Deep Energy Retrofits
Ten California Case Studies

By
Jeremy Osiris Fisher

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Committee in charge:
Professor Galen Cranz, Chair

Professor Gail Brager

Assistant Professor Duncan Calloway

Doctor Iain Walker

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Abstract

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This research documents and demonstrates viable approaches to deep energy retrofits (DERs) using existing materials, tools and technologies. A DER is meant to save 50% or more of the energy use in a home through extensive upgrades in the building enclosure, heating, cooling and hot water equipment, and often incorporates appliance and lighting upgrades as well as the addition of renewable energy. To date there are few DERs actually implemented, and even fewer have undergone controlled studies of energy end-use monitoring and analysis. Ten Northern California DER case studies are described in detail through first hand experience in co-managing the Lawrence Berkeley National Laboratory DER energy monitoring project. The qualitative descriptions are augmented by interviews with the homeowners, contractors and designers, followed by an analysis of the monitored energy data and building diagnostic test results.

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. Superinsulation and extreme air tightness, 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%. However, this strategy was shown to significantly reduce the heating energy, therefore allowing for greater variability in user behavior while still achieving deep energy savings. In most cases, the project goals of deep energy reductions were achieved. However, based on the current ecological climate, it is suggested that green house gas emission reductions should be one of the goals of DERs. 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.

Table of Contents

Table of Figures

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1 INTRODUCTION

To date there are few deep energy retrofits (DERs) actually implemented, and even fewer have undergone controlled studies of energy end-use monitoring and analysis. Ten Northern California DER case studies are described in detail through first hand experience in co-managing the Lawrence Berkeley National Laboratory (LBNL) DER energy monitoring project. The qualitative descriptions are augmented by interviews with the homeowners, contractors and designers, followed by an analysis of the monitored energy data and building diagnostic test results. The given case studies show how these ten DERs are designed, built and used, while identifying components of each retrofit that were effective, and those that were not. The research analyzes how design, construction and user behavior influence energy performance, and how additional non-energy benefits such as comfort, health and life safety are addressed. Additionally, the research provides clarification on the difference between site energy savings and the reduction of green house gas emissions. The ultimate objective is to provide recommendations for developing guidelines for future DER implementation based on monitored energy performance data and analysis.

2 BACKGROUND

In 1943 Winston Churchill stated, "First we shape our buildings, then they shape us." Based on years of research on existing buildings and how they are used, Stewart Brand modified the quote to: "First we shape our buildings, then they shape us, then we shape them again-ad infinitum" (Brand 1995). Brand highlights the importance of planning for renovations, as they are an intrinsic part of the human dwelling experience. Buildings have been renovated, re-purposed and re-used throughout human history, evolving together with the occupants to better fit their needs.

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 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 code. 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, 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 these 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. Finally, it looks at barriers to achieving deep energy savings. This literature review is meant to provide a 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 (W. H. Stern 1957) (Ennis 1956). 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 crises 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, 2011). 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 and Rinaldi 2010).

Goldman (1985) compiled building performance data from 115 retrofit programs across America. 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 was 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” (ibid, 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 (Hirst, Goeltz, and Trumble 1987). The measures were focused on improving the building shell and water heating system, no heating or water heating equipment was replaced. The resulting energy savings averaged 15%, but had been predicted to be greater than 50%. 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 (ibid).

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, that often rely on partial annual utility bills or energy data, and without 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 did not include the majority of the heating and hot water energy from natural gas. Furthermore, each of the individual programs performance metrics is not consistent 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 inaccurate.

There is a vast discrepancy between the predicted savings based on "technical potential", and the actual savings achieved. Retrofit programs have not typically sub-metered 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 the traditional retrofit programs were not systemic approaches to save energy, but 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 today requires a 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 also fail to report actual measured whole house energy reductions. Despite this, the concept is key in order to save more energy through retrofits than has been achieved in 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. The report also emphasizes 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. Both the achieved savings and reporting methodology has been criticized in the literature, especially in comparison to the technical potential. The programs that have monitored their energy performance do not use consistent reporting metrics, and have consistently 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 Obama administration has revitalized government support for energy efficiency and invested significantly in the potential of 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 are enabling states, municipalities, and utilities to expand and develop large-scale retrofit programs, 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).

On the state level, California's Assembly Bill (AB) 32 and the associated Long Term Energy Efficiency Strategic Plan (CPUC 2008) is an attempt to dramatically reduce energy consumption and green house gas emissions over the next 40 years, and have become a driving force behind statewide funding for retrofits and energy efficiency. Besides ARRA funding, the California Public Utilities Commission (CPUC), who regulates privately owned utility companies, helps fund energy efficiency programs and research through Assembly Bill 1890 (September 2006). The electric Public Goods Charge and the natural gas Demand Side Management charge fund CPUCs energy efficiency programs; both surcharges are applied to each utility customers bill and amount to approximately 1% of the electricity and 0.7% of the gas bills. The CPUC authorized $3.1 billion in funding for energy efficiency programs for the 2010-2012 program cycle (California Public Utilities Commission 2007). That is 60% of what the federal government allocated for the entire country through ARRA in 2008. California is ahead of the curve in energy efficiency.

The revitalized federal, state and local utility support for energy efficiency in existing homes is refreshing to say the least. However, significant obstacles to drastic energy reductions in housing remain. There is a frenzy of cities, organizations, and contractors who are trying to get their hands on the money, and such an abrupt charge to the finish line is bound to cause some less than desirable outcomes, especially if not everyone knows where the finish line is or how we will get there. Without proper experience and training, a retrofit can in fact create unhealthy conditions in buildings, for example, mold and moisture issues. 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, it is proving to be very difficult to actually get people to participate, and recent 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 green house gas emission reductions, far greater savings are needed. Much deeper energy savings have been proven possible through what are now known as Deep Energy Retrofits (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 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 non-profit group, Affordable Comfort, Inc. (ACI) has been raising awareness through their *Thousand Home Challenge* (THC) initiative, which aims to get 1,000 homes across America to save more than 70% of their energy through DERs. The THC 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 $48,000 for homeowners performing DERs, and more if they meet Passive House, THC, or Zero-Net Energy (ZNE) 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 their behavior plays 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 superinsulated 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 (ibid).

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 1981b), *Superinsulated houses, a survey of principles and practice* (Shurcliff 1981a), *The Superinsulated Retrofit Book* (Argue and 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 President Reagan slashed funding for energy efficiency programs. 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

Engineers and researchers in Europe were not hindered by lack of government interest in the 1980's. The baton had effectively been passed to Europe. 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 $kWh/m^2/yr$ (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 air tightness tested below 0.6 air changes per hour at -50 Pascal 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 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 $kWh/m^2/yr$ (2.3$kWh/ft^2/yr$; 7925 $Btu/ft^2/yr$) and the air leakage, as tested with a blower door, can be up to 1 ACH_{50}. The program is currently in its pilot stage but IPHA has scheduled it to be fully launched by the end of 2011 ("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 (Herkel and Kagerer 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 combisystems 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. The average heat exchange efficiency was 84%. 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 additional 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 (ibid).

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 (ibid, 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 Projects 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 our 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. (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" (ibid, 1153). 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 (ZNE) buildings are the ultimate goal of the building industry in order to reduce green house 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 and 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 (ibid).

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 (ibid, 48).

2.3.3 DERs make a comeback in the United States

In California, the Pacific Gas and Electric Company (PG&E) performed a well-documented research project on DERs that began in 1990. The project was called The Advanced Customer Technology test for Maximum Energy Efficiency (ACT^2), and hypothesized that greater energy savings can 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, 1). The original idea was based on a claim from Amory Lovins that you could save 75% of the energy in a building for less than it would cost the utility to supply that energy. In order to test this hypothesis, PG&E funded the R&D, design, construction, monitoring and analysis of 8 different case studies in northern California. They used a very strict economic model to assess cost-effectiveness based on the cost of energy production and distribution (ibid). The project was therefore biased towards what made economic sense for the utility company, not for the customer. It was an experiment to see what utility companies could do with the money being spent on demand side management.

In addition to new commercial and residential construction, there were two residential retrofits completed in the ACT^2 project. The first was in Stockton, Ca. and was a 2,200-ft^2 single-story residence built in 1979 to Title-24 standards, which required R-19 ceiling insulation and R-13 wall insulation. The retrofit included a wide range of measures including a combisystem condensing water heater providing baseboard hydronic heating and domestic hot water (DHW), a super energy efficient refrigerator, all CFL lighting, and attic/fireplace/duct improvements. The home had a spa and pool and the ACT^2 team installed efficient pumps and a pilotless ignition device for the spa. Due to the fact that the home was already insulated in a relatively mild climate, and the strict use of the cost-effectiveness test described above, little could be done "cost effectively" to the building shell, so the only improvements were to increase attic insulation from R-19 to R-30, and seal several ceiling penetrations. Total energy savings, when weather normalized, was 54.2% of the energy that was being consumed by the home in the base case year (ibid, 6).

The second single-family home retrofit was in Walnut Creek, Ca. It was a 1,578-ft^2 single-story home built in 1969, prior to Title-24. Appliances were replaced with high efficiency modern equipment, and the additional measures included a combisystem baseboard hydronic heating and DHW with a condensing boiler, a combined refrigerator water heater, CFL lighting, increased attic insulation from R-19 to R-30 with a radiant barrier, exterior R-11 wall insulation, deciduous shade trees over west windows, insulated front door, conditioned crawlspace and an evaporative pre-cooled condenser. Weather-normalized energy savings of 51% were measured against the base case year (ibid, 8).

The goal of 75% energy savings was not quite achieved in either case study, but both demonstrated that whole-building integrated design is successful in producing greater cost-effective energy savings than had previously been considered possible, and serves as one of the first well-documented case studies on DERs. A few of the important lessons that the participants learned from this research include:

- Perform an energy audit prior to the design of a retrofit
- Establish budget prior to construction
- Assemble the appropriate design team for the project
- A better economic assessment would have been a simple payback or ROI, as opposed to avoided cost of supplying energy
- Only install reliable equipment from reputable companies
- Use an experienced and reputable contractor that is "bought in" and collaborating with the team from the beginning
- Installation of advanced and new equipment often requires additional time and money, and needs commissioning to function properly
- Commissioning is a necessary step in the process
- Operation and maintenance of a building requires a reputable service company and/or a manual for the building owners and operators to be able to control their building efficiently
- Energy performance models are accidents waiting to happen. It is a subjective exercise, dependent on the individual "turning the knobs' of the model. Calibration of models to match existing buildings monitored energy use helps eliminate errors, but is still prone to inaccuracies (ibid).

Unfortunately, the ACT^2 project got little attention and was not taken any further than the few published papers that were reviewed in this research. However, much can still be learned from these case studies and it is important to learn from previous attempts at deep energy savings.

In a review of existing DERs in the United States, Less (2010) identified a total of 24 projects. 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 energy models and predicted energy savings as opposed to monitored data, and even among these, the performance metrics varied greatly. 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 and Torcellini 2005, 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. 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 2010b). 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 2010b, 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 (J. Straube and 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 openly challenged by BSC (John Straube 2009a) (John Straube 2009b). This has been a somewhat heated debate over the last few years, threads of which are on various blogs and forums (Very Recent Passivhaus Article 2009) (Brinkley 2007) (Thoughts on Straube's 2nd Passive House article 2009). Straube started the debate by criticizing certain aspects of the standard, particularly the climate independent energy targets, the cost effectiveness of these performance requirements and the constraints that these put on designers without necessarily delivering lower energy consumption compared to other methods. He also argues that similar performance is achieved in a number of Building America case study homes and DERs that were easier and less expensive to implement. Not only BSC, but also members of the Florida Energy Center and other groups have expressed concern about this as well. Straube challenges the Passive House dogma in order to spark a conversation about the science and philosophy behind the standard. He was met with a lot of anger and intensity from the Passive House community, which has still not been effectively resolved.

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.

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 the fearless 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 square footage, occupancy and zip code (Wigington 2008). The kWh value returned from this spreadsheet reflects what the designers of the 1000 Home Challenge think would be extremely low energy usage for the home. 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. The research for this report was a response to the first meeting of the NCC, hosted by PG&E in San Francisco. 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 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. All of the case studies in this report were funded by the homeowners and although California is usually ahead of the curve on energy efficiency, especially in the residential sector, the NCC, and the CPUC need to follow the lead of Massachusetts, New York and England by funding and studying many more DERs.

2.4 Barriers

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 nation wide? 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 entire way of life must be changed. This is the most important and challenging barrier to achieving deep energy reductions. Additionally, there are very real economic challenges, as most DERs cost around $100K, and 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.

2.4.1 Consumer

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 in 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.

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" (Energy and Savings 2005). While others have emphasized the difference between energy efficiency, which "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, which 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, as both approaches to saving energy are necessary in order to achieve deep energy savings. The former is technology based, and the latter is primarily a result of human behavior, although technologies such as occupancy sensors and programmable thermostats can also help reduce energy consumption. The majority of retrofits have been focused on reducing heating, cooling and DHW energy through technological solutions, but in order to reduce green house gas emissions, we must accept that "whole house energy" must be saved, including all of the plug loads and occupant based energy consumption.

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 (M. Moezzi and 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).

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. 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, including computer and entertainment systems (EERE 2008). The trend in the United States towards larger homes with far more appliances and services that are constantly consuming energy represents an increase in material and energy consumption, resulting in rapidly increasing green house gas emissions from the residential sector.

Low Energy 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 (Stern 1985, 3). 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 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 green house gas emissions related to residential end-uses (Koomey 1996) shows that MELs are the single most important area in the building sector for reducing green house gas emissions. MELs are the fastest growing end-use in our homes, and are expected to double in the next 20 years (Parker, Fairey, and Hendron 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 and Eastment 2006). The more efficient a home gets in regards to space conditioning and hot water heating, the more important these MELs become.

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 2010). These advancements are very important and have proven to be quite successful in improving efficiency. 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:

- Enabling computer power management
- Manually unplugging devices that draw standby power when not in use
- Manually turning off devices that are left on but not used
- 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
- 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 600kWh 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 (2). 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 (ibid, 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, Fairey, and Hendron 2010). Therefore, MELs are even more important to address in milder climates.

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 Conference 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 AB32 in California.

2.4.2 Economics

The cost of DERs is an obvious barrier for widespread implementation. In order to adequately assess the issue, it is important to put a DER within the context of a home remodel, and the fact that few homeowners renovate their kitchen or bathroom based on a payback period. A DER is an expensive undertaking. Actual costs depend on local labor rates, condition and age of existing building, size, goals of retrofit etc. However, costs of projects reviewed rarely fall below $100K. As the up-front cost of a retrofit is most often the driving decision maker for the majority of Americans, the expense must be addressed if DERs are going to be implemented on a large scale.

At this time, an energy retrofit featuring air sealing and super insulation cannot compete with the 'sexiness' of a major kitchen or luxury bathroom renovation, even though they can be similar in costs (Henderson and Mattock 2008). However, 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 indoor environmental quality, health and safety, acoustics, convenience and reduction of greenhouse gas emissions. Therefore, in order to adequately assess the economics of a DER, these NEBs must be quantified in terms of their economic value to the homeowner.

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 (iv).

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 and 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 up front 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. 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. Their 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 are great examples of this.

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, and \$133K was the most expensive. However, they only funded the energy efficiency upgrade portions of the retrofits, averaging \$32,000 per home (National Grid 2011). 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 (ibid). 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.

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, 2).

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 green house gas emissions, 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.

In Germany, the costs of Passive Houses are now understood to be cost effective when looked at the entire lifecycle of a building, and are expected to become more cost effective as market penetration increases: Material and equipment costs will be reduced due to demand and the industry will become more familiar with the construction methods, also reducing labor costs (Herkel and Kagerer 2011, 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 (ibid).

2.4.3 Industry

The third and final barrier to widespread DER implementation is the AEC industry. The fundamental problem is a lack of experience in producing very 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. At this time, there is actually an incentive for contractors to produce inefficient, cheap homes; the faster the job and the cheaper the materials used, the higher the profits realized. 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 green house gas emissions through DERs, we need to develop trainings 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 three areas of focus for successful implementation within the AEC industry: Simple design, high quality construction practices and good building science.

<u>Simple Design</u>
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, superinsulated home in Saskatchewan, Canada – 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 first hand 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 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, 11). 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 iteration, 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) and the National Association of the Remodeling Industry (NARI) both have educational programs, including excellent green building certification programs that are integral to DERs. 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, for example, is currently not addressed by BPI, but 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, it should be illegal not to perform a QII, and the service should not have a cost premium. 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 the drastic energy reductions to which California has committed. Improvements in air tightness have a tremendous effect on overall heating energy use and have been heavily documented throughout the literature (Ueno 2010, 14) (Wray et al. 2002) (I. S. Walker and M. H. Sherman 2003). Despite this, few architects specify air tightness 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. Air tightness 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, (J. Straube and 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, Leaman, and Ruyssevelt 2001, 154). Improved monitoring of energy use in homes that have been retrofitted is necessary in order get more reliable data for adequate performance evaluation and improvement.

2.5 Putting it all together

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 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. Furthermore, there is virtually zero information available connecting the GHG reduction goals of AB 32 and the energy saving goals of DERs. Therefore, this research aims to fill this gap by providing detailed methodology for end-use energy monitoring and reporting of ten DER case studies, including both site energy and GHG emission reductions.

3 STATEMENT OF THE PROBLEM

California passed AB 32 in 2006, committing the state to reducing green house gas 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). While many consider this drastic reduction necessary, how are we going to do it?

In 2009, the residential building sector consumed 22% of the United States annual energy (Residential Energy Consumption Survey (RECS) 2011). There is a growing trend to increase energy efficiency in homes through building codes and standards; California's Title 24 is a great example, having saved $56 billion in energy costs since its implementation in 1978 (California Green Building Strategy 2010). However, these codes and standards are geared towards new construction and there is currently no regulation of energy used 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 2011). Meanwhile, new construction is at an all-time low. Therefore, within the building sector, our existing building stock is where both energy efficiency and energy conservation will have the greatest impact in helping us achieve our challenging energy and carbon reduction goals of AB 32.

Weatherization and energy efficiency retrofit programs have proven that 10 - 20% energy savings in existing homes is easily attainable (Goldman 1985) (Fuller et al. 2010). However, in order to meet AB 32 in California, the Scoping Plan explains that our existing buildings will have to be 40% more energy efficient by 2020, and net-zero energy by 2050. It also plans to monitor the performance of selected low energy homes, and achieve 70% energy reductions from 2008 levels in 25% of the existing homes in California by 2020 (CPUC 2008). The Federal government has also recognized the importance of drastic 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 what has historically been achieved in weatherization and retrofit programs.

The goals set out before us are not going to be easy to achieve. 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 understood in the industry, and is essential in order to meet the goals of AB 32.

4 SIGNIFICANCE

A Deep Energy Retrofit (DER) is the 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 (Lubeck and Conlin 2010, 3). The Affordable Comfort Institute (ACI) sets the bar even higher by defining a DER as 70% 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 began the Thousand Home Challenge (THC) initiative, where they plan to get 1,000 homes across America to meet the challenging goal of 70% energy savings.

California's AB 32 has committed the state to a Zero-Net Energy future, requiring us to make drastic changes to our current patterns of consumption. As shown above, the greatest potential for drastic energy reductions is in our existing building stock. Real metrics and methods for monitoring and reporting site and source energy, as well as GHG emissions are needed in order to provide informed guidance for successful implementation.

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, ten DER case studies have been equipped with energy monitoring equipment. The analysis that follows includes data from the continuous monitoring of the total gas and electricity used by each occupied home, together with measurements of individual end-uses, giving an in depth analysis of how and where energy is being saved and consumed, and whether or not they are meeting their goals of deep energy reductions.

5 METHODS

This research is a mixed-methods analysis of ten DER case studies; it combines both qualitative project descriptions and quantitative analysis of monitored end-use energy data. Each home in this study has undergone a series of building diagnostic tests to characterize the home. For long-term testing, each home was equipped with both gas and electricity end-use monitoring equipment. The diagnostics quantify the construction quality of each home based on two parameters – air leakage and thermal performance. Air leakage is quantified by a blower door test, and thermal leakage is demonstrated using infrared thermography. Whenever possible, monitored whole-house energy data is converted into kWh and compared to pre-retrofit energy data from utility bills. User behavior is examined using the monitored data in several ways including baseline energy use and discretionary energy uses. The diagnostic and long-term monitored energy performance data, combined with qualitative descriptions and analyses of each case study, results in a thorough documentation of the cause and effect of deep energy savings in these homes. The methods for data acquisition and analysis are described in detail below.

5.1 LBNL DER Research Project Definition

This research is based on the ongoing LBNL DER research project presented in the introduction. The objectives are to measure the energy consumption of ten case study homes, and to break down their energy consumption into end-uses. Continuous monitoring of the total gas and electricity used by the home, together with measurements of individual end-uses, including space heating and cooling, water heating, ventilation systems, appliances, plug loads, and lighting, yields an in-depth analysis of how and where energy is being consumed. Temperatures and relative humidity were also measured in the occupied spaces. All homes are occupied during the monitoring period of up to two years. The end result is to provide recommendations to the U.S. Department of Energy for developing implementation guidelines for DERs.

There has been very little continuous monitoring of the energy used by deeply retrofitted homes, particularly end-use breakdowns that allow the identification of components of the retrofit that were effective, from an energy stand point, and those that were not. The energy monitoring methods develop in this research adds substantially to the existing body of knowledge and make it much easier for future deep energy retrofit studies to be undertaken on a larger scale.

5.2 Case Study Selection Process

The test houses were selected as a sample of convenience from volunteers. The initial list of volunteer homes was compiled over several years from homeowners who are interested in having low energy homes. The volunteers found out about LBNL's work on residential energy use by attending seminars and presentations given by the Principal Investigator, Iain Walker, and other LBNL staff, or working directly with LBNL staff on other projects, and by recommendations from other volunteers. In addition, volunteers were solicited through ACI, NCC, The Passive House Institute, Bay Area Build it Green and personal contacts of the researchers. The criteria for house selection were based on the characteristics of the retrofits and the timescale of the study. This study targeted homes where deep retrofits had been undertaken before June of 2011. The homeowners paid for their retrofits and LBNL staff came in after completion in order to install the monitoring equipment.

The case study homes have gone through diagnostic tests of envelope and duct leakage combined with home characteristics collected by measurement, observation, and construction documentation. After a home was deemed a feasible case study based on phone conversations and/or a review of construction documents, an initial site visit was conducted. 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.

If the initial site visit demonstrated retrofit techniques that could feasibly achieve 50% or greater energy savings, and the homeowner agreed to participate, then they were sent an LBNL "Consent To Participate in Research" Form. Upon receiving the signed consent form, and coordinating with the contractor, if necessary, the diagnostic testing and energy monitoring equipment installation was scheduled with the homeowner.

