33. This HERS score should be interpreted keeping in mind that actual net-site energy usage was 2.4 times the predicted level (see Table 46 below).

Monthly total gas and electricity consumptions are pictured below in Figure 124. Total monthly usage is strongly weather dependent, with the heating season usage skyrocketing above the spring and summer values, when only hot water is provided by the solar combisystem. The home was not occupied during December and January, and usage in February and March reflects the new occupants. Electricity usage is slightly lower on a monthly basis with the new occupants. The DER targeted net-zero electricity on an annual basis, which it did not achieve. This was probably partially due to low output from the PV system which produced only 2,879 kWh annual, while it was predicted to produce 4,126 kWh by the energy model. Likely culprits are variation in weather and adjacent shading not included in the energy model.

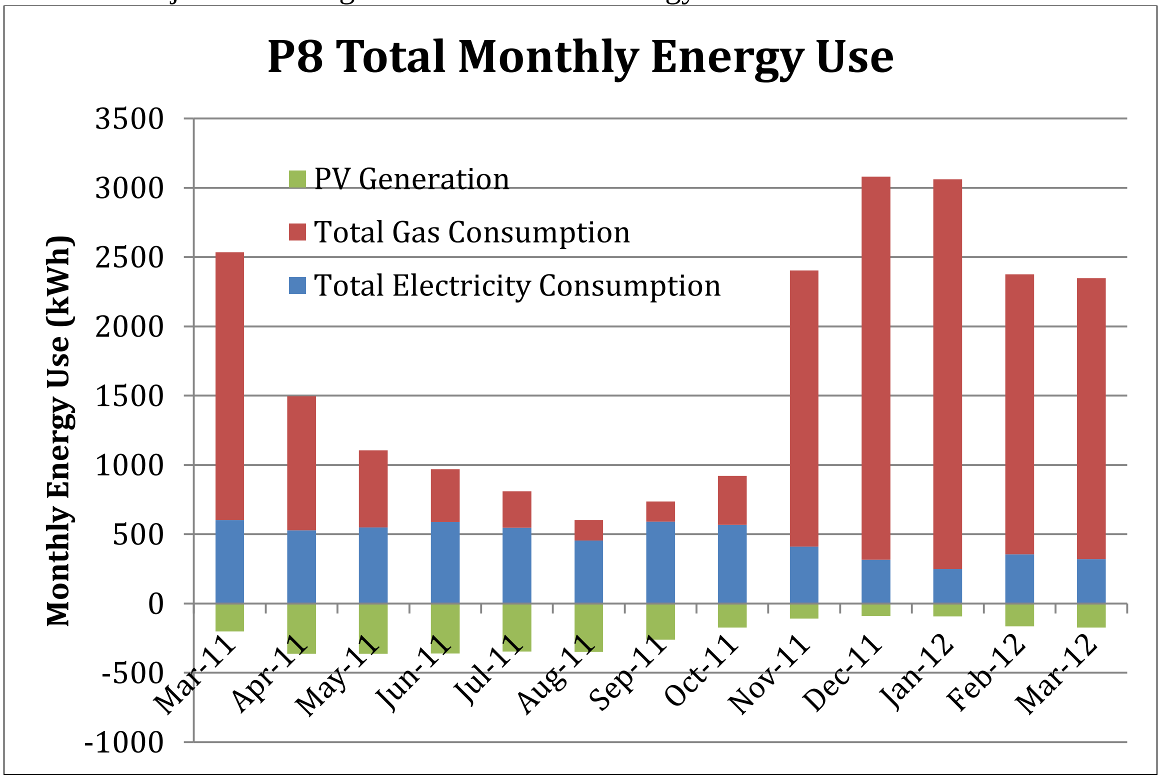


Figure 124 - P8 Total Monthly Energy Use

Hourly profiles are pictured of whole house electricity consumption, net-consumption and PV production in Figure 125, Figure 126 and Figure 127. The whole house consumption profile shows a home that clearly reduces levels of consumption at night, but still consumes ~400 watts continuously throughout the year. Daytime consumption levels are approximately double the nighttime levels, with morning, mid-day and evening peaks. The net-electricity profile shows the home going net-negative consistently across all months of the year during hours of peak PV production. The PV system clearly has some Western orientation, as the hourly output peaks in the afternoon as late as 4pm in June and September.

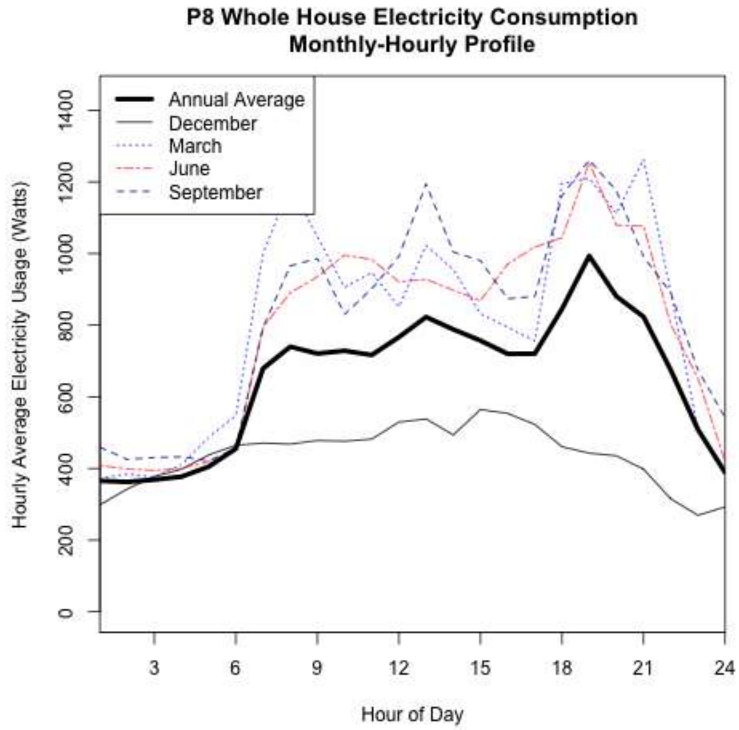


Figure 125 - P8 Whole House Electricity Consumption, Monthly-Hourly Profile

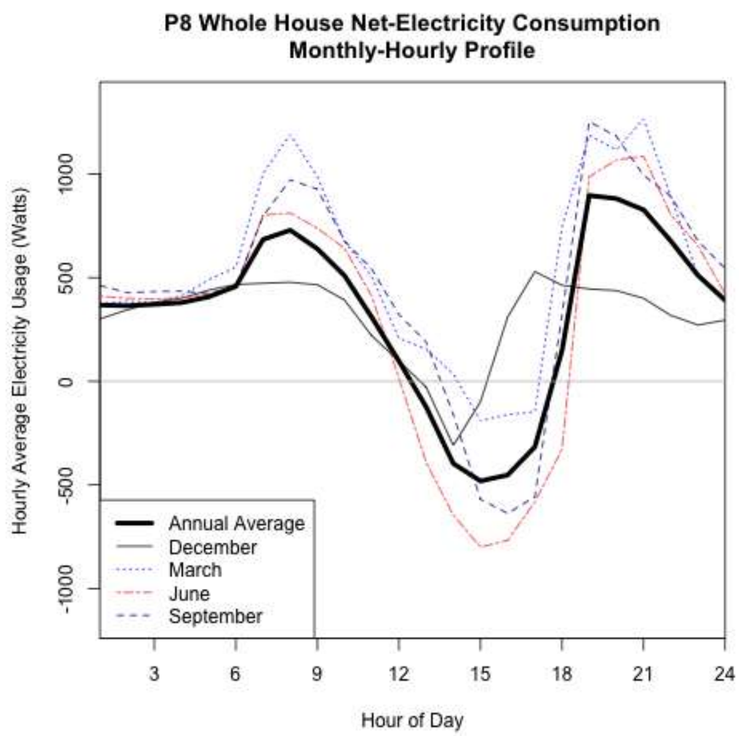


Figure 126 - P8 Whole House Net-Electricity Consumption, Monthly-Hourly Profile

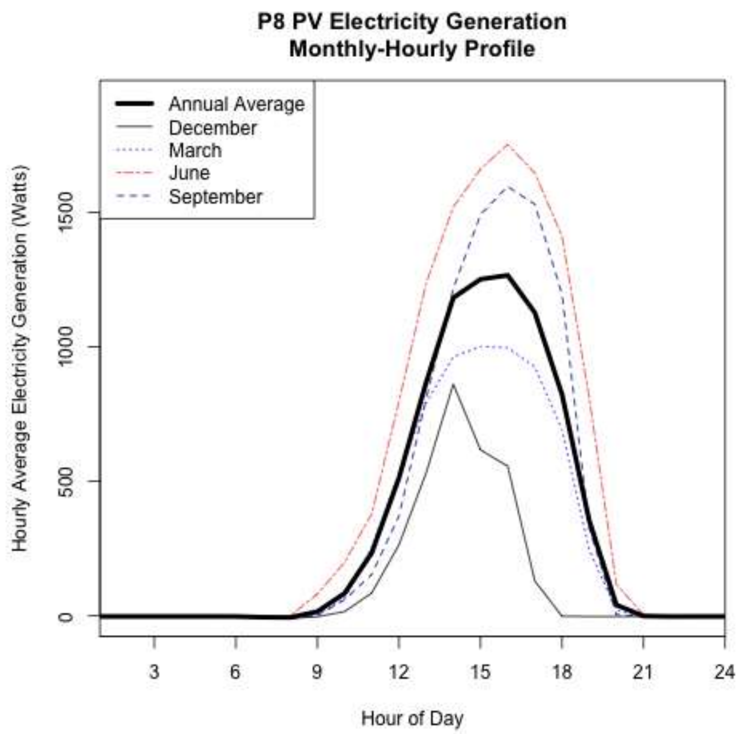


Figure 127 - P8 PV Electricity Generation, Monthly-Hourly Profile

End-Uses

The annual energy end-uses are summarized below in Table 46 and Figure 128, and the monthly end-uses are pictured in Figure 129. The combined heating and hot water system ("Heating" below) with solar thermal is the largest energy use in the home, by far. The actual combined energy usage of heat and hot water is 2.2 times the predicted consumption by the model. All other loads are consistent with the end uses from the other moderate-to-high usage homes (P3, P9 and P10). The hydronic pumps, as well as the greywater and rainwater pumps consume a significant amount of energy in this home (1,100 kWh).

	P8 Actual	P8 Modeled
Floor Area	1627	1627
# of Occupants	4	4
Heating and Hot Water	14340	6123
Cooling	0	0
Pumps	1100	0
Hot Water	0	1028
Ventilation	0	0
Combined HVAC and Domestic Hot Water	***15440***	***7151***
Appliances	1746	1448
Lights	936	475
Plug Loads	1842	2047
Combined Appliances, Lights and Plugs	***4524***	***3970***
Annual Total	***19965***	***11121***
PV Production	2879	4126
Annual Net	***17086***	***6995***

Table 46 - P8 Site Energy End Use Summary

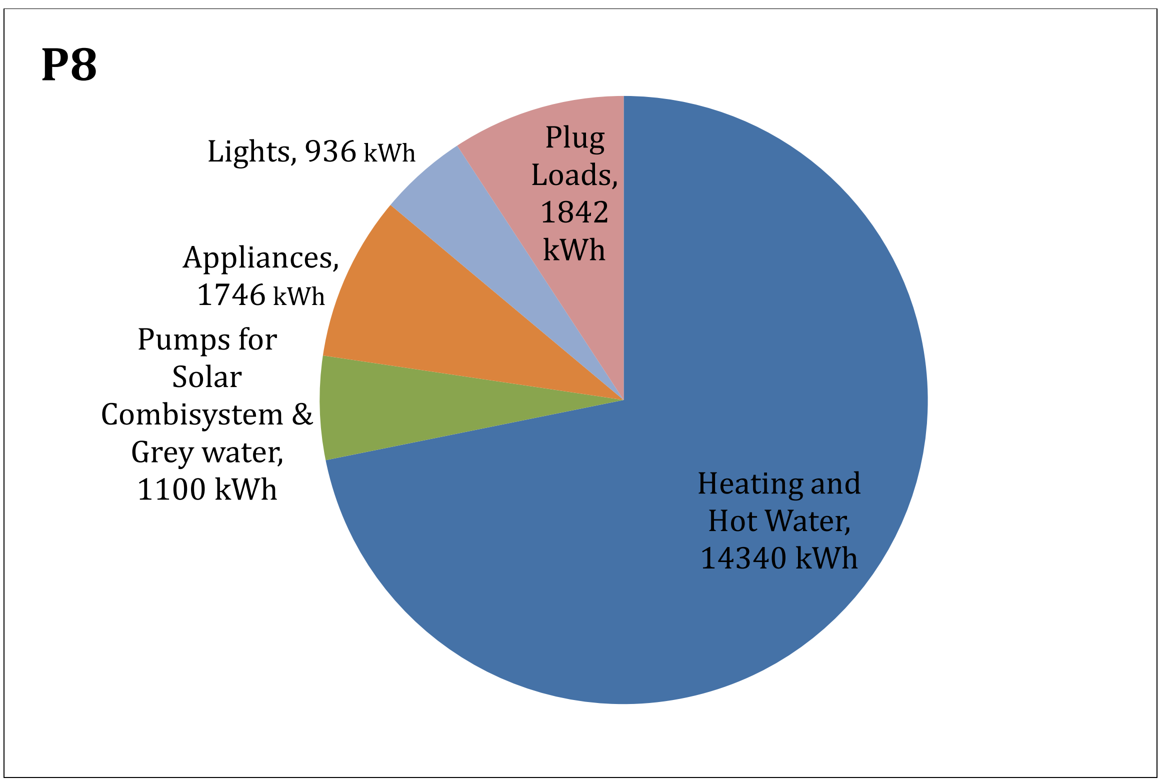


Figure 128 - P8 Annual Energy End-Uses

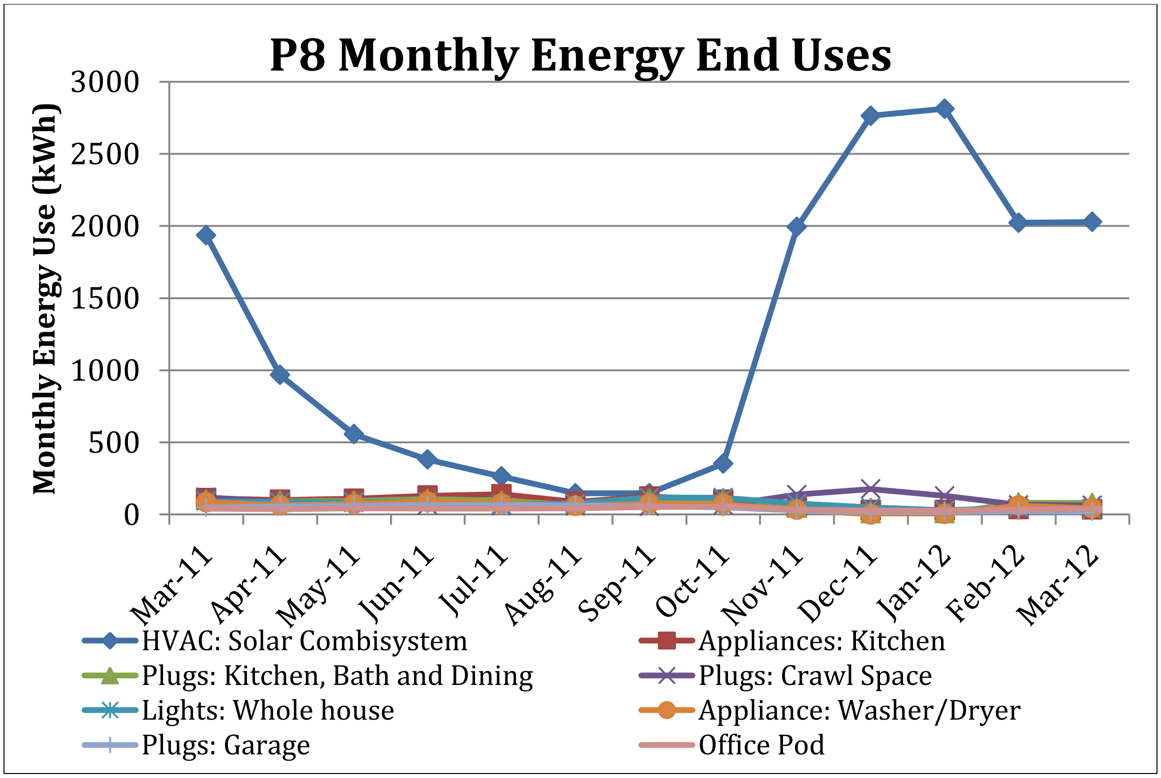


Figure 129 - P8 Monthly Energy End-uses

User Behavior

The baseload in P8 is the third highest of all case studies, with 278 Watts, which translates to approximately 2,434 kWh per year. This value is based upon the consumption of the family that moved out in November of 2011. This is 14.2% of the annual total net-site energy consumption. Discretionary energy use represents roughly 21% of the energy monitored to date. Overall, energy conservation was not a priority of the original occupants in P8. Furthermore, the heating and hot water energy is so high that to target baseload in this home will not have much impact. Issues with the solar combisystem and the excessive pumping energy need to be further assessed.

IEQ Summary

Monthly temperature and relative humidity means and standard deviations are presented in Table 47 below. Only part-year data was gathered in P8 due to the change in occupancy during December 2011 and January 2012. Months without data are indicated with "NA". Monthly mean temperatures varied from approximately 64 to 73 degrees F. Temperatures were consistently lower in the master bedroom than in the living room, which could be the result of thermostat set points in a highly zoned home. The low temperature in February was during an unoccupied period, so it should not be seen an austerity measure. Wintertime set points appear to be right around 68 or 69 degrees, and no mechanical cooling is provided, so summer temperatures floated with ambient conditions. Monthly mean relative humidity varied from approximately 51% to 68%, with seven of the ten months with data exceeding the recommended 30% to 60% range. Average temperatures during these months were around 69 or 70 degrees, so high absolute humidity must have been present. This could have resulted from the sensor's proximity to the master bathroom, whose exhaust fan was measured at only 27 CFM—far below its rated airflow.

Summary of Temperature and Relative Humidity by Month								
	Temperature				Relative Humidity			
	Living Room		Master Bedroom		Living Room		Master Bedroom	
Month	Mean	SD	Mean	SD	Mean	SD	Mean	SD
January	NA	NA	NA	NA	NA	NA	NA	NA
February	63.5	3.4	NA	NA	50.9	5.3	NA	NA
March	66.1	3.0	66.4	1.7	56.2	5.4	64.7	3.6
April	68.8	2.7	67.3	1.7	54.8	4.8	58.9	4.5
May	69.5	2.0	68.2	1.3	55.6	3.3	59.8	4.6
June	71.5	2.3	68.9	1.6	56.3	4.6	62.1	4.1
July	71.9	2.0	69.1	1.9	57.1	3.0	63.4	3.0
August	71.7	1.6	70.1	1.3	57.9	2.6	61.8	3.1
September	73.4	2.6	69.5	2.0	57.9	3.0	65.4	3.8
October	72.7	2.4	68.8	2.0	60.3	3.9	67.5	4.4
November	68.2	2.2	66.2	1.8	55.6	5.1	63.3	6.3
December	NA	NA	NA	NA	NA	NA	NA	NA

Table 47 - P8 Summary of Temperature and Relative Humidity by Month

Hourly average temperatures are pictured for winter and summer months in Figure 130 below. While winter temperatures were not high, they show very little variation throughout the day, which suggests that little if any thermostat set back was used. No mechanical cooling was used in P8, and summer temperatures are consistent from month-to-month, with variation of only two degrees throughout the day.

The temperature difference was calculated between the living room and the master bedroom for those months where both sensors were installed. The results are summarized in Figure 131 below. The mean temperature difference was 2.3 degrees with a standard deviation of 2 degrees F. 19.1% of the monitoring period was spent with temperature differences outside of the ACCA recommended range of +/- four degrees. The home's hydronic heating system is highly zoned, so potentially the temperature differences were purposeful.

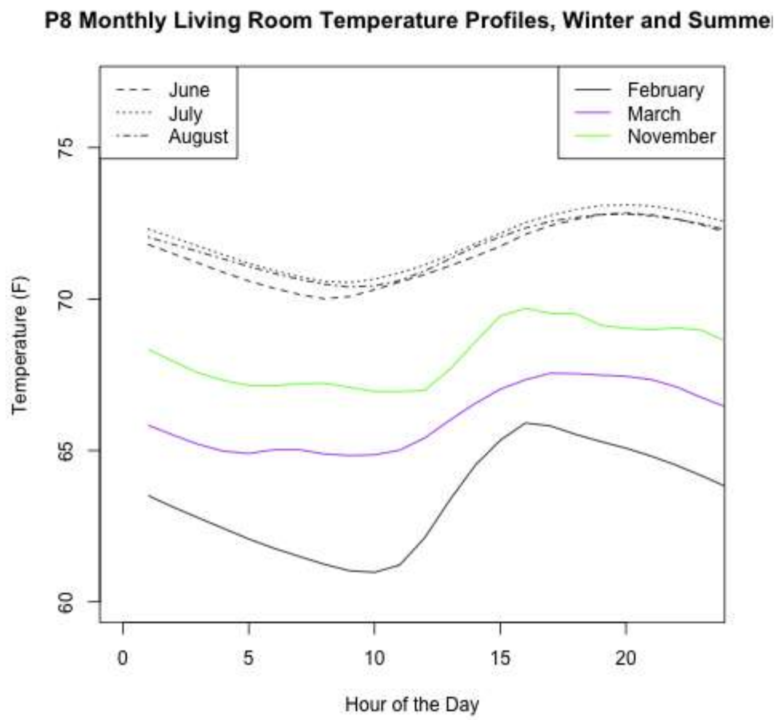


Figure 130 - P8 Living Room Hourly Temperature Profiles, Winter and Summer

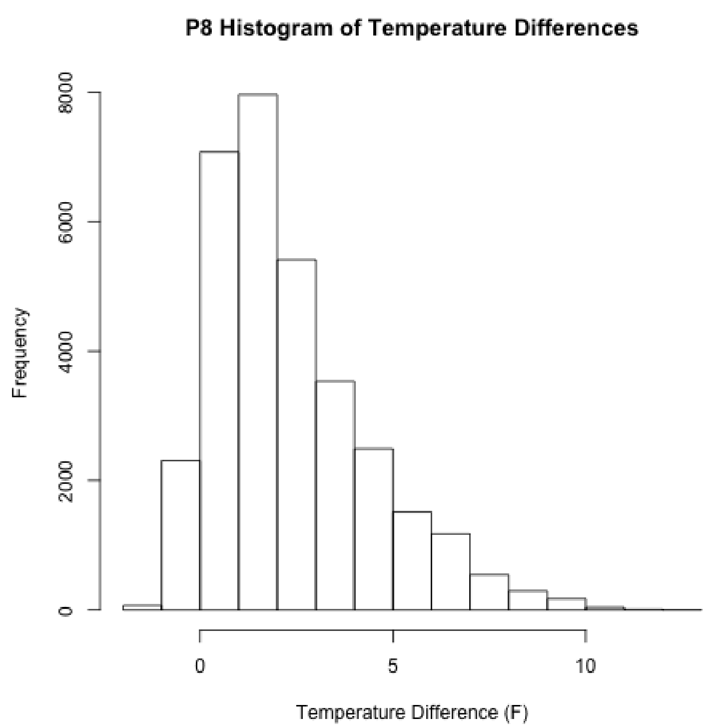


Figure 131 - P8 Histogram of Part-Year Temperature Differences, Living Room to Master Bedroom

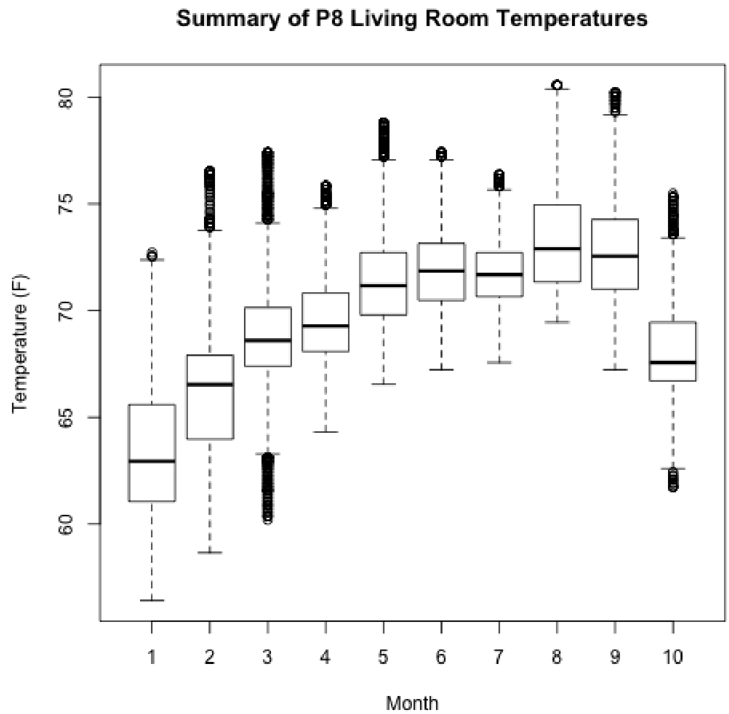


Figure 132 - P8 Summary of Living Room Temperatures

The relative humidity was elevated in P8 for some substantial periods of time outside of the recommended 30% to 60% range (pictured in Figure 133 and Figure 134 below). The proportion of the monitoring period that indoor relative humidity was below, within and above the recommended range is summarized in Table 48 below. The living room had elevated humidity for approximately 20% of the year, but the master bedroom had high humidity nearly 72% of the monitoring period. In the living room, the longest sustained period above 70% RH was just under six hours, but it was above 60% continually for one period of 22 days. In the master bedroom, RH was above 70% continually for 1.7 days and was above 60% for 22.4 days. Such sustained periods of high humidity are troubling.

Proportion of Time Relative Humidity was Below, Within and Above the Recommended Range			
Location	**Below 30%**	**30% to 60%**	**Above 60%**
Living Room	0%	80%	20%
Master Bedroom	0%	28%	72%

Table 48 - P8 Proportion of Time Relative Humidity Was Below, Within and Above the Recommended Range

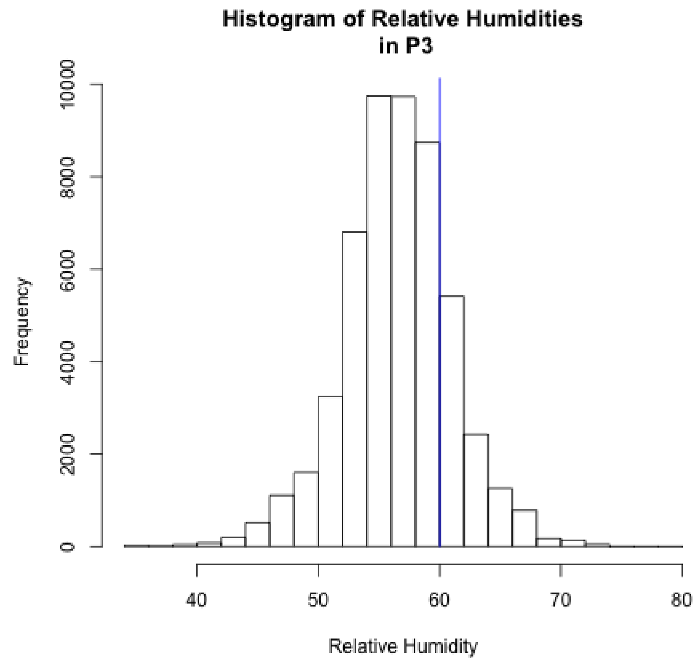


Figure 133 - P8 Histogram of Living Room Relative Humidity

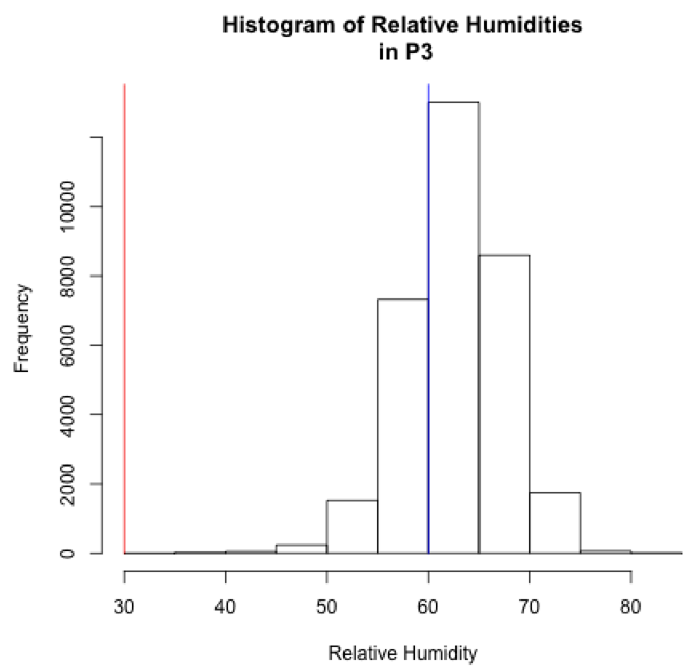


Figure 134 - P8 Histogram of Master Bedroom Relative Humidity

4.8.4 P8 Overview

Unfortunately, the owners of P8 moved out in November 2011, and a full year of monitored energy use has not been gathered for a single family, rather our data represents two separate families. This is beneficial in a way, as it allows us to tease out some effects of the occupants on the home's energy usage.

The performance problems with the combined solar space and hot water heating system that were discovered through our energy monitoring will likely go unresolved. These issues may simply be the result of poor placement of the system and substantial pumping energy and distribution losses. Or, the thermal envelope might be so poor in P8, with air leakage at 9.3 ACH_{50} and minimum levels of insulation throughout, that the combisystem usage simply reflects these large loads. Clearly, not enough thought was put into system placement or increasing the efficiency of the envelope. For comparison, P10 has the exact same system installed in a similar size home with fewer occupants, and P8 uses more than double the combined heating and hot water energy. Even with high efficiency combustion and solar input, it may simply be that such advanced systems cannot compensate for lackluster envelope performance. Additionally, the pumping energy for the greywater, rainwater and hydronic heating systems were significant, amounting to ~5% of the whole house energy use. Further research on pumping energy in these systems is needed.

The data collected show fairly high energy user behavior, nominal construction quality, and far higher gas use than expected for the solar combisystem. It is apparent that far more attention went into making the project a "green" renovation (such as recycled materials, rainwater and greywater re-use, low emitting paints etc.) rather than a deep energy retrofit. This is understandable as the original intent was to achieve LEED for Homes Platinum certification, not deep energy savings. This illustrates how setting clear and well-defined project goals is essential to success in a DER. The owners of P8 believed that high levels of energy efficiency would follow from pursuing the highest level of LEED for Homes certification, but that was not the case. Spray foam insulation, solar PV and solar thermal did not result in deep energy savings.

P8 could easily have reduced its energy use much further, mostly through a tighter and better insulated envelope. However, there were originally four occupants in the home of only 1,627 ft^2. When P8 is evaluated on a per person basis, its performance improves, becoming comparable to other project homes. In fact, it becomes one of the better performing homes (top four) in terms of net-source energy and CO_2e emissions when normalized to occupancy (See Chapter 5).

4.9 P9

4.9.1 P9 Project Description

Image 39 - P9 Post-Retrofit Exterior

General Information

P9 is a 2,850 square foot production built home in Folsom, CA that was constructed in 1998 under the Sacramento Municipal Utility District (SMUD) Advantage Home program, which promises that homes exceed California Title 24 home energy cooling requirements by 25% to 50%. Nevertheless, the homeowners were still dubious and decided to hire a home performance assessment team to do a series of diagnostic tests on the property prior to purchasing it. They hoped to determine how well the home performed as it stood and what upgrades would be required to dramatically improve comfort, reduce energy use and improve indoor air quality dramatically. These retrofit measures would then be incorporated into the tax deductible, low-interest home mortgage, which would limit the direct costs of the improvements to the occupants. As a result of this assessment and the recommendations that resulted, the property underwent what amounted to a home performance-style deep energy retrofit in 2006, with annual utility bill cost savings of 54%. P9 has served as a regional model for home performance retrofit programs, and it helped to establish the home performance model as a vital policy means of reducing residential energy use in California.

The multitude of pre-purchase diagnostic testing used in this case is worthy of discussion, as these tests directly drove the retrofit decision-making process. The contractor measured temperature stratification between the floors, with the upper level 6.6 degrees Fahrenheit (F) warmer than the downstairs, with the downstairs zone calling for heat. All room HVAC airflows were also measured, which found that rooms with very different load profiles were being delivered similar air volumes. In addition, the air handler created excessive pressure imbalances with doors closed. Measured values of pressure difference across bedroom doors were 44pa, 42pa and 19pa. Envelope and duct work airtightness measurements revealed 1,879 CFM_{50} for the building envelope, and 103 CFM_{25} for duct leakage, amounting to 7.4% of the 1,400 CFM nominal air handler flow. Both of these values are considered better than average.

P9	Pre-Retrofit	Post-Retrofit
ENVELOPE		
Wall Insulation	Poorly installed Fiberglass batts - R13	Fiberglass batts - R13, improved installation and air sealed in kitchen & under stairs, insulated attic knee wall.
Attic/Roof Insulation	Blown fiberglass	Increased to R40
Foundation Insulation	Uninsulated Slab on grade	Garage ceiling R19 batts did not fill joist space, filled with cellulose.
Windows	Double pane Vinyl frame, Low-E	Added interior foam filled plantation shutters
Air Leakage	1,879 CFM_{50}	1,227 CFM_{50}, 2.4 ACH_{50}
MECHANICAL		
Heating	78 AFUE forced air furnace, 100kBtu/hr	96 AFUE two-stage condensing furnace, disabled 2nd stage to limit capacity to 35kBtu/hr
Cooling	Old 3.5 ton, 8 or 10 SEER	2 ton, 17 EER with evaporatively cooled condenser coil, charged refrigerant, replaced txv
DHW	40 gal gas tank	40 gal gas tank, insulated, recirc pump
Ventilation	Bath and kitchen exhaust	*Nightbreeze* integrated into 350W air handler serving two zones. Bath exhaust, multi speed range hood
Distribution	R6 foil faced flex duct, unbalanced	Installed balancing dampers, repositioned ducts, buried in attic insulation, added return duct from master bedroom, jumper ducts, 2" MERV 8 filter, and adjustable registers with curved grills.
LIGHTS/APPLIANCES/MEL	Incandescent	11 Watt LED recessed can fixtures, mix of CFL and LED everywhere else, New Appliances exceed Energy Star by 10-15%, Smart powerstrips on all A/V and Computers
RENEWABLES	None	None

Table 49 - P9 Retrofit Summary Table

Infrared thermography identified weak points in the home's insulation and air barrier at a number of locations, including attic knee walls, an architectural archway, the slab-wall intersection and the framed floor between the garage and upstairs living space. The HVAC system was also directly assessed, with approximately 1350 CFM of air handler airflow to either the downstairs or upstairs zones. The manufacturer recommended a similar 400 CFM/ton value for of the 3.5 ton air conditioner. However, the air handler was very large and excessively noisy, drawing 1,061 Watts while operating. The contractor also determined the gas furnace to be over-sized by a factor of 2.5. Ultimately, the home assessment team attributed the stratification problem in the home to the very high airflow and high delivery temperature of the over-sized heating system. Finally, the combustion safety testing revealed no health of safety problems.