The ideal project had a minimum of one-year pre-retrofit utility bills in order to calculate the savings associated with the retrofit. However, for an array of reasons, only three of the ten case studies could actually acquire the pre-retrofit utility bills. For these homes, the average annual energy use of a California single-family home was used.

The most challenging aspect of this process was actually finding ten viable case studies. Initially far more than ten homes were selected by the research team as feasible case studies. However, upon further investigation an array of challenges deemed the projects invalid, including:

- *Location*
  All projects needed to be within a few hours from Berkeley, Ca., as the researchers had to do the diagnostics and equipment installation, as well as potential site visits during the monitoring period. A number of projects were found both outside of California, as well as in Chico, Redding, and Los Angeles, which were too far of a distance to travel for the purposes of this research.
- *Would not achieve 70% savings*
  Although the actual savings cannot be known prior to monitoring, two projects opted out of participating because they had been monitoring their energy use, or tracking utility bills, and found that they did not reach the required savings. In actuality, if the project saved 50% we were still interested, but these projects chose not to participate.
- *Schedule*
  Two projects could not be included as the design phase was still incomplete, and the actual retrofit would not be completed within our time frame.
- *New Construction*
  Many projects which are implementing the high level of energy efficiency measures needed to achieve the required savings are actually new homes, or have modified the original building so much that they could not be included in our study.
- *Budget*
  On one occasion a project fell through because the homeowner decided that the deep energy savings were too expensive to actually go through with, and a less aggressive retrofit was carried out.

Due to the difficulty in finding enough DERs in the area, getting ten projects up and running took longer than expected. The first energy monitoring equipment was installed in August 2010, and the final installation was completed in October 2011. Therefore, this report will not include a full year of monitored data for most of the homes.

5.3 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 Goals

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
- 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 intimately interested in their energy use patterns and are actively seeking ways to reduce their consumption; access to this data at no cost increased probability of 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 set-up 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., and as a result, minimal data loss occurs.

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, 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 are definitely 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 selected electricity meter and data logger is *Brultech Research Inc., ECM-1240 Multi-Channel Wireless Home Energy Monitor*; see Appendix A for detailed specifications of all energy monitoring equipment. Each meter has seven data channels. 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, the *Elster AMCO G4 200CFH Gas Meter with pulse output* was installed. The meter 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.

The temperature and relative humidity is monitored using *Onset HOBO Temperature/Relative Humidity Sensors.* These are very small (2.5" x 3") stand-alone sensors that are placed in inconspicuous locations in every house; typically each project has two sensors, providing data for different zones. The T/RH is sampled every 12 minutes, based on storage capacity of the device, at this resolution the data must be downloaded and then the device is re-launched every six months. The .csv data is exported via USB connection to a computer. Thus far these devices have performed extremely well and have not lost any data. The only problem we had was user error in that we set one of the devices to record temperature only, and did not check the box for relative humidity, but only found out upon downloading the data six months later.

Set-Up and Communication Procedure

The monitoring equipment set-up 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 sub-meters were connected to the gas appliances. The CTs and pulse counters were then connected to the energy monitor – the *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.

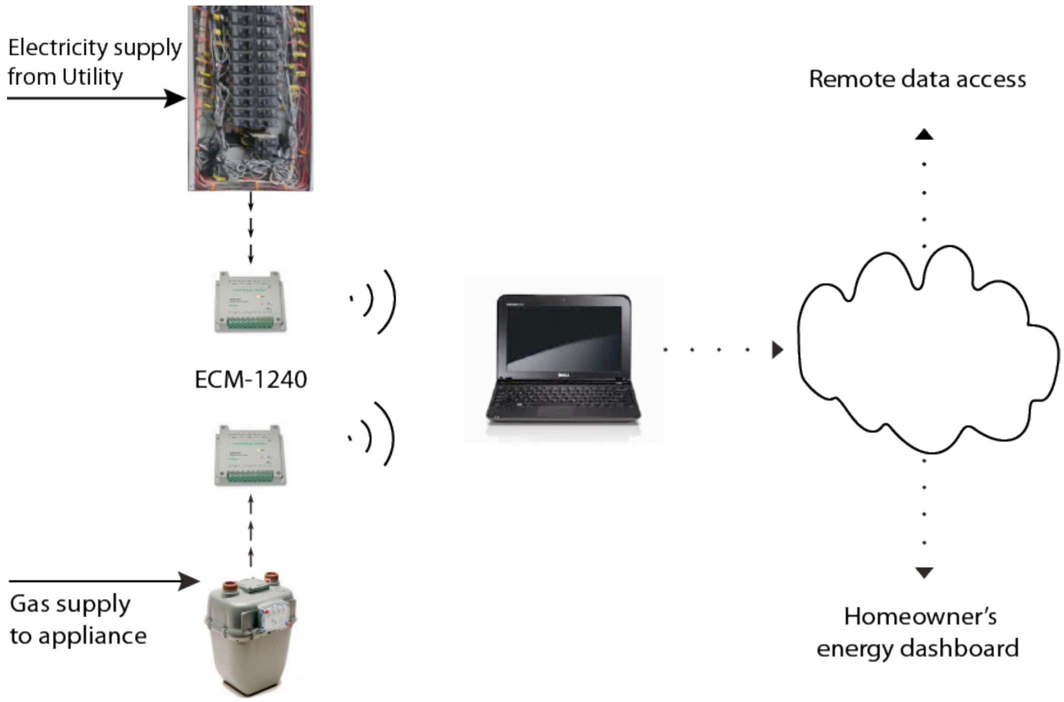


Figure 1 - Communication Schematic

During initial set-up, each channel must be configured based on the number of circuits and size of CTs, or if pulse counting is necessary, this must be specified. The computer runs 24-7 with the *Brultech Engine G* software application that decodes the data packets sent from the monitoring devices. All data is stored in an sqlite3 database on the laptop hard drive. Data was originally exported from this database in real-time 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 small company called *Check-It* (Check-It Solutions 2008).

5.4 Qualitative Data Collection and Analysis Methodology

Careful descriptions of each case study are a very important aspect of this research. In order to learn what works and what does not in these DERs, we must thoroughly understand the goals of the client, the design intent, the construction process, and the materials and construction methods used. Each home has a unique story to tell, and these stories can help inform future DER enthusiasts. Without this, the monitored energy use data is devoid of meaning, as there would not be any basis for understanding the results. Therefore, a significant portion of this research has been to account for all aspects of the retrofit as accurately as possible through site visits and first hand observations, as well as semi-structured interviews (See appendix B for interview guide), and un-structured communications regarding each project with the homeowners, architects, engineers and contractors that were willing to engage in the research.

The results are reported in the "Project Description" section of the findings. Each project, P1 through P10, is introduced with a general description and then broken down into the major retrofit components of: building enclosure, heating ventilation and air-conditioning (HVAC), domestic hot water (DHW), appliances, plug loads, lighting and renewable energy systems. Additionally, a summary table for each project's pre- and post-retrofit measures is provided in the Discussion chapter.

The project descriptions are important for understanding the uniqueness of each project, as well as providing a basis for the monitored energy results. Every project had very different goals, budgets, designers, contractors and users. The subjects in this case are the homeowners, contractors and designers. All subjects were contacted after the retrofit was completed, except for P6 and P7, so the research had no influence over the retrofit measures taken in each home. The qualitative descriptions are from first hand 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 there wasn't sufficient information recorded regarding their pre-existing condition.

5.5 Building Diagnostics

Building diagnostics are a series of tests used to qualitatively and quantitatively assess building performance, including the building enclosure, HVAC system, and IAQ. Most existing buildings get their ventilation from air infiltration through the building enclosure. However, one third to one half of the space conditioning energy has been claimed to be due to air leakage to outside through the building enclosure and ducts (M. H. Sherman and Matson 1997), which has proven that making tighter buildings and controlling the ventilation to meet IAQ requirements such as ASHRAE 62.2 creates healthier buildings and reduces space conditioning energy use. Due to this, all low energy buildings now aim for minimum air infiltration; therefore, testing for air tightness can also give insights into construction quality, and help locate leakage pathways that could be sealed for further reductions in envelope leakage.

In each deep retrofit project home, diagnostic tests of building enclosure air leakage, duct leakage and ventilation flows were carried out. Ideally, these tests would be carried out both before and after the retrofit process in order to assess changes in envelope air tightness 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. In these homes, other parties such as home performance contractors and energy consultants sometimes carried out blower door depressurization and other tests. If available, we used those results for comparison, but in a number of cases no assessment was made prior to retrofitting, so no comparison is available. 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. As a result, this report will not focus on IAQ or ventilation flow diagnostics, but instead relies on the blower door and duct leakage tests as well as IR infrared thermography to assess the construction quality of each home.

Description of the Tests Performed

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. A number of performance metrics are attainable from these test procedures, for the purposes of this research, the following metrics will be reported:

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

The multi-point blower door depressurization test uses a blower door to measure airflow at a number of different house-to-outside pressure differentials. A least-squares analysis is then used to fit this pressure-flow data to the power law flow equation below, which is adjusted to measure flow through an orifice with the pressure exponent n = 0.5.

$Q = C\ (\Delta P)^n$

This fit provides the leakage coefficient (C) and the pressure exponent (^{n}), which are then used to calculate the airflow (Q) in cubic feet per minute (CFM) at exactly 50 Pa. This value is then converted to ACH_{50} using the volume of the house (V_h) and multiplying by 60 minutes.

$ACH_{50} = Q(60)/V_h$

Q/ft^2_{SA} is used to evaluate construction quality in regards to air tightness, and normalizes the ten case studies to eliminate bias due to house size.

ELA is used to measure the "effective leakage area" by quantifying the leakage area orifice in square inches, and nACH represents the natural air changes per hour, meaning how many times the air volume of the house is replaced under natural conditions. The methodology for quantifying these values has been developed at LBNL, for more detailed information see (M. Sherman 1995).

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. Distribution system leakage is a key factor in determining energy losses from forced air heating and cooling systems. 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 then plugged into a model that is used to calculate the duct leakage to outside (Dickerhoff, I. Walker, and M. Sherman 2004, 1).

IR camera thermography was used to assess thermal leakage through the building enclosure. 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 and 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.

5.6 Quantitative Data Collection Methodology

<u>Data Acquisition and Lessons Learned</u>

The free software program *LogMeIn* is used to log into the on-site computer from any location with an Internet connection. Through *LogMeIn*, raw .csv data files are exported from the database twice monthly on the 16th and the 1st of each month. These files are saved on the site-laptop and on an LBNL web-based data storage site, and they are downloaded and stored on an external hard drive and a desktop PC at LBNL.

The data collection process was not always easy. Once the challenging set-up process was complete, each project computer had to be checked several times a week in order to confirm that data was in fact being recorded, and that the data actually made sense. There were times when the energy monitors dropped data for various reasons such as:

- Computer crashed (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
- Wireless signals were not consistently received due to obstructions between the computer and the monitor, requiring a wireless repeater to be installed.

Or, there were also instances when either the electrician changed the layout of the circuits so our settings were wrong, or we connected a CT wire on the wrong channel, leading to incorrect data. In these cases we had to go to the home and move wires or CTs around in order to correct the problem.

Half of the homes in the study have PV; therefore their electrical meters are Net-Meters, meaning they move both forward and backwards. The data collection software was able to account for this as well as monitor total consumption, as opposed to just net-electricity consumption, which was necessary for our energy use reporting goals.

The natural gas data was collected using a sub-meter at all but one of the gas appliances in the home. Since the sub-meters were expensive and required several hours of labor to install, the utility bills were used to get the total gas consumption per month, and then subtract out the sum of all other sub-metered data to get the remaining appliance monthly gas consumption. However, utilities bill in the very low resolution units of Therms, and our meters measure in cubic feet, and the billing cycles don't fall on the first and last day of the month, but seem to vary throughout the year. So, because a Therm contains roughly 100 cubic feet of natural gas, a client might get billed for 6 Therms even though they used anywhere from 601 to 699 cubic feet. Due to this margin of error, using the subtraction method on a monthly basis could result in a negative number for the gas use (in cubic feet) for the un-monitored appliance. On an annual basis, this error is reduced to an acceptable level, but the monthly end-use is inaccurate. Unfortunately, this was something we did not fully understand until the monitored data was analyzed and then combined with the gas bill data.

Another challenge encountered in the gas end-use monitoring was in regards to combisystems. A combisystem supplies both DHW and space heating using a single water heater. Three of the ten homes had these systems and with the selected monitoring equipment it was not possible to disaggregate these two loads. In order to do so, the monitoring equipment would have had to be much more complex and would require an entirely different set up, including water flow meters and temperature sensors. So for these systems we are only monitoring the gas use of the boiler, which supplies both DHW and space heating.

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. Utility bills are not good sources of data. Ideally the use of utility bills would not be necessary for data collection, but in this research they were used to subtract the sub-metered data from in order to find the unmonitored gas appliances annual energy use.

The wiring of the electrical panel governed to what extent we could separate our loads. Some of the homes were old and had completely mislabeled breakers, and others were very well organized and separated for each end-use, resulting in variation of what loads were separated out in each project home due to existing site conditions. Additionally, each monitor has seven data channels, and each channel can handle up to four CTs; therefore similar loads were often combined onto one channel. What could not fit onto the monitor was calculated using the subtraction method similar to what was described above with the gas loads. The sum of all monitored loads would be subtracted from the whole house electricity, and the result would be the unmonitored loads. 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. This creates less room for error and requires less work during the data analysis process.

Eventually all project homes were collecting data without any issues, although some homes seemed more prone to problems than others, usually computer crashes. Each of the two-week files contains over 22,000 rows and 14 columns of data. The first few months were spent combining each of these massive spreadsheets into monthly end-use files, which were too large to effectively use. In order to facilitate monthly and annual data analysis, the .csv- exporter software was modified by the manufacturer to calculate hourly averages from the database; this created smaller files for quicker analysis of longer time periods and saved a lot of time. Additionally, a few macros in excel were created to deal with sections of missing data and combine the hourly data files into monthly totals for quick monthly end-use analysis. These two modifications saved hundreds of hours of work.

5.7 Quantitative Data Analysis Methodology

The collected data was analyzed in order to provide insights into how DERs are being used, what retrofit techniques are working, and which ones are not. Due to time constraints, unfortunately not every home has a full year of monitored energy use in this report. Energy end-uses are categorized based on the electrical circuit layout of each home and similar loads are combined to simplify data analysis. Whole house gas and electricity is also analyzed and both are reported in kWh for the simplicity of using one equivalent unit of energy. The metrics used to evaluate whole house energy consumption is an important topic of discussion. Depending on whether energy use intensity (EUI), energy per house, energy per occupant, site or source energy, or a carbon metric is used, each of the case studies ranks differently. As a solution, all necessary information is provided in order to extrapolate any desired metric for those homes that have an entire year of monitored data.

Monthly Energy End-uses

The collected end-use data was exported from the sqlight3 database into a .csv format providing hourly averages that were then run through an excel macro that combined these hourly averages into monthly kWh totals for each end-use. The hourly average data simplifies the monthly and annual energy end-use analysis and is presented in the form of line graphs and pie charts. The raw data has a resolution of ten seconds and can be used for a range of different analyses. For this report, it was used to calculate each projects baseline energy use.

User Behavior

In order to analyze behavior based energy use, annual energy end-use pie charts are presented for each case study. User behavior can best be examined by quantifying discretionary energy use. Discretionary energy use normally includes all plug loads, small appliances, and everything that does not fit into the space conditioning, DHW, major appliances or lighting end-use categories. However, although the occupant controls lighting energy and it is a necessary end-use, the level of energy used for lighting can also be greatly reduced through efficient fixtures and careful management. Therefore, this report will examine discretionary energy use by showing the percentage of energy used by each end-use, and the reader can decide whether or not to include lighting.

Additionally, in the mild climate of the San Francisco Bay Area, one could argue that space conditioning is in fact a discretionary energy use. The thermostat set point is indeed controlled by the user and can be adjusted to conserve energy if so desired. In order to assess this, the monitored interior temperatures of each home will be shown in conjunction with the heating energy.

The energy being consumed when no one is home or actively “using” the home is known as the electric baseload. 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. The baseload is presented as the 5^{th} percentile of whole house electricity use in Watts. In other words, 95% of the time the electrical load is greater than the baseload.

Each project had a different number of observations, or data points of whole house electrical load averaged over one hour. Therefore, the calculated baseload and the number of observations are given for each project.

Whole House Energy Use

Whole house gas energy from utility bills, and monitored whole house electricity data is combined for each home, showing total monthly kWh of gas, electricity consumption and electricity production from PV if applicable.

For the projects that had a full year of monitored data, annual energy use was compared to the pre-retrofit utility bill data when available. This is a preliminary comparison; in order to accurately compare pre/post-retrofit data, it should be weather normalized using the closest National Oceanic Atmospheric Administration (NOAA) weather station. By normalizing all space conditioning loads based on heating degree-days, climatic biases are eliminated, resulting in a fair comparison of energy consumption. However, approved NOAA data for these homes is not yet available for 2011, and the weather normalization will happen for the final DOE report once a full year of monitored data for all ten projects has been collected, and the approved NOAA data for 2011 is released.

Source Energy and Carbon Equivalent (CO_{2e})

When comparing energy use from a societal point of view, or if we are interested in CO_2 production as well as overall energy use, we need to convert site energy to source energy. Site energy is helpful in understanding the performance of the home but source energy is often a better choice for making policy decisions (such as utility subsidies for energy efficiency measures). Roughly $^1/_3$ of our electricity is lost between the production at the power plant and the end-use in the home (Deru and Torcellini 2007). The associated environmental impacts of this difference, including green house gas emissions, is important to understand in the context of this research and in the goals of reducing green house gas emissions through DERs. Changing fuel mixes and time of use also changes the conversion factor from site to source energy. However, based on extensive research (ibid), a factor of 3.095 will be used for converting California site electricity to source energy, and a conversion factor of 1.095 for natural gas site to source energy.

For projects with an entire year of monitored energy use, the total green house gas emissions (GHGs) of the energy used in each home is given using the carbon equivalent (CO_{2e}) metric developed by Deru and Torcellini (2007), as well as (U.S. EPA Office of Atmospheric Programs 2011).

> GWP is an index that describes the radiative characteristics of well-mixed greenhouse gases. It represents the combined effect of the times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide (CO_2). GWP is an index for estimating the relative global warming contribution of atmospheric emissions of 1 kg of a particular greenhouse gas compared to emissions of 1 kg of CO_2. This document uses the following GWPs based on a 100-year time horizon: 1 for CO_2, 23 for methane (CH_4), and

296 for nitrous oxide (N_2O). The equivalent CO_2 emissions are calculated with these GWPs (Deru and Torcellini 2007, 2).

Based on the above research, CO_{2e} values specific to California fuel mixes in electricity production are used, resulting in 0.775 lbs. of CO_2 per kWh of delivered electricity. This includes the GHGs associated with the extraction, processing and delivery of the primary fuel to the power plant, as well as the electricity production, distribution and consumption. Natural gas is converted to CO_{2e} using the value of 0.12 lbs of CO_2 per ft^3 of gas used on site. This includes the GHGs in the fuel extraction, processing and delivering, as well as the CO_2 released on-site during combustion (U.S. EPA Office of Atmospheric Programs 2011).

Energy Performance Metrics

As mentioned in the literature review, there has been a poor track record of consistent methodologies in reporting energy performance in buildings. In addition to the complexity of the site vs. source energy, and CO_{2e} metrics explained above, there are multiple other metrics that can be used for reporting whole house energy consumption (Deru and Torcellini 2005). The energy use intensity (EUI), is often reported in $kWh/m^2/yr$, $kBtu/ft^2/yr$, or $kWh/ft^2/yr$, and is a very popular metric, but is biased in favor of larger buildings. For example, if the same amount of energy were used in a small house and a large house, the EUI of the large house would be smaller, yet the environmental impact is by no means smaller. Also, exterior surface area increases less than floor area so simple geometry implies that on a per square foot basis, there is a bias in favor of larger homes. Energy use per occupant is a very interesting metric as it reflects user-behavior. However, it tends to bias higher occupancy homes, and occupancy changes over time. Some of the other metrics being used are total house energy, and total energy costs, both often compare pre- vs. post-retrofit data, and sometimes a percentage savings. Energy costs are not a focus of this research, and as mentioned above, total house energy can be complicated: site or source energy, do you include pools and pumps and outdoor energy use, is pre-retrofit data available? The problem of consistent reporting metrics across all retrofit programs that was discussed in the literature review is therefore quite understandable, there is no simple and correct metric to use, and it depends on what you are trying to demonstrate. 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.

In response, the Building Science Corporation created something called the "Mileage Box" (Ueno 2010a), which is supposed to emulate the mileage sticker found on new cars. This energy label lists all of the necessary information to extrapolate any of the metrics listed above. This study uses the mileage box concept to show multiple ways of quantifying monitored annual whole house energy use. Our mileage box includes a CO_{2e} number, and all source and site electricity and natural gas used on the property, reported in kWh. Additionally, it lists the square footage and occupancy of the building. An example of the mileage box follows below.

PX (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Total CO_{2e}	Site Net-Electricity	Area
XXXX lbs	XXXX kWh	1,630 ft^2
Total Source Energy	Site Natural Gas	No. of Occupants
XXXX kWh	XXXX kWh	4

Figure 2 – The "Mileage Box"

6 FINDINGS

Each Deep Energy Retrofit (DER) is unique, varying significantly from one another, therefore challenging 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.

6.1 P1

Figure 3 - P1 Pre/Post-Retrofit

6.1.1 P1 Project Description

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 entirely uninsulated, 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 air tightness 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.

<u>Building enclosure</u>

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 extruded polystyrene (XPS) 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 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 faces.

Air leakage

The homeowner explains, "I was a Passive House pioneer in the Bay Area, so people thought I was crazy" he said, "and I was getting on everyone's nerves, including my friend who was the contractor. No one understood how important air tightness is, in Europe people understand the importance of air tightness, but here people are afraid of it and think it will rot their home" (P1 Homeowner Interview 2011). 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 home, like many Passive Houses, has an ERV providing whole house balanced, filtered ventilation. An ERV is an enthalpy recovery ventilator, now commonly referred to as an energy recovery ventilator. It is a heat recovery ventilator with an added feature of moisture recovery. In this product moisture is recovered through a rotating desiccant wheel. All bathroom and kitchen exhausts are ducted to the ERV located in the attic with foil faced R-6 insulated flex ducts. The exhaust air is then blown across a heat exchanger and the enthalpy wheel, where the fresh air supply from outside captures the heat and moisture of the exhaust air, returning it to the home via the supply ducts in every bedroom and the living room. This home has a total of five supply outlets and three returns.