The contractor established a set of performance and energy saving goals, including specific, measurable performance targets for duct leakage, envelope leakage, and fan flow. With this list in hand, the homeowners decided that comfort, health, and safety were their primary goals for the retrofit. Their second priority was cost-effective energy reductions, whose mortgage-financed costs were less than the expected energy cost savings. These priorities are reflected in the occupant's calculation that comfort improvements were selected with a simple return on investment (ROI) of 2.7% and other efficiency measures were invested in with a simple ROI of 10.5%. The final net-cost of the home improvements for the project was calculated to be $15 per month.

Building Enclosure

The building enclosure of P9 was improved in a number of ways, but the existing home was already insulated to code, and major envelope intervention was not an option or a goal for the homeowners. Insulation in the attic had been disturbed and poorly installed, so it was fixed and the thickness was increased to achieve R-38 everywhere. This attic insulation work also included a partial burying of the HVAC ducts, as well as insulating and air sealing the attic access door. The attic knee walls were originally poorly insulated with fiberglass batts, which were reinstalled properly during the retrofit and covered with a sealed layer of foil-faced polyisocyanurate foam board. The floor framing above the garage had only been insulated with 5.5" fiberglass batts, which rested on the garage ceiling, effectively leaving the floor above it uninsulated. The cavities were dense packed with blown cellulose insulation. The kitchen and dining rooms were updated, and a new, larger kitchen window was installed. This required reconstruction of the exterior wall along the length of the kitchen, which again revealed poorly installed fiberglass batts that were replaced with properly installed batts. Moreover, some of the existing low-e windows had been installed backwards, with the coating on the incorrect glass surface.

Air Leakage

This air sealing was facilitated by fixing the incomplete garage fire blocking, which was intended to isolate the attached garage from the rest of the house per local code. Work continued until the goal identified by the home performance contractor was achieved.

Ventilation

In addition to the *nightbreeze* ventilation system described below, spot exhaust ventilation was added in the bathrooms using an Energy Star certified, low-sone (a measure of loudness) exhaust fan, as was a variable speed kitchen range hood exhaust fan.

Heating and Cooling

The upgrades to P9's mechanical systems comprise the majority of the retrofit efforts. As described earlier, the existing mechanical systems were over-sized, very noisy and unbalanced, causing comfort problems, wasting energy and drawing pollutants in from the attic. The retrofit measures included equipment replacement and duct system refurbishment and partial redesign.

The existing minimum efficiency gas furnace was replaced with a 96 AFUE 2-stage condensing gas furnace, with the second gas valve stage permanently disabled, so that the unit can only operate at its 35 kBtu/hr setting. This new unit had a fan with an ECM motor, which could provide proper airflow for heating, cooling and nighttime ventilation. The existing 3.5 ton air conditioner was approximately SEER 8 or 10, and it was replaced with a smaller 2 ton model, with an evaporatively cooled outdoor condensing unit, which significantly increases energy performance at high outdoor temperatures (see Image 40 below). This technology is well suited to the hot-dry climate of the California Central Valley region and has an EER rating of 17. The refrigerant charge of this new unit was verified during commissioning, and a malfunctioning thermal expansion valve was identified and replaced on the evaporator. Additional cooling is provided using a *nightbreeze* nighttime ventilation system, which is integrated into the central air handler (see Image 41 below). This unit acts as a “free-cooling” economizer, providing large volumes of cool outdoor air at night, which offsets compressor based cooling during the day. The HVAC return plenum has a thermostatically controlled outside air damper, which routes the return air either from the house or entirely from outside. An “intelligent” thermostat/controller is used to control this system to a target indoor temperature, and it uses measured outdoor weather patterns and a variable speed air handler to achieve optimal control, without over-ventilation or over-cooling.

Image 40 - P9 Outdoor Evaporatively Cooled Consdensor

Image 41 - P9 NightBreeze Ventilative Cooling Controller

Retrofits to the forced air distribution system were also numerous. They included room-by-room load calculations, the addition of air balancing dampers, installation of an additional return air duct from the master bedroom, duct sealing, elimination of sharp bends, and the replacement of several registers that were too large for the reduced system airflow, using engineered metal grills.

Additionally, new ceiling fans were installed with automated thermostatic control, and they use an engineered, true-airfoil blade design to increase their effectiveness. These fans allow higher thermostat set points with equivalent comfort for the occupants.


Image 42 - P9 True Airfoil Ceiling Fans to Assist In Non-Compressor Cooling

DHW

The original 40-gallon natural gas tank water heater was not replaced during the retrofit. However, a demand hot water pump was installed to reduce water waste. The pump cross-connects the hot and cold water lines under the sink. A button below the lip of the countertop starts the pump, which pumps the tepid water in the hot water pipe into the cold water pipe and back to the water heater. When a temperature sensor detects hot water reaching the fixture, it automatically shuts off. There is one under the sink of the master bath and a second under the kitchen sink. Without the pump it took over a minute to get hot water while wasting the water down the drain. With the pumps it takes 20 seconds with zero water waste. However, it does not necessarily save heating energy. The other two bathrooms are very near the hot water heater so pumps were not needed.

Appliances
New Energy Star washer, dryer, refrigerator and dishwasher were installed as part of the kitchen remodel.

Plug Loads
Numerous timer-controlled power strips and efficient electrical components are used throughout the home to reduce electrical loads wherever possible. For example, the homeowner identified and eliminated 180 watts of stand-by power in his A/V and computer equipment using a smart power strip that turns on and off at a programmed time.

Lighting
A whole house lighting retrofit has been completed, with brand new LED units in all recessed fixtures. All other lighting is fluorescent, with a variety of timers and motion sensor controls to limit waste.

Additional Information
P9 is an exciting DER because of the relatively efficient nature of the existing home, the limited invasiveness of the retrofit, and its relatively low cost. Unlike the majority of other deep retrofit projects, P9 does not include a large scale insulation retrofit, and the project left the home looking almost exactly as it did prior to the start of work, but performing very differently. The homeowners were faced with a very typical California home built to a relatively high utility energy standard, yet they were able to achieve 63% reduction in electricity and 49% reduction in natural gas usage based on our monitoring.

4.9.2 Building Diagnostic Results

Blower Door
Envelope air leakage was reduced from 1,879 CFM_{50} to 1227 CFM_{50}.

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH
P9	1227	2.44	0.18	0.39	69.80	0.14

Table 50 - P9 Post-Retrofit Blower Door Results

A home performance contractor performed extensive blower door testing of P9 prior to the retrofit. Pre-retrofit CFM_{50} was 1879 and was reduced 35% to 1200. The blower door was used throughout air sealing to measure progress and find leakage areas. Our CFM_{50} value is slightly higher than measured during the 2006 retrofit, which is not surprising, given the tendency of building airtightness to degrade with time.

Duct Leakage

During the retrofit, the contractor measured total duct leakage at 25 Pa. Pre-retrofit total was 103 CFM and post-retrofit was 40 CFM, for a reduction of 61.2%. The retrofit goal was to be less than 4% of fan flow (1200 CFM). We performed Delta Q testing after the retrofit, and total supply leakage to outside was 10 CFM and return leakage was 15.

Ventilation Airflows

The 62.2 whole house continuous mechanical ventilation requirement for P9 is 61.1 CFM. Continuous mechanical ventilation is not provided. Kitchen and bathroom airflows were measured during diagnostics. All bathroom fans failed to meet 62.2 requirements, but the kitchen range hood performed well. It could not be measured on medium or high, as those airflows were outside the calibration range of the instrument being used. A Nightbreeze night ventilative cooling system is used, where the central air handler is used to bring in 100% outside air. Contractor measurements of the air handler flow in cooling mode were 1,295 CFM, which we assume to be the ventilation airflow during night breeze operation.

Location	**Speed**	**Airflow (CFM)**
1st Floor Bathroom	Single	39
2nd Floor Bathroom	Low	36
2nd Floor Bathroom	High	48
Master Bathroom	Single	33
Kitchen	Low	130
Nightbreeze	Single	1,295

Table 51 - P9 Ventilation Airflow Measurements

4.9.3 Monitored Data Results

Whole House Energy Use

P9 (Pre) - WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e
62,981 kWh	36,597 kWh	16,716 lbs
Occupants	Area	HERS Rating
-	3,144 ft²	-

P9 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e
26,766 kWh	17,005 kWh	7,561 lbs
Occupants	Area	HERS Rating
4	3,144 ft²	70

Figure 135 - P9 Pre- and Post-Retrofit Mileage Boxes

Annually, P9 used 17,005 kWh in net-site energy, a reduction of 54% from its pre-retrofit net-site consumption of 36,597 kWh. When converted to source energy, P7 saved 58%, from 62,981 to 26,766 kWh. In absolute terms, P9 reduced the largest amount of source energy consumption of any DER project home—36,215 kWh. At the same time, it is the single highest consumer of net-site energy. Depending on the metric used, P9 was either a wild success or a failure. The CO_2e emissions were reduced 55%, from 16,716 to 7,561 pounds. The average CA single family home uses 20,061 kWh net-site energy, 36,737 kWh net-source energy and 9,346 pounds of CO_2e. Overall, energy use in P9 is slightly lower than the typical CA home, but the pre/post-retrofit savings are very impressive, especially for an already insulated, modern home.

Monthly electricity and gas consumptions are pictured below in Figure 136. The energy use in P9 is clearly heating dominated. Whereas the cooling energy used in the hot Central Valley is almost non-existent, with possibly a ~100 kWh per month increase over use in February through May. The nighttime ventilation system is probably providing the bulk of cooling comfort in P9, suggesting that non-compressor based cooling can be successful in a home with a reasonable envelope in a hot-dry climate. In addition to energy reductions, nighttime cooling offers substantial peak-load savings, which is the primary goal of SMUD—the local electric utility. Such peak load reductions offer substantial energy cost savings opportunities for customers with tiered electricity rates.

Pre-retrofit monthly net-site energy consumption is compared with post-retrofit monitored data in
Figure 137 below. Savings were achieved across the seasons, suggesting heating, cooling and miscellaneous reductions, such as lighting and plug loads. The greatest savings are at both the peak cooling and heating months and show that the retrofit techniques were very effective at reducing the space conditioning loads.

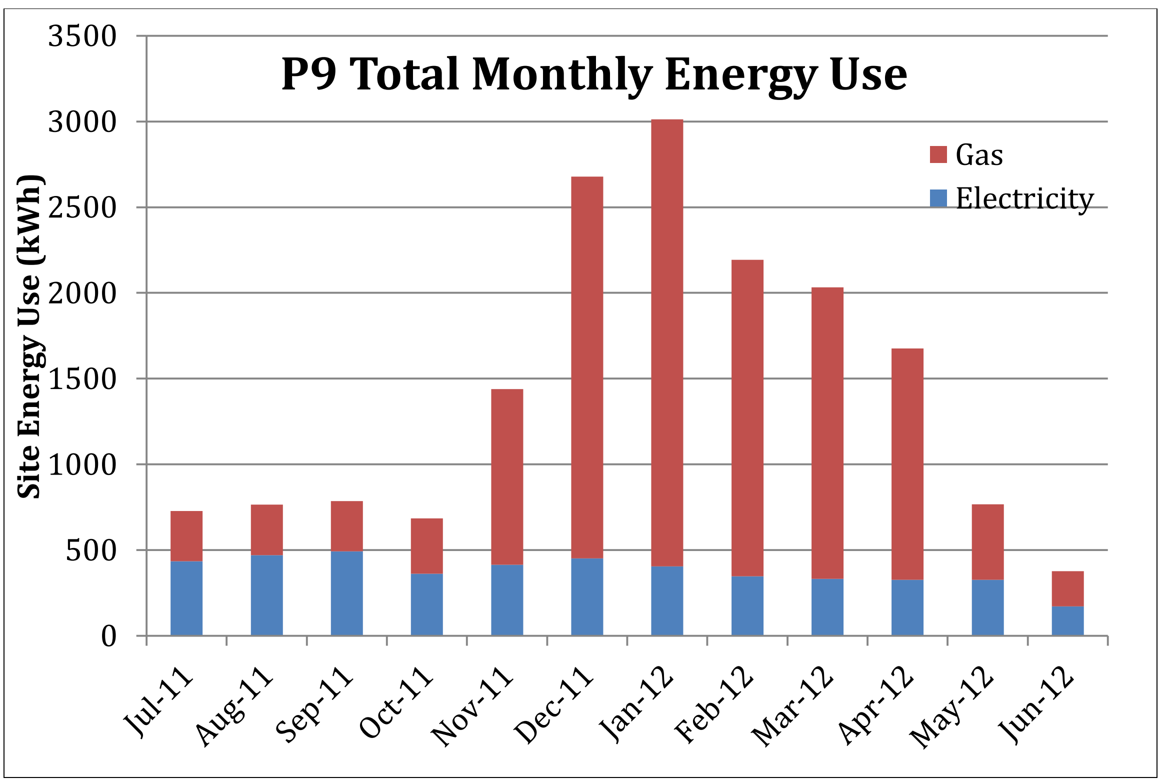


Figure 136 - P9 Total Monthly Energy Use

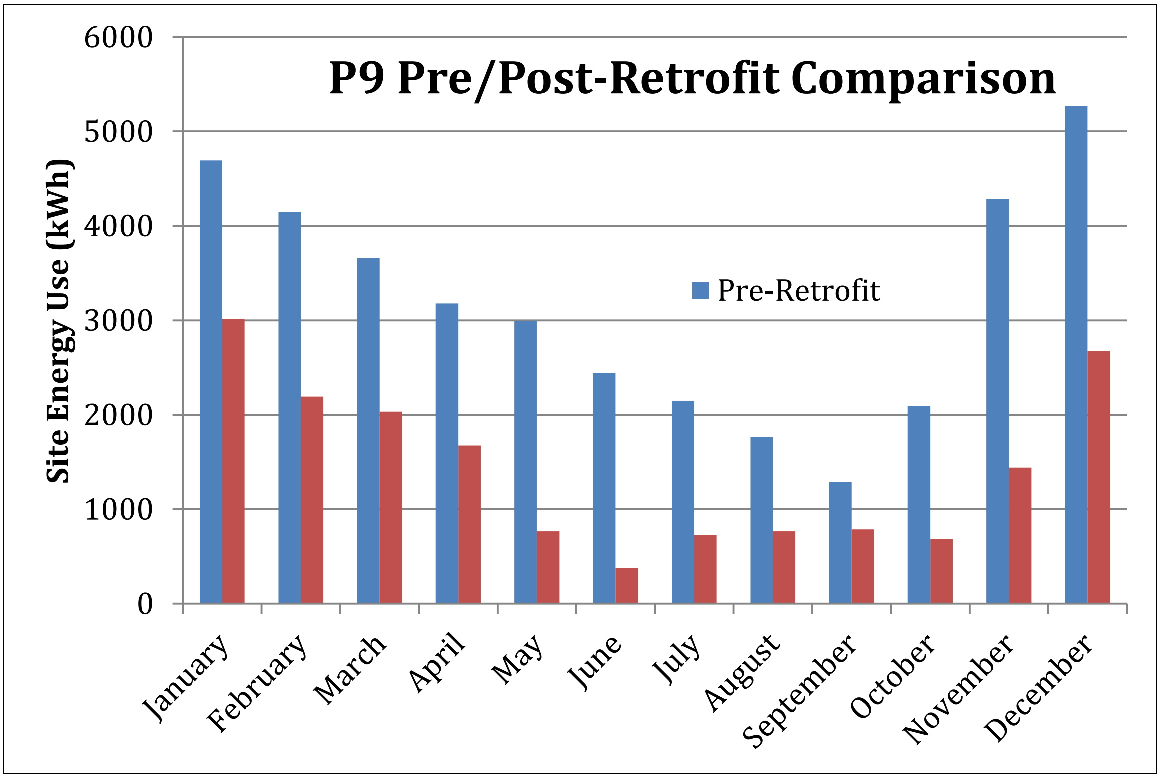


Figure 137 - P9 Pre/Post-Retrofit Comparison

Figure 138 shows the typical seasonal hourly profile of electricity use in P9. It is likely that the family was on vacation in June. The peaks are visible in morning and in the evening, which are likely lighting and space conditioning schedules. The high peak in September is likely related to cooling, as is the elevated nighttime power draw, which could be the air handler.

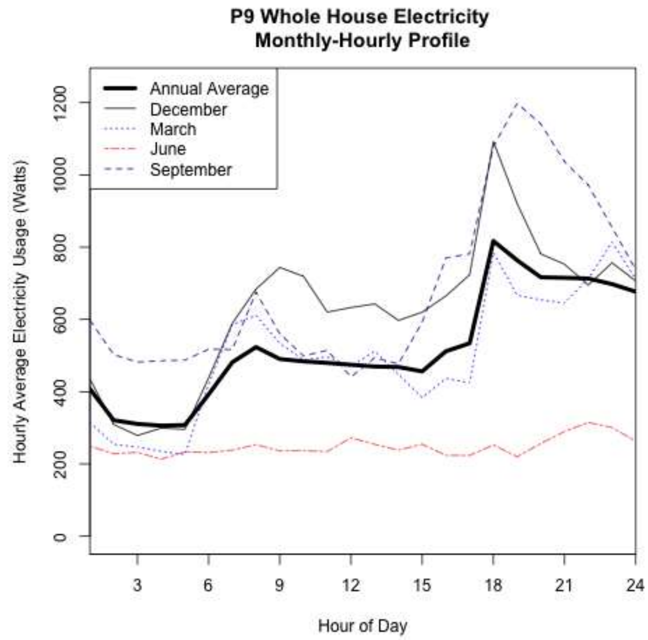


Figure 138 - P9 Whole House Electricity Consumption, Monthly-Hourly Profile

End-Uses

The annual energy end-use summaries are provided in Table 52 and Figure 139 below, and monthly end-use data are pictured in Figure 140. Heating and hot water energy dominate the usage in P9. Combined HVAC and hot water energy usage accounts for 74% of net-site annual usage. Heating, hot water and cooling energies are all lower than predicted by the energy model, but fan energy is greater. Cooling energy and fan energy differences can be explained by the nighttime cooling, which could not be modeled appropriately. Due to the use of night ventilation and a whole house fan, the cooling load is very small in this home, a commendable result of the retrofit since the home is located in Folsom, where the average high temperatures are in the mid 90’s in July and August. Plugs loads are dramatically lower than predicted in the model, suggesting that efforts by the occupants have paid off in reducing these end uses. Lighting energy use was higher than predicted, despite installation of LED recessed fixtures throughout. Exterior lighting may have been responsible for this.

	P9 Actual	P9 Modeled
Floor Area	3114	3114
# of Occupants	4	4
Heating	7954	9261
Cooling	259	929
Central Air Handler(s)	713	437
Hot Water	3665	5832
Ventilation	0	0
Combined HVAC and Domestic Hot Water	***12592***	***16460***
Appliances	1952	2016
Lights	1485	796
Plug Loads	975	4202
Combined Appliances, Lights and Plugs	***4413***	***7014***
Annual Total	***17005***	***23474***
PV Production	0	0
Annual Net	***17005***	***23474***

Table 52 - P9 Site Energy End Use Summary

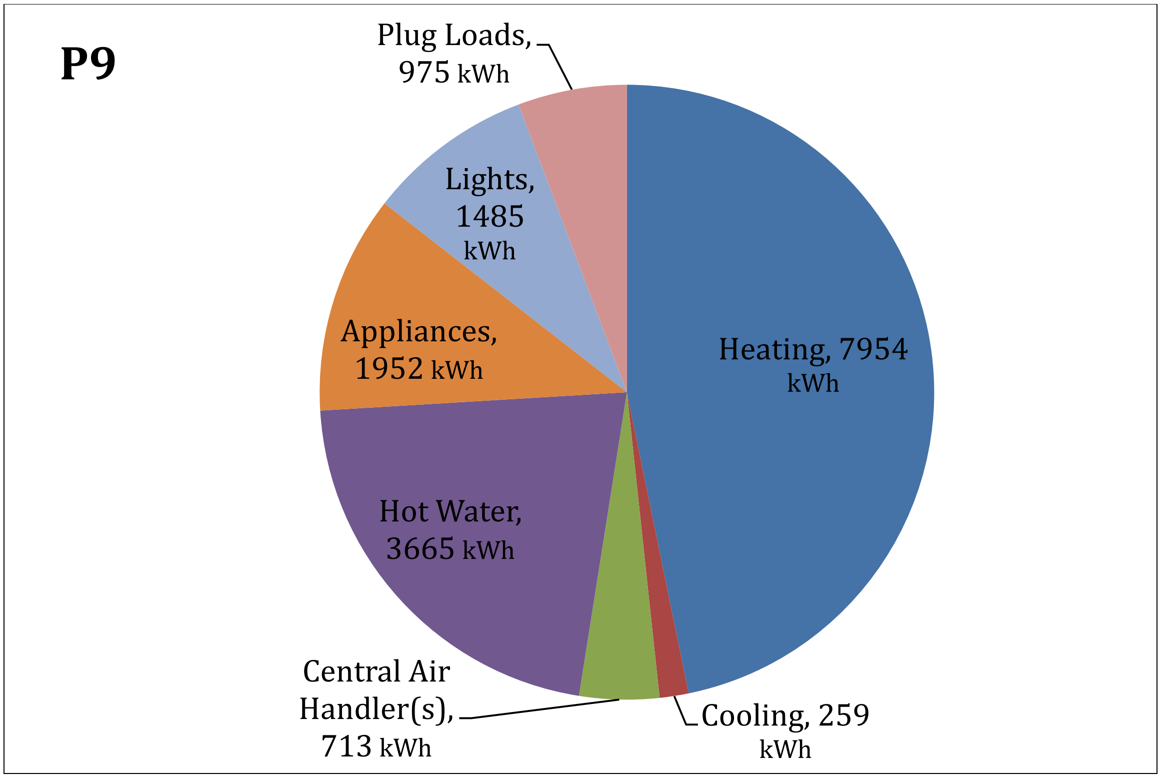


Figure 139 - P9 Annual Energy End-Uses

The monthly end-uses are obviously dominated by the furnace and air handler. These uses, as well as hot water, show very clear increases in winter below in Figure 140. The tank water heater is located in the unconditioned garage, making it particularly dependent on lower outdoor temperatures. The increase in appliance energy is actually a result of the imperfect monitoring methodology using utility bills measured in therms to subtract the total monitored gas use of all other appliances. On an annual basis this normalizes, but on a monthly basis there are some noticeable discrepancies.

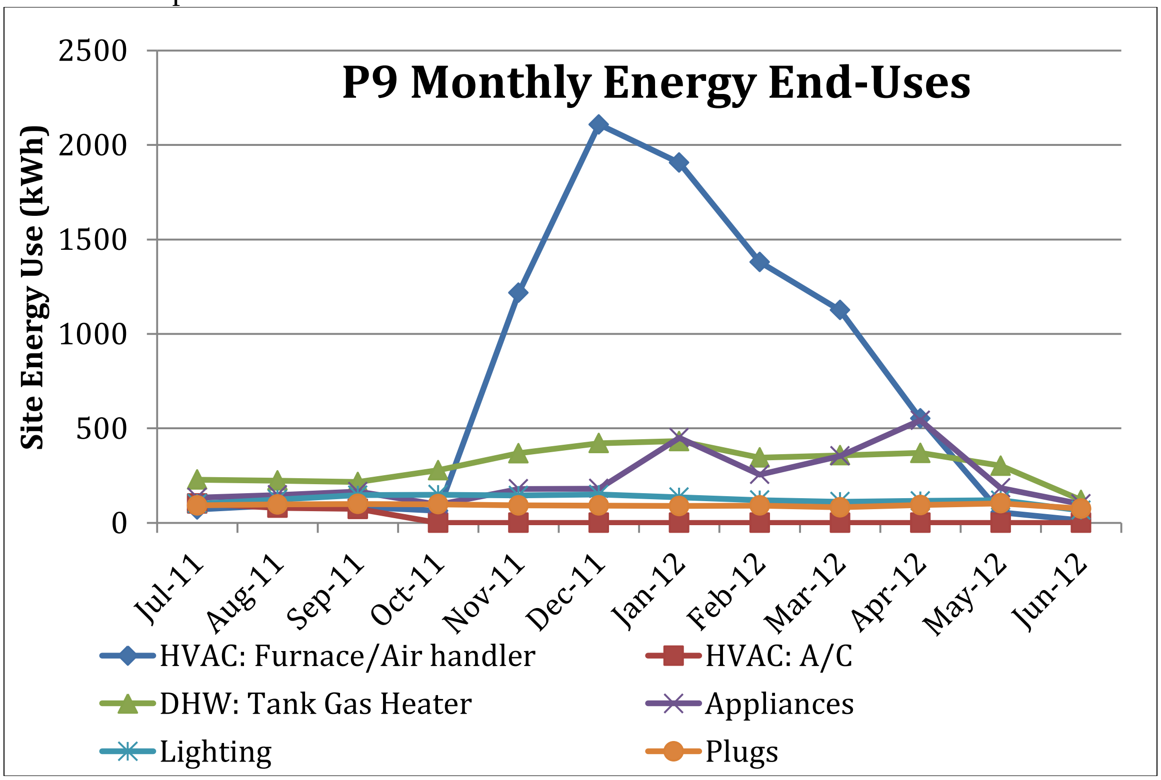


Figure 140 - P9 Monthly Energy End-uses

User Behavior

The baseload in P9 is 154 Watts, totaling 1,348 kWh, or 8% of the total energy use. This low usage is commendable, and is likely the result of smart power strip usage and other conservation efforts.

The home is clearly heating dominated. The family does an excellent job at controlling plug loads, using power strips and smart strips for nearly all plug loads in the home. Additionally, it is clear that the evaporative cooling and nightbreeze ventilation strategies are extremely effective in the Folsom climate, while still maintaining very high comfort standards.

IEQ Summary

The monthly 1st and 2nd floor temperature and relative humidity means and standard deviations are presented in Table 53 below. Monthly mean temperatures in P9 varied between approximately 65 and 80 degrees F. Significant increases in average temperature occurred from June to August, which reflects the minimal use of compressor cooling and reliance on night time cooling strategies (pictured for the 1st floor in Figure 143 below). The summer temperatures maintained in P9 were quite a bit higher than in the other project homes, with monthly averages at or near 80 degrees F. The Central Valley location of P9 is a much more demanding cooling climate than most other project homes, with 1,470 base 80 cooling degree days, versus 128 in Berkeley and Oakland or 456 in Sonoma or Petaluma. The hourly average temperature during the cooling season never exceeded 80 degrees, so comfort was rarely sacrificed. Nighttime pre-cooling achieved an hourly average temperature reduction of three to four degrees F (pictured in Figure 141 below). Monthly mean relative humidity varied from approximately 34% to 54%. The monthly mean relative humidity in P9 was in the desirable 30-60% range every month of the year.

Summary of Indoor Temperature and Relative Humidity by Month								
	Temperature				**Relative Humidity**			
	1st Floor		**2nd Floor**		**1st Floor**		**2nd Floor**	
Month	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
January	66.1	1.5	70.5	2.0	43.1	3.9	34.6	4.7
February	65.4	2.6	69.3	3.4	45.6	2.6	37.3	3.4
March	67.8	1.2	71.1	1.4	45.9	4.1	38.9	5.1
April	69.7	2.8	72.7	3.0	50.0	3.9	43.5	4.5
May	71.8	2.4	74.3	2.9	45.4	4.1	39.6	4.1
June	75.7	3.6	78.5	4.4	41.1	2.4	34.7	2.4
July	76.4	2.0	78.8	2.4	42.1	3.3	36.9	3.4
August	77.3	1.6	80.0	2.1	39.1	2.7	33.5	3.0
September	NA	NA	NA	NA	NA	NA	NA	NA
October	70.2	2.1	72.7	2.3	53.7	2.2	48.0	2.5
November	66.9	1.3	70.1	1.6	50.9	2.4	43.5	3.4
December	66.0	1.7	70.7	2.1	42.9	2.3	33.8	3.5

Table 53 - P9 Summary of Indoor Temperature and Relative Humidity by Month

The temperature differences between the 1st and 2nd floors are pictured in Figure 142 below. The 2nd floor was consistently warmer than the 1st floor, with an average temperature difference of 3.3 degrees F. ACCA recommends that interior temperatures be within +/- four degrees F of one another, but P9 spent 24.1% of the year outside of this range.

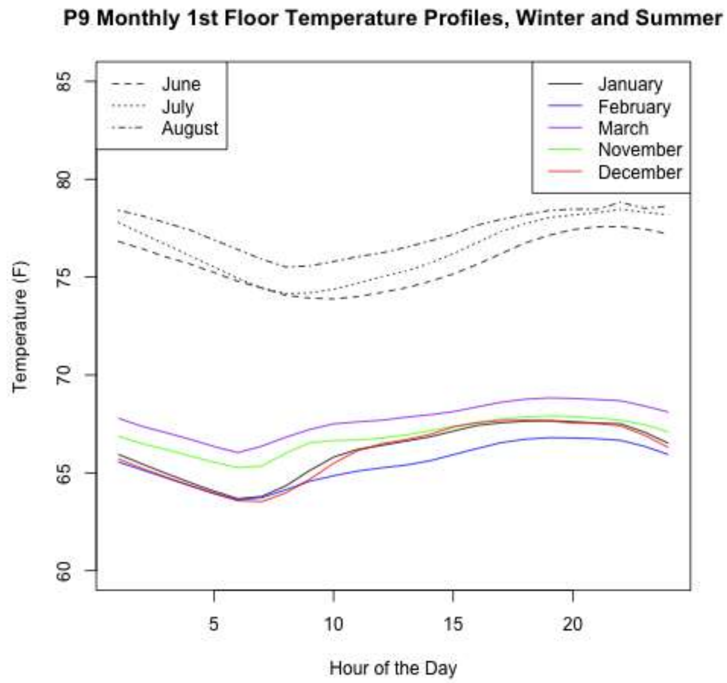


Figure 141 - P9 Monthly Profiles of 1st Floor Temperature, Winter and Summer

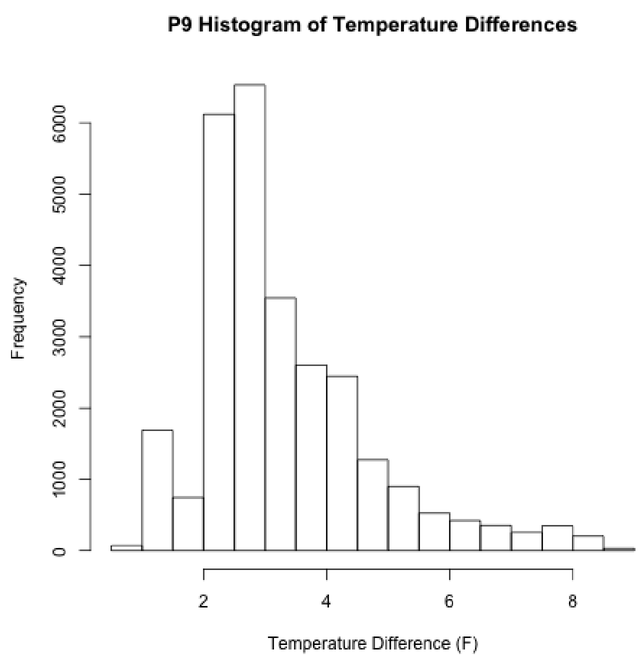


Figure 142 - P9 Histogram of Temperature Differences

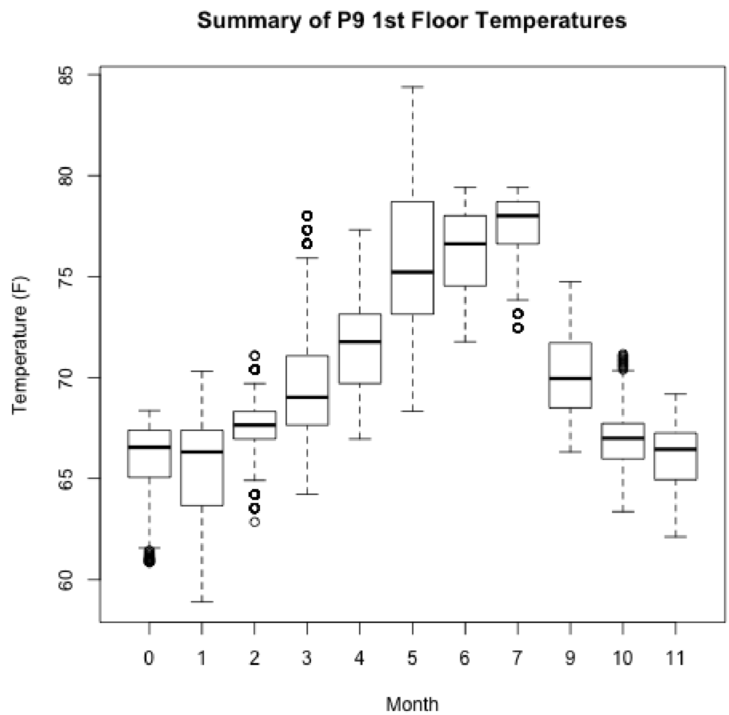


Figure 143 - P9 Summary of 1st Floor Temperatures

The proportion of time that P9 spent below, within and above the recommended range of 30 to 60% relative humidity is pictured in Table 54 below. Only 5% of the 15-minute periods throughout the year were below 30% and none were above. Monthly 1st floor relative humidity summaries are provided in Figure 144 below.