The kitchen range hood in P1 is just a recirculation fan with a grease trap. Air is exhausted from the kitchen via an ERV return vent in the ceiling located adjacent to the cook top. There has been some speculation on the efficacy of this technique in removal of kitchen pollutants by various building scientists at LBNL. However, it is a recommended kitchen ventilation technique by the Passive House Institute, as there is a significant amount of heat produced in the kitchen that can easily be recovered. However, further research is needed to assess its effectiveness in removing indoor air pollutants and moisture.

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, very simple adjustable 500 Watt electric resistance baseboard heaters were installed in each room, resulting in a very inexpensive and reliable heating system, with 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 is not a big deal for him since his office is at home and he enjoys being directly involved with the heating energy use in the home. The downside is that the source energy used for electric resistance heating is a penalty in the Passive House requirements and is one of the reasons the home did not achieve Passive House certification.

Based on the interview, if given another opportunity, 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 he couldn't find anybody to help him figure out if it would work or not. The ERV manufacturer told him to make one himself (P1 Homeowner Interview 2011). 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. 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).

Appliances
All appliances are new and Energy Star labeled, including a gas range, 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

In an interview with the homeowner, he 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 net-zero energy without meeting the Passive House standard, it's hard to do better than net-zero."

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 happily 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.

6.1.2 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

Figure 4 - P1 Blower Door Results

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 6. Other structural systems, such as the steel "strong wall" (figures 7-8) used on both levels of the top and bottom, were visible, as was the steel bracket that holds the cable used to support the deck in figure 9. 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 10.

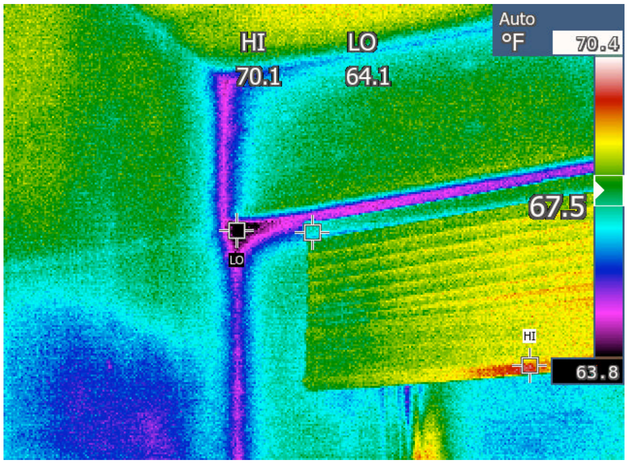


Figure 5– P1 thermal bridge at structural beam

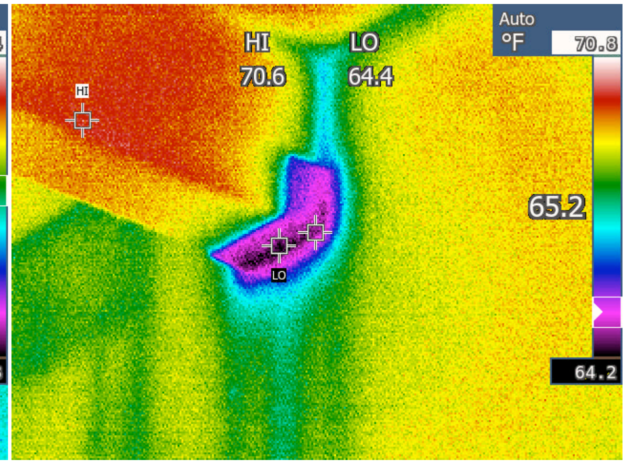


Figure 6– P1 thermal bridge at structural beam, metal bracket-cold spot

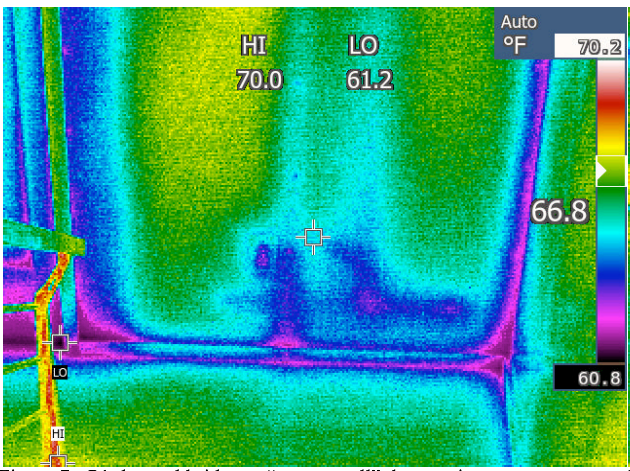


Figure 7 - P1 thermal bridge at “strong wall” downstairs

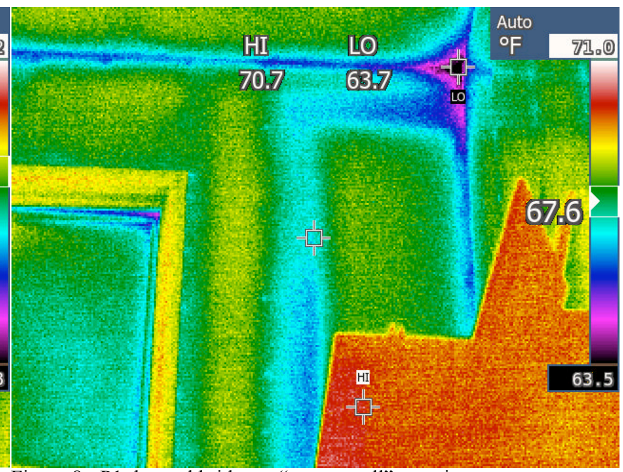


Figure 8 - P1 thermal bridge at “strong wall” upstairs

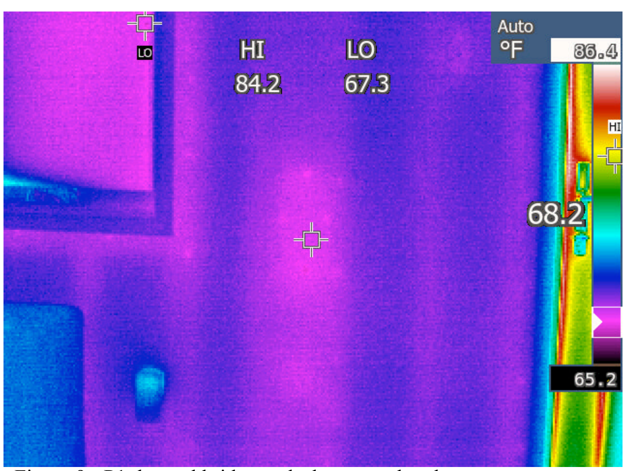


Figure 9 - P1 thermal bridge at deck support bracket

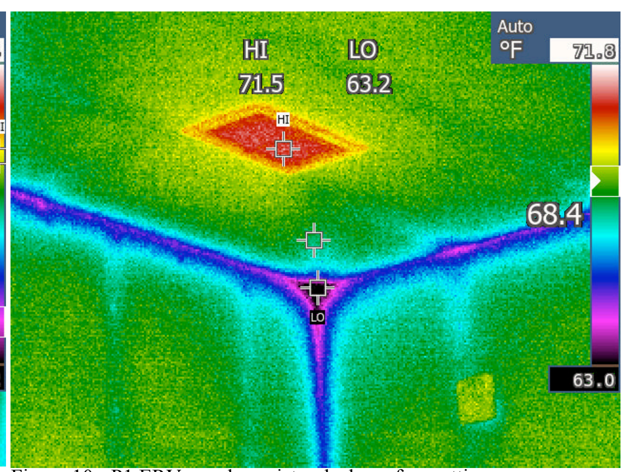


Figure 10 - P1 ERV supply register, leakage from attic

6.1.3 Monitored Data Results

Monthly End-uses

Figure 11 presents the monthly energy end-use data, and shows how DHW dominates the other end-uses. Additionally, the electric resistance heating system is being used far more than one might imagine for a Passive House. The high-resolution data reveals that the heaters are on for long periods of time and in most every room throughout the heating season, although the office and bedrooms downstairs are heated more than the kitchen, living room and master bedroom upstairs. Once the electric heating energy is converted into source energy, it will increase by a factor of 3. Also of note is the energy consumed by the ERV. Although not a large user, over the course of the year it used 946 kWh, or 10% of the entire site energy. The homeowner allowed us to install a very detailed array of monitoring equipment to evaluate the efficiency of the ERV and to find out if in fact the excessive fan energy is justified through the heat recovery in this climate, or not. We are still collecting data and the results will be published in a future paper.

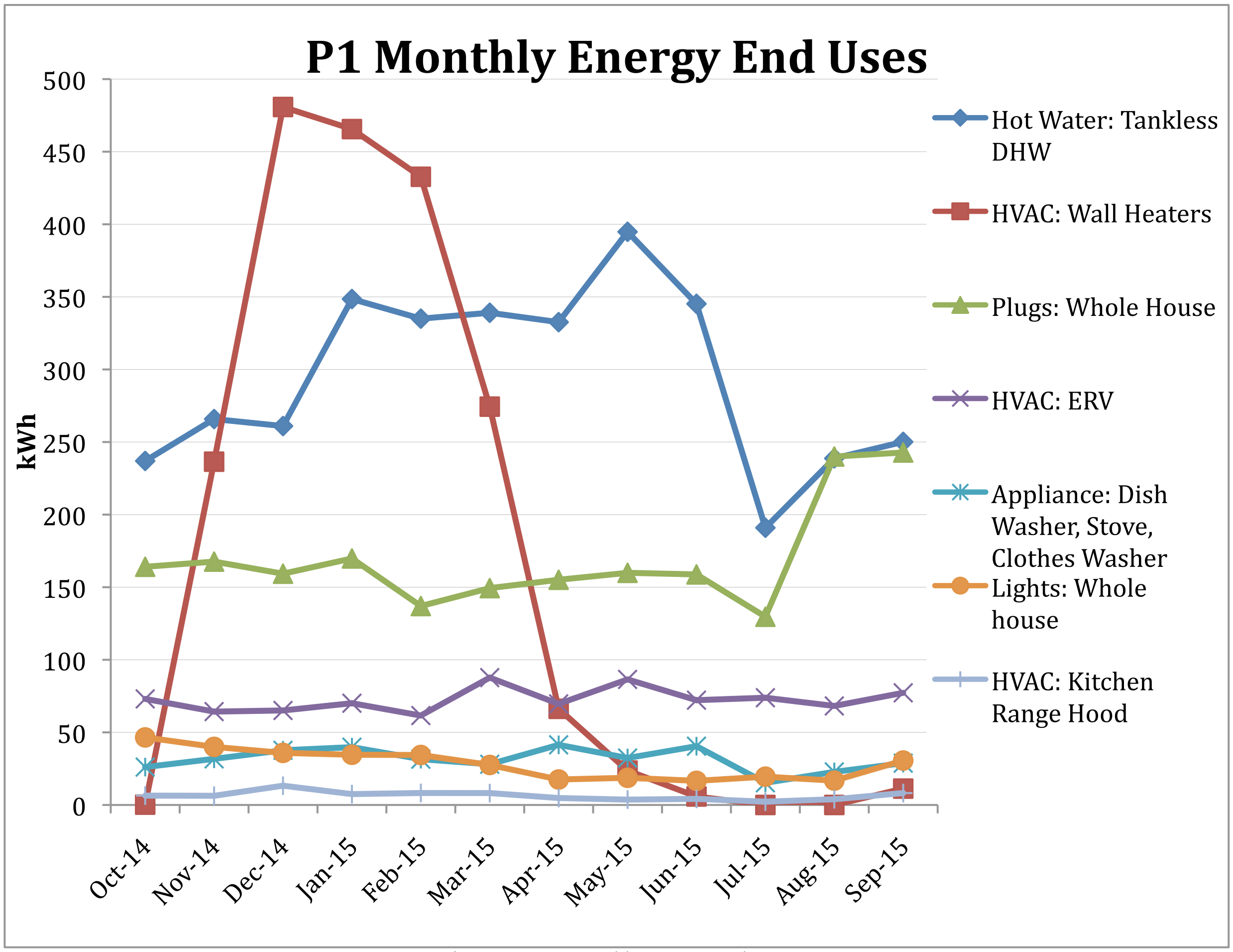


Figure 11 - P1 Monthly Energy End-uses

User Behavior

The baseload in P1 is 212 Watts, with 8,760 observations. Subtracting the electricity used by our monitoring equipment (which includes two netbook computers and three energy monitors) of 25 Watts, gives a baseload of 187 Watts.

DHW is the largest load in the home, which is logical since there are four occupants. Heating is the second largest, and MELs (represented in figure 11 on the channel titled "Plugs: Whole House") is the third. Lights are a very small portion of the total energy use in this home, if added to the MELs, the discretionary energy load is 24% of the whole house energy use.

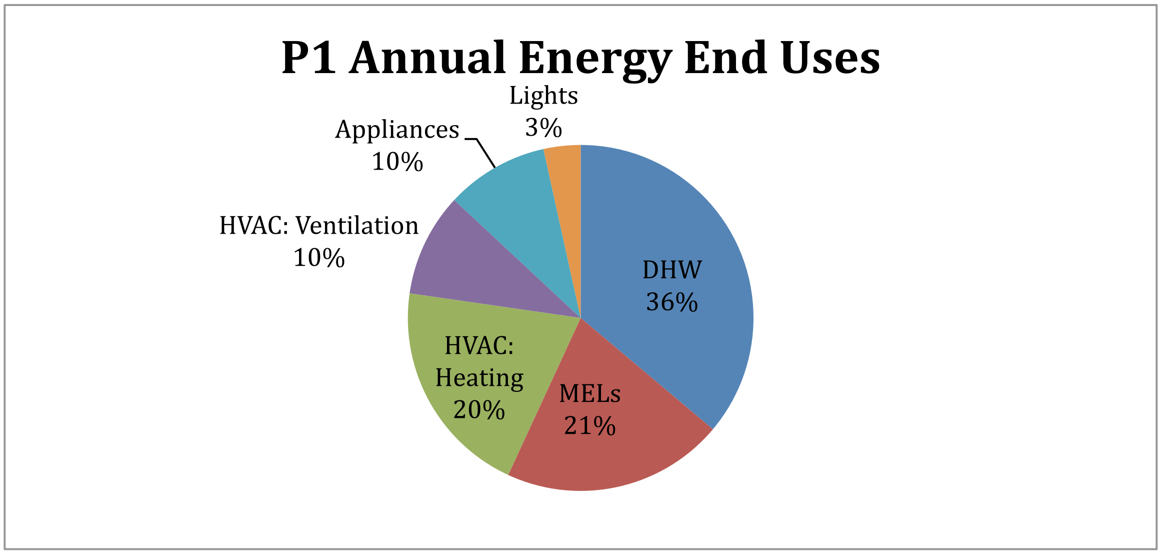


Figure 12 - P1 Annual Energy End-uses

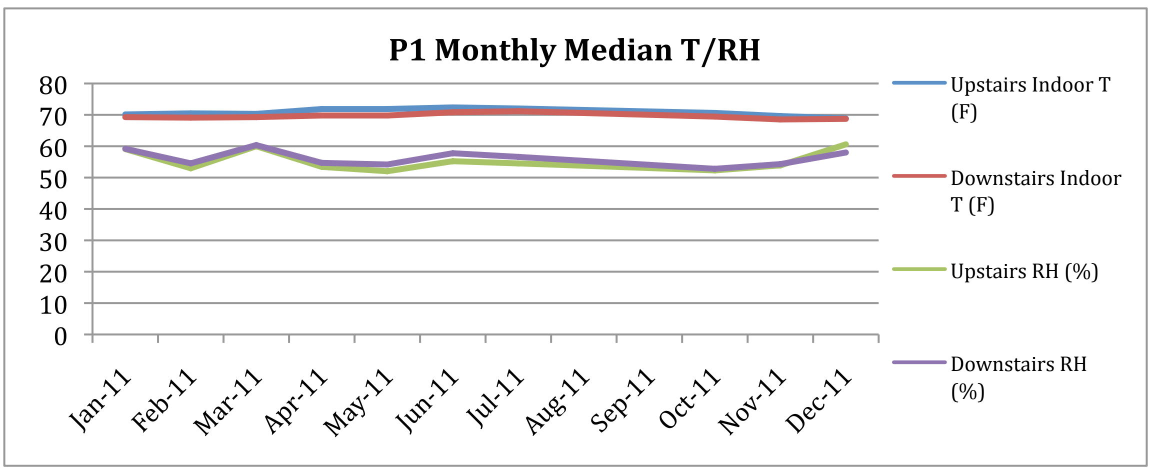


Figure 13 - P1 Indoor T/RH

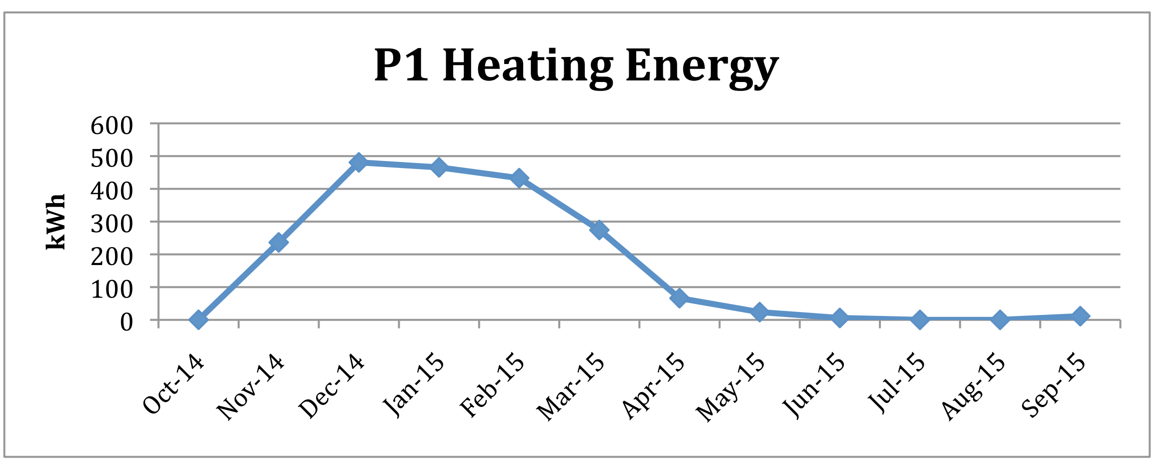


Figure 14 - P1 Heating Energy

The Passive House design principles and the heating system did achieve a very stable and comfortable home, as seen in figure 13. However, figure 14 shows that this came with a penalty of nearly 6 months of heating.

Whole House Energy Use

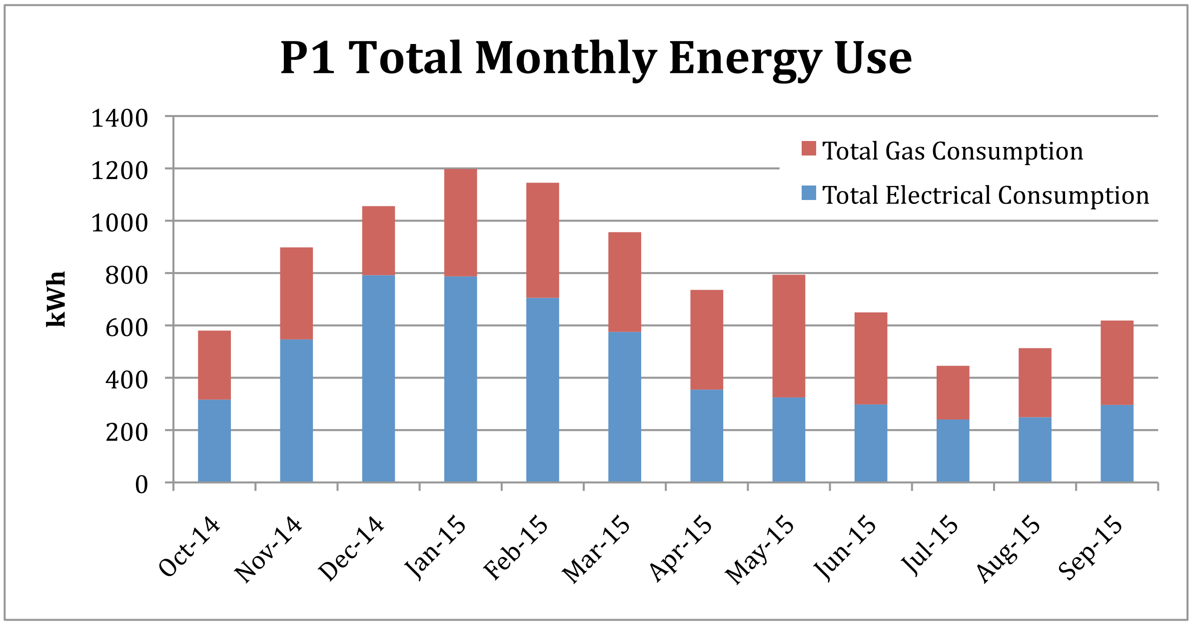


Figure 15 - P1 Total Monthly Energy Use

P1 is an interesting case study that demonstrates some of the problems with performance metrics, as well as a very important finding about fuel switching for space conditioning. If we are interested in percentage savings of pre- vs. post-retrofit, then P1 does not appear to be performing as well as we had hoped for a DER, with a 28% site energy savings, largely due to doubling the occupancy and the change from a small gas floor furnace to electric resistance baseboard heaters in every room.

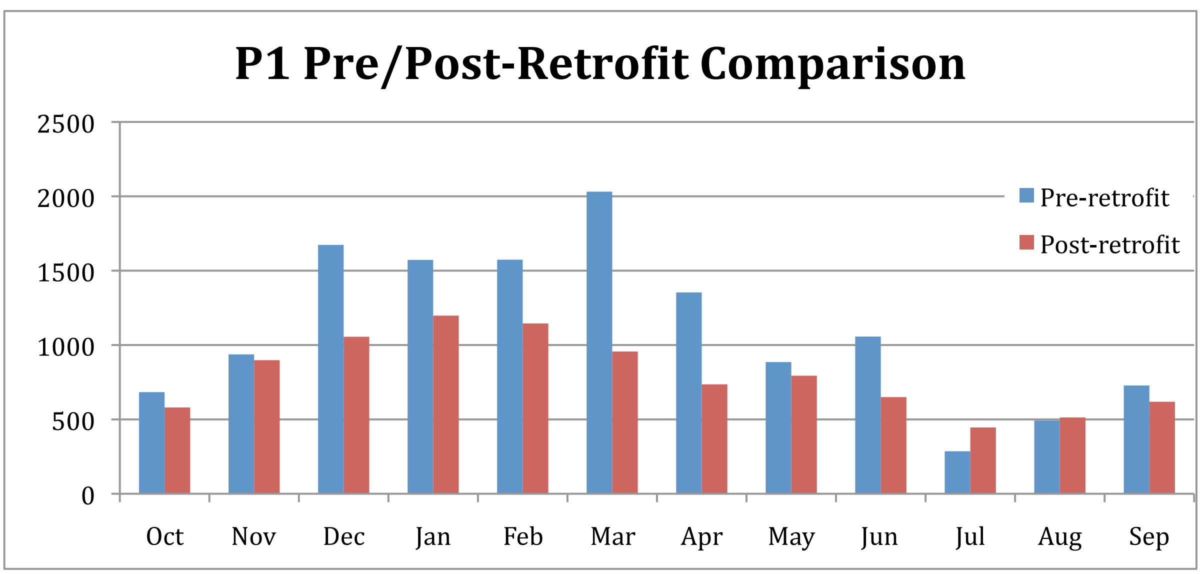


Figure 16 - P1 Pre/Post Retrofit Site Energy Comparison

However, the retrofit does have double the occupancy, double the conditioned floor area, and is far more comfortable, based on the interview with the homeowner. So these facts must be considered in conjunction with the monitored site energy performance comparison shown in figure 16.

When converted to source energy, the project is using 11% more energy than it was pre-retrofit, and the CO_{2e} is 5% less than the pre-retrofit emissions. This is a significant finding and will be further discussed in the following chapters.

P1 (Pre) - MONITORED WHOLE HOUSE ENERGY USE			P1 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Total CO_{2e}	Site Net-Electricity	Area	Total CO_{2e}	Site Net-Electricity	Area
6,195 lbs	2,400 kWh	960 ft²	**5,888 lbs**	5,487 kWh	1,630 ft²
Total Source Energy	Site Natural Gas	No. of Occupants	Total Source Energy	Site Natural Gas	No. of Occupants
19,334 kWh	10,873 kWh	2	21,474 kWh	4,103 kWh	4

Figure 17 - P1 Mileage Box

6.2 P2

Figure 18 - P2 Exterior and insulated attic with air handler

6.2.1 P2 Project Description

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 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 net-zero energy project, and all gas consumption was switched to electricity, with the intent to offset all site energy usage with site-generated energy from photovoltaics. 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 powder room 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 polyurethane spray foam (SPF) was placed in the crawlspace/basement ceiling and against the roof deck in the 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.

<u>Air Leakage</u>
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 air tightness. However, due to the goal of minimal impact to existing finishes, eliminating air leakage altogether was not possible.

<u>Ventilation</u>
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. These air handlers use electronically commutated motors (ECM), which can continuously vary air flow 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.

<u>Heating, Cooling and DHW</u>
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. 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.

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 both the heating and DHW loads, as well as the cooling loads, and using significantly less energy than the previous model.

Appliances
The Kitchen was upgraded to the most efficient Energy Star appliances including an induction 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 server rack larger than most small commercial buildings, 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 base load 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.

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.

6.2.2 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	SLA (ELA/ft^2_{FA})
P2	2260	5.67	0.32	0.59	124.60	0.27	0.00031

Figure 19 - P2 Blower door results

<u>IR Thermography</u>

The IR images reveal that P2 is still very leaky and has missing insulation in various locations, visible from the exterior in figures 20 and 21, and from the interior in figures 23-31. 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 22. 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 Figures 26-28).

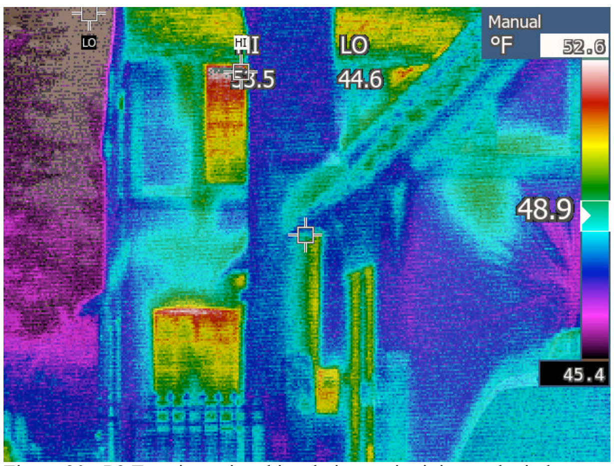


Figure 20 - P2 Exterior, missed insulation at rim joists and windows

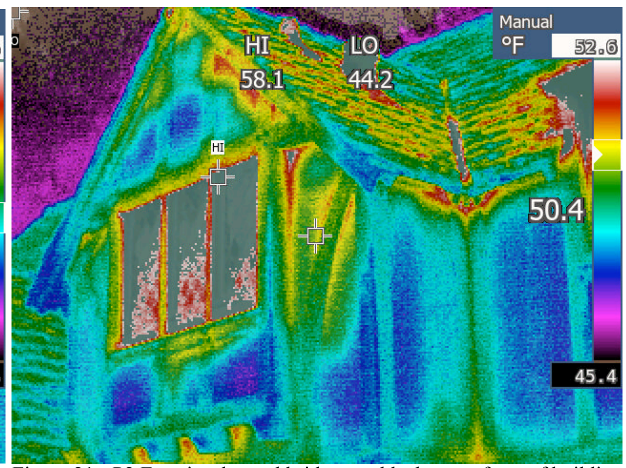


Figure 21 - P2 Exterior thermal bridges and leakage at front of building

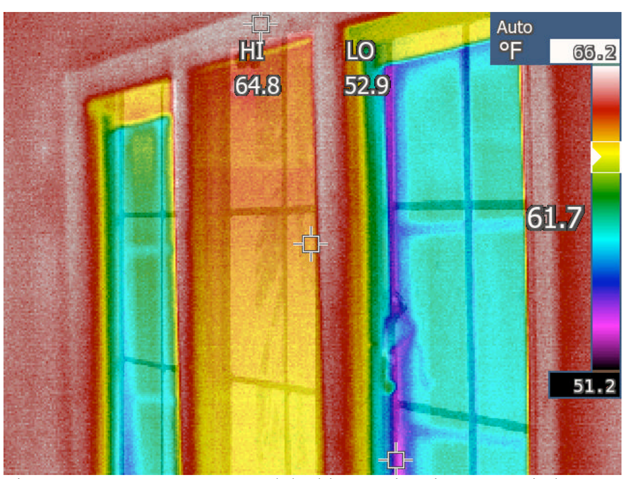


Figure 22 - P2 Tenants removed double pane interior storm windows

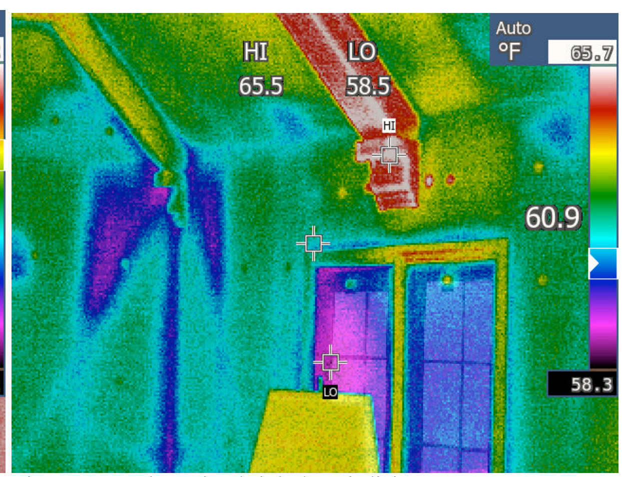


Figure 23 - P2 thermal and air leakage in living room

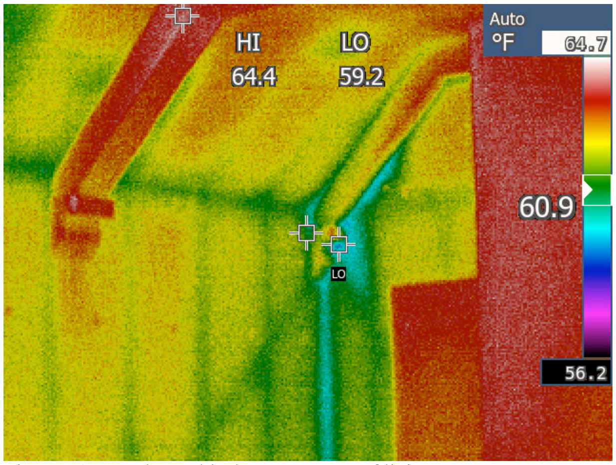


Figure 24 - P2 Thermal leakage at corner of living room

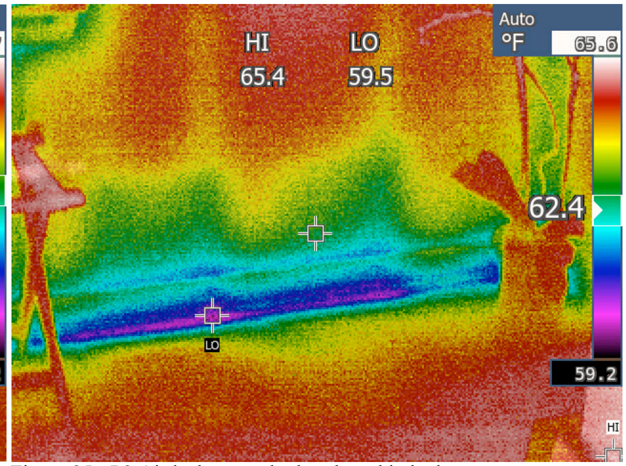


Figure 25 - P2 Air leakage under baseboard in bedroom

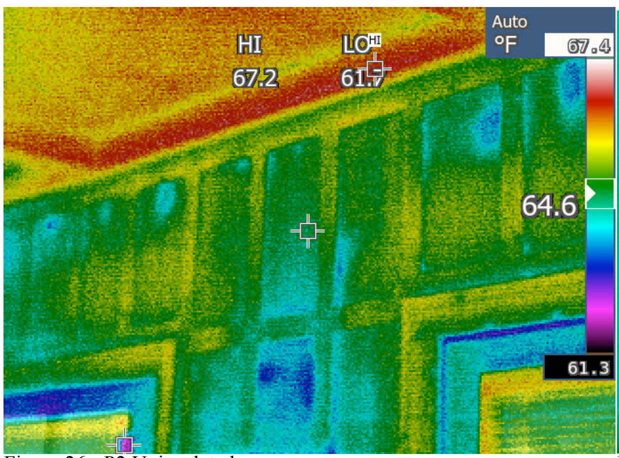


Figure 26 - P2 Uninsulated sunroom

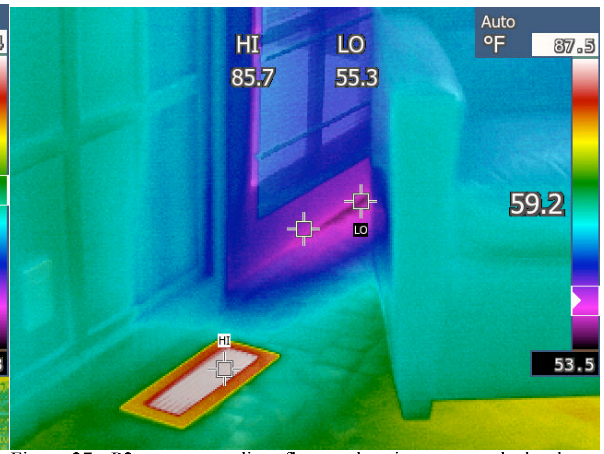


Figure 27 - P2 sunroom radiant floor and register next to leaky door

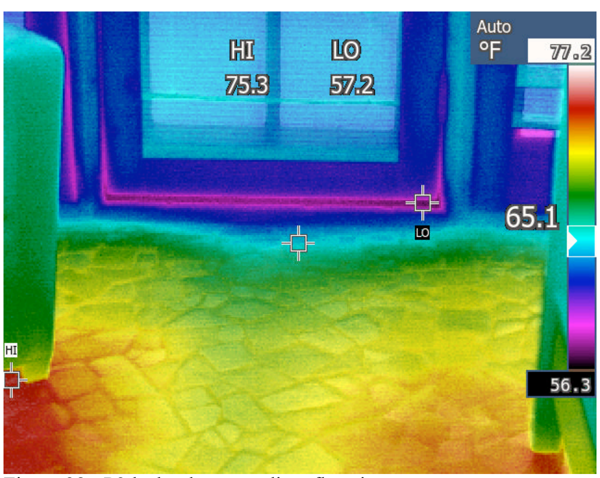


Figure 28 - P2 leaky door at radiant floor in sunroom

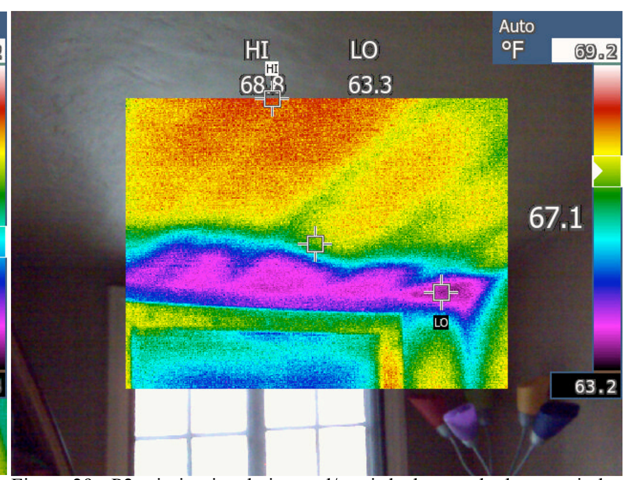


Figure 29 - P2 missing insulation and/or air leakage at bedroom window

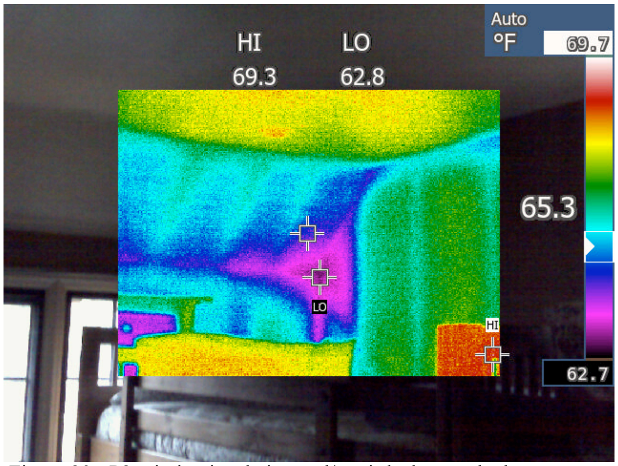


Figure 30 - P2 missing insulation and/or air leakage at bedroom

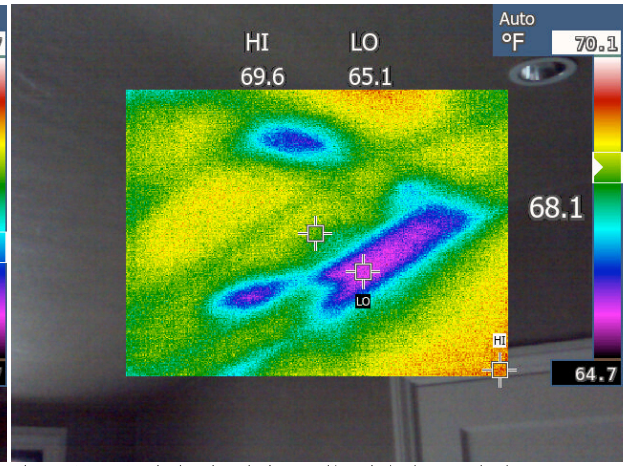


Figure 31 - P2 missing insulation and/or air leakage at bedroom

6.2.3 Monitored Data Results

Monthly End-uses

Figure 32 shows the monthly energy end-uses in P2. The two highest peaks are from 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, 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.

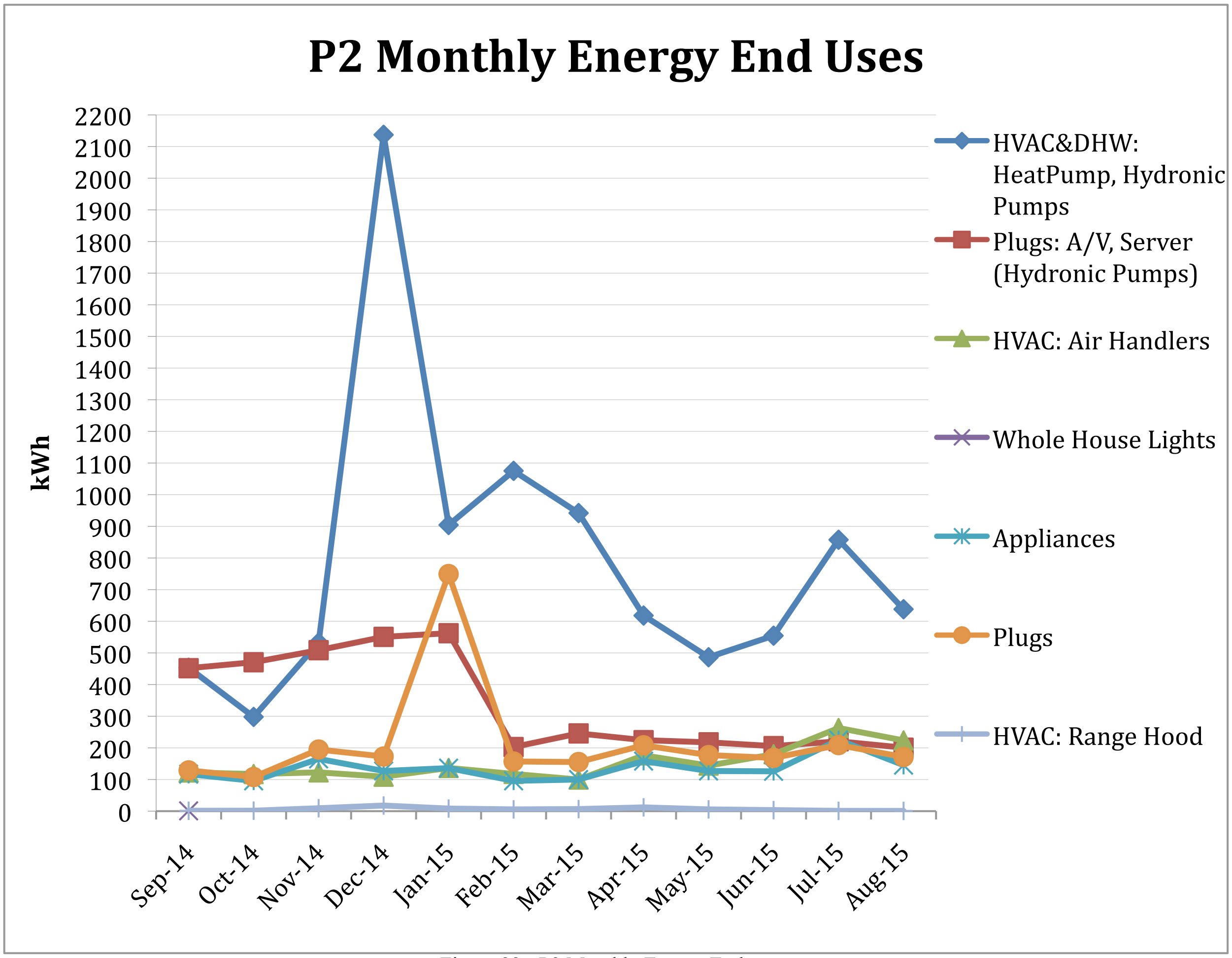


Figure 32 - P2 Monthly Energy End-uses

<u>User Behavior</u>

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 632 Watts with 9,480 observations, less our monitoring equipment of 15 Watts, gives a baseline of 617 Watts. This is the highest baseline of all the case studies. As mentioned above, the server rack and A/V equipment is what is really driving the baseline and MEL use up, and it is unclear whether or not the current occupants use the server. 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. The discretionary energy use shown below is quite high in P2 due to these loads, totaling 40% of the whole house energy use if lights are included.