Proportion of Relative Humidity Was Below, Within and Above the Recommended Range			
Location	**Below 30%**	**30% to 60%**	**Above 60%**
1st Floor	0 %	100%	0%
2nd Floor	5%	95%	0%

Table 54- P9 Proportion of Time Relative Humidity Was Below, Within and Above the Recommended Range

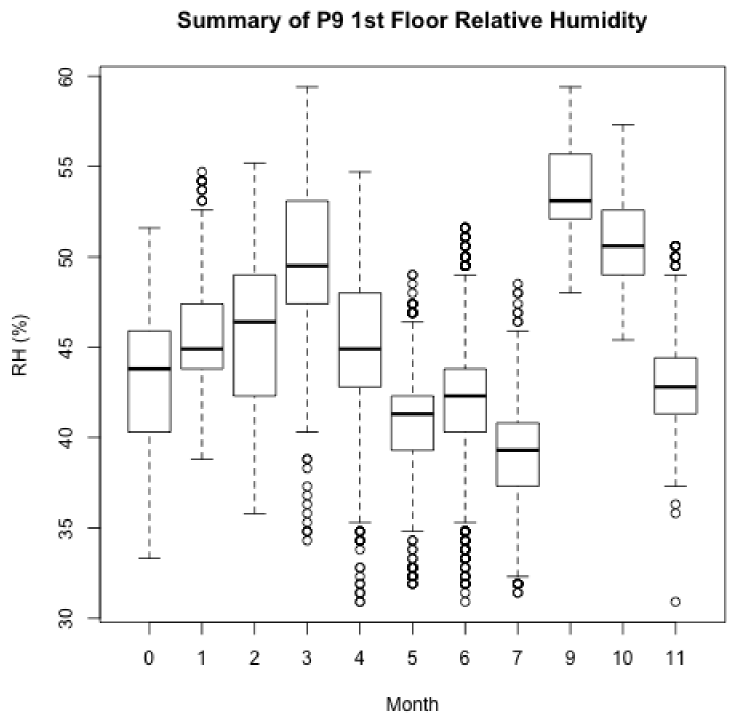


Figure 144 - P9 Summary of 1st Floor Relative Humidity

4.9.4 P9 Overview

P9 is a unique DER as it demonstrates a low cost solution for deep energy savings in a relatively new and already efficient home. Probably the most exciting element of P9 is its cost, which the owner estimated to be a net increase of monthly mortgage cost of only $15. This was achieved because cost-effectiveness was used as a decision making tool during the whole process. Solutions were evaluated and selected or rejected for their cost-effectiveness, as well as contributions to IEQ. Similarly, improvements in the envelope and HVAC equipment were specified in measurable, verifiable ways. Only by targeting decisions and efforts towards these specific goals, was P9 able to achieve such impressive results.

The retrofit of P9 could be considered an extreme home performance upgrade rather than a typical DER. The project was much less invasive, took less time, required fewer resources and achieved impressive energy reductions. Energy savings were pursued effectively across all major end-uses, with the exception of hot water. The nighttime pre-cooling system, increased daytime set-points and the evaporative condensing unit have proven to be very effective at reducing the air conditioning energy use in the summer. This is a great solution for low energy cooling in hot dry climates. Additionally, the homeowner has eliminated unnecessary energy use and tracks the monthly utility bills closely, showing a dedication to low energy behavior.

P9 illustrates the importance and variability in DER performance assessment metrics. Percentage reductions were good, at 54% net-site and 58% net-source. At the same time, P9 reduced more absolute source energy than any other project home. This is likely the result of its aggressive electricity reductions in cooling, fan power, plug loads and lighting. Finally, its net-energy performance was not terribly impressive, with the highest net-site energy consumption in this research (just below the CA single family average). P9 illustrates how the goals of a deep energy retrofit and of a low-energy home can diverge, and that a low-energy home is not required to achieve dramatic energy reductions.

4.10 P10

4.10.1 P10 Project Description

Image 43 - P10 Pre- and Post-Retrofit

P10	**Pre-Retrofit**	**Post-Retrofit**
ENVELOPE		
Wall Insulation	None	3.5” low density SPF – R13 5.5” low density SFP in garden room – R19
Attic/Roof Insulation	None	7.5”- 9.5” low density SPF – R25-R32
Foundation Insulation	None	4.5”- 6” low density SPF – R16-R22
Windows	Single pane wood frame	Most windows replaced with 2 Pane, Low E, Argon, Aluminum Clad – U: 0.29-0.34 SHGC: 0.23-0.32
Air Leakage		1,455 CFM_{50}, 6.1 ACH_{50}
MECHANICAL		
Heating and DHW	Wood fireplace	Woodstove, 75% thermally efficient, 2 panel solar thermal combisystem with 96% efficient condensing gas boiler, 120 gal storage tank, zone controlled underfloor hydronic heating
Ventilation	None	Bath and kitchen exhaust
Distribution	None	Insulated Pex
LIGHTS/APPLIANCES/MEL	Old, dark, inefficient	Energy Star appliances, CFL, LED & Halogen lighting, skylights and solatubes, medium MEL
RENEWABLES	None	3.3 kW PV, two solar thermal panels

Table 55 - P10 Retrofit Summary Table

General Information

P10 is a retrofit project located in Pacifica, CA, on the coast just south of San Francisco. This home has great historical and personal meaning for the homeowners, and they undertook a deep energy retrofit of the property in order to preserve a family heirloom, create a very low-impact home and have a comfortable and modern place to retire. The original 700 square foot cottage home was built by the current homeowner's father in the mid-1930's as a weekend-retreat for the family. Over the years the cottage was added onto, totaling 1,503 ft^2 prior to the DER. The occupants were faced with a dim, poorly lit, entirely uninsulated structure, which was in desperate need of an aesthetic and energy upgrade. The owners' primary goals for the project were to: (1) maintain the heirloom nature of the home, (2) make it as energy efficient as possible, and (3) make the home a viable space for retirement through changes in the layout and comfort. While the architectural and mechanical designs of the project were done by experienced low-energy designers, the construction and mechanical subcontractors were much less experienced. The owners remarked upon mistakes that were made by their plumber, for example, that may have reduced the effectiveness of their combined heating and hot water system.

Building Enclosure

As an uninsulated structure, P10 required a comprehensive insulation and airtightness retrofit to increase its efficiency. The mixed crawlspace and basement foundation was insulated on the underside of the sub-floor using low-density spray polyurethane foam (SPF) insulation. A variety of joist depths required that some areas of the sub-floor be insulated with a mixture of 4.5" and 6" of SPF. Our inspection of the sub-floor insulation indicates that with very tight quarters in the crawlspace, less-than-perfect installation quality was achieved around the band joist. The existing 2X4 above grade walls were stripped of plaster and were filled with low-density SPF. The 190-ft2 addition walls were built using 2X6 lumber and also filled with SPF. The exterior wall that contained the exposed chimney was completely rebuilt, but the designer moved the chimney to the inside of the thermal and air boundary, significantly reducing the thermal bridge. The existing roof was made from large timbers and did not contain any attic space for insulation. The exposed beams of the timber frame were maintained, and a new structural roof of 2x12 lumber was added on top of the existing structure. This new cavity was sprayed with low-density SPF to a depth of 7.5" on the front roof and 9.5" on the rear portion of the roof.

Nearly all of the existing single-pane, wood frame windows were replaced with double-pane, low-e, wood framed units. This meant eliminating some very old curved glass windows in the living room, which were partly salvaged by combining two of them into a site-built double-pane window, used in the dining room.

Air Leakage

The home was never tested for airtightness as part of the retrofit process. Our testing represents the first results on what was assumed to be a tight home, with spray foam insulation throughout. The structure remained relatively leaky, achieving an airtightness level only on par with typical new homes. During the blower door testing, remaining air leaks were found around the chimney and many were identified at the bottom of the staircase leading from the living area down to the garage access door.

Ventilation
No continuous mechanical ventilation is provided in P10, but exhaust ventilation was installed to remove contaminants at the source. Energy Star, low-sone (a measurement of sound volume) bathroom exhaust fans were installed in each bathroom. A 380 CFM kitchen exhaust fan was also installed in the ceiling above the range. Diagnostic testing revealed that the kitchen exhaust fan was pulling less than one third of its rated airflow. This problem was not remedied, because kitchen exhaust fan operation is rare, according to the occupants. The occupants also report that they regularly open windows to provide fresh air during acceptable outdoor conditions.

Heating and DHW
With this newly insulated envelope, the mechanical system in the home was replaced for maximum efficiency and integration with renewable energy supply. Heating was originally achieved in P10 using an open-air wood-burning fireplace. During the retrofit, the homeowners decided to install an efficient wood stove, and a solar combined space and water heating system with 80 square feet of solar thermal flat-plate panels mounted on the roof. The wood stove is used intermittently, and it is rated with a maximum output of 35 kBtu/hr, a 6 hour burn time and minimum 75% combustion efficiency. The solar panels are used to heat a 120 gallon insulated solar storage tank located in the unconditioned garage. A 96% efficient natural gas boiler is mounted in the side of the storage tank and provides any back up heating required for domestic hot water or space heating (see Image 44 below). Domestic hot water is delivered through a home run manifold system served directly from the storage tank, which has an internal heat exchanger for the solar loop. Prior to insulating, PEX tubing was stapled to the underside of the sub-flooring along with aluminum fins, which were then buried in spray foam. Space heating fluid is pumped through these closed loops in the floor system, and uses an external heat exchanger to exchange heat between the tank and the loop. A system of pumps and a large manifold serve as the central distribution point of hot water to the 7 thermal zones in P10. Each zone has a thermostat, which controls a valve on the manifold.

Image 44 - P10 Solar Combisystem Tank in Garage

Image 45 - P10 Space Heating Distribution Pipes, Insulated but with Large Gaps, in Garage

The homeowner revealed that the plumbing contractor might not have had experience in this type of installation. There is a lot of hot water plumbing located in unconditioned space, and the pipe runs were not originally insulated. The occupants eventually insulated them, but our inspection revealed numerous gaps, and relatively thin pipe insulation (see Image 45 above). While the system was carefully designed to meet the building loads, the occupants have reported some performance problems. During installation, the project plumber convinced the homeowners to extend the in-floor radiant tubing to the addition zones; however, the mechanical engineer did not include this in their design. In addition, the homeowners have repeatedly struggled with the system's inability to comfortably heat the living room zone of the home. This is the largest zone, with two piping loops and the longest distribution length. The problems have been particularly acute when a temperature set-back is used at night with modestly low outdoor temperatures (~45 degrees F), and the system cannot recover to comfortable temperatures in the a.m., even with 4 or more hours of operation. The PEX tubing is installed underneath a ¾" plywood sub-floor with a nominal ¾" of wood flooring on top of that, all of which presents a thermal barrier and capacitance, which likely slows the heating system response. But this fails to explain why the issue only appears to exist in the one room.

Appliances

All major appliances were replaced with Energy Star certified units.

Plug Loads

The homeowners are dedicated to reducing their energy use and are using the monitored data to adjust their behavior. There is a TV and a DVR, a small office with a computer, small kitchen appliances and a small aquarium.

Lighting

The lighting retrofit began with a thorough design effort to utilize daylight wherever possible. This effort included installation of numerous skylights, solar tubes (see Image 46 below) and translucent interior doors (see Image 47 below), which allow for transmission of light from rooms with windows into the interior of the home. All remaining lighting needs are met with a mix of LED, CFL and halogen MR-16 bulbs.

Image 46 - P10 Solar Tube for Daylighting in Bathroom

Image 47 - P10 Translucent Door Panel to Bring Daylight Deeper Into Home

Renewable Energy

As a final effort to reduce the home's environmental impact, a solar PV system was installed on the roof. This 3.33 kW system is grid-tied and net-metered.

Additional Information

P10 has shown exemplary dedication to providing passive lighting, and the occupants have made serious efforts to reduce MELs as much as possible. Overall, P10 is an exemplary project that both preserved historical character and meaning, while at the same time making huge advancements in comfort and energy efficiency.

4.10.2 Building Diagnostic Results

Blower Door

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH
P10	1455	6.1	0.29	0.85	75.4	0.28

Table 56 - P10 Blower Door Test Results

Ventilation Airflows

The 62.2 whole house continuous mechanical ventilation requirement for P10 is 39.6 CFM. No continuous mechanical ventilation is provided. Kitchen and bathroom exhaust airflows were measured during diagnostic testing. It is notable that while the kitchen ceiling exhaust fan did meet the 100 CFM 62.2 requirement, it does not use a range hood, so 62.2 requires 5 kitchen ACH by a continuously operating fan in the space. In this home, a continuous kitchen fan at 77 CFM is necessary.

Location	Airflow (CFM)
Master Bathroom	76
2nd Bathroom	112
Kitchen Ceiling	110

Table 57 - P10 Ventilation Airflow Measurements

4.10.3 Monitored Data Results

Whole House Energy Use

P10 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Net-Source Energy	Net-Site Energy	Total CO_2e
7,727 kWh	7,697 kWh	2,522 lbs
Occupants	Area	HERS Rating
2	1,706 ft^2	25

Figure 145 - P10 Mileage Box

The annual net-site energy and net-source energy, as well as CO_2e emissions of P10 were 7,697 kWh, 7,727 kWh and 2,522 pounds, respectively. Notably, the source energy usage was less than site energy, which results from being an annual net-exporter of electricity. No pre-retrofit data are available for P10. Using the project's HERS score of 25, P10 is projected to consume 75% less site energy than the HERS reference home. When compared to the average single family CA home, P10 uses 62% less net-site energy, 79% less net-source energy and has 73% reduction in CO_2e emissions. These impressive results were achieved while completely re-envisioning the home for its future use during the occupants' retirement.

Monthly post-retrofit electrical and gas consumptions, as well as PV production are pictured in Figure 146 below. From April through September, P10 produces more electricity than it consumes. Gas energy use is clearly dominated by heating demand. Gas usage during warmer months is very low, sometimes zero, which is the result of the solar thermal hot water system.

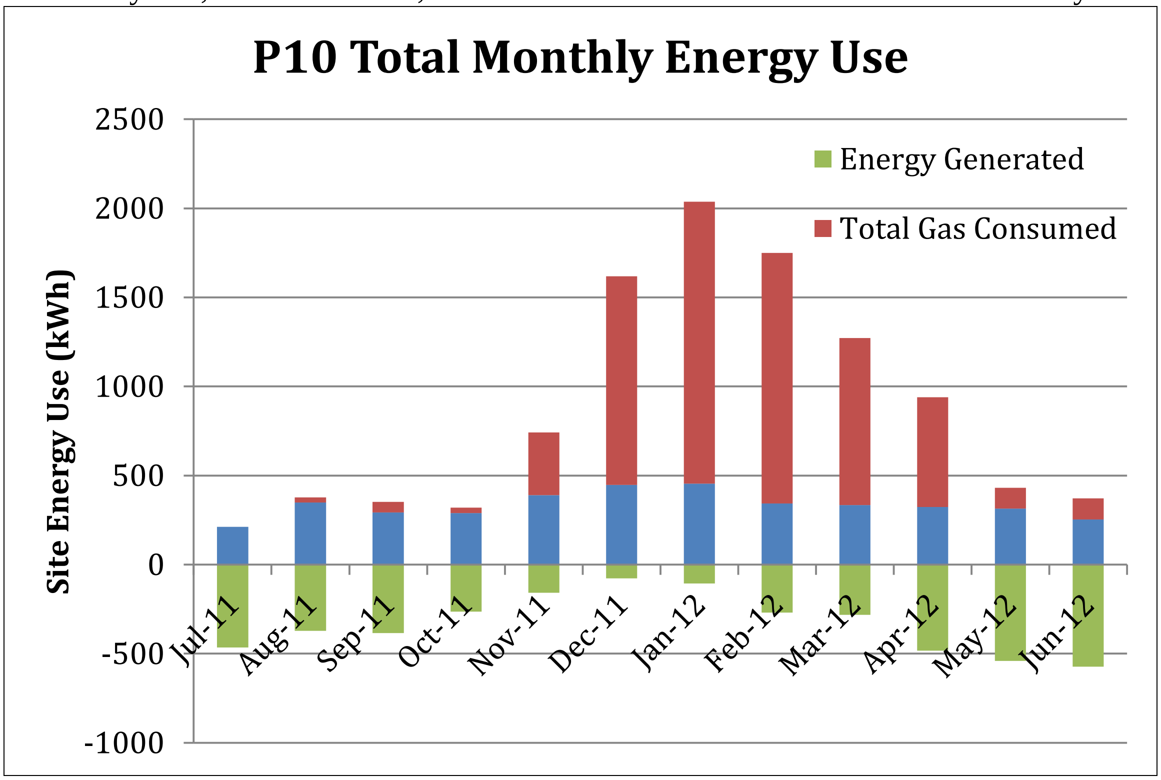


Figure 146 – P10 Total Monthly Energy Use

Hourly demand profiles of whole house electricity, net-electricity and PV production are pictured below in Figure 147, Figure 148 and Figure 149. Hourly average electricity demand, across the seasons, is above 300 watts at night, which suggests a fairly high baseload. Slight increases in consumption occur throughout the day, but their relative size suggests that a lot of the electricity demand in P10 is not occupant driven. Net-hourly electrical consumption drops below zero during periods of high production, except during December. The reason is clear from the PV production profile, which shows dramatically reduced output from the system during December. To the extent that PV output is reflective of solar thermal performance, very little hot water or heating energy is being provided by solar during the peak heating months.

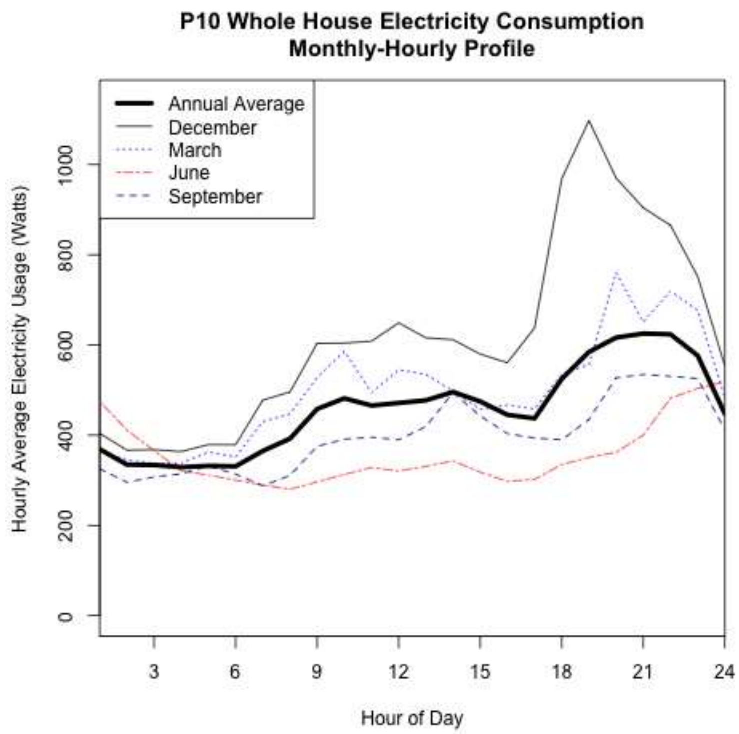


Figure 147 - P10 Whole House Electricity Consumption, Monthly-Hourly Profile

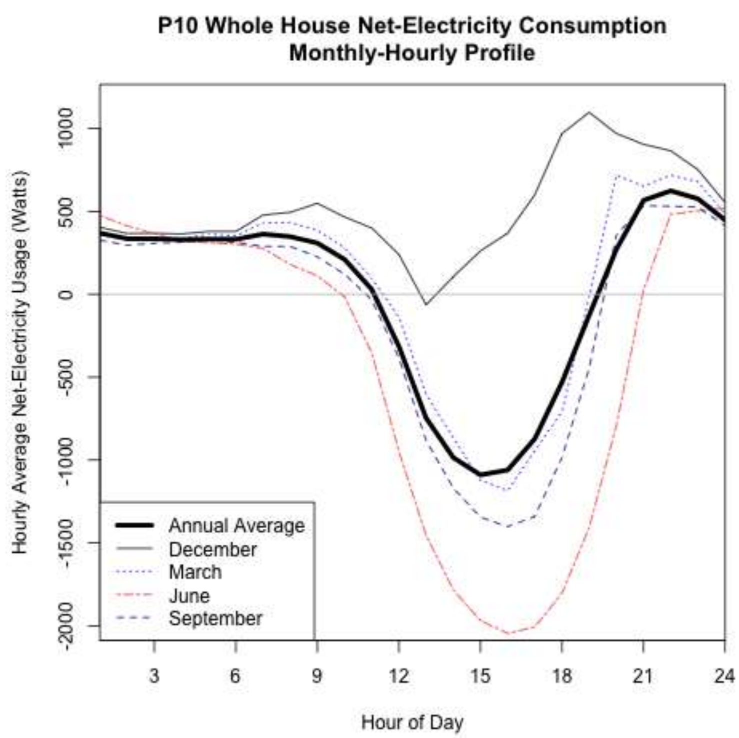


Figure 148 - P10 Whole House Net-Electricity Consumption, Monthly-Hourly Profile

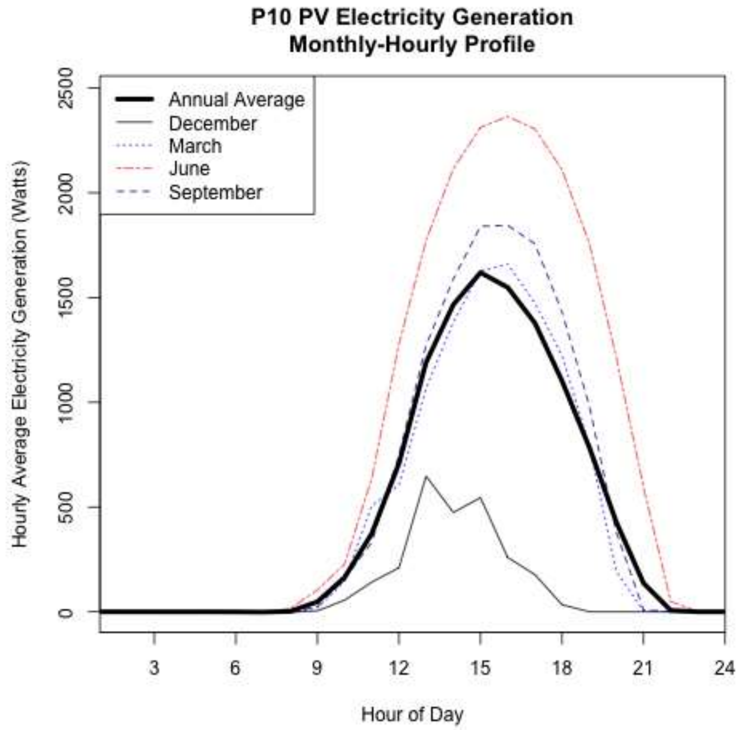


Figure 149 - P10 PV Electricity Generation, Monthly-Hourly Profile

End-Uses

The annual energy end-uses are summarized in Table 58 and Figure 150 below, and monthly end-use data are pictured in Figure 151. Energy usage is dominated in P10 by the combined heating and hot water appliance ("Heating" below includes hot water), which uses almost twice as much energy as the combined plugs, lighting and appliances. This latter collection of uses is very similar to those in the other DER project homes. Combined heating and hot water systems could not be modeled in the energy simulation tool used, yet the annual totals were actually predicted fairly well (within 5%).

	P10 Actual	P10 Modeled
Floor Area	1706	1706
# of Occupants	2	2
Heating and Hot Water	7165	7507
Cooling	0	0
Pumps	611	0
Hot Water	0	741
Ventilation	0	0
Combined HVAC and Domestic Hot Water	***7776***	***8248***
Appliances	1333	1704
Lights	857	492
Plug Loads	1707	1916
Combined Appliances, Lights and Plugs	***3897***	***4112***
Annual Total	***11672***	***12360***
PV Production	3976	4294
Annual Net	***7696***	***8066***

Table 58 - P10 Site Energy End Use Summary

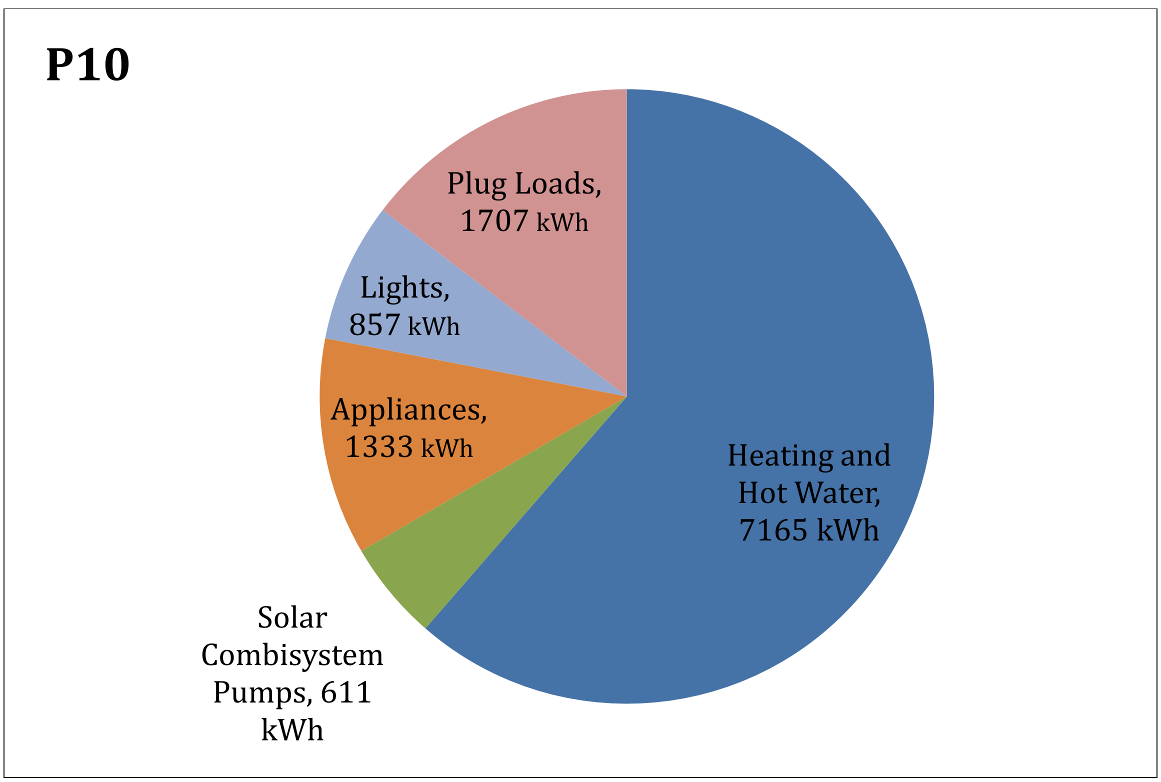


Figure 150 - P10 Annual Energy End-Uses

The monthly end-uses show the dominant presence of the combined heating and hot water system, which used a peak of 1,600 kWh in a single month. Some unidentified but significant appliance energy uses appeared in the winter and early spring of 2012, but disappeared by May.

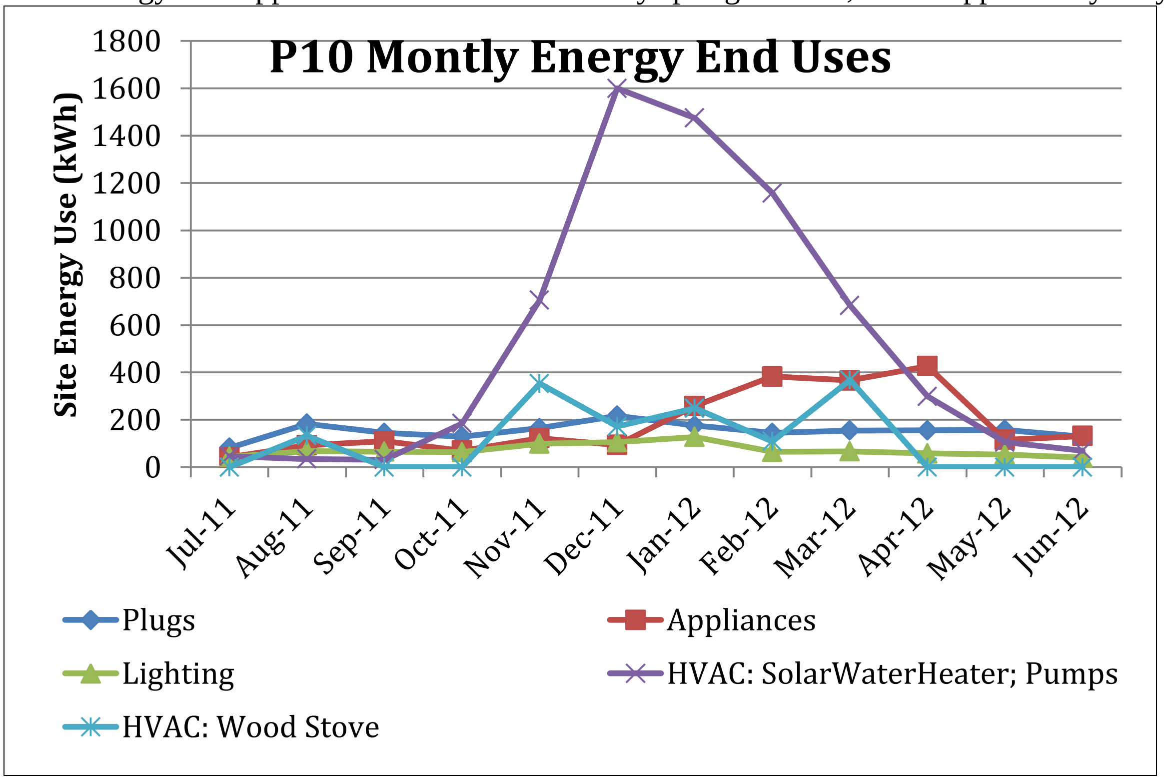


Figure 151 - P10 Monthly energy End-uses

User Behavior

The baseload in P10 was 198 watts, which translates approximately to 1,730 kWh per year. This was 22.5% of annual net-site energy consumption. The discretionary energy use makes up 54% of the energy used to date. Due to some mysterious combinations of loads on the electrical panel, it is assumed that the lighting circuits also have some plug loads mixed in but we were unable to identify the specific loads.

Temperature and Relative Humidity

The P10 monthly indoor temperature and relative humidity means and standard deviations are presented in Table 59 below. Monthly average temperatures ranged from approximately 64 to 71 degrees F. Temperatures are notably lower in the master bedroom, which is its own heating zone. An informal discussion with the occupants suggests that the master bedroom always has a closed door and window open overnight, all months of the year. The temperature profiles pictured in Figure 152 below, suggest that a four-degree winter nighttime thermostat setback is used, and that it takes the system approximately five to six hours to fully regain temperature. The occupants have complained that the heating system inexplicably does not fully maintain winter comfort, even during fairly mild overnight temperatures. Nevertheless, winter month average temperatures in the living room are at comfortable levels, right around 68 degrees F.

Monthly mean relative humidity ranged from approximately 51% to 71%. During every month of the year, the master bedroom relative humidity averaged greater than the recommended 30-60% range. This occurred even during months with average temperatures around 70 degrees. Monthly average relative humidity around 70% may be cause for concern.

Increased absolute humidity in the master bedroom could result from: (1) two adults sleeping in a confined space with a closed door, (2) high humidity, coastal air infiltration during sleeping, or (3) as a result of the master bathroom and its use for showering.

Summary of Indoor Temperature and Relative Humidity by Month								
	Temperature				Relative Humidity			
	Living Room		Master Bedroom		Living Room		Master Bedroom	
Month	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
January	67.6	3.2	64.6	2.5	55.0	8.3	65.8	9.1
February	66.8	2.7	64.0	1.6	55.6	4.1	64.7	3.4
March	68.8	2.0	64.9	1.5	50.8	4.3	63.3	3.1
April	70.4	2.2	66.6	2.0	51.5	4.0	62.0	3.6
May	70.7	2.6	67.4	1.5	51.4	4.9	60.9	2.7
June	71.9	3.4	69.2	2.0	51.9	5.8	59.9	2.9
July	71.1	3.1	68.9	2.1	56.4	5.6	62.8	3.1
August	70.7	2.2	68.5	1.9	58.3	3.7	64.8	2.7
September	69.4	1.8	67.6	1.5	61.6	2.9	66.7	2.0
October	68.1	2.1	67.1	2.2	66.2	2.6	69.7	2.9
November	68.2	2.3	64.3	1.2	59.5	6.3	70.6	6.0
December	68.0	1.9	63.8	1.1	56.2	3.5	68.7	3.4

Table 59 - P10 Summary of Indoor Temperature and Relative Humidity by Month

The temperature differences between the living room and master bedroom are pictured in Figure 153 below. The master bedroom was colder than the living room for nearly every 15-minute period of the year, and on rare occasions the master bedroom was more than 15 degrees cooler. The average difference was 2.8 degrees F. P10 spent 21.6% of the year outside of the ACCA recommended range of +/- four degrees F. To a large extent, this was purposeful and does not necessarily reflect a problem with the home. Rather it was the result of sleeping preferences and thermostat set points.

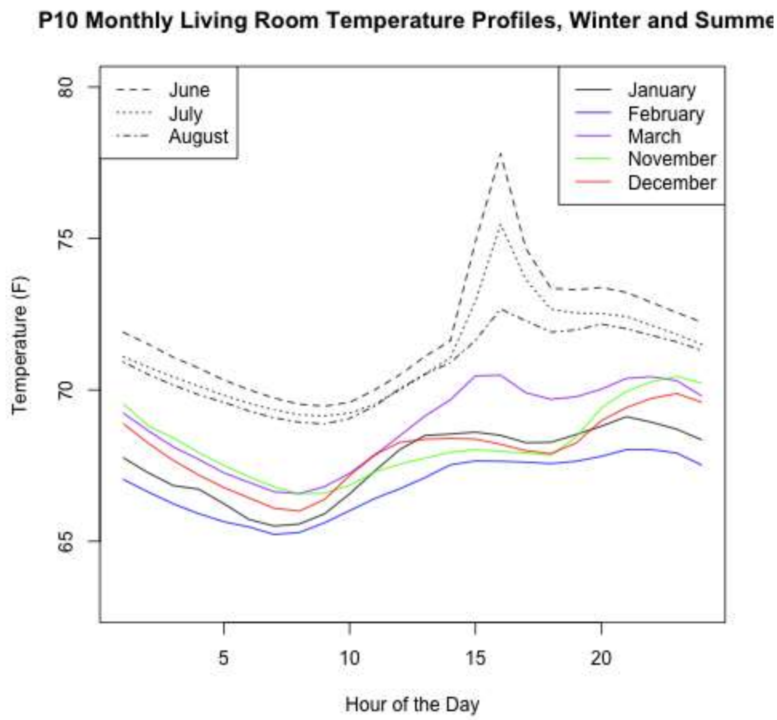


Figure 152 - P10 Monthly Living Room Temperature Profiles, Winter and Summer

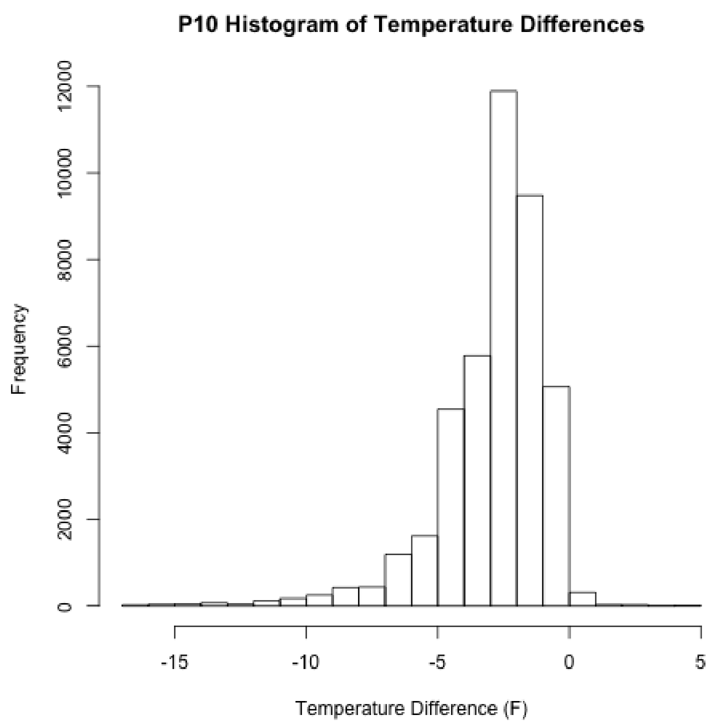


Figure 153 - P10 Histogram of Temperature Differences

As noted above, the master bedroom had elevated monthly mean relative humidity throughout the year. Table 60 below shows the proportion of the year that relative humidity was below, within and above the recommended 30-60% range. Fully 82.1% of the year had relative humidity greater than 60% in the master bedroom, and even in the better controlled living room area, the upper threshold was exceeded almost 30% of the year. P10 is less than one mile from the Pacific Ocean, and it receives ample amounts of fog and mist, which likely contribute to these high levels. Nevertheless, indoor relative humidity was controlled below 80%, with sustained levels over 70% only occurring once for a period of 1.2 days. Three independent ten day periods were continually greater than 60%, with 16.3 days being the longest single period above 60%. Monthly relative humidity in the master bedroom and living room are pictured in Figure 154 and Figure 155 below.

Proportion of Time Relative Humidity Was Below, Within and Above the Recommended Range			
Location	**Below 30%**	**30% to 60%**	**Above 60%**
Living Room	0%	71%	29%
Master Bedroom	0%	18%	82%

Table 60 - P10 Proportion of Time Relative Humidity Was Below, Within and Above the Recommended Range

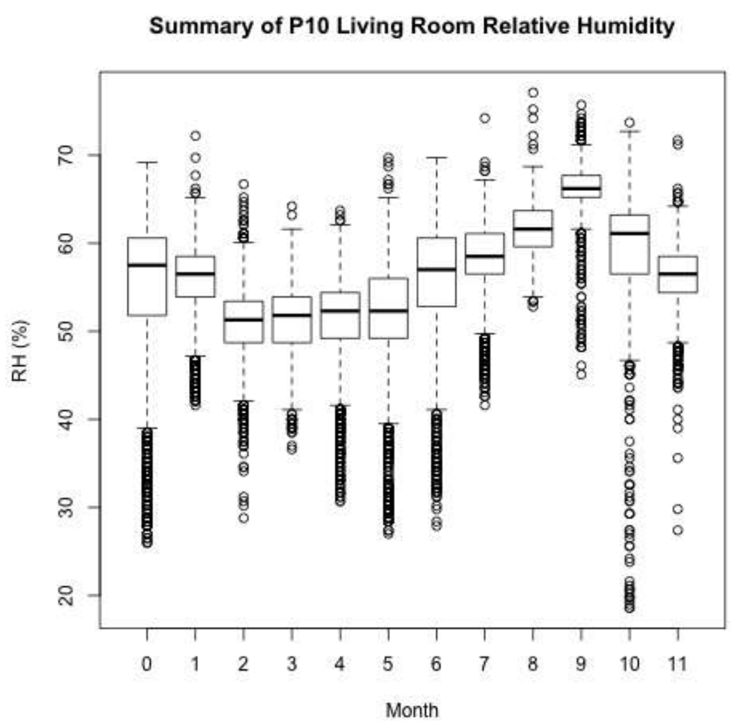


Figure 154 - P10 Summary of Monthly Living Room Relative Humidity

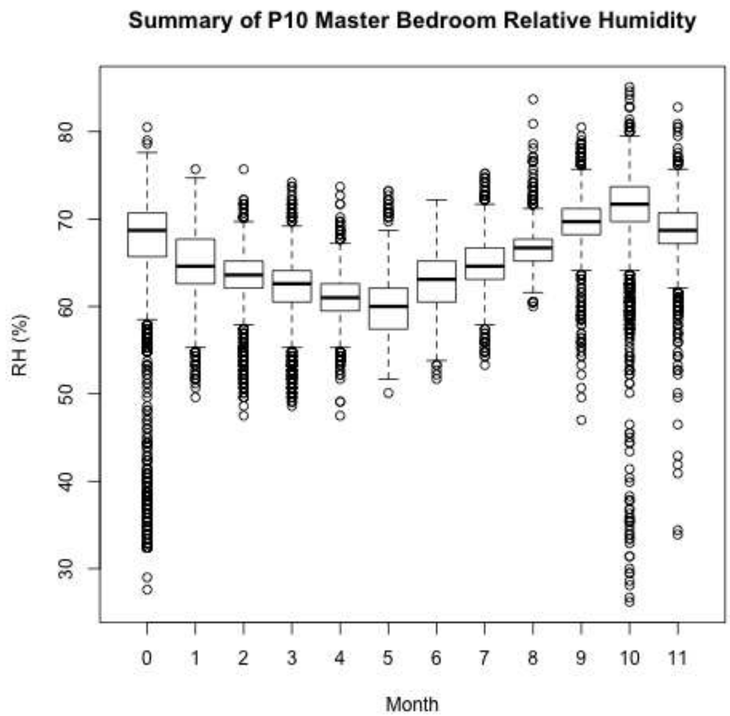


Figure 155 - P10 Summary of Monthly Master Bedroom Relative Humidity

4.10.4 P10 Overview

P10 was able to fulfill the owners' goals of sustainability, energy efficiency, historic preservation and revitalization of a family heirloom. P10 is the second lowest consumer of net-source energy in this research. This is mostly the result of the predominance of heating and hot water gas usage, which does not carry a source energy penalty, and the net-annual exportation of electrical energy. For comparison, P3, a certified Passive House with solar thermal and a mini-split heat pump used 11,138 kWh of net-source energy, and P10 used only 7,727 kWh. P3's gas usage was very low, so the total was dominated by electricity. While the home may not be performing as expected in terms of heating energy, comfort and relative humidity, the low electricity use of the occupants has allowed this project to achieve a 79% net-source energy reduction from the CA average and a HERS score of 25.

The homeowners have reported problems with the solar combisystem and similar to P8, gas use has been higher than expected. P10's PV system output in December suggests that very little, if any, solar energy goes to space heating in the winter months.

P10 used both solar thermal and solar PV systems as the two primary contributors to energy performance. Due to the location, this may not have been a good investment, given the availability and consistency of the solar resource. Prior to making these investments, P10 would have benefitted from significant further envelope improvements, which would have made the home both lower energy and more comfortable. The easiest and lowest cost improvement would have been in air leakage, which was measured at 6.1 ACH_{50}. Consistent with results from other project homes, air leakage was not a primary goal of the retrofit, and as a result, great outcomes were not achieved.

5 CASE STUDY CROSS COMPARISON

Monitoring end-use energy has been extremely valuable, helping create a detailed understanding of where, when and how much energy is being used in these DERs. The data and online energy dashboard have also helped homeowners better understand their own energy use. Malfunctioning or unnecessary energy uses were discovered and remedied in several case study homes, due to the combination of the dashboard, and the attention of the homeowners and our research team. Each case study is unique, offering different insights and important lessons learned that can be used to further our understanding of DERs and successfully implement them in the future. A cross comparison of the trends, successes and challenges in each case study, and how this research could lead to even deeper energy savings in the future is discussed below.

5.1 Many Paths to DER

Table 61 below shows the wide range of building characteristics encountered, including vintage, size, occupancy, cooling degree-days and HERS rating. This high level of diversity is likely to hold true for DERs drawn from a wider sample because of the variability in existing home construction, location and occupancy.

Project ID	Location	Year Built / Year Retrofitted	CA / Building America Climate Zone	Heating Degree-Days (base 65)	Cooling Degree-Days (base 80)	Floor Area Pre / Post (ft^2)	# of Occup-ants Pre / Post	HERS Index 2006
P1	Berkeley, CA	1904 / 2008	3 / Marine	2909	128	960 / 1630	2 / 4	72
P2	Palo Alto, CA	1936 / 2008	3 / Marine	2563	486	2780 / 2780	NA / 2	55
P3	Sonoma, CA	1958 / 2010	2 / Marine	2844	456	1937 / 2357	NA / 1	25
P4	Petaluma, CA	1940 / 2010	2 / Marine	2844	456	1540 / 2510	2 / 2	36
P5	Point Reyes Station, CA	1920 / 2010	3 / Marine	3770	11	800 / 905	NA / 3	86
P6-N	Davis, CA	1932 / 2011	12 / Hot Dry	2702	1470	1179 / 1462	4	28
P6-S	Davis, CA	1934 / 2011	12 / Hot Dry	2702	1470	1496 / 1496	4	37
P7	San Mateo, CA	1910 / 2011	3 / Hot Dry	3042	108	3288 / 3288	2 / 2	76
P8	Oakland, CA	1915 / 2008	3 / Marine	2909	128	1440 / 1627	NA / 4	33
P9	Folsom, CA	1998 / 2006	12 / Hot Dry	2702	1470	3114 / 3114	NA / 4	72
P10	Pacifica, CA	1934 / 2008	3 / Marine	3770	11	1503 / 1706	2 / 2	25

Table 61 - Project Summaries

“NA” is indicated if number of occupants or floor area pre-retrofit is unknown.

Table 62 below compares the retrofit solutions between homes in our study. A wide variety of measures were employed, demonstrating the breadth of available paths to deep energy savings. Achieving energy reductions in existing homes requires flexibility. All DERs are constrained by the existing site, building, equipment and fuel types, and all projects are likely to uncover significant unforeseen obstacles once construction commences. No particular technological or behavioral solution is required for success. Despite the diversity evident in Table 52, there were several trends among these case studies that are discussed in detail below.

	P1	P2	P3	P4	P5	$P6_N$	$P6_S$	P7	P8	P9	P10
Building Enclosure											
Super Insulated (100% > T-24)			X			X	X				
Highly Insulated (50% > T-24)	X				X						
Insulated (Meets T-24)		X		X				X	X	X	X
All Triple Pane Glazing			X								
All Double Pane Glazing	X	X		X	X	X	X			X	X
Passive House Standard <0.6 ACH_{50}			X								
<3 ACH_{50} (recommended level)	X		X		X					X	
Energy Star V. 3 <5 ACH_{50}	X		X		X					X	
HVAC											
Heat/Energy Recovery Ventilation	X	X	X		X						
Electric Resistance Heating	X				X						
Heat Pump Heating and Cooling		X	X								
A/C with Evaporative Cooling										X	
Solar Thermal Combisystem			X						X		X
Night Ventilation Cooling				X		X	X			X	
DHW											
Electric Resistance					X						
Heat Pump		X									
On Demand Condensing Natural Gas	X			X				X			
Tank Natural Gas										X	
Solar Thermal w/ Condensing N. Gas Backup			X			X	X		X		X
User Behavior											
Baseload Below 225 Watts	X			X	X	X	?	X		X	X
Baseload Above 225 Watts		X	X						X		
Renewable Energy											
PV		X	X	X		X	X		X		X
Solar Thermal			X			X	X		X		X

Table 62 - P1-P10 Retrofit Comparison

5.1.1 Building Enclosures

One unexpected finding was that the majority of the homes in this study did not achieve the level of building enclosure performance expected for DERs. Air leakage was greater than $5ACH_{50}$ in 6 of the eleven homes (see Table 63 below). Given the level of intervention in each of these retrofits described above, far greater airtightness could have been achieved. It is apparent in some project homes that airtightness was not one of the key project goals or intentions of the designers, contractors or homeowners. Projects have consistently shown that if airtightness is a key goal, it can be reduced to much lower levels (P1, P3, P5 and P9). Although insulation levels were also lower than expected in most homes, airtightness is probably cheaper and easier to achieve than high R-values. But our results suggest that in CA climates, neither extreme insulation nor high airtightness levels are required to achieve deep energy reductions, but can instead be off-set with occupant conservation measures.

Comparison of Blower Door Test Results for All Project Homes							
ID	**CFM_{50}**	**ACH_{50}**	**CFM_{50}/ft^2SA**	**CFM/ft^2FA**	**ELA (in^2)**	**nACH**	**SLA (ELA/ft^2FA)**
P1	271	1.1	0.063	0.166	10.3	0.05	0.00004
P2	2260	5.7	0.325	0.588	124.6	0.27	0.00031
P3	151	0.4	0.019	0.064	8.3	0.02	0.00002
P4	1983	5.4	0.322	0.790	110.0	0.26	0.00028
P5	292	2.4	0.097	0.323	14.0	0.10	0.00011
P6 North	991	5.1	0.222	0.678	49.4	0.18	0.00023
P6 South	1114	5.6	0.247	0.745	55.9	0.20	0.00026
P7	5336	10.8	0.790	1.623	300.6	0.72	0.00064
P8	2397	9.3	0.476	1.474	130.6	0.63	0.00056
P9	1227	2.4	0.183	0.394	69.8	0.14	0.00016
P10	1455	6.1	0.288	0.853	75.4	0.28	0.00031

Table 63 - Comparison of Blower Door Test Results for All Project Homes

P3 is the only project that achieved Passive House certification, although P1 and P5 were also guided by the same principles. Based on our data, the extensive retrofit approach of P3 (using superinsulation, triple pane windows and extreme airtightness) is unnecessary in most California climates (IECC Zone 3) in order to achieve deep energy savings. However, those DERs guided by Passive House principles consistently used the least space conditioning energy and maintained the most consistent, comfortable temperatures. This allowed for greater variability and leniency in occupant behavioral patterns, while still remaining a low energy home. In the context of DERs implemented across the US, energy performance independent of occupant conservation efforts is essential, and these homes were capable of delivering this. In order to deliver more robust deep retrofit results across the population, particularly in colder climates, projects will need better performing envelopes than those used in these project homes.

We consider <3 ACH_{50} to be a reasonable target for DERs, however, only four of the eleven project homes achieved this. Not surprisingly, three of the four homes were designed with the Passive House standard in mind, which stipulates extreme airtightness. These homes had high levels of intervention in the envelope, which made it easier to achieve higher levels of airtightness. P4 and P10 are examples of homes with very significant envelope intervention, where the opportunity to achieve greater airtightness was not seized. Those homes that do not fully remove either interior or exterior cladding may not be able to achieve this target. Our findings suggest that for such homes, a goal of <5 ACH_{50} is achievable.

Building enclosure improvements could have been more aggressive in the majority of these homes. Greater airtightness is achievable and recommended. Code compliant insulation levels can be sufficient in this climate, but if the siding is to be replaced, then exterior insulation should also be installed. These recommendations should be viewed in a mild-climate context. Space conditioning is not necessarily the largest load in CA homes. According to RASS (2008), single-family homes in forecast zone four (P3, P4, P6-N&S and P9) use 5,715 kWh (gas) for water heating and only 4,689 kWh (gas) for space heating. Whereas in zone five (P1, P2, P5, P7, P8 and P10), space heating is nearly double water heating consumption. Energy reduction measures should first and foremost be targeted based on how energy is used in the home. This requires home inspections, assessments, and potentially modeling and/or energy budgeting efforts.

5.1.2 Keep it Simple

A trend was observed in some deep retrofit projects to use overly complex, custom engineered HVAC solutions. These systems tended to be costly in terms of money, reliability and comfort.

In P2, P3, P8 and P10, cutting edge HVAC systems were installed that did not perform as expected. Complex HVAC integrated with DHW and/or envelope systems is not a solution in and of itself. Both P8 and P10 paired solar combisystems with nominally insulated and air sealed building enclosures. Both homes used more energy for heating and hot water than other projects that had better enclosures and no solar energy input. These systems could have performed better, but storage volume and panel area were too small, and distribution systems had problems in both projects. Similarly, the overly complex HVAC systems seen in P2 and P3 suffered from costly performance issues. In P2, the heat pump combisystem failed and was replaced, and in P3, the mini-split head unit and thermostat had to be moved in order to stop extreme short cycling and provide acceptable comfort levels. The general contractor for P3 has subsequently done similar projects, with more simplified solutions, and he has found them satisfactory. Solar thermal systems may be very good energy savings solutions for hot water in California, but they were not observed to contribute substantially to space heating loads when integrated into a single system. This is mostly likely due to the mismatch between heat demand and solar input during winter months.

On a similar note, P4 installed an add-on to its PV system that claimed to provide both pre-heated ventilation air and improve PV panel efficiency by cooing the backside of the panels. However, information gathered from the manufacturer revealed that in order to move enough air to actually cool the panels would require a fan whose power demand was greater than the resulting increase in PV output. This frustrating purchase is still used to provide pre-heated ventilation air to the basement office and living room. This system added cost and complication to the project without improved performance. Money would have been much better spent simply purchasing additional PV generation capacity or increasing the airtightness level beyond 5.4 ACH_{50}.

Our recommended approach starts with optimizing the building enclosure and utilizes the most efficient, simple, off-the-shelf HVAC systems in order to achieve deep energy savings. Simpler systems do not require custom engineering, can be more easily maintained and repaired, do not cost dramatically more, and can provide comparable or superior energy performance. Examples of successful, off-the-shelf solutions include mini-split heat pumps, high-efficiency gas furnaces, heat pump water heaters, and tankless gas water heaters. But simplicity does not solve all problems. For example, P1 used electric resistance baseboard radiators—a very simple heating system. These were chosen at the last minute as a cheap, easy solution to satisfy code officials. Unfortunately, the home actually increased its source energy consumption, due to a switch from gas heating to resistance electric. This occurred despite extreme airtightness, an ERV, above-code insulation and a tankless condensing water heater.

5.1.3 Deep energy retrofit versus Low Energy Home

DERs are often planned and discussed as low energy home projects, seeking very high levels of performance. Yet, a DER does not need to be a low energy home, and it is important to differentiate between these two different goals. Homes that are high energy users can be deeply retrofitted without resulting in a low energy home. Post-retrofit energy use can be similar to average household levels—P2, P7 and P9 provide examples of this. In contrast, homes beginning with relatively low energy use are required to become truly low energy homes in order to meet the reduction goals of a DER. In addition to DER goals, designers, builders and owners may wish to pursue low energy use, but this can require substantial further investments. Obviously low energy use goals contribute to DER success, but it is not correct to assume that all DERs will resemble high performance homes, such as zero-net energy homes or Passive Houses.

5.1.4 Efficiency + Conservation

All these DER projects were a combination of technology/envelope and human-based solutions. Some projects were balanced in their approach, whereas others relied more heavily on one end or another of the spectrum. All projects recognized the need to improve the building enclosure, upgrade HVAC and water heating equipment, and perform appliance and lighting upgrades. Deeper energy reductions were then achieved by either pursuing further technology/envelope measures or through occupant conservation efforts.

While nearly all project homes achieved deep energy cuts, the homes highlighted in this research may not perform similarly with different occupants and in different climate zones. If similar projects were rolled out across the US, deep energy savings may not be feasible where occupants are less willing to conserve. Greater improvements may be necessary to overcome occupant effects on a house-by-house basis.

Both technology/envelope and human-driven DER projects can achieve impressive energy performance and reductions. P3 is an example of a technology/envelope driven project, with far and away the highest levels of insulation and airtightness, as well as both solar thermal and PV. This certified Passive House just barely met its Thousand Home Challenge Option B threshold of 4,796 kWh (net-usage was 4,534 kWh). On the other hand, P4 used a base level of insulation, airtightness and equipment, but the occupants were very actively engaged in energy conservation in the home. P4 easily met its 6,241 kWh Option B Threshold (net-usage was 3,214 kWh), making it the first home to officially meet the Thousand Home Challenge in CA. Both homes used 75% less net-site energy than the average CA single family home, but they used very different deep retrofit strategies.

Occupants can reduce MELs energy usage by targeting baseload energy reductions. (Sanchez *et al.*, 1998) found that 20% of MELs electrical consumption was due to phantom loads, or "consumed while in stand-by mode." Targeting this baseload is attractive to homeowners, because they can get the same service and utility from their appliances and devices, while using less energy. Baseload reduction requires no deprivation, such as not watching television.

The baseload electricity demand and estimated annual consumption in each project home are shown below in Figure 156. Baseloads varied from 42 to 562 Watts, averaging 203 Watts. These values were converted to an annual kWh baseload consumption estimate (values written on each bar in Figure 156), which varied from 372 to 4,926 kWh, averaging 1,778 kWh. These baseload consumptions accounted for 8% to 72% of the total net-site energy consumption of the project homes, with an average of 21%. In those homes with disaggregated heating, baseload annual estimates were also compared with the heating energy use. Ratios of baseload energy to space heating ranged from 0.17 to 5.18, with an average of 1.6. On average, the baseload electricity consumption in the project homes exceeded the heating energy usage. This was mostly the result of three projects—P3, P5 and P7—outliers with very low heating energy and the relatively high annual baseload estimates; all other homes had ratios less than one.

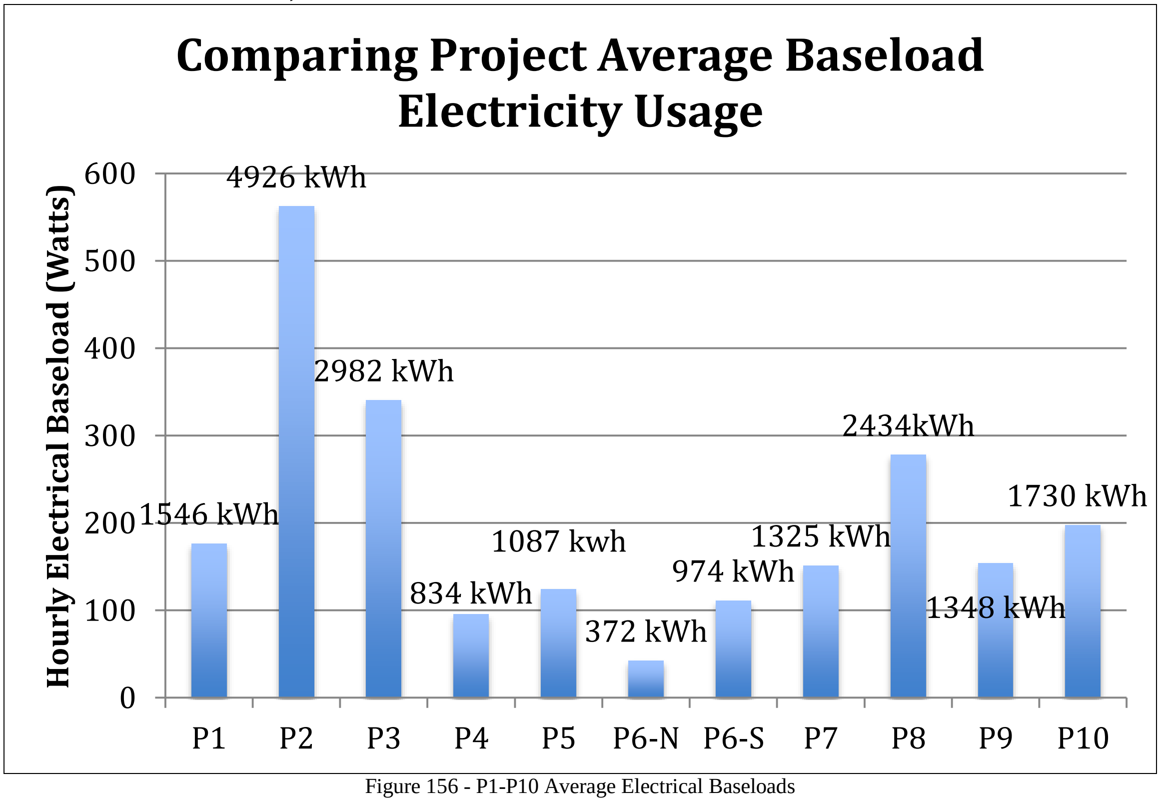


Figure 156 - P1-P10 Average Electrical Baseloads

Baseloads were higher than expected in the DER project homes. Ventilation equipment in P1 and P3 contributed approximately 70-80 watts continuously, which in P1, was approximately 42% of the baseload. Other contributors to high baseload included home office, audio visual and networking equipment, as well as outdoor lighting. Baseload reductions were an opportunity for deeper, low-cost energy savings in almost all project homes. Even those occupants who engaged in phantom load reductions had obvious room for improvement. Creative means for reducing these end uses should be developed and used in all DERs, such as whole house off-switches or smart home energy management tools.

Finally, it is worth noting that the interplay between efficiency and conservation may vary depending on climate. It is a paradox of DERs that deep savings may in fact be more difficult to achieve reliably in mild climates, because the envelope loads are a smaller fraction of the total energy usage. In mild climates, the traditional strategies of energy reduction through insulation, air sealing and improved equipment have less overall impact on total consumption. The remaining energy uses are more occupant driven and are notoriously difficult to control through design measures. Heating accounts for an average of 58% of total household energy use in US homes with >7,000 HDD and only 28% in homes with fewer than 4,000 HDD. Clearly, the DER strategies will not be the same in these varying climates. An 80% heating energy reduction in these two zones—an admirable and achievable DER goal—would result in an average household reduction of 22% and 46%, respectively. Super-insulation, triple pane windows and extreme airtightness do not automatically result in a DER. The most effective retrofit measures may be overlooked unless a careful investigation of how energy is used in the home is undertaken.

5.2 Whole House Energy Performance Metric Comparison

The energy and carbon performance of the DERs included in this research are presented in Table 64, Table 65 and Table 66 below. The tables show energy performance using several metrics, including site energy, source energy and carbon emissions, normalized by house, by occupant and by square foot of floor area. This has been done for pre-retrofit energy usage (where available), post-retrofit energy usage and percentage reduction in energy use.

Pre-retrofit energy usage was weather normalized for P1, P2, P4, P7 and P9 as described in the methods section above. Source energy and CO_2e emissions were calculated as described in the methods section.

The results in Table 64 are per house and best reflect the energy bill changes that an occupant would experience. The high variability in the results reflects the different strategies taken in each case. In particular, site and source energy savings can be dramatically different, such as in P2, where the home went from using natural gas to an all electric home. The percent savings also vary significantly if we look at total source energy—from a savings of 96% to an increase of 12%. However, all the homes ended up with either substantial carbon reductions or with low carbon emissions compared with those of an average CA single family home[13]. The per person results in Table 65 may be the most meaningful, because fulfilling the human need for shelter is the ultimate purpose of home energy use. The biggest difference in savings between Table 64 and Table 65 is for P1, whose occupancy doubled post retrofit. This resulted in a source energy percentage change going from a 12% increase to a 44% reduction. Notably, most homes with pre-retrofit usage data do not have pre-retrofit occupancy data; we have no idea how many people lived in the home before the retrofit. Table 66 presents energy normalized by floor area, which is by far the most common metric used in energy analyses and home ratings. This metric has the unfortunate effect of rewarding larger homes that actually use more energy—the opposite of what a DER is trying to achieve. For example, P5 (a small house with three occupants) has the worst performance in Table 66 despite being a low energy using home. P1 is the only home with pre-retrofit data that added substantial floor area. It increased its net-source energy use on a per house basis, but it achieved significant reductions on a floor area basis.

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[13] CO_2e emission reductions were greater than net-source energy values, because national average site-to-source conversions were used for net-source calculations, whereas the CO_2e was calculated using emissions data from the electrical utility servicing the homes. Utility CO_2e emissions per kWh electricity were approximately one third the national average.

Energy Per House

	Net-Site Electricity (kWh)			Site Gas (kWh)			Total Net-Site Energy (kWh)			Net-Source Electricity (kWh)			Source Gas (kWh)			Total Net-Source Energy (kWh)			Total Net-Carbon Emissions (lbs CO2e)		
	Pre	**Post**	**%[14]**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**
P1	2,392	5,428	(127)	11,160	3,986	64	13,552	9,414	31	7,559	17,153	(127)	11,383	4,066	64	18,942	21,218	(12)	5,829	4,714	19
P2	5,787	15,791	(173)	34,496	0	100	40,284	15,791	61	18,288	49,901	(173)	35,186	0	100	53,474	49,901	7	17,094	9,086	47
P3		3,626			909			4,534			11,457			927			12,383			2,449	
P4	2,473	(1,212)	149	9,696	4,426	54	12,169	3,214	74	7,815	(3,829)	149	9,889	4,514	54	17,704	685	96	5,291	1,069	80
P5		6,318			284			6,602			19,965			290			20,255			3,749	
P6-N		1,937			2,374			4,311			6,120			2,421			8,541			2,061	
P6-S		3,187			8,030			11,217			10,071			8,191			18,262			5,038	
P7	6,248	3,000	52	25,000	5,596	78	31,248	8,596	72	19,744	9,479	52	25,500	5,708	78	45,244	15,187	66	13,570	3,959	71
P8		2,746			14,340			17,086			8,677			14,627			23,304			7,302	
P9	11,987	4,402	63	24,610	12,603	49	36,597	17,005	54	37,879	13,911	63	25,102	12,855	49	62,981	26,766	58	16,716	7,561	55
P10		(105)			6,419			7,697			(331)			6,547			7,727			2,522	
Avg. CA Home	7,605			12,456			20,061			24,032			12,705			36,737			9,346		

Table 64 - Energy Use Per House

California Average Home is based on 2009 California Residential Appliance Saturation Survey (RASS) for Single Family homes (CEC 2010)

[14] "%" in Table 64, Table 65 and Table 66 means percentage reduction from pre-retrofit baseline. Usage increased in some cases, and those are reported as negative savings. For example, P1 increased net-site electricity for an increase of 127%.

Energy Per Person																					
	Net Site Electricity (kWh)			**Net Site Gas (kWh)**			**Total Site Energy (kWh)**			**Net Source Electricity (kWh)**			**Net Source Gas (kWh)**			**Total Source Energy (kWh)**			**Total Net Carbon Emissions (lbs CO2e)**		
	Pre	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**
P1	1,196	1,357	(13)	5,580	996	82	6,776	2,353	65	3,779	4,288	(13)	5,692	1,016	82	9,471	5,305	44	2,915	1,178	60
P2		7,896						7,896			24,950						24,950			4,543	
P3		3,626			909			4,534			11,457			927			12,383			2,449	
P4	1,237	(606)	149	4,848	2,213	54	6,084	1,607	74	3,907	(1,914)	149	4,945	2,257	54	8,852	343	96	2,646	534	80
P5		2,106			95			2,201			6,655			97			6,752			1,250	
P6-N		484			593			1,078			1,530			605			2,135			515	
P6-S		797			2,008			2,804			2,518			2,048			4,565			1,259	
P7	3,124	1,500	52	12,500	2,798	78	15,624	4,298	72	9,872	4,739	52	12,750	2,854	78	22,622	7,594	66	6,785	1,979	71
P8		687			3,585			4,272			2,169			3,657			5,826			1,825	
P9		1,101			3,151			4,251			3,478			3,214			6,691			1,890	
P10		(52)			3,209			3,848			(165)			3,273			3,864			1,261	
Avg. CA Home	2,171			3,578			5,749			6,860			3,649			10,510			2,677		

Table 65 - Energy Use Per Person

Energy Per Square Foot Floor Area																					
	Net Site Electricity (kWh)			**Net Site Gas (kWh)**			**Total Site Energy (kWh)**			**Net Source Electricity (kWh)**			**Net Source Gas (kWh)**			**Total Source Energy (kWh)**			**Total Net Carbon Emissions (lbs CO2e)**		
	Pre	Post	%	Pre	Post	%	Pre	Post	%	Pre	Post	%	Pre	Post	%	Pre	Post	%	Pre	Post	%
P1	2.49	3.33	(34)	11.63	2.45	79	14.12	5.78	59	7.87	10.52	(34)	11.86	2.49	79	19.73	13.02	34	6.07	2.89	52
P2	2.08	5.68	(173)	12.41		100	14.49	5.68	61	6.58	17.95	(173)	12.66		100	19.24	17.95	7	6.15	3.27	47
P3		1.54			0.39			1.92			4.86			0.39			5.25			1.04	
P4	1.61	(0.48)	130	6.30	1.76	72	7.90	1.28	84	5.07	(1.53)	130	6.42	1.80	72	11.50	0.27	98	3.44	0.43	88
P5		6.98			0.31			7.30			22.06			0.32			22.38			4.14	
P6-N		1.32			1.62			2.95			4.19			1.66			5.84			1.41	
P6-S		2.13			5.37			7.50			6.73			5.48			12.21			3.37	
P7	2.01	0.96	52	8.03	1.80	78	10.03	2.76	72	6.34	3.04	52	8.19	1.83	78	14.53	4.88	66	4.36	1.27	71
P8		1.69			8.81			10.50			5.33			8.99			14.32			4.49	
P9	3.85	1.41	63	7.90	4.05	49	11.75	5.46	54	12.16	4.47	63	8.06	4.13	49	20.23	8.60	58%	5.37	2.43	55
P10		(0.06)			3.76			4.51			(0.19)			3.84			4.53			1.48	
Avg. CA Home	4.82			7.89			12.70			15.22			8.05			23.27			5.92		

Table 66 Energy Use Per Square Foot Floor Area

Figure 157 shows post-retrofit net-energy uses and CO_2e emissions per house. Post-retrofit net-site energy usage ranged from 3,214 to 17,086 kWh, averaging 9,588 kWh. Net-source energy usage ranged from 685 to 49,901 kWh, averaging 18,566 kWh. CO_2e emissions ranged from 1,068 to 9,086 pounds, averaging 4,501 pounds. Comparing these DER averages against the average CA single-family home results in reductions of 52% net-site, 49% net-source and 52% CO_2e emissions.