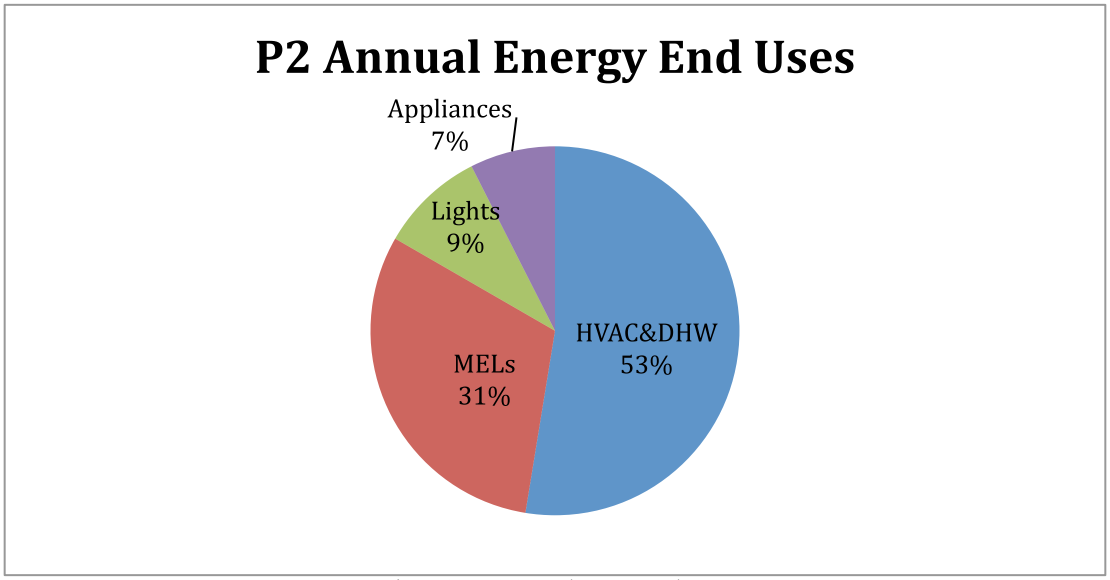


Figure 33 - P2 Annual Energy End-uses

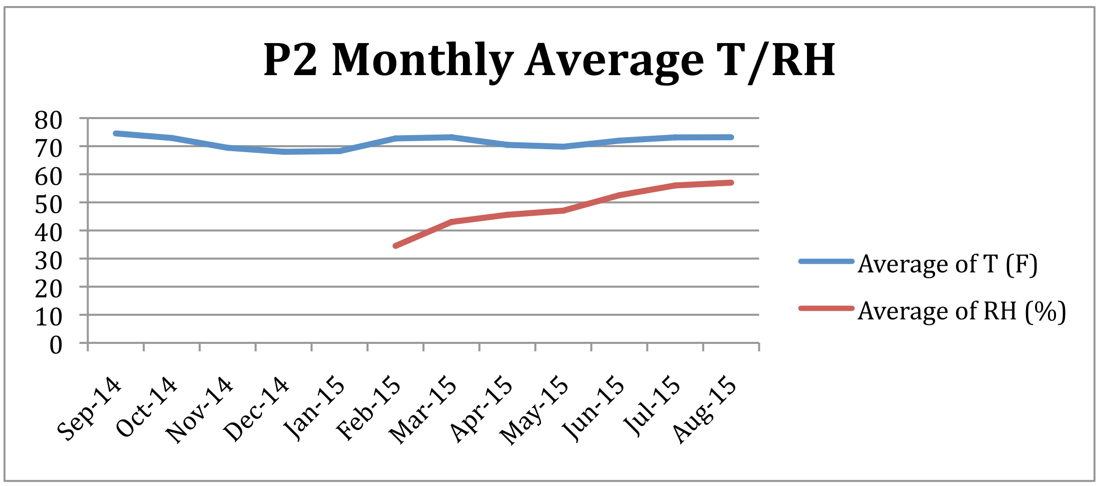


Figure 34 - P2 Indoor T/RH

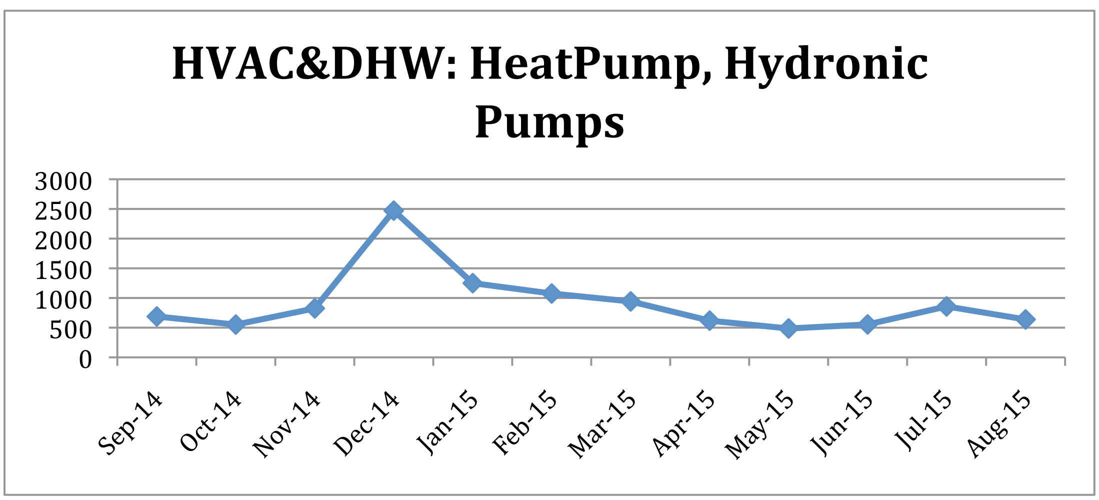


Figure 35 - P2 Heating/Cooling and DHW Energy

Whole House Energy Use

Figure 34 shows that the home was kept very warm all winter, and there is also a visible spike in both the heating and cooling energy use in figure 35. The heating and cooling loads are also very noticeable in figure 36 below; December and January alone consumed more energy than other case studies did in an entire year. However, this was in large part due to the malfunctioning heat pump and temporary electric water heater.

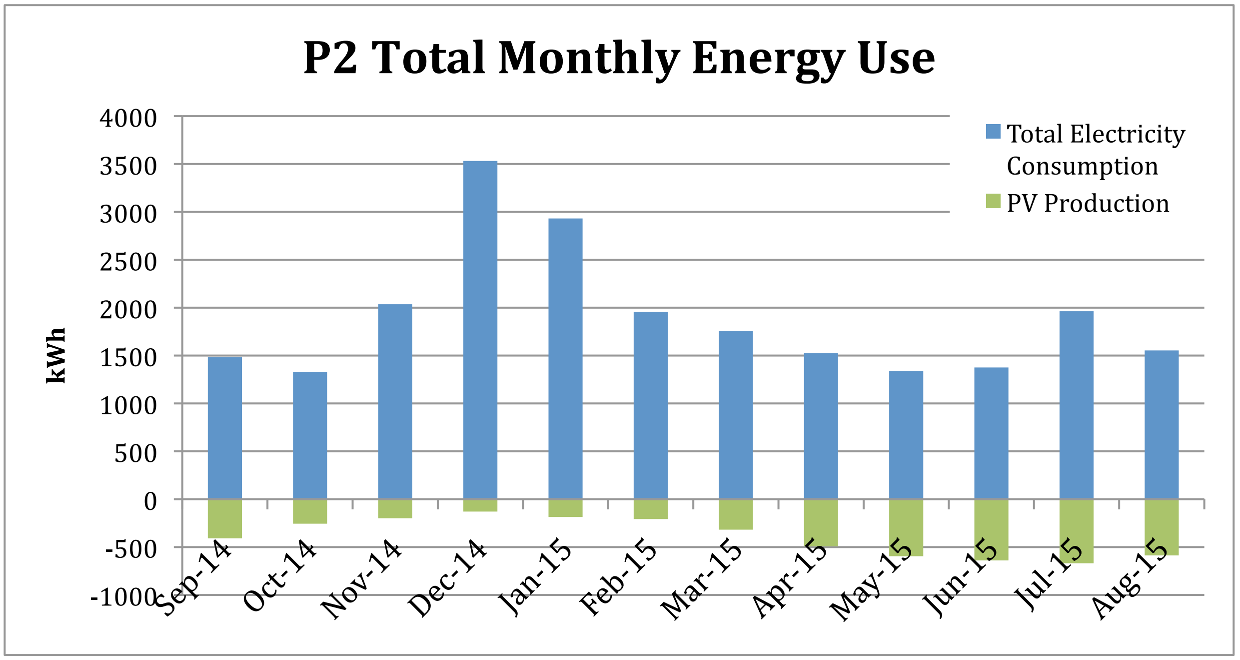


Figure 36 - P2 Total Monthly Energy Use

The notable aspect of this retrofit is in the percentage of site energy savings from the pre-retrofit use shown in figure 37. Although not achieving zero-net energy (ZNE) as the design intended, the project has shown 56% annual site energy savings, not an easy achievement.

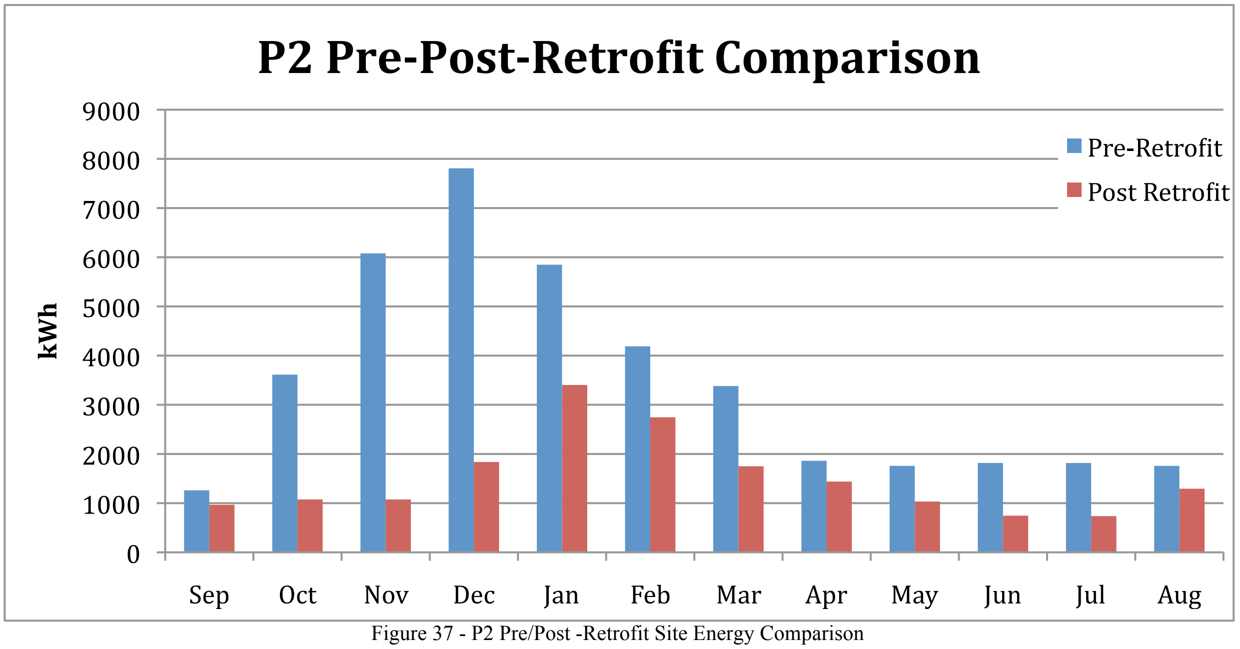


Figure 37 - P2 Pre/Post -Retrofit Site Energy Comparison

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 (kind of fuzzy here, 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. 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 and 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 of the CO_{2e}. This is not very specific, and although it must be considered in the GHG calculation, an accurate quantification of the CO_{2e} per kWh for this particular situation, including transmission and distribution losses of the purchased renewable energy, does not exist. Therefore, the post retrofit mileage box below represents the lower GHG emissions of the actual electricity purchased through the Palo Alto Utility Company. The carbon offsets from the RECs should be considered as an improvement on the GHG emissions, but since there is no specific quantification of these offsets, they will not be included in the mileage box below.

P2 (Pre) - MONITORED WHOLE HOUSE ENERGY USE			P2 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Total CO_{2e}	Site Net-Electricity	Area	Total CO_{2e}	Site Net-Electricity	Area
16,085 lbs	6,129 kWh	2,780 ft^2	**5,881 lbs**	18,097 kWh	2,780 ft^2
Total Source Energy	Site Natural Gas	No. of Occupants	Total Source Energy	Site Natural Gas	No. of Occupants
49,476 kWh	35,349 kWh	1.5	31,797 kWh	0 kWh	1.5

Figure 38 - P2 Mileage Box

Based on the calculations presented above in figure 38, without considering the RECs, P2 has reduced the CO_{2e} 63%, and the site energy 36% from pre-retrofit levels.

6.3 P3


Figure 39 - P3 Front and Rear of home

6.3.1 P3 Project Description

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 air tightness, 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 (i.e., buildability, cost, energy, etc.) 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 (REMOTE Wall Study 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 air tightness. 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. The head is typically considered somewhat unattractive; see figure 40 below.

Figure 40 - Wall unit of mini-split heat pump. Source: www.drenergysavervirginia.com

Many homeowners do not want the wall units to be visible. 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 set-up 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. There is a gas oven and range, a microwave, a dishwasher, a front-loading clothes washer and a condensing electric dryer. All 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.

6.3.2 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	SLA (ELA/ft^2_{FA})
P3	151	0.43	0.02	0.06	8.30	0.02	0.00002

Figure 41 - P3 Blower door results

6.3.3 Monitored data results

Monthly End-uses
The scale of figure 42 below has been minimized for easy viewing, and in contrast to other projects, there are no real drastic differences between all of the end-uses. As the building enclosure is so robust, the space conditioning loads are minimal (apart from the first few months where there was a problem with the heat pump and additional space heaters were used).

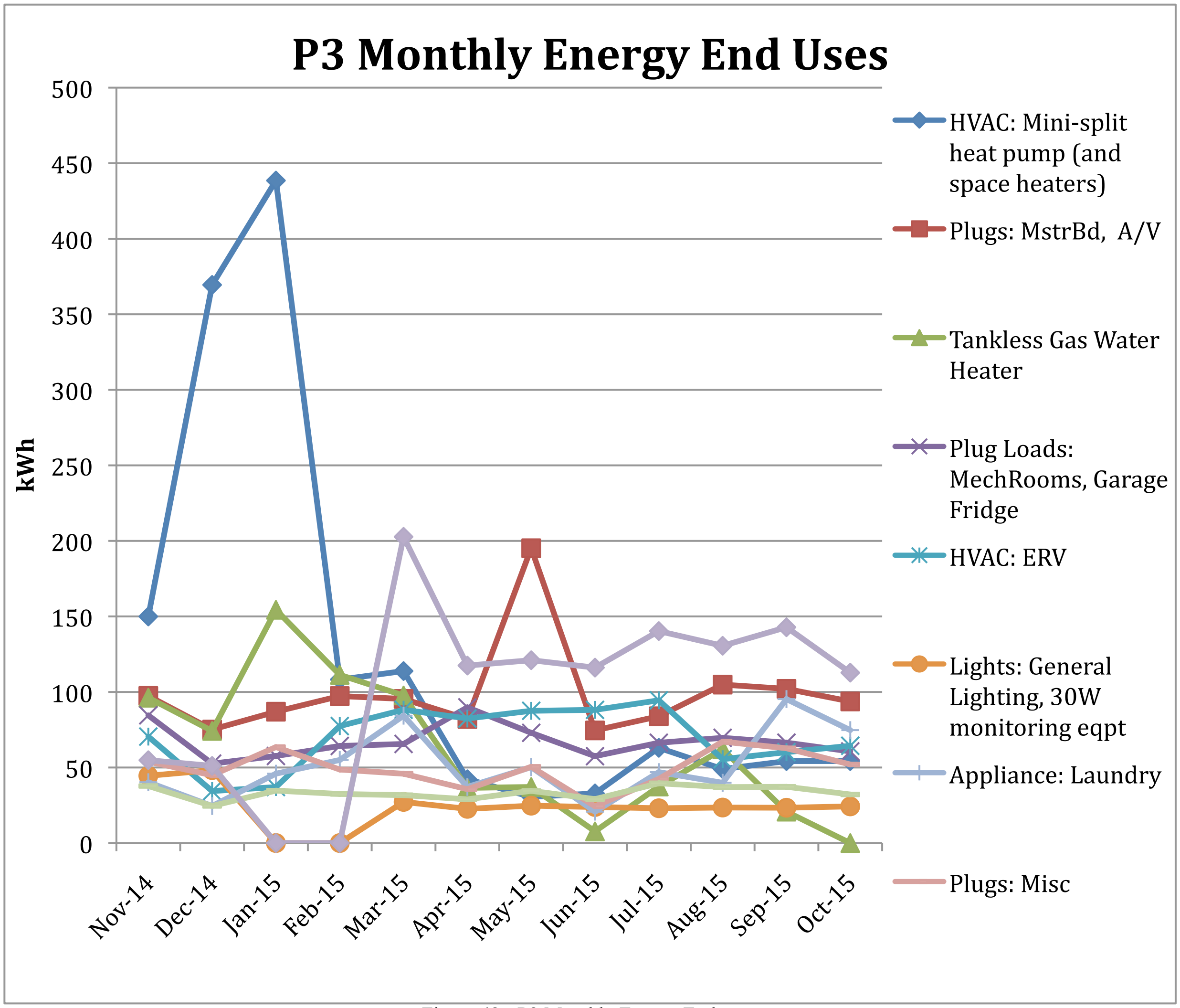


Figure 42 - P3 Monthly Energy End-uses

Since the space conditioning loads are so low, and the plug loads are so high in P3, this case study is a great example of how MELs and behavior-based end-uses affect the overall performance of ultra efficient homes.

<u>User Behavior</u>

The baseload in P3 is the second highest of all the case studies, averaging 484 Watts, with 4,078 observations. Note that both our monitoring equipment, as well as Davis Energy Groups is on 24 hrs/day and consuming an average of 45 Watts, resulting in a baseload of 439 Watts.

The ultra efficient building envelope and the high baseload makes this house somewhat different than other homes in the study. Not only are MELs the largest single end-use, as shown in figure 43, but there are also more MELs mixed in with other monitored channels, such as the irrigation and fountain pumps with the living room and bath lights. The second refrigerator is a significant load that could be 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. The total discretionary energy use is difficult to assess accurately due to the combination of certain loads in the electrical panel, but it is estimated by identifying load profiles and use frequency averages from the high-resolution data to be 50% of the whole house energy use.

Figures 44 and 45 show that the occupant keeps interior temperatures above 70 degrees Fahrenheit, while maintaining a peak heating load of just over 400kWh in January, including the malfunctioning heatpump and additional space heaters.

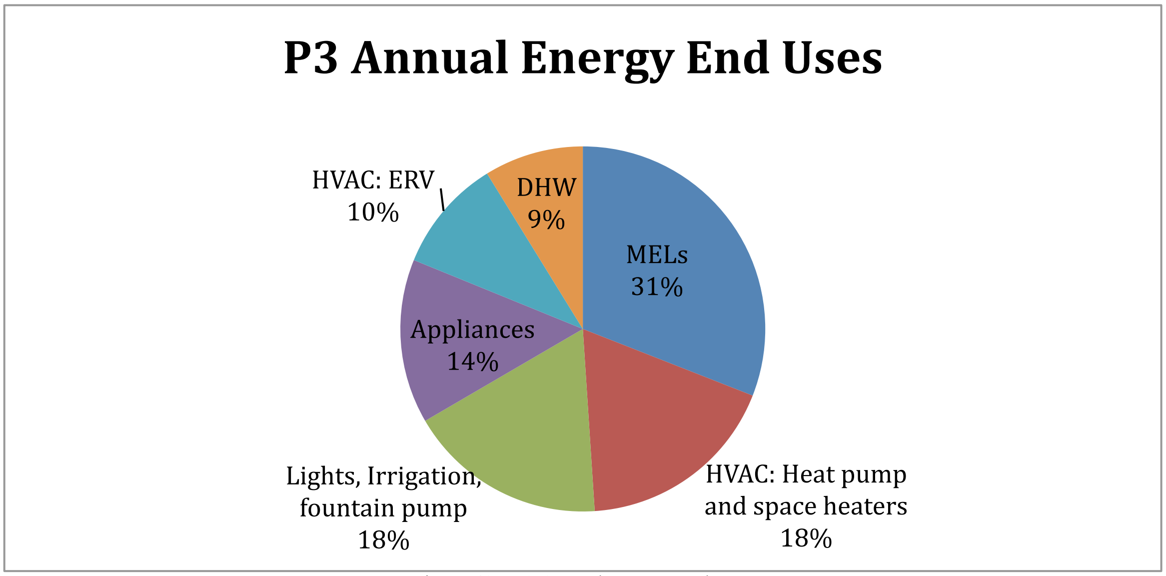


Figure 43 - P3 Annual Energy End-uses

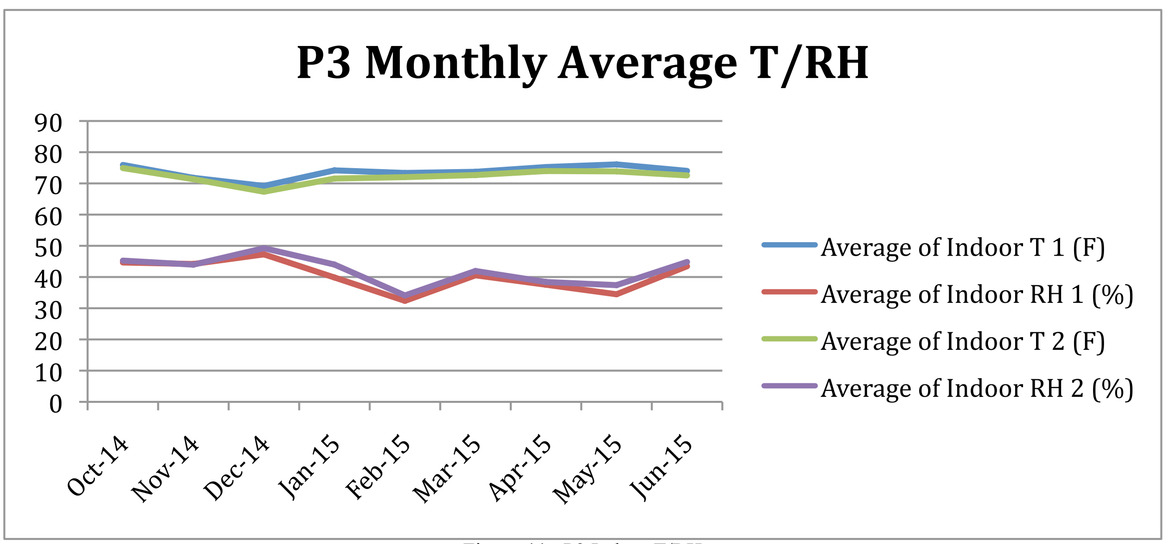


Figure 44 - P3 Indoor T/RH

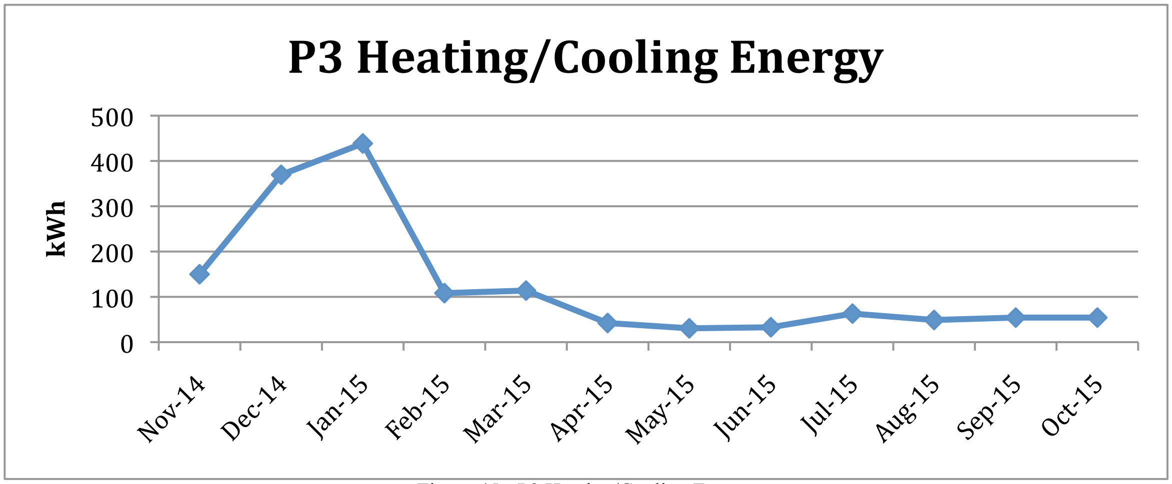


Figure 45 - P3 Heating/Cooling Energy

Whole House Energy Use

The monitoring equipment was installed before the PV system was connected. Once it was connected in mid-January, changes had to be made in order to accurately monitor the electricity use with the PV. When that was finally fixed in mid February, we had lost reliable data for the end of January and the beginning of February, making both months whole house energy data invalid, as visible in figure 46. Luckily all of the end-use data was still usable.