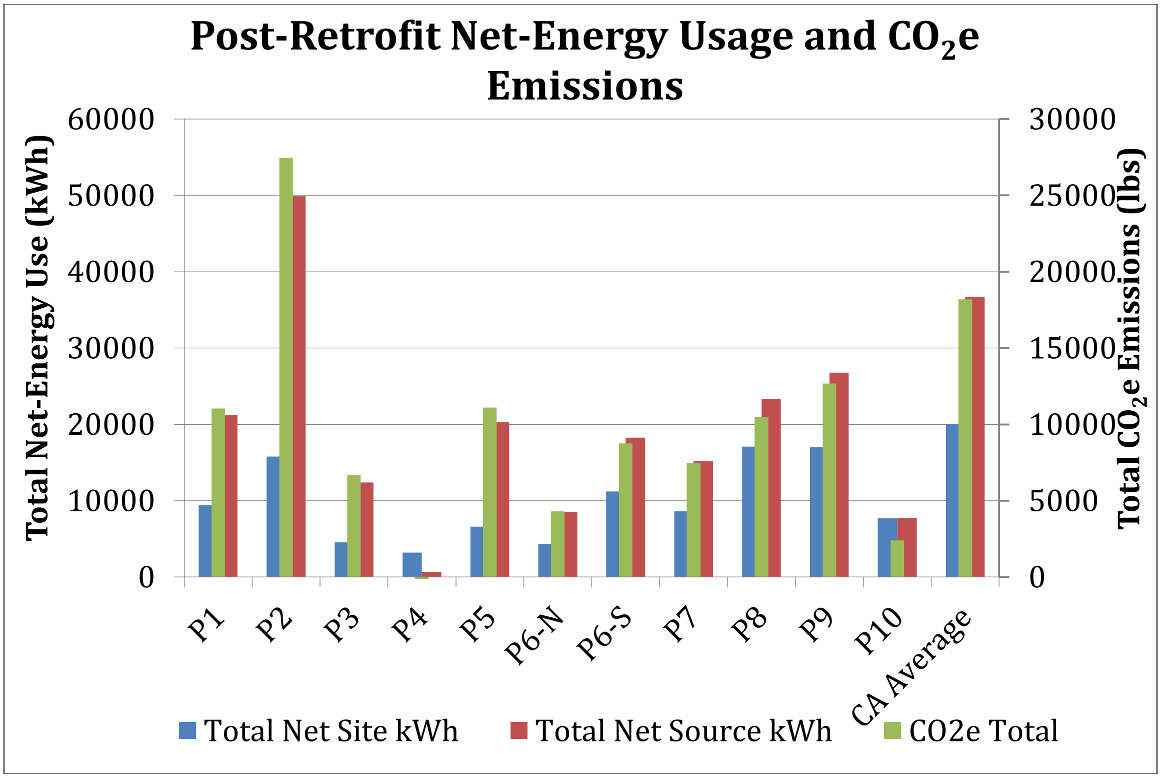

Figure 157 - Post-Retrofit Net-Energy Usage and CO_2e Emissions

Figure 158 shows the weather normalized site energy savings ranging from 31% to 74% for projects with pre-retrofit data (P1, P2, P4, P7 and P9), with an average of 58%. This suggests reasonable levels of success across the board. However, source energy savings tell a different story and ranged from a 12% increase in energy usage to a reduction of 96%, for an average reduction of 43%. CO_2e reductions ranged from 19% to 80%, averaging 54%. The divergence in performance between net-source energy and carbon emissions resulted from the lower carbon content of electricity provided by PG&E in 2009 (56% less than the national average).

Figure 159 shows the total change in annual net-energy (including on-site generation) and emissions of CO_2e, again for those projects with pre-retrofit data. Net-site energy reductions varied from 4,138 to 24,492 kWh, averaging 15,966 kWh. In two project homes (P2 and P7), net-site reductions were greater than the annual consumption of an average CA single-family home (20,061 kWh), and a third home (P9) reduced just barely less than the CA average. Net-source energy changes varied from an increase of 2,276 kWh to a reduction of 36,215 kWh, averaging 16,918 kWh. Reductions in CO_2e emissions ranged from 1,116 to 9,611 pounds, averaging 6,423 pounds.

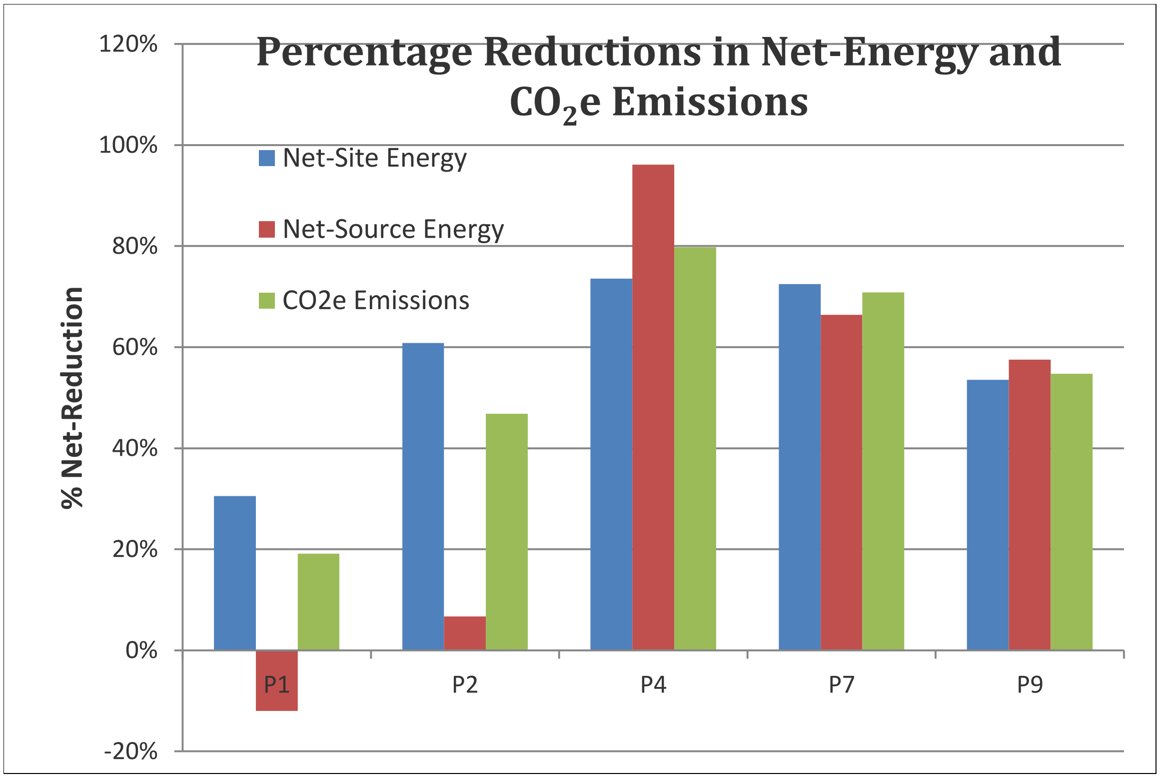

Figure 158 - Percentage Reductions in Net-Energy and CO_2e Emissions

Keeping in mind a sample size of five homes, pre-retrofit net-site consumptions were used to group homes into two categories: (1) <15,000 kWh/year (P1 and P4) and (2) >30,000 kWh/year (P2, P7 and P9). Absolute net-site energy reductions in these groups averaged 6,546 kWh in the former and 22,246 kWh in the latter. Clearly the potential to reduce energy usage and carbon emissions was greatest in high-consuming pre-retrofit homes. Homes using nearly double the regional average energy should be preferentially targeted for DERs, where retrofit measures will be most cost-effective and their impacts will be greatest. Homes with annual pre-retrofit consumption nearly half the regional average will have limited abilities to cut energy use in an absolute sense.

These findings demonstrate the very wide range in net-energy use that can be expected from DERs, and it also illustrates the crucial importance of performance metrics and how they are used to assess projects and inform decision making. We will illustrate the importance of performance metrics by using one or two projects to show how the metric chosen can have a major impact on the outcome, and the reasons for the shift in relative success.

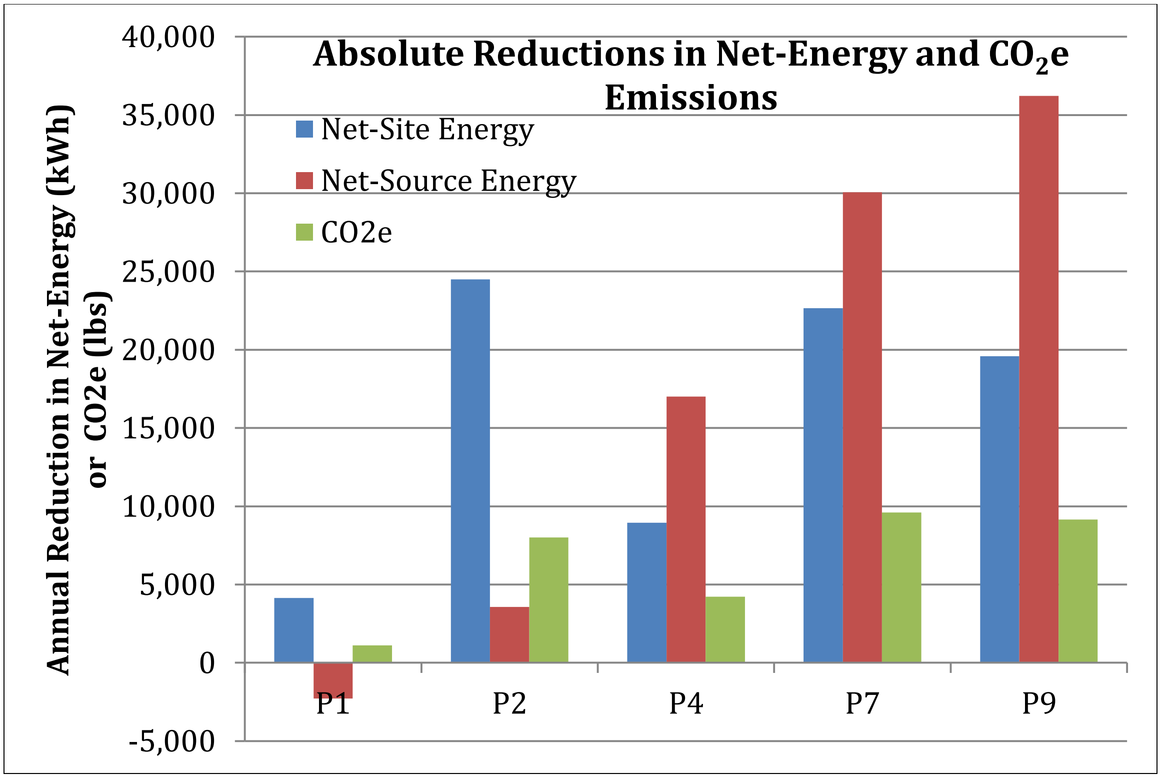

Figure 159 - Absolute Reductions in Net-Energy and CO_2e Emissions

In Figure 160, both homes are performing well on a site energy basis (at less than 1/4 the average California home). In terms of net-source energy, P3 uses 18 times as much as P4. This is because P4 uses natural gas for space and domestic water heating, whereas P3 uses an electric mini-split heat pump and has fairly high plug and lighting loads. Both homes have solar PV systems, but P4 is a net-exporter of electricity on an annual basis. Ultimately, P4 uses very little electricity and the bulk of its total energy use is natural gas for space heating, whereas P3, which is a certified Passive House, uses very little heating and cooling energy, but it is electric, and its overall energy usage is dominated by other electrical uses in the home. The predominance of electrical energy use in P3 and the absence of it in P4 is what lead to this dramatic difference between the homes' source energy performance.

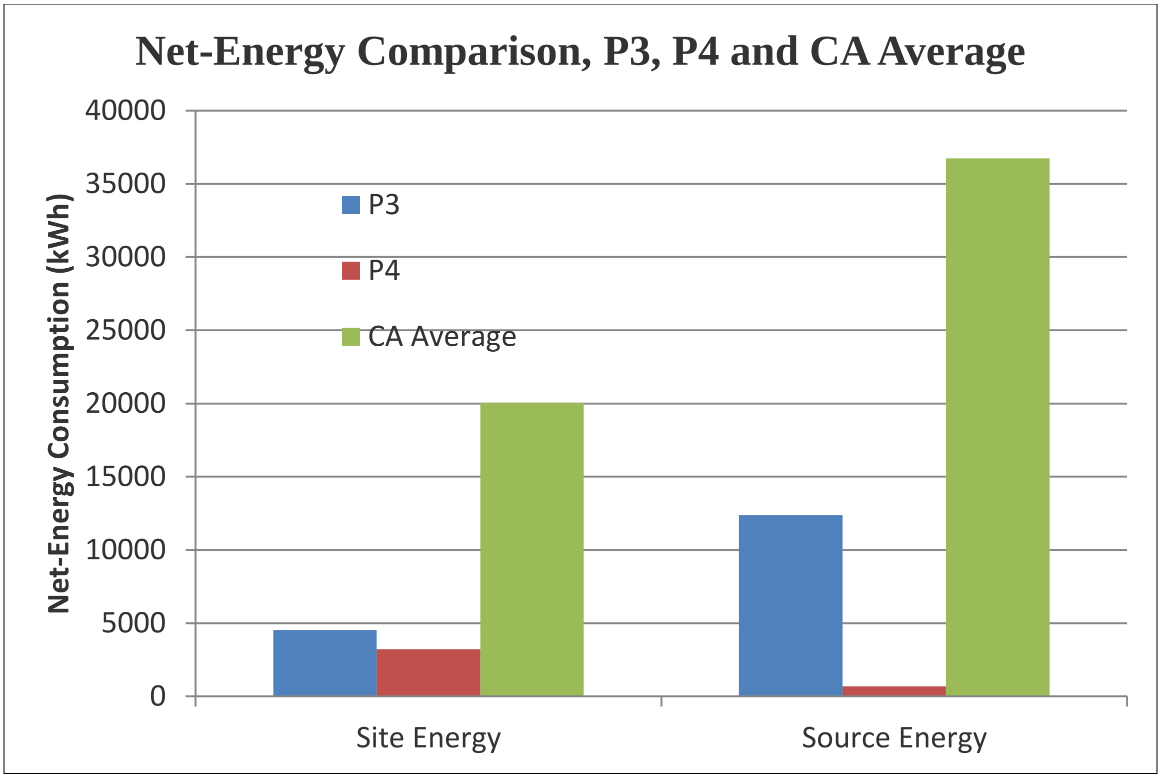

Figure 160 - Net-Energy Comparison, P3, P4 and CA Average

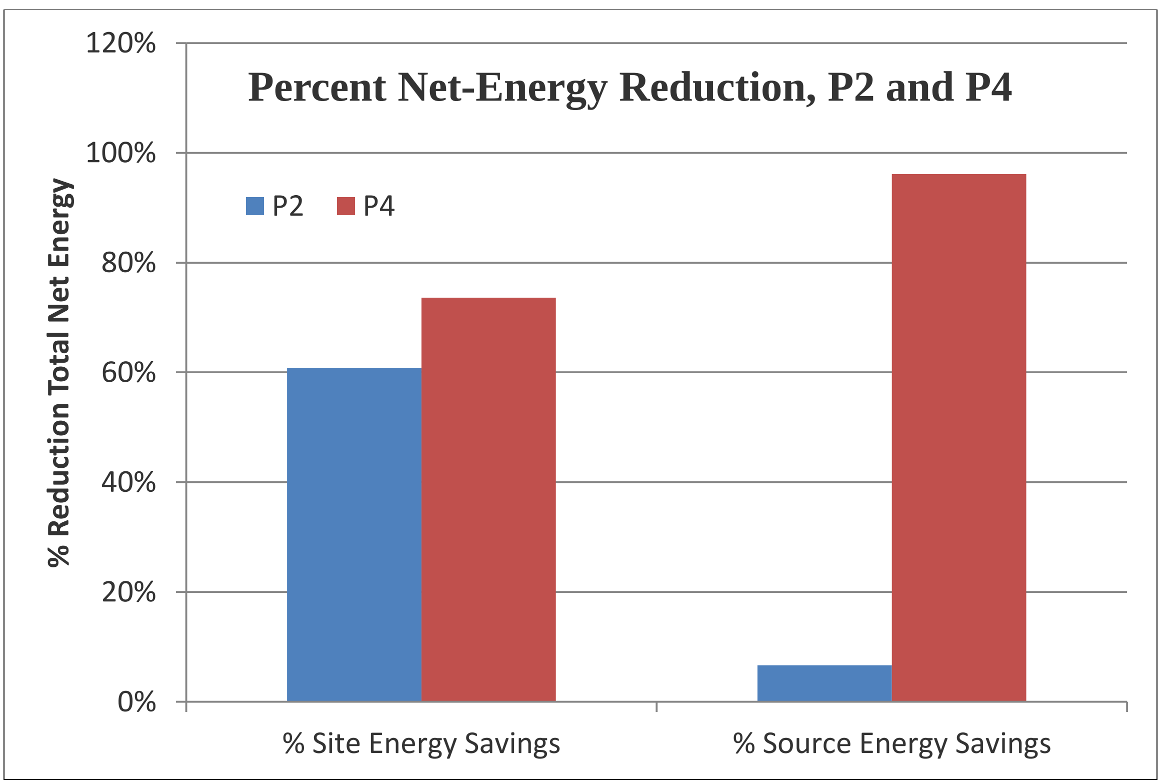

Figure 161 - Percent Net-Energy Reduction, P2 and P4

It might be thought that percentage net-energy savings would be an unbiased performance metric in a DER, yet Figure 161 illustrates that fuel mixes and retrofit measures can have a dramatic impact on project performance. When P2 and P4 are compared on percentage net-site energy reduction, they appear to perform similarly. However, the conversion to percent net-source energy reduction shows a drastic shift. P4 has achieved 14.4 times the percentage net-source energy reduction that P2 has, despite their similar percent site energy performance. The reasons for this are that both homes began as users of natural gas for space and water heating, and P2 shifted to an all-electric home, whereas P4 maintained its fuel-types.

Figure 162 below illustrates how DER success can vary greatly, depending on normalization by house, person or floor area. Figure 162 shows the percentage net-source energy reduction for the three normalization metrics at P1. The home performs poorly on a per-house source energy basis, but it fairs significantly better on a per-person and per-square foot basis, with 44% and 34% reductions respectively. During its retrofit, P1 both increased its floor area from 960 ft^2 to 1,630 ft^2 as well as doubled its occupancy, going from two to four occupants. Homes without dramatic changes in floor area or occupancy are stable across these metrics.

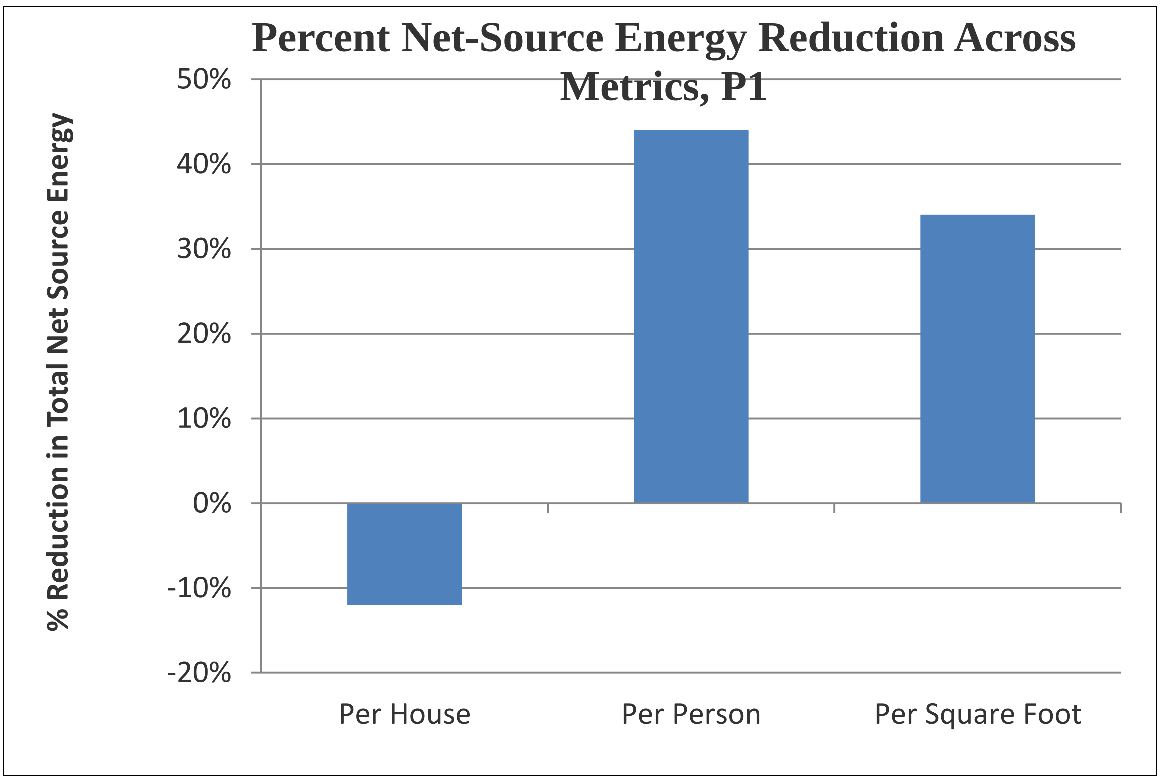

Figure 162 - Percent Net-Source Energy Reduction Across Metrics, P1

So far, the net-source energy use of P1 and P2 does not appear very impressive for a DER, yet when these projects are assessed by CO_2e emissions, they perform at least reasonably well. Table 64 shows the poor net-source energy reductions of P1 and P2, with a 14% increase and 7% decrease respectively. Yet, their CO_2e emissions reductions were 18% and 47% respectively. This illustrates how carbon emissions do not align exactly with source energy conversions, and it is important to keep in mind which value one hopes to reduce. As noted elsewhere, the CO_2e impact of electricity provided by PG&E in 2009 was 56% less than the national average. If these retrofits were located somewhere with "dirtier" electricity, then this CO_2e benefit would disappear, and results would be more similar to net-source energy values.

5.3 Taking These DERs to Zero-Net Energy

The feasibility of taking existing homes to zero-net energy performance has been questioned in the literature (Henderson and Mattock, 2008). The final net-site energy consumptions have been used in this research to calculate the required Standard Test Conditions (STC) PV panel wattage that would bring the homes to ZNE (see Table 67 below). These calculations assume a southern panel orientation with a panel pitch of 7:12[15]. We have calculated these required wattages in both San Francisco and Sacramento, using low and high energy generation estimates (Endecon Engineering, 2001). Different requirements are listed for zero-net site energy and zero-net source energy.

Project ID	**STC PV kW Required for ZNE**							
	Site Energy				***Source Energy***			
	San Francisco		Sacramento		San Francisco		Sacramento	
	Low	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
P1	6.8	5.5	6.5	5.2	4.9	3.9	4.6	3.7
P2	11.5	9.2	10.9	8.7	11.5	9.2	10.9	8.7
P3	3.3	2.6	3.1	2.5	2.8	2.3	2.7	2.2
P4	2.3	1.9	2.2	1.8	0.2	0.1	0.1	0.1
P5	4.8	3.8	4.5	3.6	4.6	3.7	4.4	3.5
P6-N	3.1	2.5	3.0	2.4	2.0	1.6	1.9	1.5
P6-S	8.1	6.5	7.7	6.2	4.2	3.4	4.0	3.2
P7	6.2	5.0	5.9	4.7	3.5	2.8	3.3	2.6
P8	12.4	9.9	11.7	9.4	5.3	4.3	5.1	4.1
P9	12.3	9.9	11.7	9.3	6.1	4.9	5.8	4.7
P10	5.6	4.5	5.3	4.2	1.8	1.4	1.7	1.3

Table 67 - Required STC PV kW Array for Zero-Net Energy Performance

All homes require substantial PV arrays in order to reach ZNE. Small to medium system sizes are common (P1, P3, P4, P5, P6-N, P7 and P10), but some are quite large (P2, P6-S, P8 and P9). Notably, a number of these homes already have PV systems installed. If we use the national average cost for systems (Galen Barbose *et al.*, 2011) <10kW in 2010—$7.30 per watt— the unsubsidized cost of reaching zero-net site energy ranges from $90,448 for P8 in San Francisco to $12,898 for P4 in Sacramento.

5.4 Energy End-Uses

The monitored energy end-uses for each project home are summarized in Table 68 and pictured in

[15] Typical roof pitches in California may in fact be less than this, but DERs in this research averaged steeper pitches for whatever reason.

Figure 164 below. All values are in site kWh consumption. Some end-uses were combined in this research (for example, combined heating and hot water in P2, P8 and P10), due to limitations in end-use disaggregation. Wherever combinations occurred, they are noted at the bottom of the table. To overcome this limitation, end-uses were combined as “HVAC-hot water” and “plugs-lights-appliances”, which could be compared across all homes. These two combined energy end uses are pictured for all project homes below in Figure 163.

	P1	**P2[1]**	**P3[2]**	**P4[3]**	**P5**	**P6N**	**P6S**	**P7[4]**	**P8[5]**	**P9**	**P10[6]**	**Avg.[8]**
Floor Area	1630	2780	2357	2510	905	1462	1496	3288	1627	3114	1706	***2080***
# of Occupants	4	2	1	2	3	4	4	2	4	4	2	***2.9***
Heating	2182	9867*	576	2751	415	489	1781	553	14340*	7954	7165*	***2088***
Cooling										259		***259***
Central Air Handler(s) or Pumps		1854		83				135	1100	713	611	***749***
Hot Water	3405		751	1720	2632	2081[7]	1219[7]	778		3665		***2031***
Ventilation	850		841		103							***598***
Combined HVAC and DHW	***6437***	***11720***	***2168***	***4554***	***3150***	***2575[7]***	***3003[7]***	***1466***	***15440***	***12592***	***7776***	***6444***
Appliances	1036	1673	1786	1142	1743	0[7]	6482[7]	5478	1746	1952	1333	***2446***
Lights	325	2105	1903	399	1034	282[7]	464[7]	290	936	1485	857	***916***
Plug Loads	1617**	5097**	2081**	1217**	593	1085[7]	1355[7]	1316	1842**	975	1707	***1717***
Combined Plugs, Lights & App’s	***2977***	***8875***	***5770***	***2714***	***3452***	***1361[7]***	***8301[7]***	***7130***	***4524***	***4413***	***3897***	***4856***
Annual Total	***9414***	***20596***	***7938***	***7268***	***6602***	***4311***	***11217***	***8596***	***19965***	***17005***	***11672***	***11326***
PV Production		***4804***	3405	***4054***					***2879***		***3976***	***3824***
Annual Net	***9414***	***15791***	***4533***	***3214***	***6602***	***4311***	***11217***	***8596***	***17086***	***17005***	***7696***	***8670***

*Homes use combisystems. Heating energy includes space conditioning and hot water.
** Plugs include a home office.
[1] P2 Heating includes cooling and hot water. Plugs include range hood. Air handler includes ventilation.
[2] P3 Heating includes cooling energy from mini-split.
[3] P4 Plugs include office lights, which couldn't be separated.
[4] P7 Plugs include outdoor lights/plugs combined
[5] P8 Lights includes bedroom plugs. Plugs include hydronic pumps and garage fridge. Heating includes hot water.
[6] P10 Heating includes wood oven and hot water. Plugs include misc leftovers.
[7] P6-North and South Hot Water, Lights, Plugs and Appliances are estimated from 10 months of data. End-use totals do not match Annual totals exactly as result.
[8] End-use averages include only those homes where uses were disaggregated.

Table 68 - Energy Consumption by End-Use, Actual, P1-P10

For those homes where heating and hot water were disaggregated, usage averaged 2,088 kWh and 2,031 kWh, respectively. Average appliance usage (2,446 kWh) was greater than either disaggregated heating or hot water, and plug loads were of a similar magnitude (1,717 kWh). Lighting was on average 916 kWh.

The variability amongst end-uses in project homes was high, particularly for combined HVAC-hot energy use. The ratio of highest to lowest HVAC-hot water user was 8.6 to 1, and was 3.3 to 1 for combined plugs-lights-appliances. Combined HVAC-hot water accounted for between 1,466 kWh and 15,440 kWh, averaging 6,444 kWh (17% and 74% of annual total consumption, averaging 54%). Plugs-lights-appliances accounted for between 1,367 kWh and 8,875 kWh, averaging 4,856 kWh (23% and 83% of annual total consumption, averaging 46%).

Seven project homes used more energy for HVAC-hot water than they did for combined plugs-lights-appliances. In the other four homes, these end uses accounted for more than half of total energy, but this occurred only in those homes with either very low heating energy (P3 and P5) or homes with exceptionally high appliance usage and low heating energy (P7 and P6-South).

An often-repeated idea is that as homes become super-insulated and very airtight, the miscellaneous energy end uses become more important or even dominant (Stecher & Allison, 2012). While these loads were very important in all DER homes, they did not dominate the totals. In fact, miscellaneous energy uses were >50% in only three of nine project homes with end-use data. This could reflect the fact that all project homes aggressively targeted plug, lighting and appliance energy uses alongside HVAC and hot water improvements. The increasing importance of plugs, lights and appliances seems to assume that these end-uses are inflexible, whereas we found the opposite. These end-uses do not automatically become a larger piece of the energy pie, if they are reduced alongside HVAC and hot water.

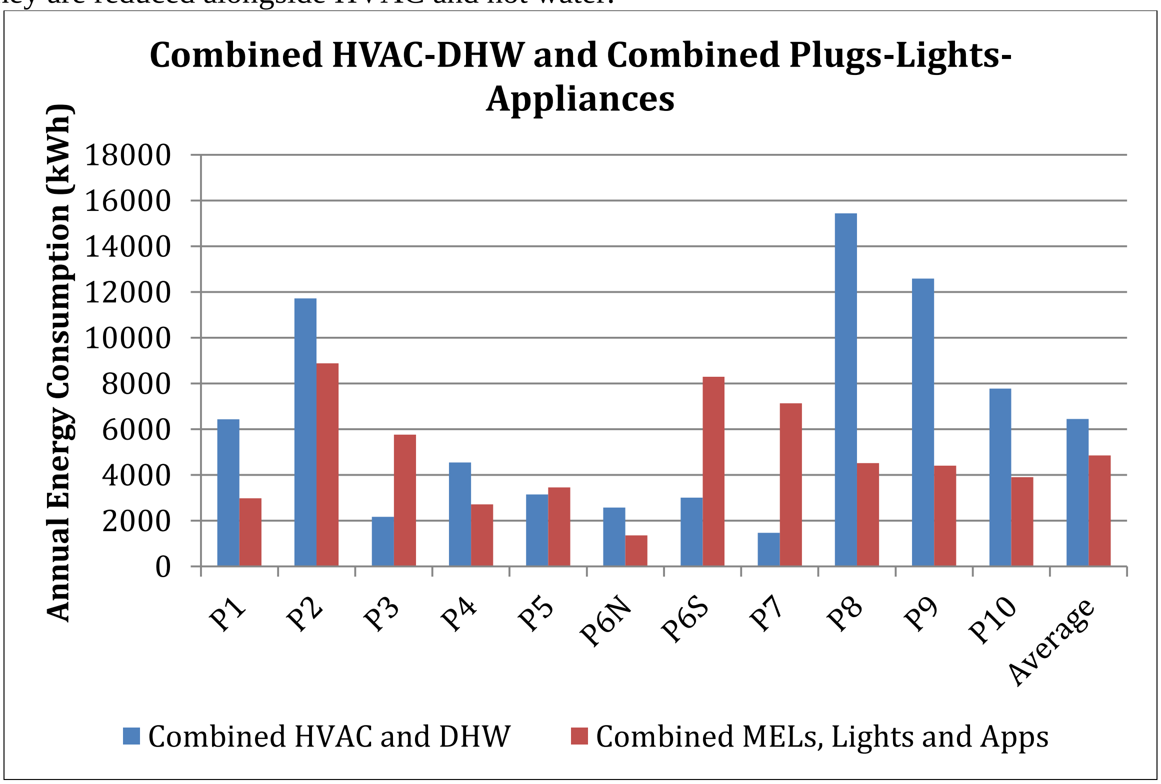

Figure 163 - Comparing Combined HVAC&DHW with Combined Plugs, Lights and Appliances Across Project Homes

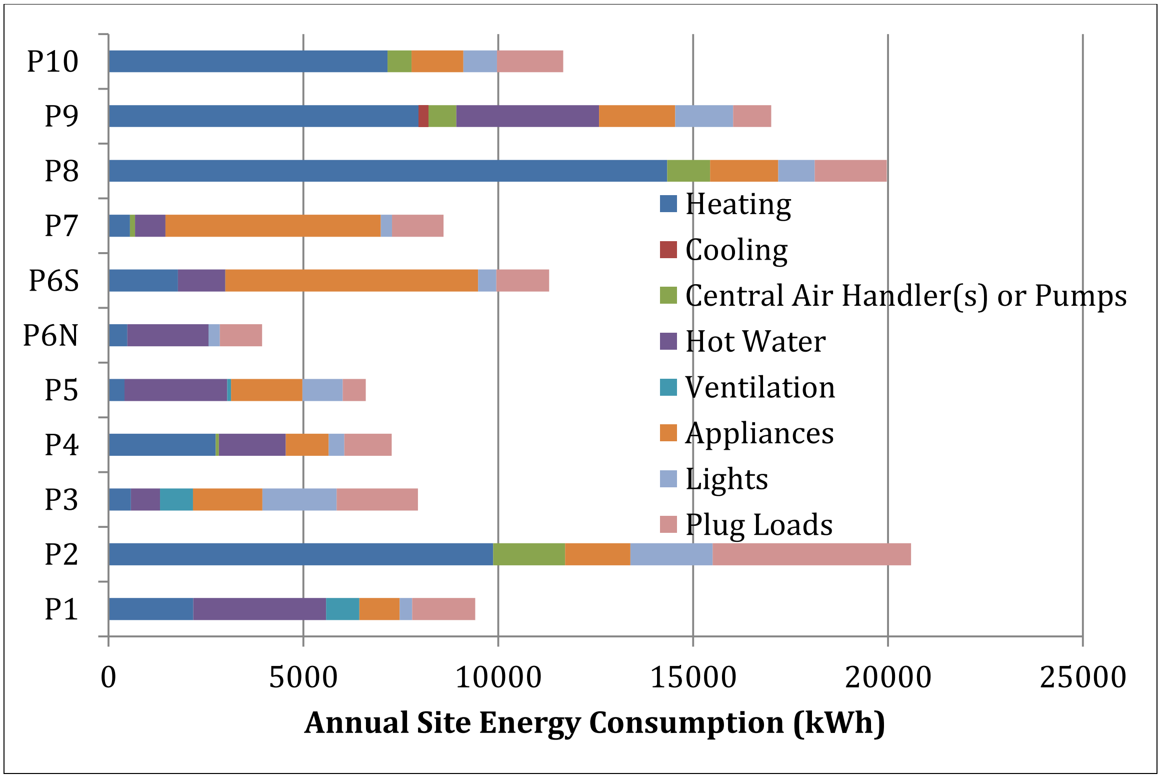

Figure 164 - End-Use Contributions of All Project Homes

Energy end-uses are compared with project home occupancy and floor areas in Figure 165, Figure 166, and Figure 167 below. Combined plugs-lights-appliances appear to be pretty stable across different occupancies, though the highest users were actually homes with the fewest occupants. The ratio of the highest user to the lowest in this end-use category was 3.3 to 1. There is something of an upward trend with energy usage increasing with floor area, but the association is very weak. These figures suggest that energy usage for plugs-lights-appliances do not vary reliably in our project homes with either floor area or number of occupants (R^2 0.08 and 0.17, respectively). This is not surprising given the mix of occupants engaged in conservation activities, and those that took a more relaxed approach. Combined HVAC-hot water energy do not vary reliably with floor area (R^2 of 0.02). This is partly due to outlier homes, such as P7, that are very large (3,299 ft^2) and provided inconsistent heat throughout the winter, as part of occupant conservation efforts, and P8 which was quite small, but used a lot of energy for heating and hot water. The ratio of highest to lowest user in this category was 10.5 to 1. Factors such as occupant behavior, envelope systems and equipment are outweighing the effects of occupant density and size in these project homes.

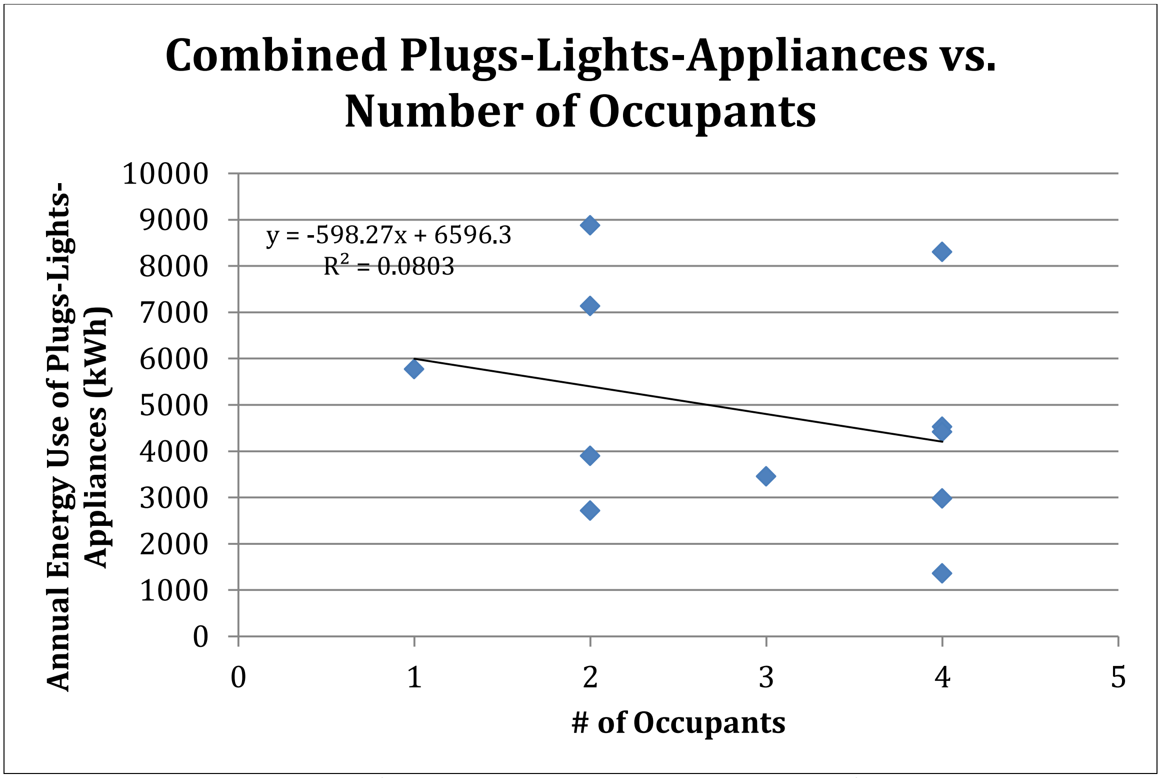

Figure 165 - Comparing the Number of Occupants and the Combined Annual Energy Usage of Plugs, Lights and Appliances

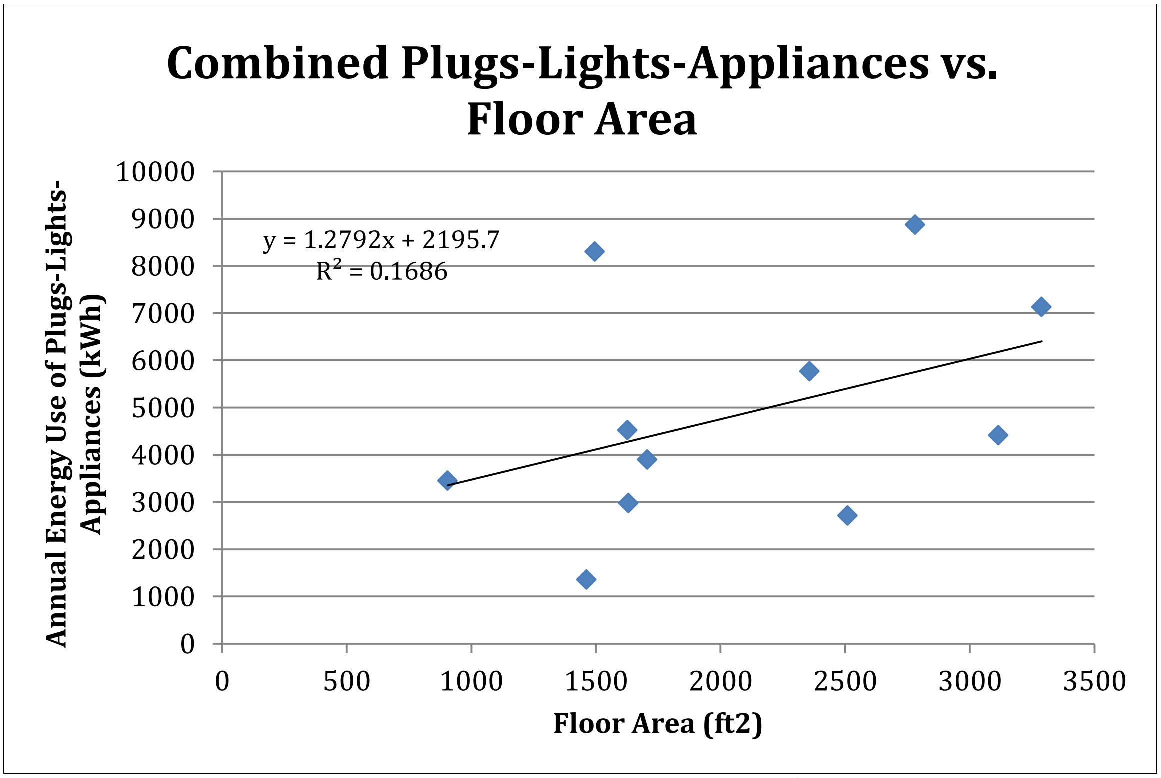

Figure 166 - Comparing the Floor Area and the Combined Annual Energy Use of Plugs, Lights and Appliances

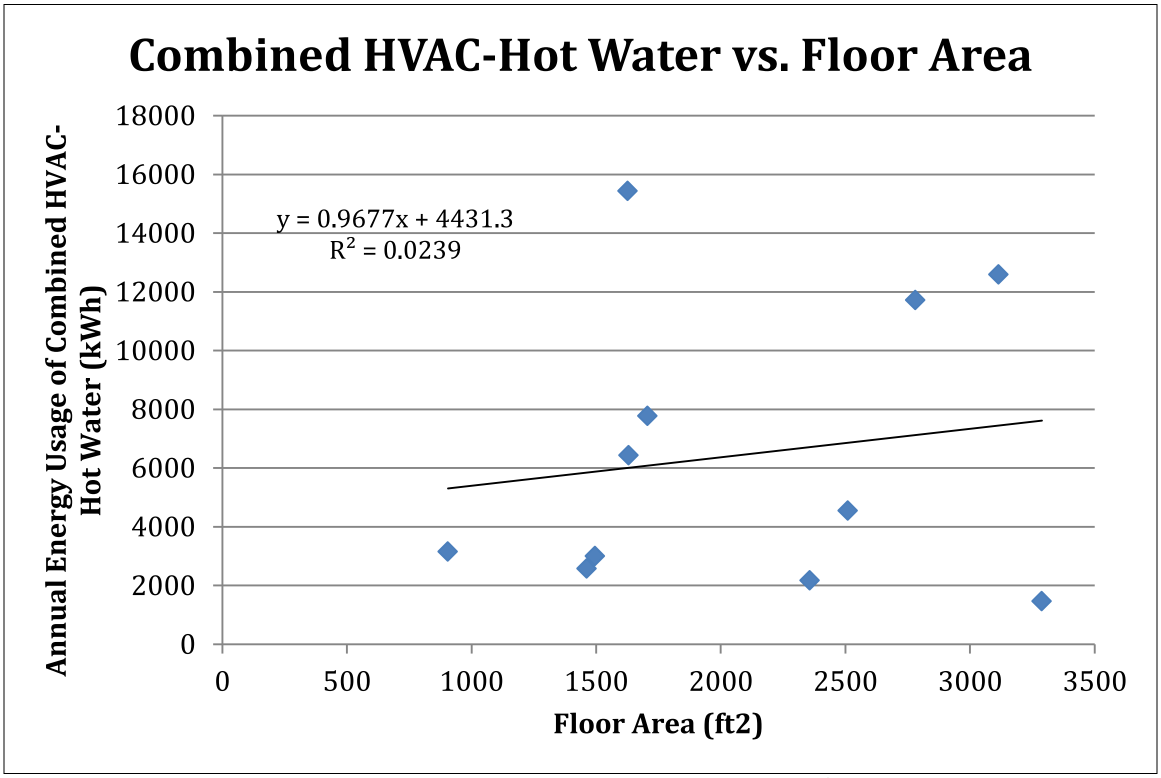

Figure 167 - Comparing the Floor Area and the Combined Annual Energy Use of HVAC and Hot Water

5.5 Monitored vs. Modeled Results

All post-retrofit homes were modeled using EnergyGauge USA software to produce energy end-use estimates and HERS scores (2006). The predicted and the actual end-use consumptions are compared proportionally in Table 69 below and in absolute terms in Table 70. The combined end-use categories of HVAC-hot water and plugs-lights-appliances are used to facilitate comparison across all projects. On average, predictions of the models were very good for these eleven homes, but the RMS errors were large. Whole house prediction RMS errors were 42%, and HVAC-hot water and plugs-lights-appliances errors were 58% and 50%, respectively. Given these errors in modeling, it came as no surprise that a comparison of HERS scores to post-retrofit energy use revealed no linear relationship (R^2 of 0.07).

In general, HVAC-hot water was responsible for the greatest proportion in whole house absolute error, with RMS error of 6,191 kWh, as opposed to 2,227 kWh for plugs-lights-appliances. Those homes with low HVAC-hot water errors tended to have low overall errors of less than 1,000 kWh (P1, P3, P5 and P10). Three of these homes were designed using Passive House principles. It is possible that increased levels of airtightness and insulation, coupled with more consistent temperatures and no austerity efforts, resulted in smaller modeling errors. Large errors were observed in P2, P4, P7, P8 and P9. The sources of these errors varied by project. P2 used much more HVAC-hot water energy than predicted, whereas the model over predicted plugs-lights-appliances in P4 by 4,051 kWh. The model over predicted P7 HVAC-hot water usage by 17,355 kWh, because the zone control and low temperatures desired by the occupants were not accounted for. HVAC-hot water energy use was under predicted in P8 by 8,289 kWh, which could have resulted from factors not included in the model, such as inefficiencies in the heating-hot water distribution system. Overall, errors were substantial, which is not altogether surprising, given the population being studied.

Some variability between actual and modeled results is always anticipated. Even if the model and the inputs were perfect, weather differences could have substantial effects in the range of 15%. The majority of errors in this research exceeded this allowance. These differences could be the result of both input errors and model errors. Input errors would be incorrect specification of equipment, window areas, orientation, shading, etc. Model errors include behavior assumptions, limited modeling ability for complex systems (combisystems, for example), etc. These results suggest that for a specific house, energy models can produce substantial errors, but averaging across DERs may provide acceptable results in aggregate.

Percentage Difference Between EnergyGauge USA Modeled and Actual Energy Use													
Load	**P1**	**P2**	**P3**	**P4**	**P5**	**P6N**	**P6S**	**P7**	**P8**	**P9**	**P10**	***Average***	***RMS Error***
Combined HVAC and DHW	-6%	-65%	-71%	39%	9%	42%	34%	92%	-116%	24%	6%	***-1%***	***58%***
Combined Plugs, Lighting and Appliances	25%	-12%	20%	60%	-4%	55%	-135%	14%	-14%	37%	5%	***5%***	***50%***
Annual Total	6%	-37%	7%	49%	3%	47%	-40%	68%	-80%	28%	6%	***5%***	***42%***

Table 69 - Percentage Difference Between EnergyGauge USA Modeled and Actual Energy Use

Absolute Difference (kWh) Between EnergyGauge USA Modeled and Actual Energy Use													
Load	**P1**	**P2**	**P3**	**P4**	**P5**	**P6N**	**P6S**	**P7**	**P8**	**P9**	**P10**	***Average***	***RMS Error***
Combined HVAC and DHW (kWh)	-389	-4,637	-900	2,859	329	1,831	1,567	17,355	-8,289	3,868	472	***1,279***	***6,191***
Combined Plugs, Lighting and Appliances (kWh)	1,000	-973	1,467	4,051	-119	1,693	-4,772	1,133	-554	2,601	216	***522***	***2,227***
Annual Total (kWh)	611	-5,611	566	6,911	210	3,524	-3,204	18,488	-8,843	6,469	688	***1,801***	***7,167***

Table 70 Absolute Difference Between EnergyGauge USA Modeled and Actual Energy Use

5.6 IEQ Comparison

DERs provide an opportunity to improve the indoor environment in homes, both in terms of occupant comfort and health. Health and efficiency improvements have been demonstrated to be compatible, particularly in degraded, aged housing (Kuholski *et al.*, 2010). At the same time, others have also voiced concern over the potential degradation in IEQ from energy retrofits, namely from reduced air exchange and poor workmanship (Manuel, 2011). In this research, IEQ has been assessed using temperature and relative humidity measurements, as well as assessments of ventilation system performance, in the context of ASHRAE 62.2 and CA Title 24 (2008) requirements.

Temperature

Monthly average temperatures for each project home are compared below in Figure 168. P4, P5, P6-North, P8 and P10 clearly maintained the lowest winter temperatures, whereas all other homes were in the range of 68 to 72 degrees F. P3 and P9 had much higher temperatures during the summer, despite the presence of mechanical cooling in both homes. When comparing between homes in a given month, the differences between the monthly minimum and maximum values vary from 6.8 to 10.7 degrees F, which suggests that a wide range of comfort levels were provided across all months. More uniformity existed between temperatures during non-heating or cooling months, with cooling months having the greatest variation between homes. When space conditioning was occurring, homes used very different approaches, leading to greater average temperature differences. Thermostat settings during heating season and mixed provision of mechanical cooling and climate differences between the Bay Area and the central valley led to greater differences during these times.

The temperature differences between sensors in the project homes are summarized by mean and standard deviations in Table 71 below. It is also indicated if the differences are from a single level or multi level home. Greater temperature consistency was achieved if the mean and the SD were both low, as in P1, P3, P4 and P6-South. P1 and P3 are both Passive House style retrofits, and temperature consistency and thermal comfort are considered primary benefits of such projects. Yet, while P3 achieved the best temperature consistency of all projects, its average indoor temperatures increased substantially during the cooling season (see Figure 168 above). P4 was retrofitted to code levels of insulation and it remained fairly leaky, yet high levels of consistency were achieved. Notably, this was between sensors on the same floor, and does not include the ground floor office, which was maintained at a much cooler temperature throughout the year. P6-South was super-insulated, which should provide for more temperature consistency, which is reflected by the very low mean temperature difference. Temperature variation was largest in P7, where the average annual temperature difference was 6.1 degrees F, which is reflective of the inconsistent heating practices in the home. This low level of heating was part of the occupant’s DER efforts.

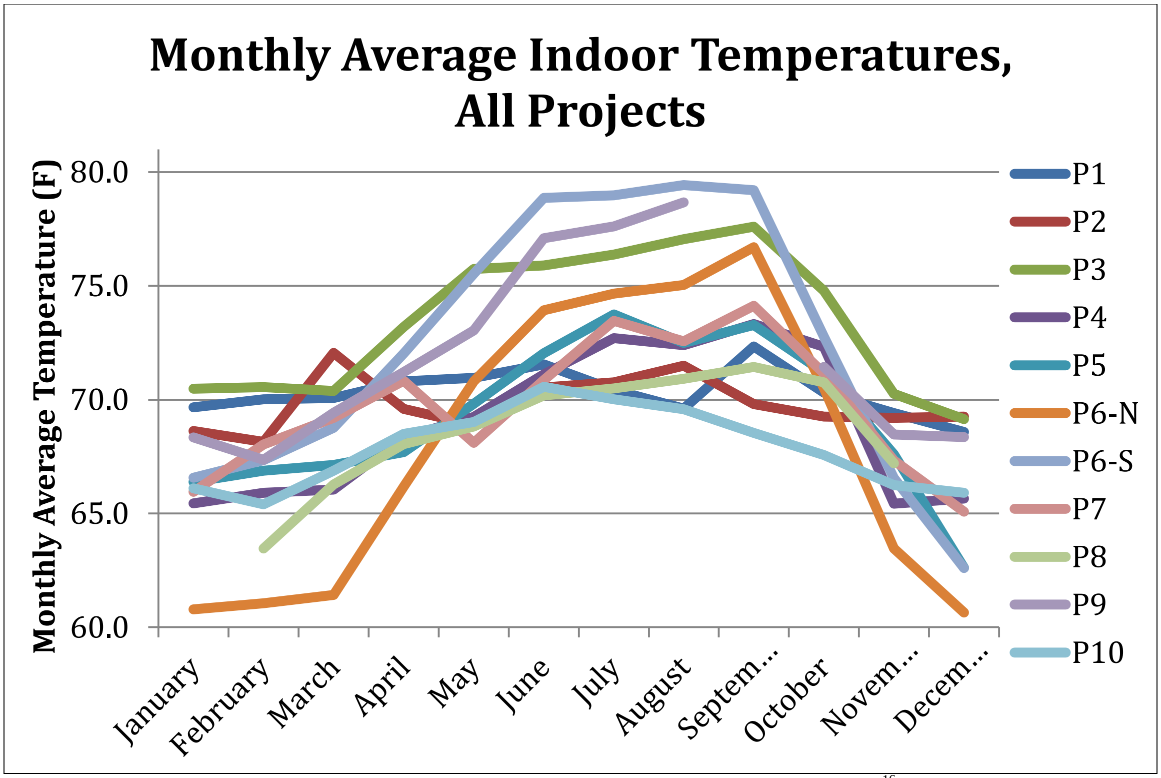

Figure 168 - Monthly Average Indoor Temperatures, All Project Homes[16]

Summary of Interior Temperature Differences			
Project ID	**ΔT (F) Mean**	**ΔT (F) SD**	**Between Multi or Single Floors**
P1	1.34	1.07	Multi
P2	2.42	2.72	Multi
P3	1.08	0.88	Single
P4	1.04	1.22	Single
P5	NA	NA	NA
P6-North	1.44	2.71	Single
P6-South	0.52	1.52	Single
P7	6.06	4.24	Single
P7	3.06	3.38	Multi
P8	2.33	2.04	Single
P9	3.27	1.40	Multi
P10	2.83	2.04	Single

Table 71 - Summary of Temperature Differences, All Project Homes

A number of things make interpretation of temperature data in homes difficult, particularly when comparing between homes, as was done above. Temperatures will vary in a home for a number

[16] P8 and P9 have one or two months of missing temperature and humidity data.

of reasons, some of which are under occupant control and others that result from the structure and its systems. It cannot simply be said that consistent temperatures are superior, or that warmer is better in winter and cooler better in summer. Individual temperature preferences vary, and the way that temperature is managed in a DER can be an essential energy reduction element that should not be discounted. For example, some projects maintained very even, uniform temperatures throughout the day and year (P1), whereas other projects used temperature variation as an energy reduction strategy (P7). Some chose to maintain lower temperatures in winter (P4, P5, P7 and P10) or higher in the summer (P9), and others used aggressive thermostat setback schedules or zoning schemes to reduce heating and cooling energy. Aside from comfort, the indoor temperatures that are maintained can have a great effect on the indoor relative humidity levels.

Relative Humidity

The monthly average indoor relative humidity is pictured for each project in Figure 169 below. Some project homes showed seasonal trends in RH (for example, P2 and P4), whereas others were relatively stable throughout the year (for example, P1 and P8). Most homes maintained monthly average RH within the recommended 30% to 60% range throughout the year, with the exceptions of P2, P8 and P10, which had some trouble during the summer and fall. The proportion of the year that was spent below, within and above this recommended range is summarized in Figure 170 below, for each location in each project home. Clearly, elevated RH was sometimes present, whereas low RH was almost non-existent. The three instances of prolonged elevated relative humidity in P4, P8 and P10 can be explained by occupant behavioral patterns. The ground floor office in P4 was largely unheated, the P8 master bedroom was near the shower with an ineffective exhaust fan, and the master bedroom in P10 had a closed door, two sleeping adults and an open window year round. Notably, none of the project homes had any visible water damage, nor was any mold or mildew visible or detected through odor.

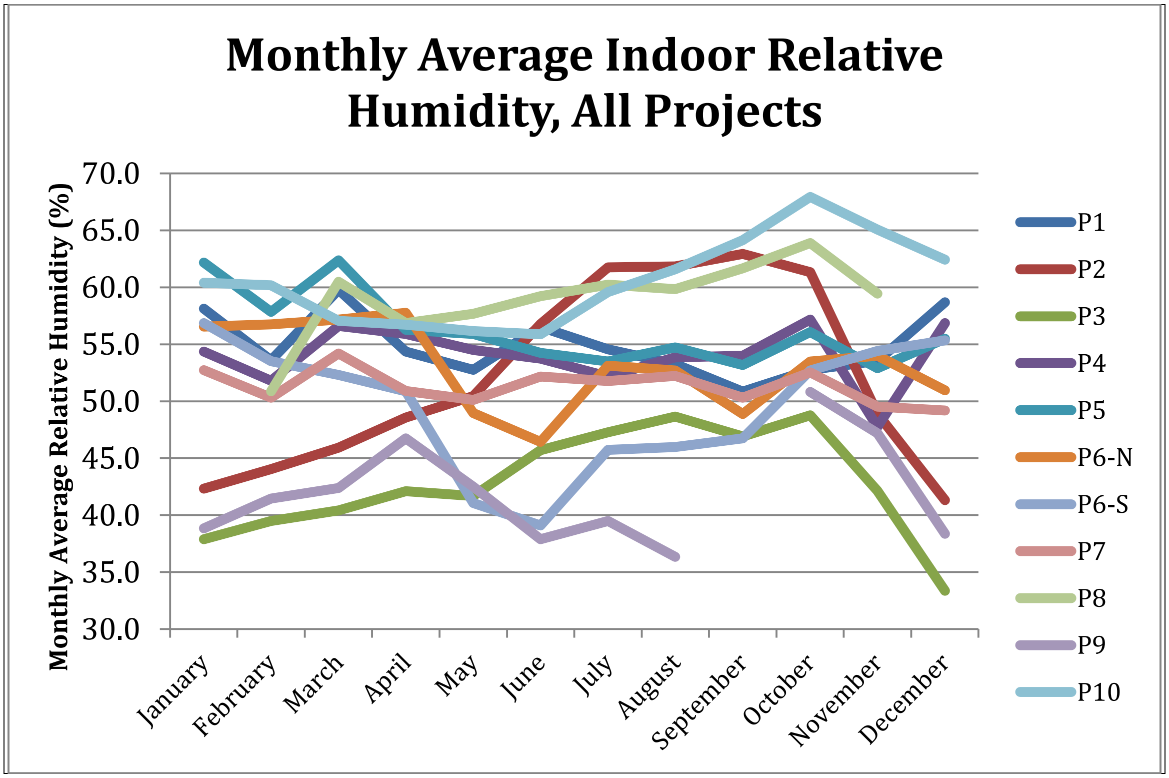

Figure 169 - Monthly Average Indoor Relative Humidity, All Project Homes

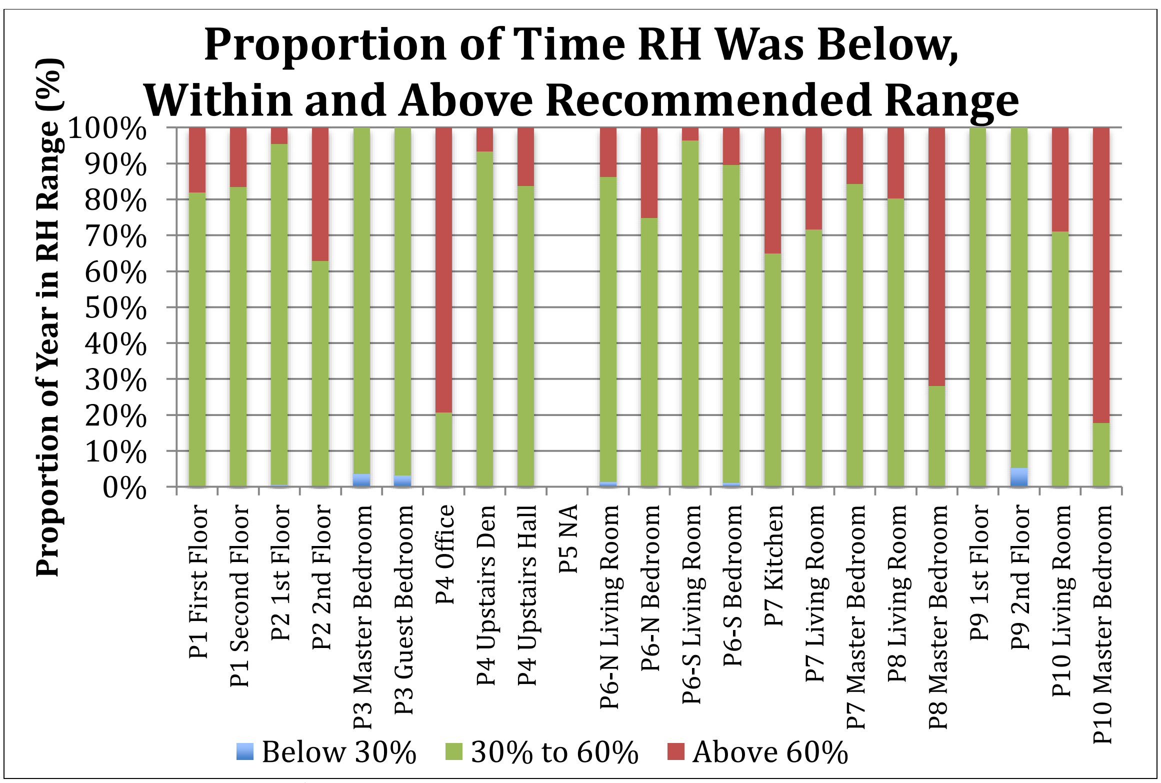

Figure 170 - Proportion of Time Indoor Relative Humidity Was Below, Within and Above the Recommended Range

Ventilation

Good indoor environmental quality is an essential element of DER projects, yet this is the parameter for which designers and engineers have the least practical guidance or design tools. IEQ is discussed below in terms of the ventilation equipment provided and its installed performance. As discussed above in section 2.4, the CA Title 24 (2008) ventilation requirements were not required by code for DERs unless they add 1,000 ft^2 or more.

ASHRAE 62.2 continuous whole house ventilation requirements for each home are summarized along with the presence of mechanical ventilation and estimated nACH in Table 72 below. Whole house mechanical ventilation was provided in only four projects, and airflows could only be measured in two homes. As a result, the presence of continuous mechanical ventilation is indicated in the table, rather than actual compliance with ASHRAE 62.2 whole house requirements. nACH values are provided to give an estimate of the average ventilation rate in homes without continuous mechanical venting (seven of eleven).

Whole house ventilation was not provided consistently in the DERs monitored for this research. Only four out of eleven projects provided continuous mechanical ventilation (P1, P2, P3 and P5), with three of these homes being inspired by the Passive House standard (P1, P3 and P5), which requires mechanical ventilation with heat recovery (MVHR) delivering 0.3 ACH. The homes that provided mechanical ventilation were typically the most air tight of homes, with the exception of P2. Continuous mechanical ventilation was provided using either central fan-integrated systems (P2) or balanced ERV systems (P1, P3 and P5). The average annual natural AER of all the project homes was estimated using blower door data, and only two homes had values exceeding the common threshold of 0.35 ACH, which means that nine homes likely should have included mechanical ventilation as part of the retrofit. P10, P9, P6 and P4 are the obvious candidates for additional mechanical ventilation. It is notable that while P4 did not provide continuous mechanical ventilation, it did use a passive stack vent to provide for nighttime ventilation and cooling during the summer and shoulder seasons, and occupant controlled supply fans were used intermittently during the winter. P9 used a nighttime ventilation cooling system, which provides substantial mechanical ventilation during cooling seasons.

It is notable that very airtight homes, such as P1 and P3, may be under ventilated if the current 62.2 fan ventilation rate method is used. The standard assumes a 0.02 CFM per square foot of floor area infiltration credit. But very airtight homes will not have such high levels of infiltration. ASHRAE Standard 62.2 Addendum N now includes a new calculation procedure—the Total Ventilation Rate Method—that removes the 0.02 infiltration credit, resulting in a higher mechanical airflow requirement. We recommend the use of this procedure for any home that is targeting extreme levels of airtightness. Passive Houses are already expected to provide mechanical ventilation at a rate of 0.3 ACH, which solves this issue as well.

Project ID	Floor Area (ft^2)	Number of Bedrooms	Whole House 62.2 Requirement (CFM)	Whole House 62.2 Requirement (ACH)	Continuous Mechanical Ventilation	nACH Estimated from Blower Door Test
P1	1630	4	53.8	0.22	Yes	0.05
P2	2780	3	57.8	0.14	Yes	0.27
P3	2357	2	46.1	0.13	Yes	0.02
P4	2510	3	55.1	0.15	No	0.26
P5	905	2	31.6	0.26	Yes	0.10
P6-N	1462	4	52.1	0.27	No	0.18
P6-S	1496	4	52.5	0.26	No	0.20
P7	3288	3	62.9	0.13	No	0.72
P8	1627	3	46.3	0.18	No	0.63
P9	3114	3	61.1	0.12	No	0.14
P10	1706	2	39.6	0.17	No	0.28

Table 72 - ASHRAE 62.2 Requirements Summary

Numerous ventilation airflows were measured in the 11 DER homes in order to assess compliance with ASHRAE 62.2 (fans were not assessed for noise or ducting criteria, only airflow). Ventilation flows measured fall into the following categories: (1) Range hood or Kitchen exhaust fans, (2) Bathroom exhaust fans, (3) ERV or HRV, (4) Whole house fans and (5) miscellaneous. Bathroom exhaust fans are required to exhaust a minimum of 50 CFM (or 20 CFM continuously) and kitchen range hoods must exhaust 100 CFM (or 5 kitchen ACH continuously). Fans were considered to fulfill requirements if the airflow could be achieved on any speed, though multi-speed fans are not specifically addressed in the standard. The compliance of installed ventilation devices is summarized in Table 73 below (all ventilation measurements performed are summarized in Table 72 above). Twenty bathroom exhaust fans were measured, and exactly half of them failed to deliver the required 50 CFM airflow. Kitchen exhausts of some sort[17] were installed in every project home. Airflows were measured in nine homes, and six were capable of delivering the required 100 CFM. All but one of the "passing" systems were able to achieve the required airflow on the lowest fan setting.