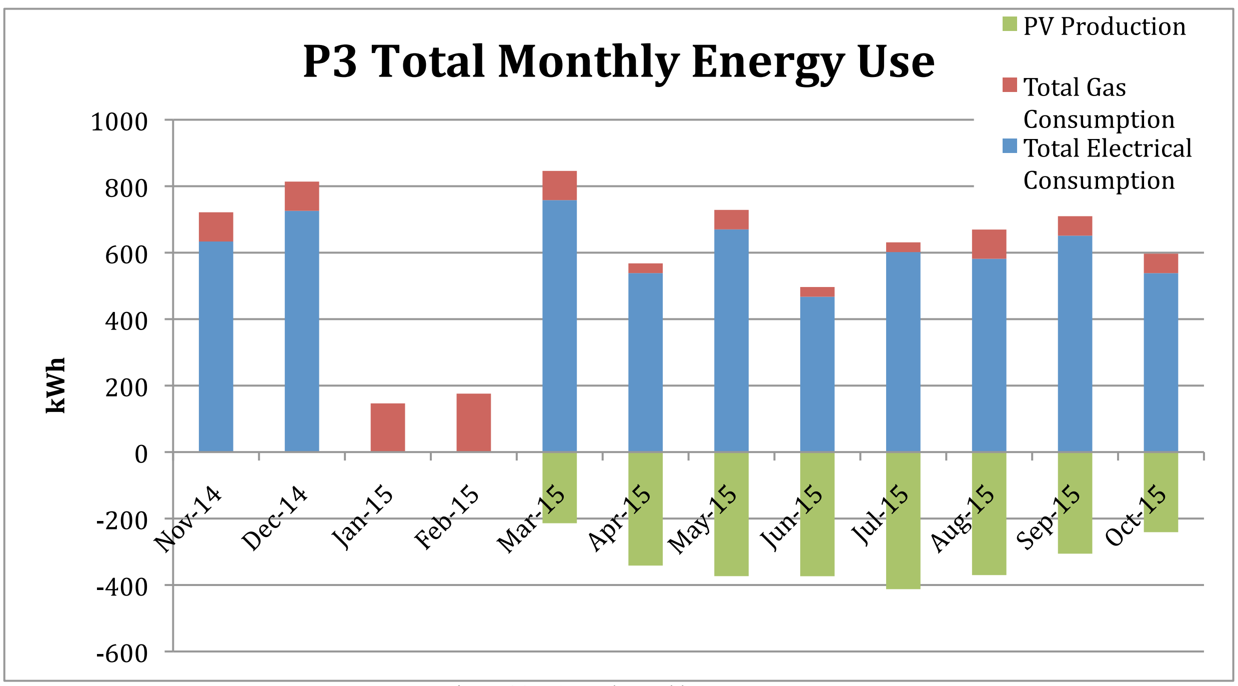


Figure 46 - P3 Total Monthly Energy Use

Unfortunately, no pre-retrofit data is available for P3. Attempts have been made to get the pre-retrofit utility bills, but have so far been unsuccessful. If they cannot be obtained, then once a full year of un-corrupted data is gathered the energy and CO_{2e} can be compared to either a code compliant California home with gas heating, or a modeled home. The post-retrofit monitored data follows below in figure 47.

P3 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Total CO_{2e}	Site Net-Electricity	Area
4,167 lbs	4,894 kWh	2,342 ft^2
Total Source Energy	Site Natural Gas	No. of Occupants
16,175 kWh	938 kWh	1

Figure 47 - P3 Mileage Box

6.4 P4

Figure 48 - P4 Pre/Post-Retrofit

6.4.1 P4 Project Description

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 their project, he? he calculated that this retrofit reduced the home's energy usage by 75%.

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 Interview 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. However, 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, 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, and a whole house fan that pulls 100% outside air, pre-heated by the *SolarWall* in the winter.

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. It is pre-plumbed for a future solar thermal combisystem, and the owner plans to use a biofuel auxiliary boiler and eliminate this unit.

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.

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. 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 24/7 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 overlooked 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 gong to reliably see 70% to 90% reductions in household energy use. P4 did not pursue super-insulation or extreme air tightness, yet it is a net-zero electrical home because of very conscientious occupants. It is also the first building in northern California to achieve the challenging Thousand Home Challenge certification. 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.

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. When asked what some of the main challenges of phasing the retrofit were, the homeowner replied: "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 Interview 2011). He also mentioned that it was a big challenge getting the contractors to understand the importance of high quality, energy efficient workmanship.

6.4.2 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 best performing home of the 4 that have a full year of monitored energy use.

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH	SLA (ELA/ft^2_{FA})
P4	1983	5.43	0.32	0.79	110.03	0.26	0.00028

Figure 49 - P4 Blower door results

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 figures 50-55.

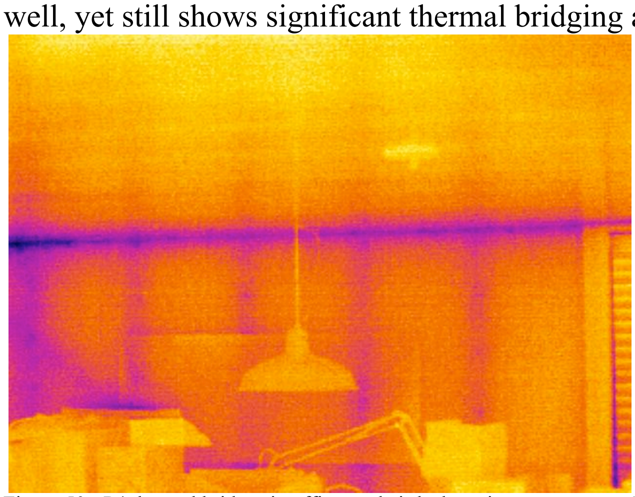


Figure 50 - P4 thermal bridges in office, and air leakage in corner

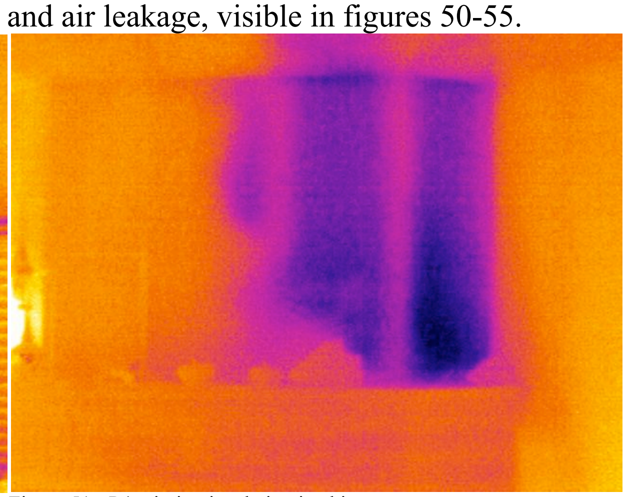


Figure 51 - P4 missing insulation in chimney

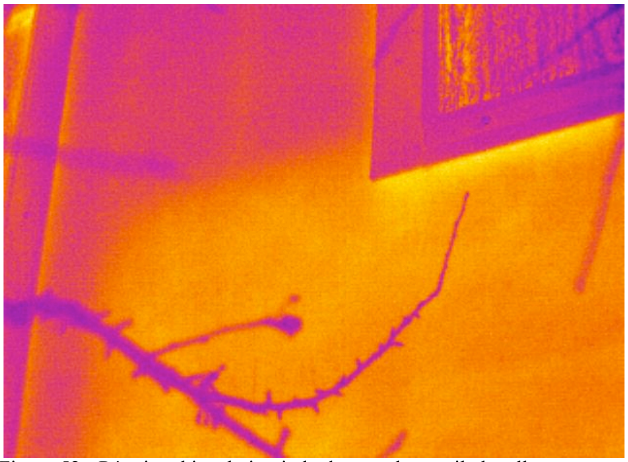


Figure 52 - P4 missed insulation in bathroom due to tiled wall

Figure 53 - P4 missed insulation around bathroom window

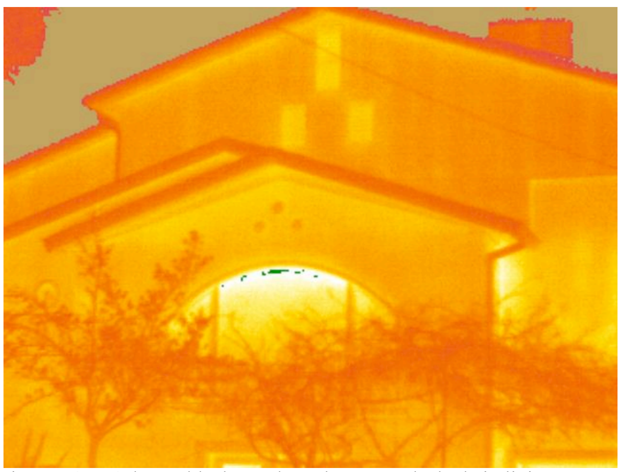


Figure 54 - P4 thermal leakage above honeycomb shade in living room

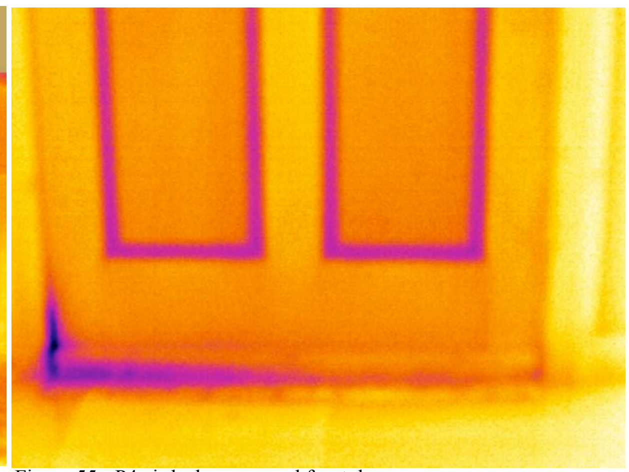


Figure 55 - P4 air leakage around front door

6.4.3 Monitored Data Results

Monthly End-uses

Despite the nominal air tightness and insulation levels at P4, the overall energy performance is commendable; this is the greatest example of a successful DER thus far. The most obvious outlier in the monitored energy end-uses shown in figure 56 below is the furnace energy from natural gas during the heating season.

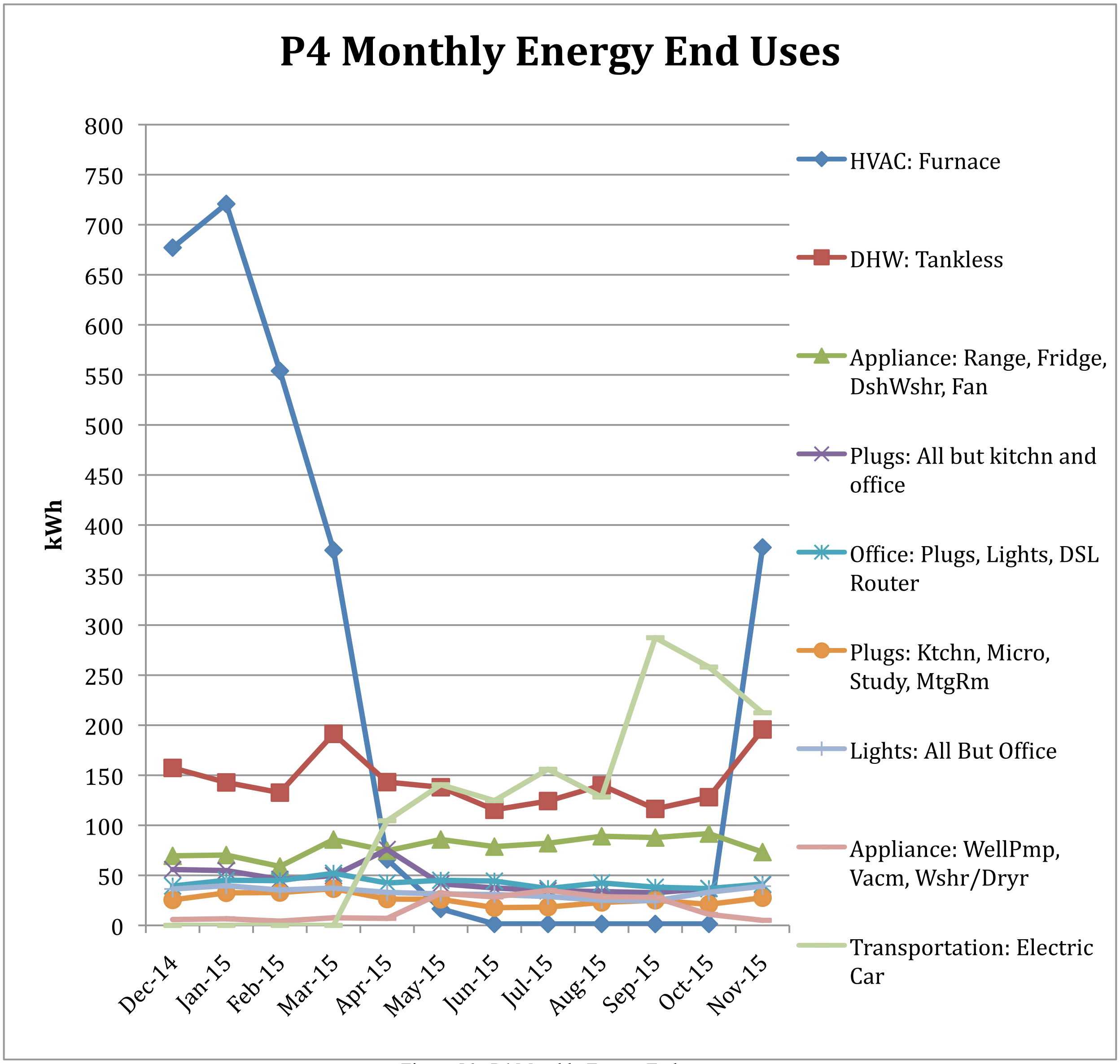


Figure 56 - P4 Monthly Energy End-uses

<u>User Behavior</u>

The consistently low MELs and baseline energy use is most impressive in this project. The baseline is 136 Watts, with 5,832 observations, less the 15 Watts of our energy monitoring equipment; the baseload is only 121 Watts, the lowest of all the case studies (although P6 is a contender). The discretionary energy use is 23% with all lights and the home office included. P4 internal temperatures are kept lower than other homes, as shown in figure 58.

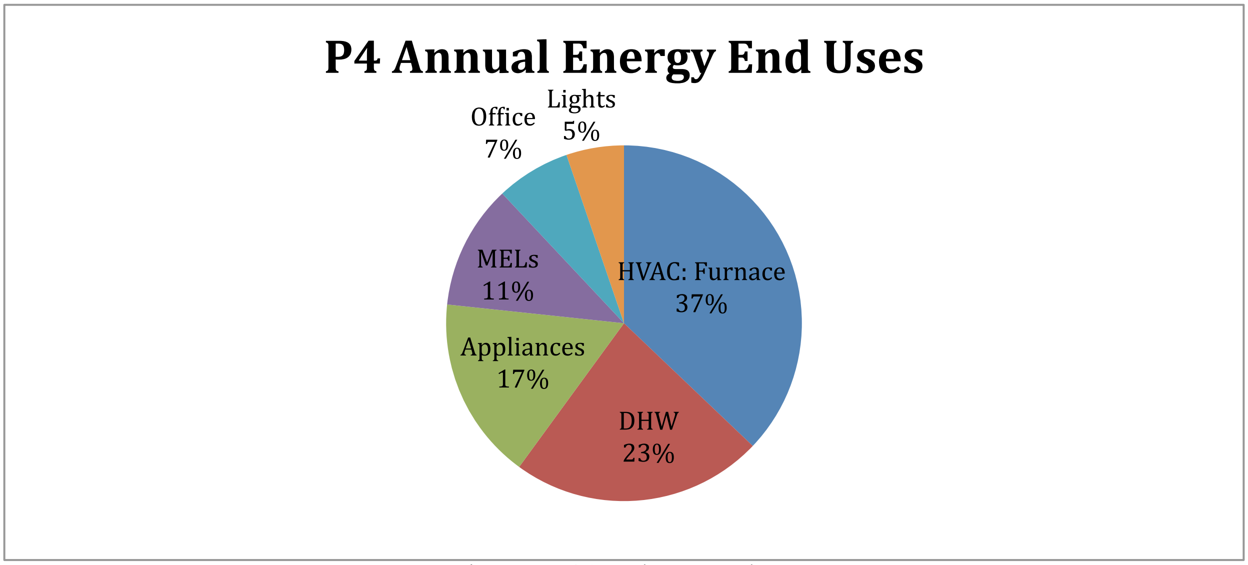


Figure 57 - P4 Annual Energy End-use

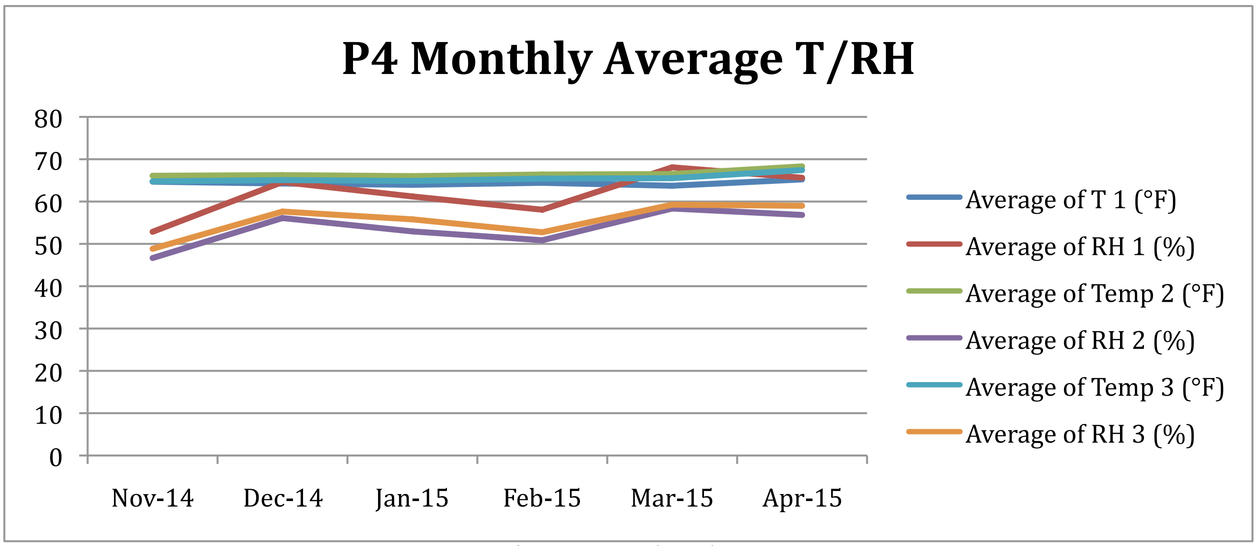


Figure 58 - P4 Indoor T/RH

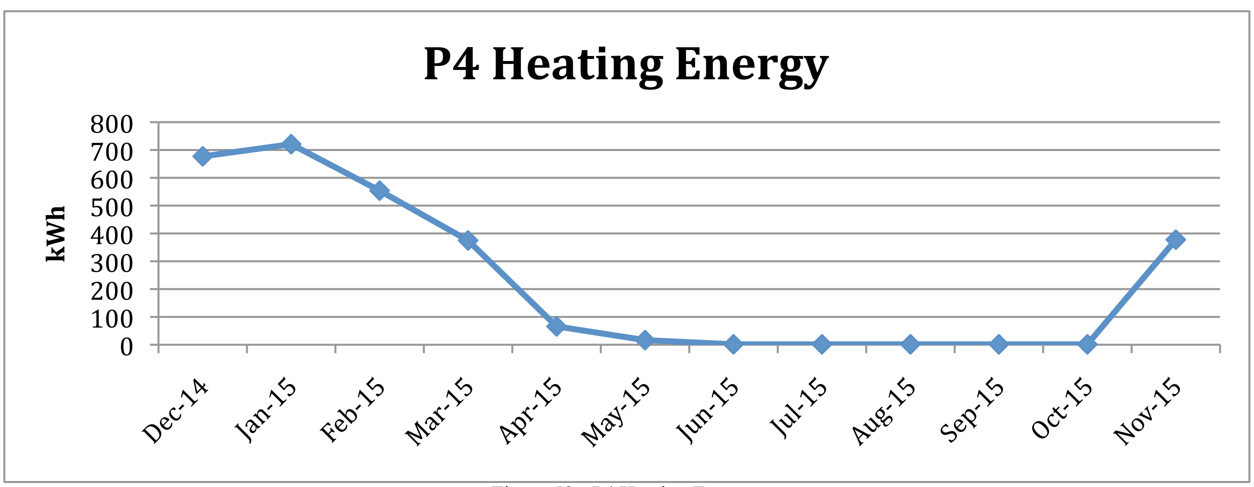


Figure 59 - P4 Heating Energy

Whole House Energy Use

The electric car energy use is not included in these totals in order to be consistent across all case studies. The consistently low electrical use in this home allows for the PV to offset 1,000 kWh more than all of the electricity use for the year. The electric car used just over 1,400 kWh since it was purchased in April.