Ventilation Equipment Performance by ASHRAE 62.2 Airflow Requirements (counts)				
Status	**Total**	**Whole House**	**Kitchen**	**Bathroom**
Pass	18	2	6	10
Fail	13	0	3	10

Table 73 - Ventilation Equipment Performance by ASHRAE 62.2 Airflow Requirements

Several notable operational issues were identified in those homes that used mechanical ventilation. The ERV in P1 was monitored for detailed performance, and its behavior was occasionally erratic. Examples of faults included the inability to adjust system operation/speed using the manual control, and system cycling between low and high speeds out of the occupant's

[17] Kitchen ventilation equipment included: (1) range hood exhausted to outside operated intermittently, (2) exhaust fan without capture hood in ceiling of kitchen operated intermittently and (3) ERV exhaust inlet operated continuously in kitchen ceiling.

control. Prior to monitoring, it was reported that this unit was initially connected wrong, and it simply re-circulated air for the first year of occupancy. P3 also used an ERV with ECM motor, and after only 8 months of occupancy, the supply air intake grill had become completely clogged with debris from yard work, despite being nearly 8 feet off the ground. This blockage caused the ERV to increase its average wattage from 61 Watts to 117 Watts (see Figure 171 below). As seen below, the ERV was unclogged near the end of June 2011, and the power draw slowly increased until another cleaning in April 2012. The blockage increased noise and contributed to imbalanced system airflow, which can affect the recovery efficiency, ventilation rate and cabinet leakage of the unit. Without monitoring, this fault would likely have gone undetected, and maintenance may not be kept up in the future. P5 uses a small ERV with the supply outlet and exhaust inlet located on the same ceiling-mounted unit (see Image 48 below). Short-circuiting may be a concern in such systems, but this issue was not addressed in our research. Several visits to the home revealed that the ERV was not turned on for part of the monitoring, but it was eventually turned on and remained so. This illustrates the "stickiness" of occupant controls—once they are on, they stay on, and once they are turned off, they stay off. P2 used HRVs integrated into its basement and attic air handlers to provide mechanical ventilation on a continuous schedule. The hourly power demand of the basement air handler is pictured in Figure 172 below. From March 2011 to early June 2011, the air handler cycled regularly at ~120 watts for eight hours, providing ventilation. From mid-June to August 2011, it never stopped ventilating, and after a few more transitions, in mid-November 2011, the unit completely ceased providing regularly scheduled ventilation. Fresh air was still brought in during system operation, but if there was no heating or cooling demand, no ventilation was provided. The attic air handler never operated on a set schedule, and no operation or ventilation was observed from early May 2011 to September 2011.

Image 48 - P5 Ceiling Mounted ERV

The resilience and reliability of a ventilation system is extremely important in an airtight home, and our observations in this research do not encourage optimism. When the majority of air exchange is provided mechanically, system faults, malfunctions and maintenance requirements become much more important. This would particularly be the case in homes P1, P3 and P5 in this research, due to their extreme air tightness.

The kitchen ventilation systems in the two Passive House style homes, P1 and P3, and in P10, are of note. P10 uses an exhaust fan in the ceiling with no capture hood. Its airflow rate was measured at 110 CFM, which would meet current CA T24 (2008) if operated continuously, but it does not. The California Code refers to ASHRAE 62.2 and requires 5 kitchen ACH continuous ventilation, if no range hood is installed. P1 and P3 use gas cook tops and recirculating kitchen range hoods, with grease and charcoal filters, rather than exhausting cooking pollutants to the outdoors. Both homes also use an ERV for continuous ventilation, with the exhaust pathways originating in the bathrooms and kitchen. This system is common in Passive Houses in the United States. In fact, the Passive House Institute US requested an interpretation of the kitchen ventilation requirements from the ASHRAE 62.2 committee, in an attempt to have this system type allowed. The 62.2 committee confirmed that the PH requirement of 35 CFM of continuous kitchen exhaust did not meet the requirements of the standard, unless 35 CFM represented 5 kitchen ACH (ASHRAE, 2011). The systems in P1 and P3 would be required to provide 242 CFM and 172 CFM of continuous kitchen ventilation, in order for their system types to meet code. This exceeds the total ERV system airflows when turned to high. But none of these homes were required to meet the code—P1 and P10 were constructed prior to adoption of 62.2 into T24 (2008), and none of them added the requisite 1,000 ft^2. This illustrates the potential problem in how ideas for DERs need additional thought to ensure both good IAQ and energy performance.

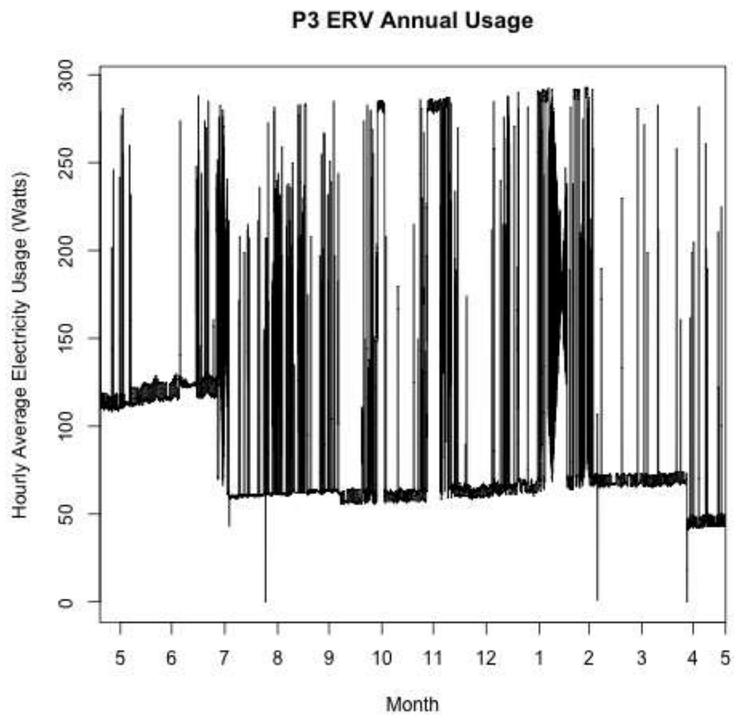

Figure 171 - P3 ERV Power Usage (One-Hour), Illustrating ERV Unclogging

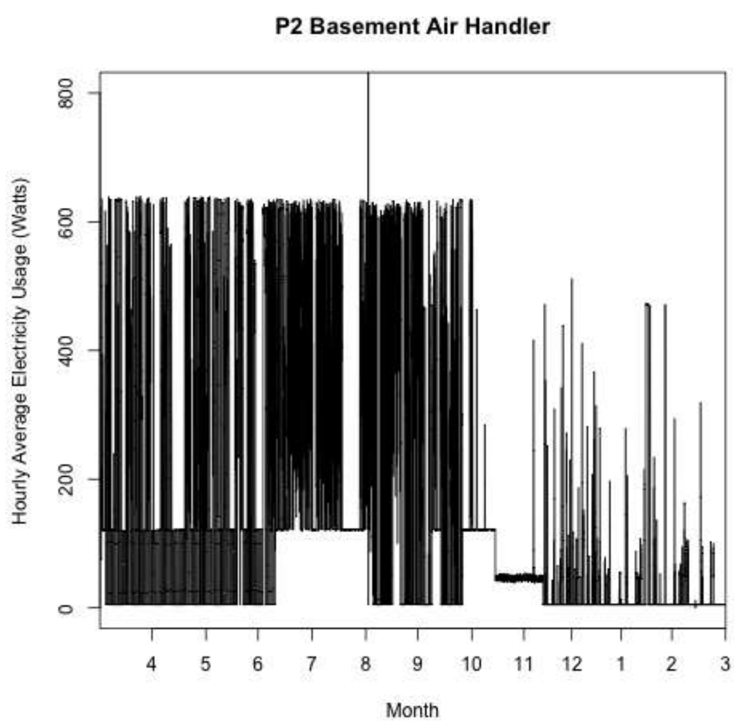

Figure 172 - P2 Basement Air Handler, Illustrating HRV Inconsistency

The kitchen in P7 also merits further discussion, due to its combination of increased airtightness and use of an historic gas range, with standing pilots. P7 has used a "house-within-a-house" approach, where the kitchen and surrounding rooms are treated as a sealed and separate zone from the rest of the home. The house and kitchen range are discussed in detail in section 4.7.1 above. The presence of a gas cooking appliance has been consistently associated with elevated indoor levels of combustion pollutants—most notably nitrogen oxides—and appliances with standing pilots are the worst offenders. The presence of a gas range has also been persistently linked with respiratory health issues in epidemiological research (World Health Organization, 2010). These issues are particularly troubling in P7, because the occupants have extensively air sealed the zone containing the gas range, and the kitchen is where most time is spent in the home, outside of sleeping. Cooking is a primary hobby of the occupants, so in addition to the pollutants emitted from the standing pilot (614 Btu/hr of gas); greater amounts are likely emitted during actual cooking activities. A large kitchen range hood was installed during the retrofit, but we are unsure how much it is used. In addition to this troubling pollutant source in an air sealed space, winter temperatures are kept quite low in the home, in order to reduce heating energy use. This leads to higher indoor relative humidity; with its associated human health problems (see section 2.4 above). Anecdotally, occupants have reported episodes of sickness, which may or may not have anything to do with these issues.

This is a limited survey of the air quality in these project homes. Pollutants were not directly measured and compared; rather, compliance with ASHRAE 62.2 was used as a metric. Still, superior indoor air quality is not being provided in these DERs in the way we would like to see it. As a minimum, homes should comply fully with ASHRAE Standard 62.2, even if the building code does not explicitly require it—just as in low-income weatherization. Homes that have been air tightened as part of a major energy retrofit should receive properly functioning kitchen and bathroom ventilation, as well as appropriate continuous whole house ventilation. In addition, these systems need to be commissioned, verified and maintained. Unfortunately, maintenance cannot be guaranteed over the life of the system. More than half of the bathroom exhaust fans measured were delivering low airflow rates, and only one project home (P5) had installed equipment that potentially complied with all current code requirements, though the kitchen exhaust and whole house airflows were not verified.

IEQ Improvements

While a number of potential IEQ problems in DERs have been noted above, most projects have also taken measures to improve IEQ. First, atmospherically drafted combustion appliances were eliminated in nearly all homes. For example, P1 used only a single natural gas floor furnace for heating and standard tank water heater pre-retrofit, and it switched to electric baseboard heat and sealed combustion water heating in the attic. All projects either eliminated gas combustion or used high efficiency, direct vent appliances (P9 kept an atmospheric draft water heater in the garage). This effort was consistent both with energy savings and reducing indoor combustion pollutants. Second, while performance issues were noted (see above), all homes added both bathroom and kitchen exhaust fans, of some sort. This suggests that even in the absence of continuous mechanical ventilation, occupants, contractors and designers see obvious value in point-source ventilation. Third, most homes that participated in this research pursued sustainability goals in addition to energy reductions, which typically meant use of low-emitting materials for at least some interior finishes. This source control can be essential in limiting pollutant exposures in newly remodeled homes. Fourth, several projects used the retrofit as an opportunity to address IEQ problems, such as moisture, noise, degradation and of course, comfort. For example, P9 used its DER as an opportunity to eliminate the transport of pollutants from the attic and garage into the home, as well as to solve noise and comfort issues through HVAC fixes. P4 had substantial structural damage from a long-undetected, hidden water leak, which could also have contributed to moisture problems, such as mold, mildew and dust mites. Finally, moisture issues were addressed preemptively in a number of projects, with installation of rain-screen siding, extension of roof overhangs, sealing of crawlspaces and careful flashing detailing. Those projects that replaced exterior siding and/or sheathing were most able to address these issues (P1, P3, P4, P5 and P10).

The DERs in this research have addressed a number of existing IEQ issues, the value of which could very well outweigh the problems noted above. No moisture issues were observed, and with the exception of P7, no IAQ problems were made obviously worse. Rather these homes were generally in better condition, were better maintained, were more comfortable and were more resistant to weather and seismic events than they were in pre-retrofit condition.

5.7 Cost of DERS

Research by the International Energy Agency has concluded that DERs only make economic sense when a remodeling project is already being implemented (*Advances in Housing Retrofit Processes, Concepts and Technologies*, 2011). When this is done, going deeper than code compliance energy efficiency levels only results in minor incremental cost increases.

We were able to obtain cost estimates for the beyond-code components of the DER for six of the eleven project homes. The average incremental cost above a 2008 Title 24 compliant remodel was $25,910, including renewable energy and consultant fees. This figure is comparable to the average $32,000 in incremental costs paid by NYSERDA in their DER pilot program (NYSERDA - Deep Retrofit 2011). For comparison, the average mid-range major kitchen remodel cost of $64,209 and the average high-end major kitchen remodel cost of $119,716. Similarly, average mid-range and high-end bathroom remodels cost $19,204, and $59,317, respectively (‘Remodeling Magazine: Cost vs. Value Report 2011-2012’, 2012). While still a major investment, the incremental cost of a DER is substantially less than the average major kitchen remodel.

The most meaningful cost metric may not be DER incremental cost, but rather is net-monthly cost of home ownership, which assumes that retrofit measures are financed. Monthly energy cost savings can then be directly compared with the monthly increase in loan payment.

Using the estimated monetary value of energy reductions[18] for each project, we calculated the total loan amount that would result in neutral net-monthly cost of home ownership. In other

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[18] 2011 California average electricity rates were used for electricity ($0.1478/kWh) and for natural gas ($0.992/Therm) (US Energy Information Administration, 2012a, US Energy

words, if $100 was saved per month in energy, then a $100 per month loan payment was assumed, and the corresponding loan principal amount was calculated for a 30-year term, with APR of 3.2%. For the five homes with pre-retrofit data, some homes increased annual energy cost (P1 and P2) and some decreased it (P4, P7 and P9). Clearly, those homes with increases in energy cost could not use any loan to achieve monthly neutral home ownership costs. Those three homes that achieved energy cost savings could finance loan principals ranging from $13,931 to $29,433 while maintaining neutral monthly ownership costs.

The change in net-monthly cost of ownership was calculated for the four projects where we had both pre- vs. post-energy savings and incremental costs. Three of four projects increased their net-monthly cost of ownership by an average of $50 (overall average was a $30 per month net-cost increase). This includes P1, which increased its estimated energy costs, due to electricity use for heating. On the other hand, P9 was able to achieve impressive estimated energy cost reductions with low incremental costs, for a net-monthly savings of $31.

Energy cost reductions were also estimated using the CA average single family home as a baseline. P2 had higher costs relative to the average, but all other homes achieved cost reductions. The monthly neutral-cost loan amounts for homes that reduced cost ranged from $9,026 to $26,897, averaging $17,210. Using the average DER cost stated above, the monthly loan payment would be $112.05. Monthly estimated costs savings (excluding P2) ranged from $39 to $116, averaging $74. The monthly increased homeownership costs (assuming average DER cost of $25,910) for a deeply retrofitted home then ranged from a $4 decrease in net-cost to a $73 increase, averaging $38 per month.

For those homes that implement successful DER as part of a remodeling project, monthly net-cost of ownership can be expected around $0 to $30. This assumes the DER is targeted at a high usage home, and that it avoids costly fuel switching. This implies that DERs can be achieved with little economic impact to the homeowner who is already remodeling, if the cost is rolled into a loan payment for the remodel.

A caveat with these calculations is that, current mortgage interest rates are low, as are delivered energy prices[19]. Low interest rates increase the amount available to spend on DERs for a given energy cost reduction, but at the same time, these cost reductions are low due to low energy costs. These two effects currently counteract one another, such that the overall conclusion about the affordability of DERS appears robust. In the future, if fuel prices increase more than mortgage rates, then DERs become easier to justify on a cost basis, but conversely, if fuel prices remain low and mortgage rates increase, then DERs will become less affordable.

Information Administration, 2012b). These calculations are conservative, as they do not include tiered or time-of-use electrical rates or excess natural gas usage over baseline amounts. Compare to 2011 national average costs of $0.1172/kWh and $1.102/Therm.

[19] National average residential natural gas prices have dropped from a 3-year (2006-2008) average peak of $1.357 per therm to 2011 levels of $1.102 per therm (US Energy Information Administration, 2012b).

6 DISCUSSION

6.1 Metrics

The results of this study illustrate how determining 'success' in a DER project can be difficult. Success depends on how energy use is assessed and how it is normalized. These performance metrics and normalization methods should be carefully considered by program designers, project teams and homeowners alike, so that an appropriate metric can be chosen that will lead them to their desired results.

One of the most distorting elements in DER performance assessment is the fuel chosen to meet different end uses. Fuel choice has a clear impact when comparing between projects, and it is also fundamentally important when a project switches from one fuel source to another during the DER. In all cases described here, such shifts have meant transferring from natural gas for space and water heating, to either all electric or electric space heating. The reasons for this switch were different in each case. In P1, electric resistance heat was affordable (low installed cost), and it was assumed that Passive House envelope measures would mean that they would seldom be used. In P2, the decision was made believing that all energy would be offset with onsite PV. At P3, a single piece of equipment was desired to meet heating and cooling needs, and a mini-split heat pump was installed as a result. At P5, there was no access to utility natural gas. Other reasons that project teams make the switch to electric include avoidance of combustion pollutants, avoidance of utility connection fees, and the sense that only electric energy can truly be offset by PV production. This has resulted in a number of projects showing poor net-source energy performance. Of course, DERs that transfer from using electricity to natural gas for heating end-uses receive significant benefits when using the conversion factors used in this report.

When pursuing a DER, we recommend choosing fuels carefully and doing so only after evaluating energy performance on a source energy basis.

While source energy and CO_2e are useful in assessing actual environmental and societal impacts of DERs, their calculation is nevertheless fraught with uncertainty. The conversion factors used are of paramount importance. In reality, these factors vary with power plant fuel mixes, time dependencies, resource extraction methods, infrastructure age and numerous other assumptions.

(Deru & Torcellini, 2007) discuss the drawbacks of using national site-to-source conversion factors, including regional variations in electricity generation methods, as well as time of day sensitivity. For example, electricity generated in California in 2010 was from substantially different sources than are used in the creation of national site-to-source conversion factors. California electricity came from 1.7% coal, 53.4% natural gas and nearly equal parts nuclear, large hydro and renewable in 2010 ('CEC', 2011). In Deru and Torcellini (2007), national grid electricity in 2004 was generated from 49.9% coal, 18.3% natural gas, 19.9% nuclear, 6.8% big hydro and only 2.3% renewables. 71.2% of national electricity generation in 2004 was from fossil fuels, compared to 55.1% in California for 2010. In 2005, average natural gas power plant efficiency was 7,920 Btu/kWh and national average coal plant efficiency was 10,410 Btu/kWh, an efficiency benefit of 23.9% for natural gas. This efficiency increase, coupled with dramatically more non-fossil energy in the California 2010 electricity mix, would support a significantly lower site-to-source electricity conversion, as 71% of California consumed electricity is generated in-state ('CEC', 2011). This suggests that the national site-to-source values used in this paper may not be representative of actual impacts of these DERs. The apparent penalty of electricity usage may be much less severe than it appears.

Similar issues arise with CO_2e calculations, as determining the carbon intensity of energy is not straightforward and is filled with many assumptions and time dependencies. The carbon emissions associated with natural gas usage may be significantly higher than is suggested by the national value of 0.399 pounds CO_2e per kWh gas. One key contributor is the increased production of 'unconventional' natural gas from shale deposits (hydraulic fracturing or 'fracking'), an extraction technology that results in emissions at least 30% greater and perhaps more than twice as much as conventional gas extraction (Howarth *et al.*, 2011). Projections by these authors suggest that natural gas from shale has higher emissions than coal over a 20 year period, and at the same time, shale gas is predicted to increase from 16% to 45% of total gas production between 2009 and 2035. The CO_2e value for electricity reported by PG&E used in carbon calculations in this report reflects the actual fuel mix used by the utility, but it does not reflect the potentially increased emissions of 'unconventional' natural gas used in its electricity generation, as noted above.

Furthermore, the CO_2e emissions associated with energy use changes over time. For example, PG&E predicts the carbon intensity of its electricity supply will drop from 2009 levels of 0.575 pounds CO_2e per kWh to 0.29 by the year 2020—almost a 50% reduction (Bruso, 2011). If this is achieved, electricity from PG&E in CA will be less carbon intensive than natural gas, and our warnings about fuel switching could transition to suggestions to switch fuels. On the other hand, DER projects located elsewhere will have different emission factors associated with their regional energy supplier—most likely these emission factors will continue to favor gas usage over electricity. Current national CO_2e conversion factors are 2.3 times as high as the PG&E electricity conversion used in this research, making the carbon penalty of electricity nearly as bad as that of source energy. US EPA (2012) provides CO_2e conversion factors for electricity in every state, as well as by eGrid sub-regions and North American Electric Reliability Corporation regions. These values can be used to assess carbon impacts of DER on regional and state-specific bases.

We have noted the tendency for retrofit programs and homeowners to rely on site energy savings as their measure of success, due to its transparency and ease of use. Yet, we have illustrated here how severely distorting such decisions can be. Programs like DOE Building America have selected annual source energy as their performance metric, which we believe is a good choice. The Thousand Home Challenge Option B Threshold is another good alternative for homes without pre-retrofit data, as it accounts for the potentially distorting factors of fuel type[20], occupancy and square footage. Potentially most valuable is the evaluation of DER projects in

[20] Fuel type is only accounted for in terms of equipment efficiency assumptions (high efficiency gas versus heat pump equipment), not site-to-source conversion factors.

terms of CO_2e emissions. Aside from aesthetic and non-energy benefits for occupants, the key driver for DER implementation is to contribute to the international effort to halt or limit the effects of climate change. Consistent with this, the results of mitigation efforts should be assessed in terms of emissions, rather than energy. Any assessment should be performed on a per-house or possibly per-person basis, but we recommend avoiding the use of a per-square foot metric, which could inadvertently limit energy reductions. The upmost care is required in DER projects so that unintentional decisions do not lead to limited source energy or carbon savings, or to an increase in usage or emissions. Careful planning and forethought are required.

6.2 Broader Implications - Sustainability and Green Building

Similar to many other retrofit programs, site energy savings were the initial metric used to quantitatively evaluate the case studies of this research. However, as more data was collected and GHG reduction goals became an integral aspect of the research, the most important metric became CO_2e.

At the 2009 Copenhagen Climate Conference, the US agreed to a 17% reduction in GHG emission reductions from a 2005 baseline by 2020. Unfortunately, the American Clean Energy and Security Act of 2009 failed to pass both houses of congress (Waxman, 2009). So, these reductions are not legally binding, nor have further goals been established, which leaves states to lead the way. The World Resources Institute has created a guide for policy makers—*Reducing Greenhouse Gas Emissions in the United States: Using Existing Federal Authorities and State Action*—that examines how existing regulatory tools and state commitments could start the US on the path towards achieving this goal absent legislation (Bianco & Litz, 2010). The report concludes that even if federal agencies and states pursue a “go getter” path, reductions will fall short of the Copenhagen pledge, albeit not by a lot. Of course, reductions necessary to limit the increase of atmospheric CO_2 concentrations to 450ppm of atmospheric CO_2 are estimated at 36-48% by 2020 and 51-64% by 2030. California’s AB32 GHG reduction bill is an exemplar amongst states, and the long term goals of California’s Energy Efficiency Strategic Plan (CPUC, 2008) lists the carbon footprint of homes and neighborhoods as an additional mechanism that will be used to meet GHG goals. As residential and commercial heating made up 7% of total US emissions in 2008, the contribution that DERs could make to this should not be overlooked.

The tendency to switch fuels to electric space and hot water heating during a DER results in higher GHG emissions with the current typical fuel mixes used to generate electricity. Even if a net-reduction is achieved, reductions would be much greater without fuel switching. The approach taken by P4, P6, P7, P8, P9 and P10, where the existing building is insulated and air sealed to the greatest extent possible, and then the most efficient natural gas heating and hot water equipment is installed, is proving to be a more affordable, simple and effective solution to lower GHG emissions. Use of electric resistance technologies should be avoided at all costs—better alternatives include heat pumps for space and water heating and induction cook tops. Furthermore, if plug, lighting and appliance electricity usage is greatly reduced through smart technologies, better appliances and occupant conservation, then source energy and carbon penalties may not exist at all.

However, GHG emissions are complex, and although this approach to DERs is most effective right now, it may not be so in the future. A recent study on how California is going to achieve the challenging goals of AB 32 (Williams *et al.*, 2011) revealed that the only possible way to meet these goals is to first maximize energy efficiency, followed by the decarbonization of electricity generation, and finally the electrification of California, including space and hot water heating in our homes. While this approach makes sense from a theoretical point of view, it creates a challenge when thinking about reducing GHG emissions in our homes through DERs in the immediate future. Also, they fail to mention the extremely important role that energy conservation and behavior must play. But, it does highlight the fact that the carbon content of electricity is a serious social issue. If we can discuss the carbon content of our utilities' power in such a way that it impacts our decisions about building design, construction, and operation, (and possibly associated energy codes), then we can exert more pressure on utilities to use more renewable energy and lower carbon fuels.

Although natural gas equipment is currently more efficient and produces less GHG emissions, there are other ecological impacts that are not being considered in this analysis. These include habitat destruction from mining, transporting and distributing the natural gas, as well as significant water contamination issues and a range of other consequences that are beyond the scope of this paper. In addition, these issues can simply be transferred to the impacts of electricity use, as natural gas is used to supplant coal.

The primary focus of a DER is to significantly reduce the heating and DHW loads through building enclosure upgrades and the simplest and most efficient natural gas or heat pump equipment available. The next step is the integration of a low energy lifestyle by reducing consumption and MELs in the home. However, reducing energy consumption in our homes is not an easy task.

DERs must set the right goals, and use the right metrics to evaluate and achieve those goals. If the intention is to reduce GHG emissions through energy efficiency retrofits, then site energy savings is not the right metric to use. Additionally, affordability should also be a goal of DERs if widespread implementation is to become a reality. There are diminishing returns on energy efficiency once you pass a certain point, leaving very few homeowners able to invest in deep energy efficiency improvements.

Water efficiency must also be considered in a DER. As the connection between water use and energy use becomes more fully understood, energy retrofits should view water use reductions—both hot and cold—as reductions in total environmental footprint. In fact, energy embodied in water extraction, treatment, delivery and disposal accounts for 4% of annual US power generation. Average energy use for water retrieval, treatment, distribution and disposal in the US is 188.03 kWh per person per year (Goldstein & Smith, 2002). For a family of four, this equals ~752 kWh/year. This would be 23.4% of the total net-site energy usage of P4. California has studied regional EUI for its water system, and the average single family home in Northern CA requires 696 kWh/year for water and 2,209 kWh in Southern CA (Klein, 2005). These values represent substantial proportions of total household energy usage. In fact, the California Energy

Commission (CEC) has begun to consider allowing energy savings associated with reductions in cold-water use to be considered against those energy conservation measures typically considered fundable by the California Public Utilities Commission (CPUC). These cold-water reductions could represent the new low-hanging fruit for providing peak-load reduction and energy conservation. DERs should pursue water use reductions with the same intensity as household energy reductions. CEC (2005) suggests that reductions should be pursued in this order: (1) hot water, (2) indoor cold water and (3) outdoor cold water.

A DER is resource efficient by nature, as it utilizes the existing structure to the greatest extent possible. Far less framing materials, concrete, and steel are used in a DER than in new construction. Many projects are also carried out in existing communities, with infrastructure that is less carbon intensive than suburban development. Although we have not accounted for the embodied energy or carbon in any of these projects, when compared to a code compliant new construction home, there is undoubtedly less embodied energy in a DER; making them an even more attractive sustainable building solution.

6.3 DER Recommendations

6.3.1 Performance Assessment and Metrics

DERs are varied projects with a multitude of metrics that can be used to assess their performance, including site energy, source energy and CO_2e, normalized by house, person and square foot. We recommend following the Building America practice of conversion to source energy use, and to consider the carbon emissions of every DER. We found that switching from gas to electricity for heating uses can have a detrimental impact on source energy and carbon emissions, even in those homes that achieved >60% site energy reductions. These metrics are somewhat less important if no fuel switching occurs. Total household energy use should be assessed on a per house or per person basis, and not on a square foot basis, which rewards adding floor area. With this in mind, a DER can be assessed in two ways: (1) reduction in energy use compared with pre-retrofit and (2) post-retrofit energy consumption target.

Reductions can be assessed proportionally—percentage reduction—or in absolute terms—total reduction. Percentage reductions have been how DERs are most commonly defined across the industry and literature. An average 58% net-site energy reduction was achieved in this study, so future DER should target a minimum of 60% reduction for site, source and carbon. Yet, the absolute reductions are more important, in that they reflect the amount of reduced resource consumption and carbon emissions attributable to a project. P4 is a good example of this, as it achieved net-source energy savings of 96%, but only reduced absolute usage by 17,019 kWh, which was less than half the reduction achieved by the largest reducer of source energy (P9). This leads to the conclusion that we should perform DERs on the average-to-high consuming homes first, where the largest absolute reductions can be achieved. A reasonable absolute energy reduction target would be the average usage of a home in the same region. Target absolute net-site energy reductions are listed in Table 74 below for each Building America climate zone, using average household usage values from the 2009 Residential Energy Consumption Survey (RECS 2011). Reductions consistent with Table 74 would constitute a DER, irrespective of proportional savings.

DOE Building America Climate Zone	Target Absolute Net-Site Energy Reduction (kWh)
Very Cold/Cold	32,649
Mixed-Humid	26,817
Mixed-Dry/Hot-Dry	19,695
Hot-Humid	19,373
Marine	19,519

Table 74 - Target Absolute Net-Site Energy Reductions by DOE Building America Climate Zone

Post-retrofit energy consumption targets are useful in several scenarios, when reductions cannot be assessed either proportionally or in absolute terms. If no pre-retrofit data is available (six of eleven projects in this research did not have pre-retrofit data), the targets should be representative of the energy use of a low-energy home, and a sufficiently challenging target for any home. Post-retrofit energy targets can be set using: (1) the Thousand Home Challenge Option B or (2) a desired percentage reduction can be applied to local/regional average usage or to energy modeling results. Only two of eleven project homes were able to achieve their Thousand Home Challenge Option B thresholds, as well as 75% reductions relative to the average CA single family home (P3 and P4). These thresholds may be too stringent. With the exception of establishing a pre-retrofit baseline by energy model, these strategies usually lead to pursuit of a low-energy home with performance substantially better than new construction. While not necessarily bad, this may push many DER beyond what would be required to achieve a >75% reduction in an existing home. This increases the cost and inconvenience to the occupants, and it furthers the notion that all DER must look like cutting-edge, net-zero style homes, whereas this research has demonstrated that deep reductions can be achieved with more modest but comprehensive upgrades. In fact, the largest absolute energy reductions were achieved in those homes with on average higher post-retrofit usage.

In most cases without pre-retrofit data, the best approach is to apply a percentage reduction to the prediction of an energy model. The DER in this research had average HERS (2006) scores of 49, which suggests that these projects use, on average, 51% less energy than code-compliant new homes of the same size/location/equipment. Homes without pre-retrofit data should target a HERS score or equivalent of 50 or less. Alternatively, they can target a 75% reduction in HERS score from the pre-retrofit model.

It is essential to recall that any metric chosen can be valuable, but the metric measuring success must be in alignment with the overall goal. If the goal is to contribute to reduced GHG emissions, then any metric based upon site energy may be counterproductive. Source energy metrics may partially reflect carbon reductions. If the goal is to reduce homeowner energy cost, then a carbon emission metric will not be useful. If EUI is used to assess projects, then the goal of overall site energy, source energy or carbon emissions may not be achieved.

6.3.2 Indoor Environment Recommendations

We must realize and accept that comfort, health and safety improvements are going to be the primary drivers of broader DER implementation. In addition, energy savings that are achieved at the expense of comfort, health or safety will not be scalable and will ultimately cost more. So, performance goals or recommendations should exist for these improvements.

- Retrofit work should be carried out consistent with the *Healthy Indoor Environment Protocols for Home Energy Upgrades*.
- Where possible, *EPA Indoor Air Plus Guidelines* should be used to achieve further improvements in moisture, durability and pollutant source control.
- Source control is the most effective way of dealing with pollutants from products and building materials. Use low-emitting materials wherever possible.
- ASHRAE 62.2 should be seen as a minimum ventilation requirement for deeply retrofitted homes. If extreme levels of airtightness are achieved (in Passive Houses for example), ventilation rates should be calculated using the Total Ventilation Rate Procedure in Addendum N of 62.2 to avoid under ventilation. Kitchen and bathroom requirements in 62.2 should be viewed as equally important as the whole house requirements. Kitchen exhaust systems are especially important in removing combustion and cooking pollutants. Kitchen exhausts with full capture hoods should be used above both gas and electric cooking appliances. Very airtight homes should provide make-up air for kitchen exhaust systems.
- All combustion appliances should be sealed combustion, direct vented units. This increases energy efficiency and avoids combustion pollutant issues. Gas cooking is an exception, provided range hood exhausted to outside is provided.
- Provide particle filtration by central air handler, ventilation supply air or stand-alone filter. Do not use ozone generating air cleaners.
- Beware of HVAC return ductwork in garages regularly used for vehicle parking or idling and with combustion appliances. These should be either very well sealed or eliminated.

6.3.3 DER Process Outline and Recommendations

Any DER at this point in time is a cutting edge demonstration project. The methods of achieving deep energy savings are being developed and refined across the country. The process outlined below is appropriate for most projects, though some elements will vary depending on the extent of the project. We find it useful to conceive of projects as either retrofits or renovations. Retrofits work within the existing home, making upgrades that improve performance, but that do not involve major reworking of the home layout, function, location and interior/exterior finishes. Examples include P2, P5, P7, P8 and P9. Renovations are much more substantial projects, and usually result in a home that does not share the form or appearance of its pre-retrofit version. Examples include P1, P3, P4, P6 and P10.

Renovations may be most appropriately planned using absolute performance targets and best-practices specifications. Pre-retrofit audits and testing are less important, because the end result will not be comparable, because heating/cooling/DHW system types are likely to change, etc. Renovations will also require larger project teams, including an architect and likely engineers. They are usually more costly, time consuming and represent greater disruption to the occupants. Retrofits may be most appropriately planned and carried out using diagnostic energy audits and the tools/methods of the home performance and weatherization industries. System types are more likely stay the same, floor areas do not change dramatically, etc. Tests on pre-retrofit systems can usually be meaningfully compared to post-retrofit systems. For example, if you plan to remove or replace ducts, do not test the ducts.

In the project planning process, it is crucial to differentiate between a DER and a low energy home. A DER can be a low energy home, but it does not have to be. Rather it should achieve significant reductions—absolute or relative—in annual household energy use. Projects like P2, P7 and P9 illustrate how post-retrofit energy use can be non-exceptional, yet substantial reductions occurred. Consistent with the retrofit-renovation framework in the above paragraph, retrofits are likely to achieve average levels of energy use, but if they began as high energy users, can be very successful DERs. Renovations have the most potential to become low energy homes, and this is most appropriate for homes with low pre-retrofit consumption, or those homes where low energy use is a goal additional to a DER. Being clear on which is being pursued in a project will determine the required extent of analysis, the technologies used, the nature of envelope requirements (code-compliant vs. enhanced), etc.