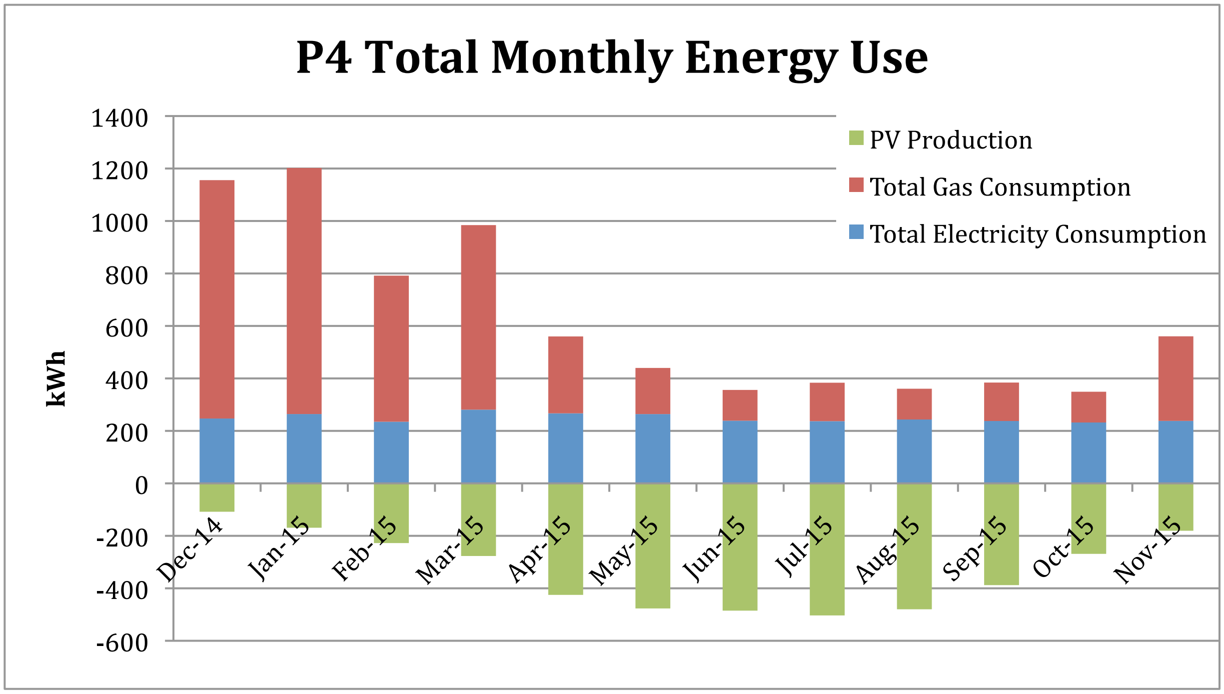


Figure 60 - Total Monthly Energy Use

As mentioned above, there is no pre-retrofit utility data, but very detailed utility bills are available beginning after the initial retrofit, which was estimated to save 75% of the energy. Without counting these initial energy savings, figure 61 shows that P4 still saved 70% of the site energy from 2003 to 2011.

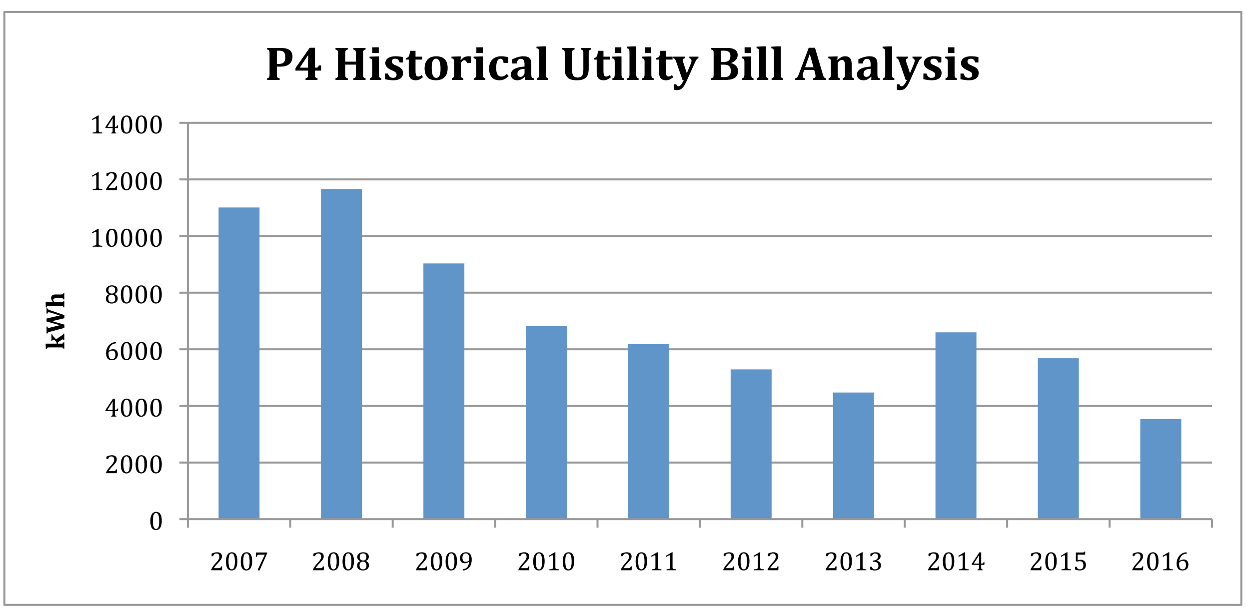


Figure 61 - P4 Historical Utility Bill Analysis

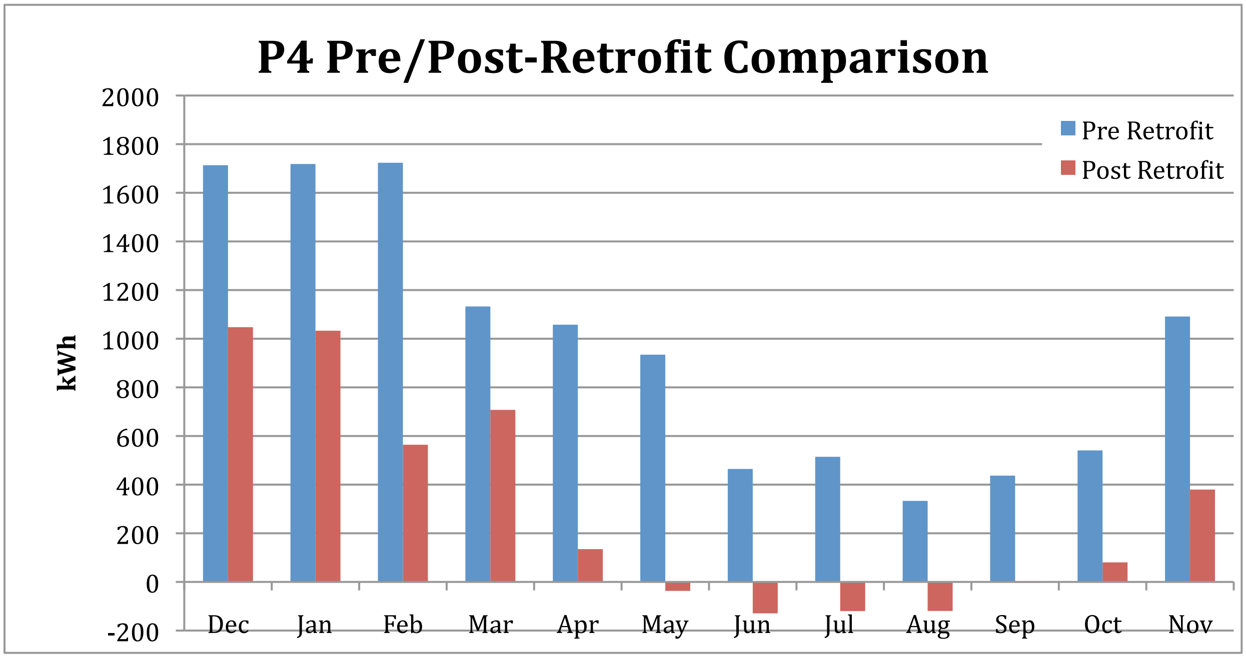


Figure 62 - Pre/Post-Retrofit Site Energy Comparison, 2003 vs. 2011

In the pre/post-retrofit comparison of 2003 and 2011 in figure 63, there has been an 82% reduction in CO_{2e} and a 90% savings in source energy.

P4 (Pre) - MONITORED WHOLE HOUSE ENERGY USE		
Total CO_{2e}	Site Net-Electricity	Area
5,748 lbs	2,607 kWh	1,540 ft^2
Total Source Energy	Site Natural Gas	No. of Occupants
18,306 kWh	9,349 kWh	2

P4 (Post) - MONITORED WHOLE HOUSE ENERGY USE		
Total CO_{2e}	Site Net-Electricity	Area
1,033 lbs	-1,004 kWh	2,510 ft^2
Total Source Energy	Site Natural Gas	No. of Occupants
1,867 kWh	4,543 kWh	2

Figure 63 - P4 Mileage Box

6.5 P5

Figure 64 - P5 Pre/Post-Retrofit

6.5.1 P5 Project Description

General Information

P5 is a small, single-story, 900ft^2 affordable housing project located in Pt. 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 air tightness. 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 four 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. This strategy also facilitated the use of exterior continuous foam insulation to eliminate thermal bridging and provide 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.

Air Leakage

The new foundation allowed for the creation of an ideal crawlspace environment. 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. Additionally, the plywood sheathing on the walls and roof 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 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.

Heating

All of the existing mechanical, electrical and plumbing equipment were torn out of 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. 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.

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.

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. The energy performance is not obviously related to highly energy conservative occupants, like other case studies, but is instead a great example of energy efficient, affordable housing.

6.5.2 Building Diagnostic Results

Blower Door

Since P5 is such a small building, it demonstrates the need to observe various different air leakage metrics in order to understand the building enclosure performance. At 292 CFM, the Q_{50} number is very small, but then looking at ACH_{50}, it doesn't appear to be a very high performance building, if compared to the Passive House standard for example. Overall, it is the third tightest house of the case studies; all three of these retrofits were guided by Passive House principles.

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH	SLA (ELA/ft^2_{FA})
P5	292	2.42	0.10	0.32	13.97	0.10	0.00011

Figure 65 - P5 Blower door results

6.5.3 Monitored Data Results

Monthly End-uses

The hot water heater is the obvious outlier in figure 66. When on, it draws 4,000 Watts until the tank reaches the set point. Replacing this with a more efficient heater is an obvious solution to achieve greater overall performance at P5.

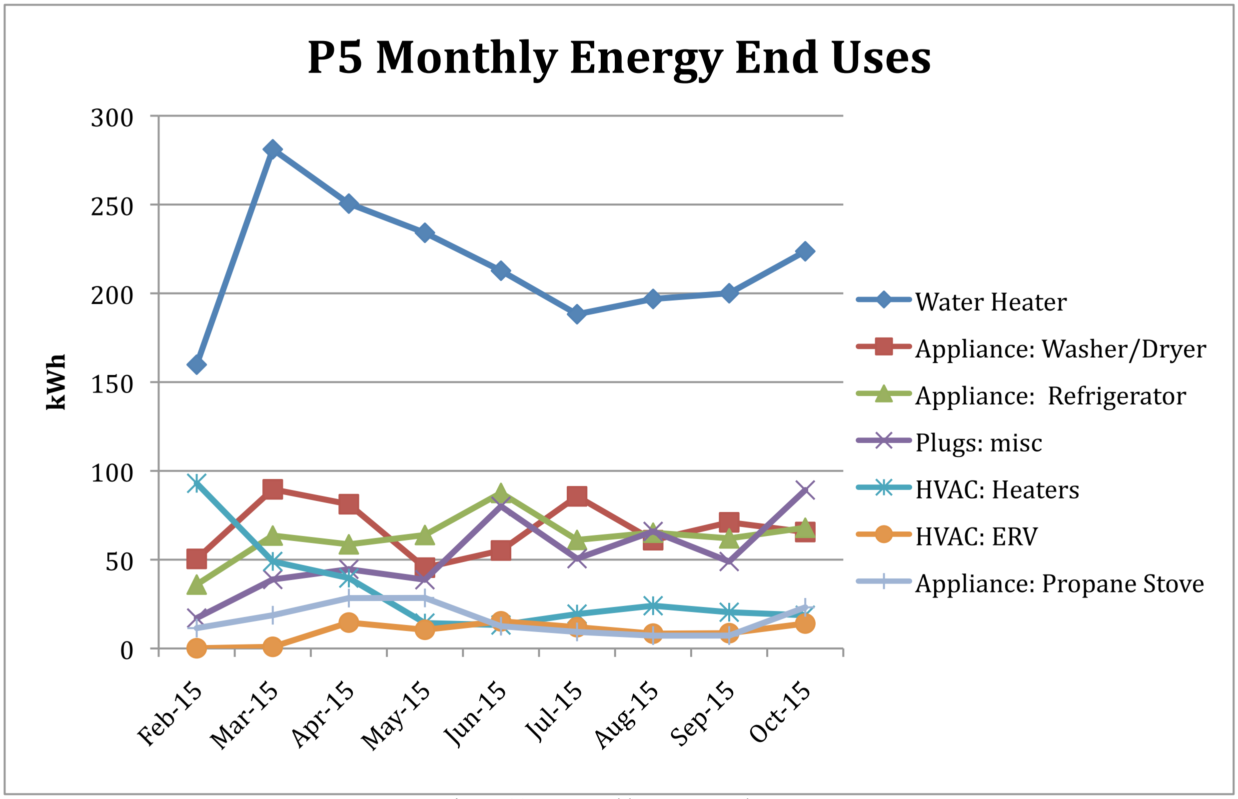


Figure 66 - P5 Monthly Energy End-uses

User Behavior

As mentioned above, the occupants have all of the standard MELs, but just less of them, and as a result, P5 plug loads are lower than those of our other homes. 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. Their baseload is 163 Watts, with 2,952 observations, less 15 Watts of our monitoring equipment, leaves a 148 Watt baseload.

Although a full year of data has not been collected, to date the DHW is the dominant load in the home. Strangely, appliances are next, however, the coldest time of year has not yet been monitored, so this is likely to change after a full year of data is collected. To date, discretionary energy use is a mere 14% of the whole house energy use! P5 is the top performer to date in regards to discretionary energy use.

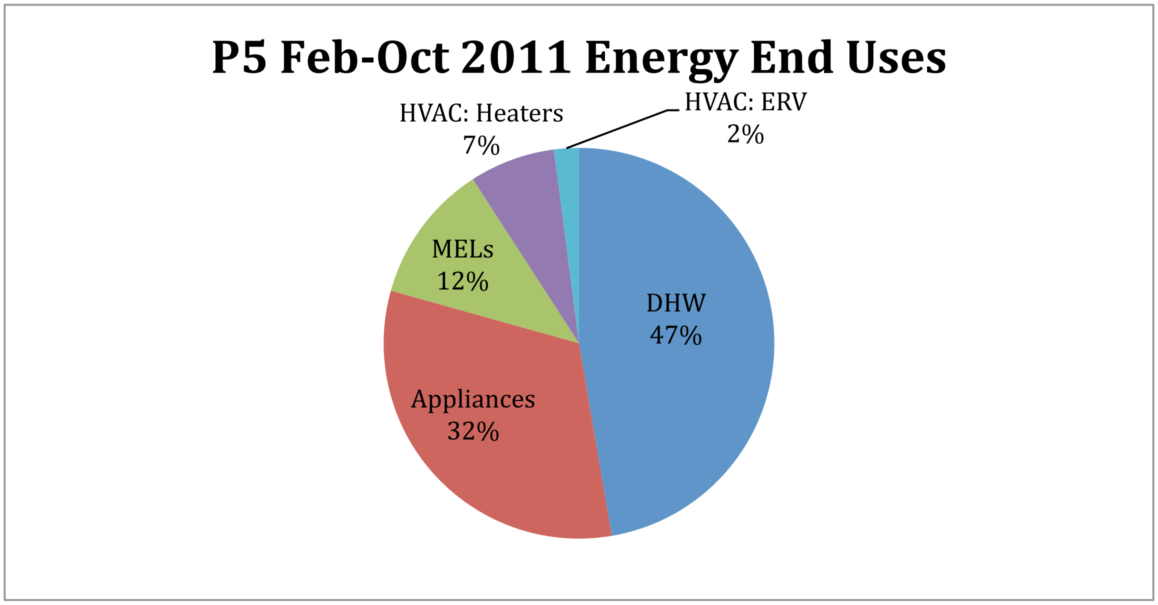


Figure 67 - P5 Energy End-uses

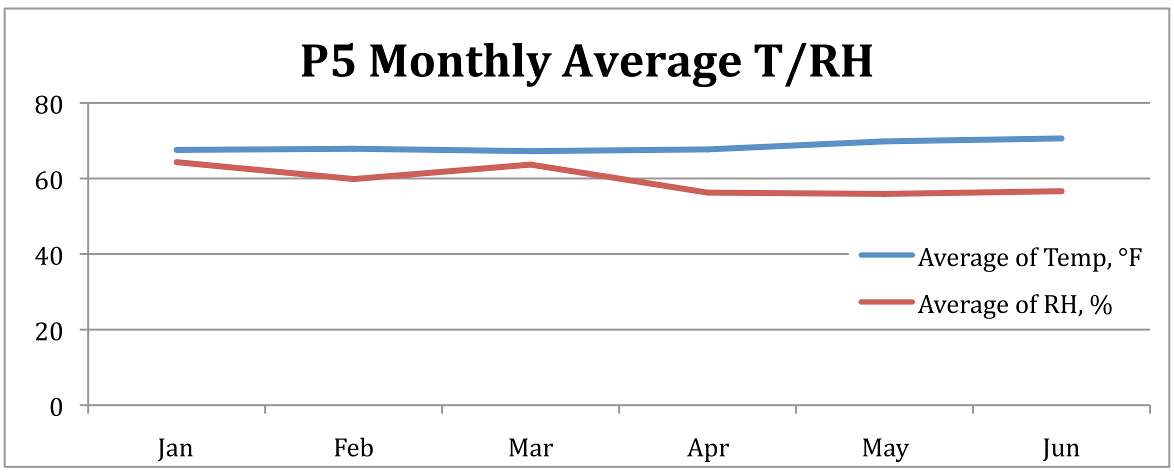


Figure 68 - P5 Indoor T/RH

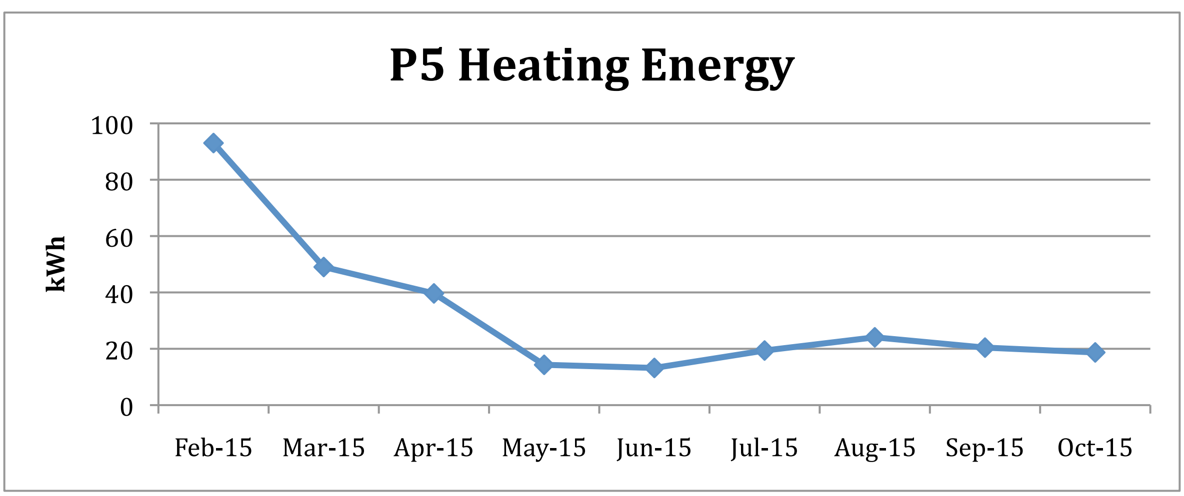


Figure 69 - P5 Heating Energy

Whole House Energy Use

Unfortunately, pre-retrofit utility bills are not available for P5. The home is quite small, which will make it look like a dense energy user when any metric that normalizes to house size is used. However, on a whole house or a per person basis, P5 should have significant advantage over some of the other projects. But, P5 is an all electric home, except for the propane oven/range, with all of the electric heating loads being met by resistance elements, rather than heat pumps. The source energy penalty associated with this electricity use is a disadvantage compared to other projects that use natural gas for space and water heating. It is also notable that no renewable energy is used on this project to offset the GHG emissions. A full year of data has not been collected yet but P5 will likely have high CO_{2e} emissions despite significant site energy savings, due to the use of electric heating.

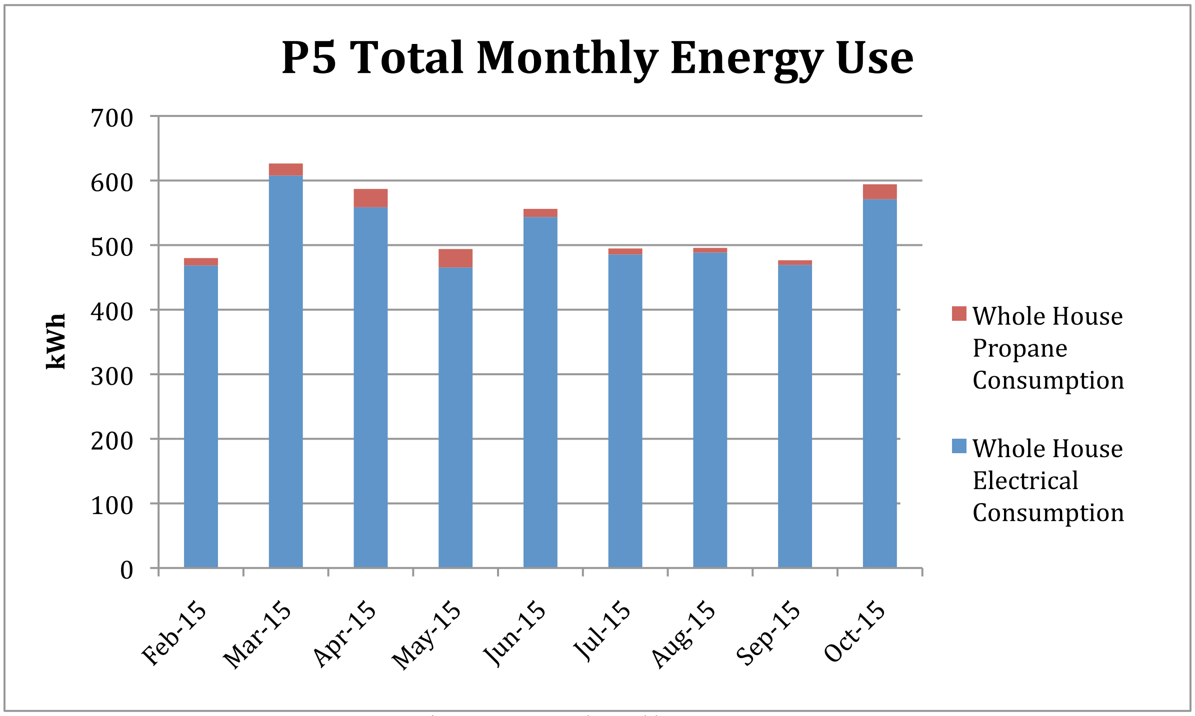


Figure 70 - P5 Total Monthly Energy Use

6.6 P6

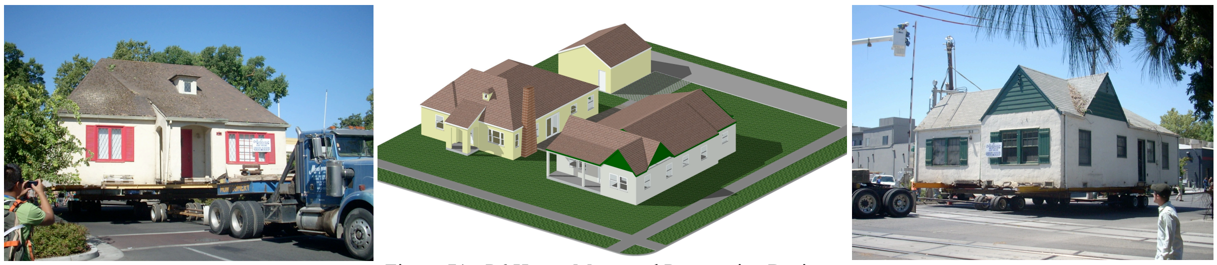


Figure 71 - P6 House Move and Perspective Design

6.6.1 P6 Project Description

General Information

P6 is located in the charming college town of 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, including a 4 kW PV array that is to be installed in January 2012. The project is applying for LEED for homes certification and has created a lot of excitement around DERs in Davis.