6.3.3.1 Process

1. Assemble Qualified and Trusted Team
    a. A DER team will likely include an energy consultant/home performance professional, a contractor, engineers and a designer.
    b. The chosen professionals must have knowledge and experience in energy efficient construction techniques and building science principles.
    c. Careful attention to detail through all phases of design and construction is essential for successful implementation.
2. Collaborative Design and Systems Thinking
    a. An integrated project delivery method is advisable in a DER. Include the architect, engineers, contractor and subcontractors from the beginning in order to holistically address all aspects of the project.
    b. Systems integrated approaches allow for creative problem solving and synergistic measures. For example, existing duct work can be extensively air sealed, or can be brought inside the building envelope, or could be eliminated entirely.
    c. Plan all aspects of the project as if it were new construction. Be as thorough as possible. Do not leave major decisions to the last minute, where cost, lead-times and convenience can result in bad decisions.
    d. Design to the energy reduction goal or target. Be specific about the energy reductions that are targeted for each end use, account for everything that will get you to your target/goal.
    e. Use energy models to test retrofit approaches but with caution. A thorough understanding of the limitations of these models is necessary, as is an experienced modeler. Many advanced system types cannot be modeled using commercial software (combisystems for example).
3. Establish Baseline
    a. Perform home inspection and energy audit.

   b. Establish energy baseline using utility bill analysis. Depending on fuel type, estimate heating, hot water, cooling and other energy categories. If bills are unavailable, use one of the methods discussed above to set a performance target.
   c. Create an electricity audit for miscellaneous devices in the home. Use a plug-in electrical meter to estimate use of appliances, entertainment centers, computers/peripherals, etc.
   d. From this baseline, establish an energy reduction goal or annual performance target.
   e. Establish non-energy goals of the project, including improvements in aesthetics, comfort, IAQ, durability, structural integrity, resale value, etc.
4. Test in
   a. Perform building diagnostic tests to quantify air leakage, duct leakage, ventilation airflows, and HVAC system performance, where appropriate. Create specific performance targets for each test that will be achieved during retrofit and can be used to verify contactor performance.
   b. Identify health and safety issues that can be solved during retrofit, such as gas or water leaks, improperly vented heating appliances, moisture or pest damage, etc. Identify paths to solving any issues, which can include either fixing a faulty gas appliance exhaust duct or eliminating it entirely.
5. During Construction
   a. Be prepared for unexpected issues to arise, such as hidden structural issues or moisture damage.
   b. Always have a trusted and knowledgeable representative overseeing the work of insulation, HVAC and other subcontractors.
   c. The work of any contractor should be verified by a third party inspector, such as HERS rater or energy auditor.
   d. Where feasible, use diagnostic testing equipment, such as a blower door, to track progress during construction.
6. Test Out
   a. The same diagnostic tests that were performed prior to the retrofit should be performed post-retrofit, in order to evaluate whether the goals were achieved or not. Blower door tests should ideally be performed prior to finishes in order to allow for additional air sealing if needed.
   b. Commission all new systems.
7. Occupancy, Monitoring and Evaluation
   a. A DER is not complete once the building is occupied, but in many ways is only beginning. The energy savings are the main focus of a DER, therefore, the energy use must be monitored and compared to the baseline in order to evaluate progress. Monitoring can occur at three levels:
      i. Minimum: consumption through utility billing data should be used.
      ii. Better: install whole house electricity meter and provide continuous feedback/access to occupant and potentially contractor.
      iii. Best: install end-use metering, with a focus on biggest energy consumers.

b. Occupants should use feedback from monitoring and make acceptable behavioral adjustments.
c. More detailed metering also allows for problems to be identified. New and sometimes complex systems often have unanticipated performance issues, which can be remedied, if identified.
d. An electricity audit of miscellaneous equipment can be just as valuable after the retrofit is complete, as DERs often include new equipment, new home offices and a variety of miscellaneous energy draws.
e. Small goals and short-term targets are easier to achieve. Have monthly energy use targets, rather than an annual target. This allows for tracking of progress and earlier discovery of trends.

6.3.3.2 Recommended Retrofit Measures

While it is tempting to think that every DER needs to be custom designed and engineered, with detailed energy modeling and extensive research, this may not be practical and will limit the widespread implementation of these projects. This is the typical dilemma between energy code prescriptive and performance paths. For reasons including, but not limited to, site and climate constraints, cost constraints, and experience of the project team, we have set out two different levels of DER prescriptive paths below—a base DER and an enhanced DER. The base specifications are intended to bring an existing, inefficient home to at least current International Energy Conservation Code (IECC) 2012. We expect energy reductions of 50-70% using this package. The enhanced path represents a low energy home that is on the path to zero-net energy, with 70% or greater energy reductions. It includes best in class HVAC and hot water systems, very good envelope, efficient lights, appliances and plug-in devices, controls to reduce miscellaneous electrical loads, and the addition of renewable energy. Both paths are comprehensive, targeting all household energy uses, which is essential to achieving deep energy reductions in all climates. Savings estimates assume that a home is largely uninsulated, with aged, inefficient appliances throughout. Envelope measures are more climate dependent, whereas HVAC, hot water, appliances and MELs apply across climates.

For a base DER, we recommend seeking code compliant levels of insulation, airtightness and equipment efficiency, while ensuring acceptable IEQ. These upgrades should be comprehensive and not piecemeal. In contrast to this simplified approach, Polly et al. (Polly, 2011) describe a detailed method using BEopt[21]™ to identify cost minimum and cost neutral home retrofit packages over a 30 year period. All example cost curves they provide fall short of a 50% source energy reduction. DERs targeting much higher savings may not need such cost-optimizing analysis, because they are “doing everything” and not targeting partial retrofit packages. Furthermore, our experience suggests that owners are not likely to select retrofit measures based upon their marginal annual costs.

[21] The BEopt™ (Building Energy Optimization) software provides capabilities to evaluate residential building designs and identify cost-optimal efficiency packages at various levels of whole-house energy savings along the path to zero net energy.

While more cost-optimal solutions certainly exist, we are confident that these prescriptive specifications can be applied to most uninsulated and poorly insulated homes with good results. Prescriptive suggestions cannot fully account for the extreme variation brought on by user behavior, and based on our findings, this important element will likely be the most cost-effective and influential aspect of achieving energy savings greater than 70%. DERs will always be most successful when occupants understand and are engaged in the operation and impacts of their home.

Some features recommended in all DERs cannot be specified in the table below. For example, priority should be placed on passive methods of meeting household needs wherever possible, including heating, cooling, and clothes drying. IEQ and durability concerns are also not specifically highlighted, but must be dealt with by the design and construction team, as discussed above.

Recommended Deep energy retrofit Measures,
Prescriptive Paths to Deep Energy Savings

	Base DER (50-70%)	**Enhanced DER (>70%)**
ENVELOPE		
Wall Insulation	R-13 Infill	R-13 Infill and >R-5 exterior continuous
Attic/Roof Insulation	R-38	>R-50
Foundation Insulation	R-13	>R-19
Windows	Energy Star	<U-0.22, climate dependent SHGC (<0.30 in moderate/cooling climates, >0.4 in Northern climates)
Air Leakage	<5 ACH_{50}	<3 ACH_{50}
MECHANICAL		
Heating and cooling	Gas: AFUE 0.90 forced air or hydronic Electric: Heat Pump with HSPF of 8.2 HSPF and Cooling SEER 14.5 or greater (CEE Tier I)	Gas: AFUE 0.95forced air or hydronic Electric: Heat Pump with HSPF of >9.5 and SEER >18 Electric: Mini-split heat pump with HSPF >12 and SEER >25
DHW	Gas: EF 0.82 Electric: Heat Pump with COP 2	Gas: EF 0.95 and solar thermal Electric: Heat Pump with COP >2.6 with solar thermal
Ventilation	ASHRAE 62.2	ASHRAE 62.2 using ERV/HRV
Distribution	Forced Air: Duct leakage <6% of system airflow, R-8 ducts outside conditioned space Hydronic: All accessible hot water piping insulated to R-2	Forced Air: Duct leakage <3% of system airflow, ducts inside conditioned space or buried in attic insulation to R-16 Hydronic: All accessible hot water piping insulated to R-3.6
LIGHTS	All compact fluorescent or LED	All compact fluorescent or LED, use occupancy sensors/controls, and use of day lighting elements, such as skylights, light tubes or light colored finishes
APPLIANCES	CEE Tier I	CEE Tier III, Use of clothes line

MELs	Energy Star Power Strips	CEE Tier III or higher Smart Power strips Whole House Off-Switch
RENEWABLES	None	>2 kW PV system

Table 75 – Recommended DER Prescriptive Measures

6.4 Future Research

Although this research has been very extensive in depth and breadth, there are various directions that it should be taken in the future. All homes were located in similar climate zones, and DER performance needs to be assessed in all US climate zones. The retrofit approaches are bound to be unique for each area, and further research is needed in order to understand what techniques are most successful in these different locations. As more DERs are built, similar case studies could be assembled into a database, including energy consumption data, detailed project specifications, and project cost data if the homeowners were willing to share. Using this database, designers, contractors and homeowners could compare the pre and post-retrofit performance data to aid in the planning of their DERs. The DOE's High Performance Buildings Database ('EERE: Buildings Database', 2011) is an existing and underutilized platform that could potentially accommodate this. The effects of occupants in DERs need to be more carefully studied, as do the technologies and feedback mechanisms that allow occupants to most easily reduce their energy consumption. The valuation of the non-energy benefits in DERs should be further studied, as this could substantially contribute to overcoming the perceived cost-effectiveness barriers of these projects, as well as provide reassurance to customers that DERs make them healthier and more comfortable in addition to just saving energy. Finally, a DER is a large investment, which should have returns in both in terms of energy, IEQ and property value. The increased property values generated by DER projects also need to be evaluated, and methods need to be developed that will recognize energy and IEQ performance in valuations by real estate professionals.

7 Summary and Conclusions

This research documents and demonstrates viable approaches to DERs using existing materials, tools and technologies. In most cases, the project goals of deep energy reductions were achieved. However, the results depend on the particular metric chosen to evaluate home performance, and different metrics require different approaches in order to be successful. Therefore, the project goals, along with the metrics used to evaluate those goals must be clearly defined from the beginning of the design phase. Based on the current concerns over global climate change, it is suggested that GHG emission reductions should be one of the goals of a DER. This leads to issues beyond the building footprint and site energy, but must also consider source energy and the carbon content of the primary fuels used to generate it. Geographical variation in the carbon content of electricity is very high, and this should be considered for DER planning purposes.

The DERs of this research have incorporated an array of innovative design and construction techniques and the most successful projects also reduced energy consumption through behavior adjustments and energy conservation measures. The energy monitoring data and graphic user interface of the energy dashboard helped interested homeowners understand and make informed decisions about their energy use. Superinsulation and extreme airtightness, such as the Passive House standard of 0.6 ACH_{50}, was found to be unnecessary in our climate in order to achieve energy savings greater than 50% in poorly insulated/uninsulated existing homes. However, this strategy was shown to significantly reduce the space conditioning energy, therefore allowing for greater variability in user behavior while still achieving deep energy savings. Still, highly insulated and very airtight homes require significant heating and cooling energy, even in relatively mild climates. Building system technology solutions were often overly complex, leading to failures, additional costs and compromised energy performance and comfort. Custom designed systems were problematic, and very little benefit was observed from the use of solar combined space and water heating systems.

We have provided recommendations for achieving deep energy reductions based on this research. The more common "baseline" DER requires a home to be updated to a current, Title-24 or IECC code compliant home. The "enhanced" DER of 70% or greater energy savings requires a significantly more intensive retrofit, including insulation beyond a single stud wall, airtightness greater than 3 ACH_{50}, and the highest performance windows, HVAC, DHW, heat recovery ventilation, lighting and appliances, with the addition of at least 2 kW of renewable energy.

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9 APPENDIX A

9.1 Monitoring Equipment Specifications

9.1.1 Energy Monitor

The ECM-1240 from Brultech Research, Inc. is a multi-channel Energy Consumption Monitor designed for use with residential electrical system. The monitor selected for this research, see figure 128, is equipped with a zigbee wireless antennae for communication with the onsite netbook. Figure 129 shows the USB dongle that is plugged into the USB port of the netbook to receive the zigbee data packets (‘Brultech Research Inc.’, 2011).

Figure 173 - ECM 1240 Energy Monitor

Figure 174 - Wireless Dongle

ECM-1240

ECM-1240 with Wireless and External Antenna Option

Note: The specifications listed below may vary depending on firmware changes.

Important Safety Consideration

WARNING!

The ECM-1240 must NOT be installed inside the electrical panel or any other panel possessing "line" voltages.

All signals connected to the ECM-1240 MUST be galvanicaly isolated from the powerline.

The CT installation along with any other task requiring the removal of the electrical panel cover MUST be performed by an electrician or qualified individual. All local electrical codes and rules must be obeyed.

CHANNEL INPUTS

The ECM-1240 consists of two type of power monitoring inputs:

- CH1 & CH2 Inputs
- AUXILIARY Inputs (AUX1 to AUX 5)

	CH1 & CH2 INPUTS
Measurement	Measures "True" or "Real" power based on current and voltage oversampling. The measurements take power factor into account. Uses automatic gain scaling. Also measures voltage and current seperately.
Input Signal:	Requires a voltage signal proportional to the input current. 333mV Full-Scale **NOTE:** The input signal MUST be galvanicaly isolated from the powerline.
Input Impedance:	20K ohm using the COM and SINGLE terminals. 40K ohm using the COM and DUAL terminals
Max Power Measurement:	65,535 Kilowatt per channel. (CH1 & CH2)
Max Current Measurement:	546 Amps based on 120V line voltage
Accuracy:	Typically +/- 1% plus CT & PT accuracy.
CT Compatibility:	Specifically designed for Brultech's "SPLIT" CTs available for 60A, 100A, 170A, 200A and 400A. Also compatible with Brultech's Micro CTs with the inclusion of a burden resistor. Compatible with any CT having 333mV Full Scale and phase error < 2 degrees CT scaling is configurable to suit the type of CT used.
Energy Measurement:	Kilowatt-Hour is calculated based on all samples and is updated every second.
Kilowatt-Hour (kWh) Resolution:	1 Watt-Second

Net Metering:	Measures directional energy to provide consumed/generated values crucial for net metering applications.
Power Resolution:	1 Watt
	AUX1 to AUX5 INPUTS
Measurement	Measures "True" or "Real" power based on current and voltage oversampling. The measurements take power factor into account.
Input Signal (AUX1 to AUX4):	Requires a current signal proportional to the input current. 52.46 mA FS
Input Signal (AUX5):	**Power Metering:** Requires a current signal proportional to the input current. 52.46 mA FS with external 20 ohm resistor accross the COM and AUX5 terminals. **Pulse Counting:** Dry contact closure between the GND and AUX5 terminals. Contacts must be isolated from outside voltage sources or electrical ground.

COMMUNICATION

The ECM-1240 has the following communications ports:

- One RS-232 Port
- Optional wireless communication port

	RS-232 Port
Connection:	Terminal strip connection: Common, Transmit, Receive
Baud:	19,200 Baud (8N1)

	Wireless Communication (optional)
	NOTE: Wireless communication is not WiFi .
Frequency:	2.4 GHz
Network Type:	ZigBee mesh network
Transmit Power	2mW
Antenna:	Internal wire whip or External 2.1dBi swivel antenna
Sensitivity:	-96 dBm
Range:	133 Feet* indoors, 400 Feet outdoors (line of sight) * Range is largely affected by the number of walls the RF signal must travel. The wall density, material and outside interference also affects the range.
Interference Immunity:	DSSS (Direct Sequence Spread Spectrum)
Baud:	19,200 Baud
Hardware:	Digi International's XBee module (www.digi.com)
Firmware:	Digi International's ZB firmware. (www.digi.com)
	Data Communication
Configuration:	Uses proprietary binary commands for initial configuration and setup.
Data Output:	Choice of three packet format types: 1. Binary (standard format) 2. ASCII 3. HTTP (requires EtherPort or EtherBee gateway)
Binary Packets:	The is the most common mode of operation. The packet data is configured for efficient data transfer using a proprietary protocol. **Packet Send Frequency:** 1 second to 255 second

ASCII Packets:	This format is now offered with newer versions of the firmware to simplify the development of custom software. **Packet Send Frequency:** 2 second to 255 second
HTTP Packets:	Using this format along with and EtherPort or EtherBee gateway, packets may be forwarded directly to a web server for processing using HTML, PHP, ASP or other web based languages. **Packet Send Frequency:** 10 second to 255 second.
Triggered Packet Send:	Immediate packet send (within one second) for power changes of a defined amount. **Trigger Threshold:** 10W to 65kW *Does not apply to HTTP mode

9.1.2 Current Transformers

Micro-40
The Micro-40 is a 40amp "donut" style current transformer. Since it is a closed-core device, the conductor of the load to be measured must be disconnected from the (de-energized) source in order to thread the conductor through the center. It is a low cost and accurate CT that is perfect for end-use monitoring as it fits into the already crowded panel without too much trouble (ibid).

Current Rating:	40A Max continuous primary current
Output:	26.23mA @ 40A Primary
Accuracy:	3% (Typically 1% on average)
Leads:	1.5m Lead Pair, 300V UL1007
Dielectric Withstanding Voltage (Hi-pot):	2500V/1mA/1min
Dimensions:	**ID:** 6.7mm (0.26") **OD:** 17mm (0.67") **Depth:** 7.7mm (0.3")

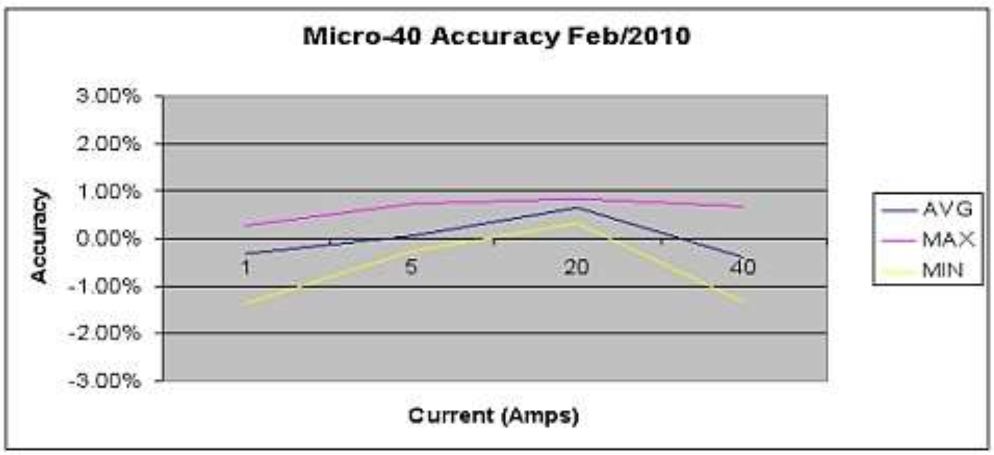
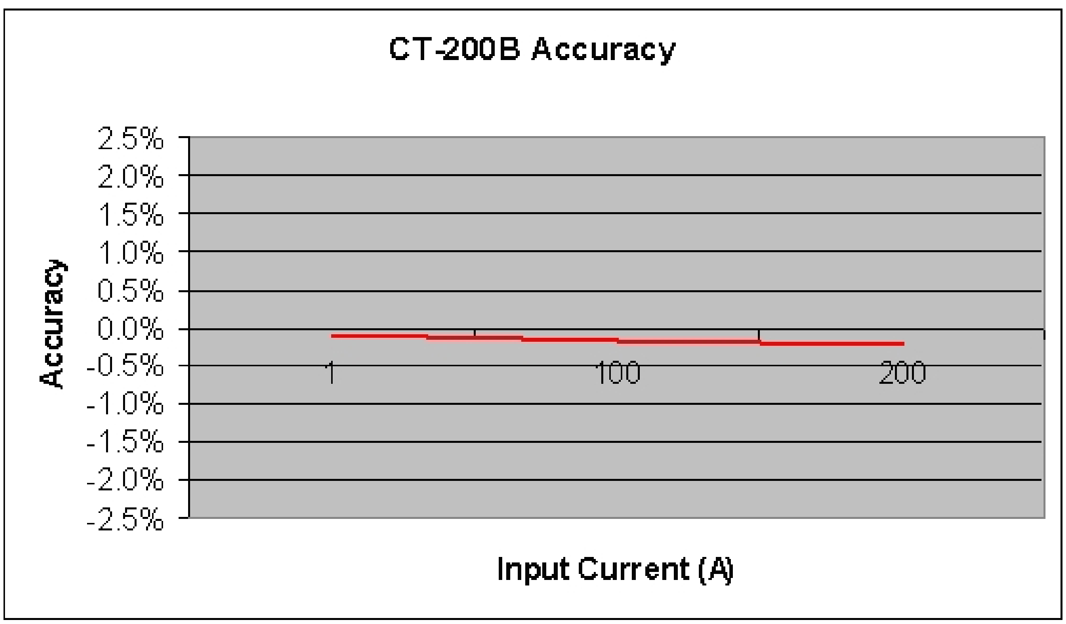


Chart from batch measurement displaying range of samples.

Split-200
The SPLIT-200 is a high quality 200amp split core current transformer. It is most commonly used for monitoring main electrical panel consumption. The Split-200 is highly accurate and maintains accuracy at low currents (ibid).

Current Rating:	200A Rated Output
Output:	333mV @ 200A Primary
Accuracy:	1%
Max Conductor Size	0.98”
Leads:	9.8 ft. cable, 300V rated
Dielectric Withstanding Voltage (Hi-pot):	2.5KV/1mA/1min
Dimensions:	2.67” OD, 0.724” W

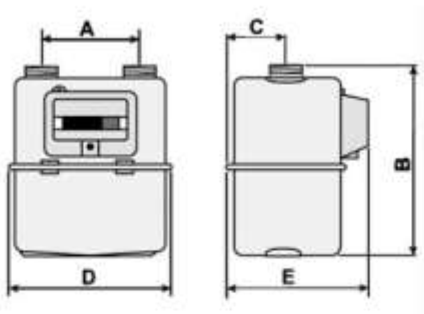


9.1.3 Gas Meters

Description

The G4 gas meter is a remarkably small, lightweight meter ideally suited to residential submetering applications. Despite its small size, the G4 meter is incredibly accurate and reliable when measuring either natural or LP gas. The G4 is classified as a 200 cubic foot per hour (cfh), non-temperature compensated gas meter with cyclometer register.

The design consists of four measuring chambers separated by synthetic diaphragms. The chambers are filled and emptied periodically and the movement of the diaphragm is transferred via a gear to the crankshaft. This shaft moves the valves that measure the volumetric gas flow. Rotations of the gear are transferred via a magnetic coupling to the index, thus assuring proper sealing of the meter's internal mechanisms. The register includes a reed pulse output for interfacing with remote (hard-wire, telephone, radio) reading and collection devices. Please note that the G4 is intended for indoor use only.

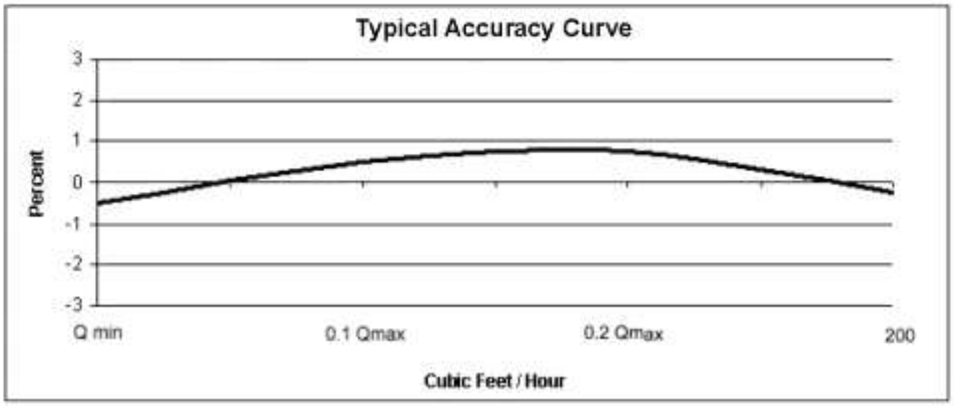


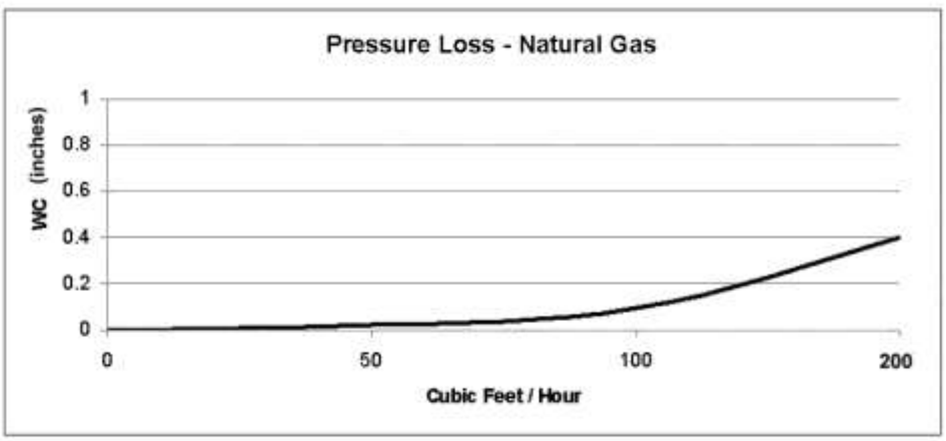
Specifications

Performance:	
Max Flow Rate (cfh)	200
Min Flow Rate (cfh)	1.4
Max Working Pressure (psi)	5
Operating Temperature	-4°F - 122°F
Register Capacity (ft^3)	9999999.9
Contact Closure:	
Pulses/ft^3	1/1
Electrical Ratings:	
Maximum Voltage	12 VDC
Maximum Current	10 mA
Resistor	None
Duty Cycle	10% On
Physical:	
Case Material	Aluminum
Exterior Finish	Powder-coated
Connection Type	Sprague #1
Gland/Cable (Supplied)	6' of 4-wire
Wire Connections	Green/brown are pulse (N/O) Yellow/white are tamper (N/C)

Dimensions

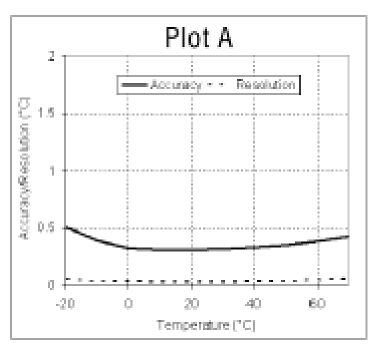
Dimensions (inches)					Weight	Connection
A	B	C	D	E	(lbs)	threads
6.0	8.5	2.6	7.6	6.5	4.5	Sprague #1





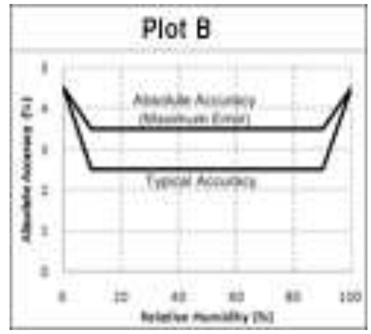
9.1.4 Temperature/Relative Humidity Sensors

Measurement range:
Temperature: -20° to 70°C (-4° to 158°F)
RH: 5% to 95% RH
Analog channels:
0 to 2.5 Vdc (w/CABLE-2.5-STEREO); 0 to 5 Vdc (w/CABLE-ADAP5); 0 to 10 Vdc (w/ CABLE-ADAP10); 4-20 mA (w/CABLE-4-20MA)



Accuracy:
Temperature: ± 0.35°C from 0° to 50°C (± 0.63°F from 32° to 122°F), see Plot A
RH: ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5%, see Plot B
External input channel (see sensor manual): ± 2 mV ± 2.5% of absolute reading

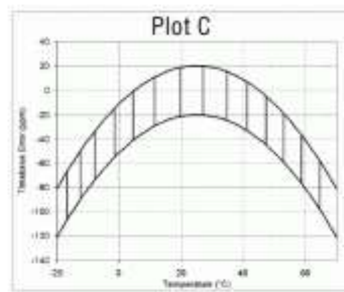
Resolution:
Temperature: 0.03°C at 25°C (0.05°F at 77°F), see Plot A
RH: 0.03% RH



Sample Rate:
1 second to 18 hours, user selectable

Drift:
Temperature: 0.1°C/year (0.2°F/year)
RH: <1% per year typical; RH hysteresis 1%

Time accuracy:
± 1 minute per month at 25°C (77°F), see Plot C
Response time in airflow of 1 m/s (2.2 mph)
Temperature: 6 minutes, typical to 90%
RH: 1 minute, typical to 90%



Operating temperature:
Logging: -20° to 70°C (-4° to 158°F)
Launch/readout: 0° to 50°C (32° to 122°F), per USB specification

Battery life:
1 year typical use

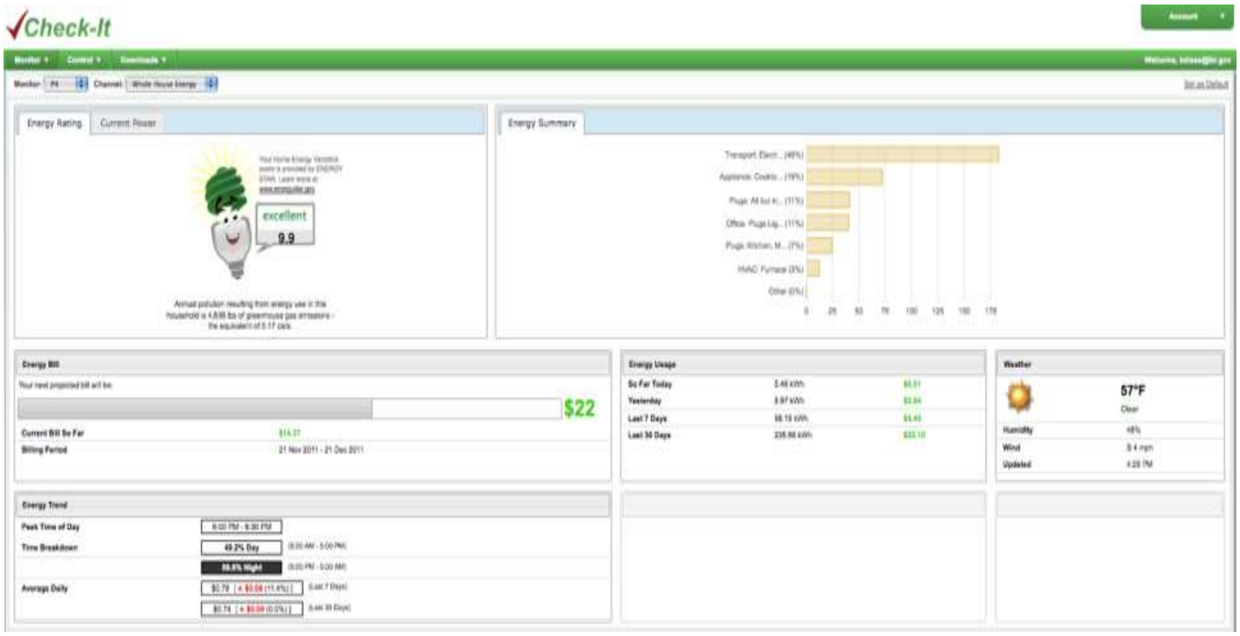
Memory:
64K bytes (43,000 12-bit measurements)

Weight:
46 g (1.6 oz)

Dimensions:
58 x 74 x 22 mm (2.3 x 2.9 x 0.9 inches)

9.2 Online Dashboard

At the beginning of the research the online dashboard "Google Powermeter" was used. Google cancelled the application in September 2011. From that point forward, we used another online dashboard that integrates well with Brultech's Engine G software called Check-it. Below are some screenshots of the type of data available, for more information go to http://www.check-it.ca.


Check-It
Energy Rating
Current Power
Energy Summary
excellent
9.9
Energy Bill
$22
Energy Usage
Weather
57°F
Energy Trend


Day
Week
Month
10 Dec 2011
Graph
Text
Energy Options
Temp Options
Energy Usage (kWh)
Temperature F
Hot Water: Tankless... (ft^3)

10 APPENDIX B

List of Acronyms

AB 32	California Assembly Bill 32
ACI	Affordable Comfort, Inc.
AEC	Architecture, Engineering and Construction industry
ARRA	American Recovery and Reinvestment Act
BECC	Behavior, energy and climate change conference
BPI	Building Performance Institute
BSC	Building Science Corporation
CFM	Cubic Feet per Minute
CFM_{50}	Cubic feet per minute at 50 Pa pressure
CPUC	California Public Utilities Commission
DER	Deep energy retrofit
DHW	Domestic hot water
ECM	Electronically Commutated Motor
ECM-1240	Energy monitoring device used to measure current, by Brultech
EER	Energy Efficiency Ratio
EERE	Energy Efficiency and Renewable Energy (Division of the DOE)
EF	Efficiency Factor (overall efficiency rating of hot water heaters)
EPS	Expanded Polystyrene
ERV	Energy (or Enthalpy) Recovery Ventilator
EUI	Energy use intensity (expressed in watts/m^2, watts/ft^2, or kbtu/ft^2)
GHG	Greenhouse Gas
GWP	Global Warming Potential
HVAC	Heating Ventilation and Air Conditioning
kWh	Kilowatt Hour
LBNL	Lawrence Berkeley National Laboratory
LED	Light Emitting Diode, an efficient type of lighting
LFG	Land Fill Gas
MELs	Miscellaneous Electrical Loads
MEP	Mechanical Electrical and Plumbing
NAHB	National Association of Home Builders
NARI	National Association of the Remodeling Industry
NEB	Non-energy benefits
NCC	NorCal Collaborative
NOAA	National Oceanic Atmospheric Administration
NYSERDA	New York State Energy Research and Development Authority
OSB	Oriented Strand Board, similar to plywood
PG&E	Pacific Gas and Electric Company
PHPP	Passive House Planning Package
PV	Photovoltaic (Solar Panels)

RECs	Residential Energy Credits
RECS	Residential Energy Consumption Survey
RESNET	Residential Energy Services Network
REMOTE	Residential exterior membrane outside insulation technique
RH	Relative Humidity
ROI	Return on Investment
SAP	Standard Assessment Procedure, retrofit for the future
SCHA	Solar Community Housing Association
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
SPF	Spray Polyurethane Foam
THC	Thousand Home Challenge
WAP	Weatherization Assistance Program
XPS	Extruded Polystyrene
ZNE	Zero net energy