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 and the crawlspace was sealed and conditioned from the interior using 2” of XPS foam, 6” of low density SPF around the rim joist and a thick polypropylene moisture barrier taped and sealed at all joints and around each pier as well as the attachment to the stem wall. 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. This was filled with dense packed cellulose insulation and the attic was 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.

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. The result was a vast improvement on the original windows but still left air gaps between the two sashes in various locations.

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. 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 continuously operating exhaust fan at low power with an occupancy sensor and timer for higher flow rates.

Heating

Each building is heated using a point source natural gas fireplace in the living room. This system is far smaller, and less expensive than any other case study. There are four occupants in each building, and to date (as of mid December) neither gas fireplace has been used.

DHW

Both homes have a solar thermal DHW system with a natural gas, condensing hot water boiler back up, and 80 gallon storage tanks. The boilers are rated at 0.96 EF.

Appliances

As there are two homes, there are also two kitchens. However, the residents are using 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.

6.6.2 Building Diagnostic Results

Blower Door

We have not been able to get the building plans yet and therefore cannot yet calculate all of the blower door metrics. 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 leakage is likely due to this.

ID	CFM_{50}	ELA (in^2)
P6 North	991	49.40
P6 South	1114	55.90

Figure 72 - P6 Blower door results

6.6.3 Monitored data results

Monthly End-uses

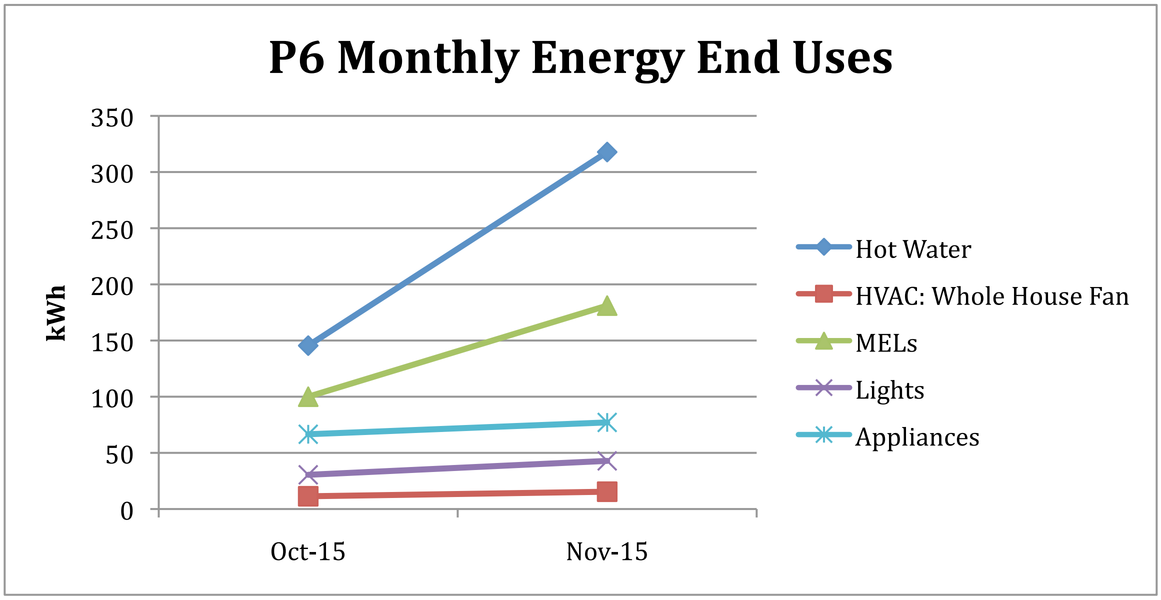


Figure 73 - P6 Monthly Energy End-uses

User Behavior

The occupants of P6 are very committed to a low-energy lifestyle. The North home has a baseload of 60 Watts with 1,101 observations; less our monitoring equipment of 15 Watts gives a baseload of 45 Watts! The kitchen is only used in the South house, so the baseload is slightly higher there at 131 Watts; less the 15 Watts of monitoring equipment gives a baseload of 116 Watts. Both of which are the lowest baseloads of all the case studies, and there are 4 occupants in each home.

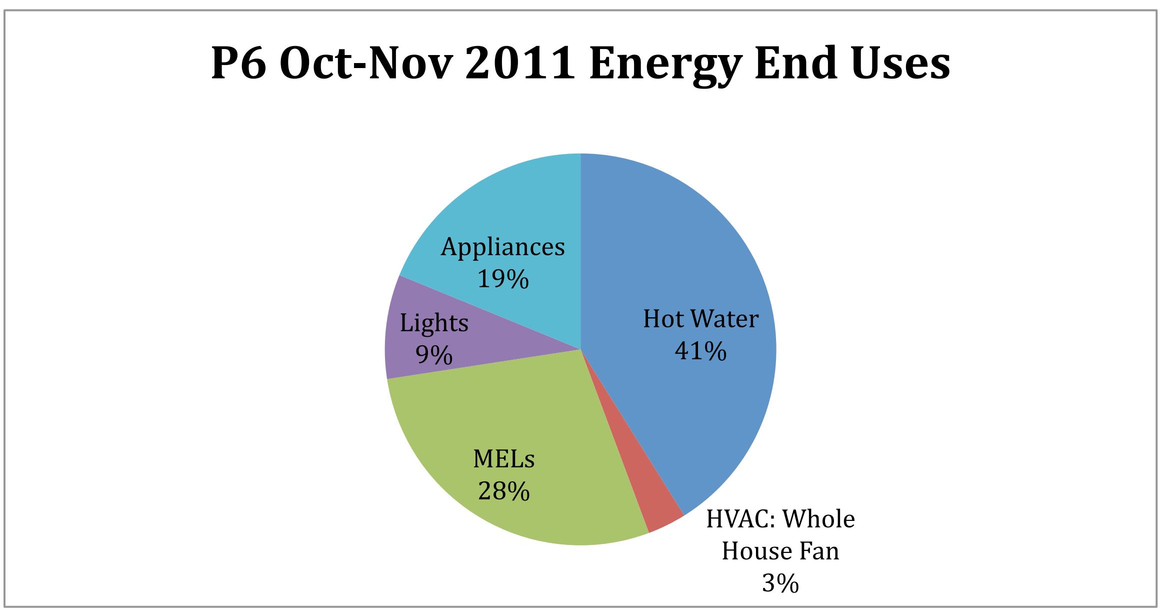


Figure 74 – P6 Energy End-Uses

6.7 P7

Figure 75 - P7 Front of home and house within a house construction

6.7.1 P7 Project Description

General Information

P7 is located in San Mateo, CA, which has used an intriguing zoned 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 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 in their home. 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.

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-year average pre-retrofit energy use was 32,211 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. 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 3,136 square feet 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 kept fully comfortable 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.

<u>Building Enclosure</u>

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. 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, was expanded slightly to the rear, and the exterior structural framing was replaced. 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. 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.

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.

<u>Air Leakage</u>

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 the contractor was 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. 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.

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 installed is 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 sub-meter in place, the occupants were informed that their stove used a cubic foot of gas every 40 minutes. 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. 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 sub-metering, 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.

6.7.2 Building Diagnostic Results

Blower Door

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH	SLA (ELA/ft^2_{FA})
P7	5336	10.82	0.79	1.62	300.62	0.72	0.00064

Figure 76 - P7 Blower door results

The pre-retrofit structure was uninsulated throughout, and a pre-retrofit blower door test measured 8,432 CFM_{50}. In addition, supply duct leakage to outside was measured at 115 CFM, and return duct leakage to outside was measured at 124 CFM.

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. But special efforts were paid to carefully seal the "house within a house" rear-L portion, where leakage-to-outside was separately measured at 431 $CFM_{50.}$ The total leakage of the rear-L, which includes both leakage to outside and leakage to the other zone, was measured as 966 CFM_{50}. This suggests that leakage area is approximately split evenly between the surfaces adjacent to the exterior and to the other zone.

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 77-80. 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 figures 85 and 86; others remain problematic, as shown in figures 81-84.

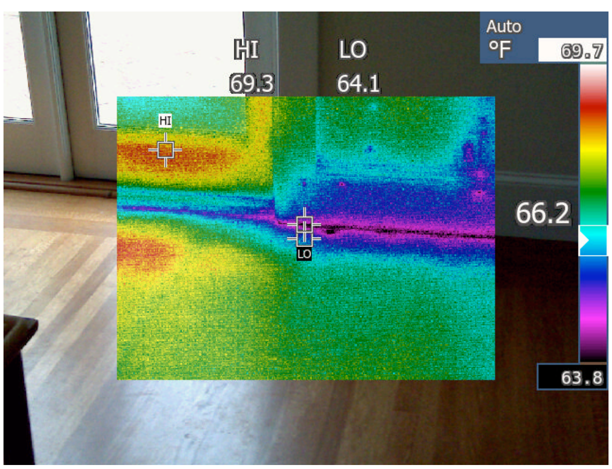


Figure 77 - P7 thermal leakage in rear L, likely concrete stem wall

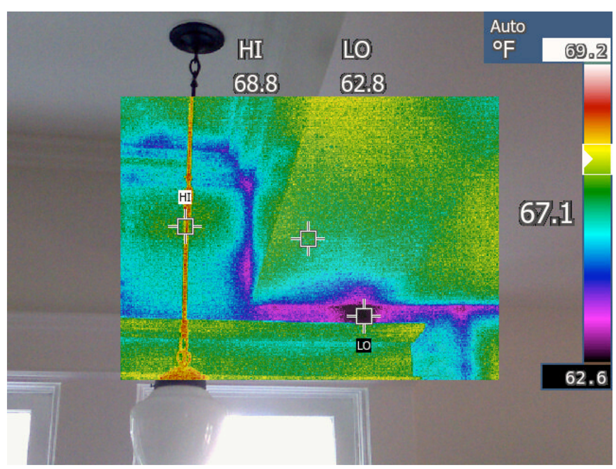


Figure 78 - P7 thermal/air leakage above kitchen sink

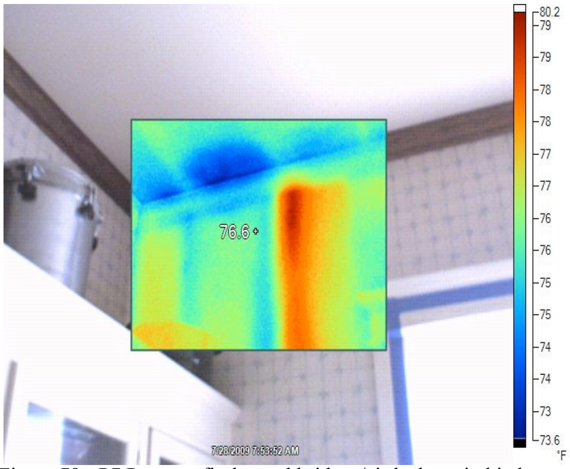


Figure 79 - P7 Pre-retrofit thermal bridges/air leakage in kitchen

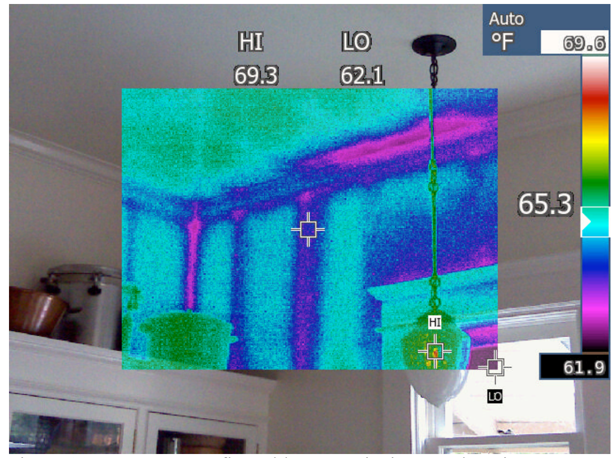


Figure 80 - P7 Post-retrofit problems persist in same location

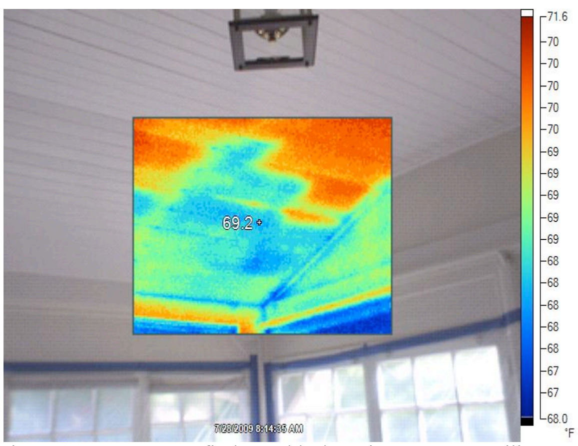


Figure 81 - P7 Pre-retrofit thermal leakage in guestroom ceiling

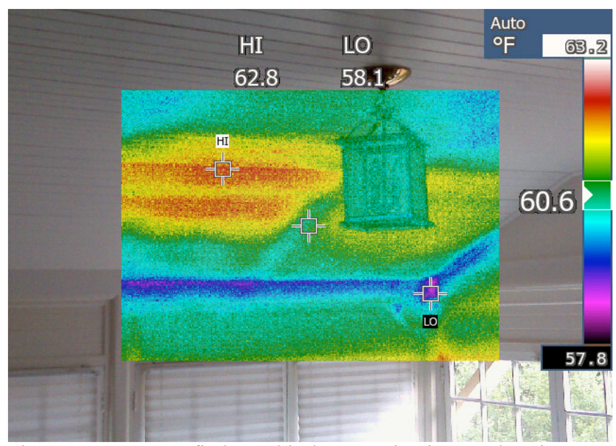


Figure 82 - Post-retrofit thermal leakage persists in same location

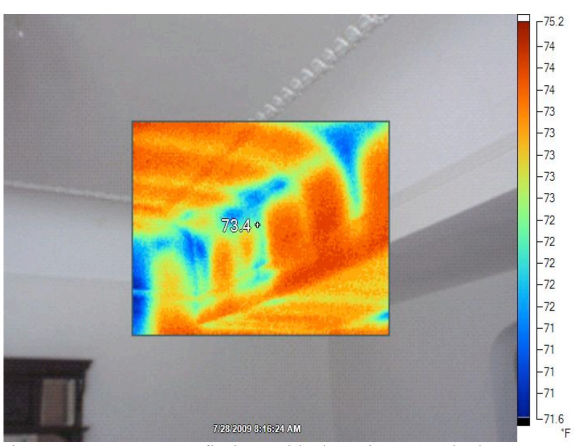


Figure 83 - P7 Pre-retrofit thermal leakage in master bedroom

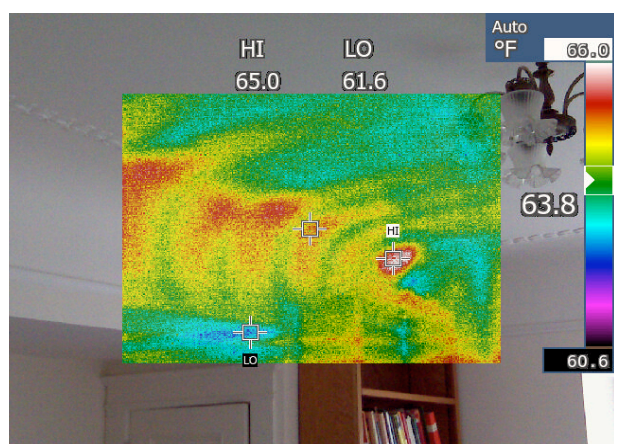


Figure 84 - P7 Post-retrofit thermal leakage persists in master bedroom

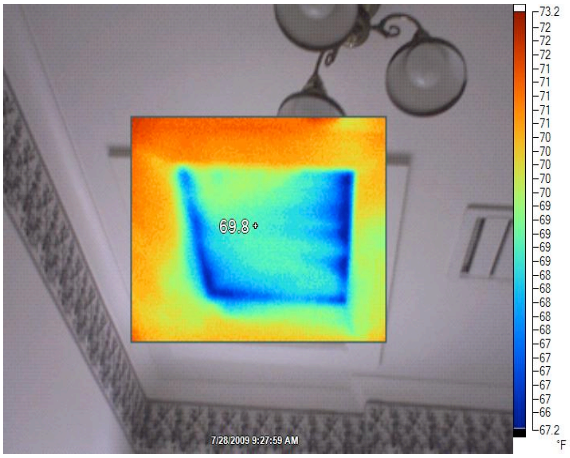


Figure 85 - P7 Pre-retrofit attic access door, very leaky

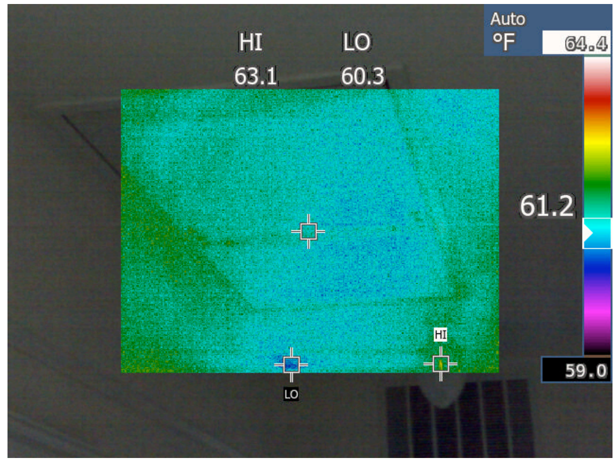


Figure 86 - P7 Post retrofit new attic door, well sealed

6.7.3 Monitored data results

Monthly End-uses

The gas range is by far the outlier in the energy use thus far. The heating season has not yet been monitored so the furnaces may surpass the gas range at some point, depending on user behavior. Apart from the gas range, P7 is most impressive for its consistent and low energy end-uses.

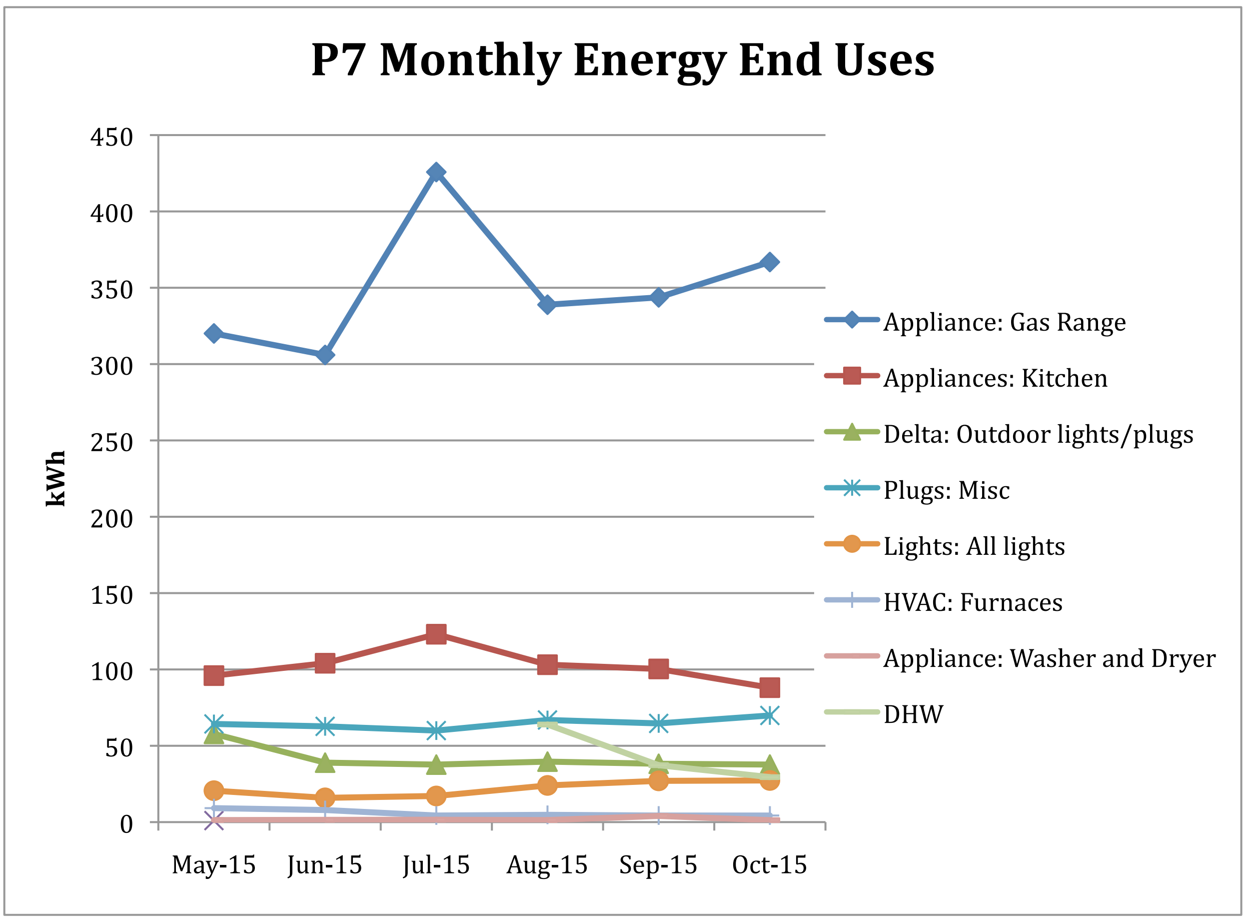


Figure 87 - P7 Monthly Energy End-Uses

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 88 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!

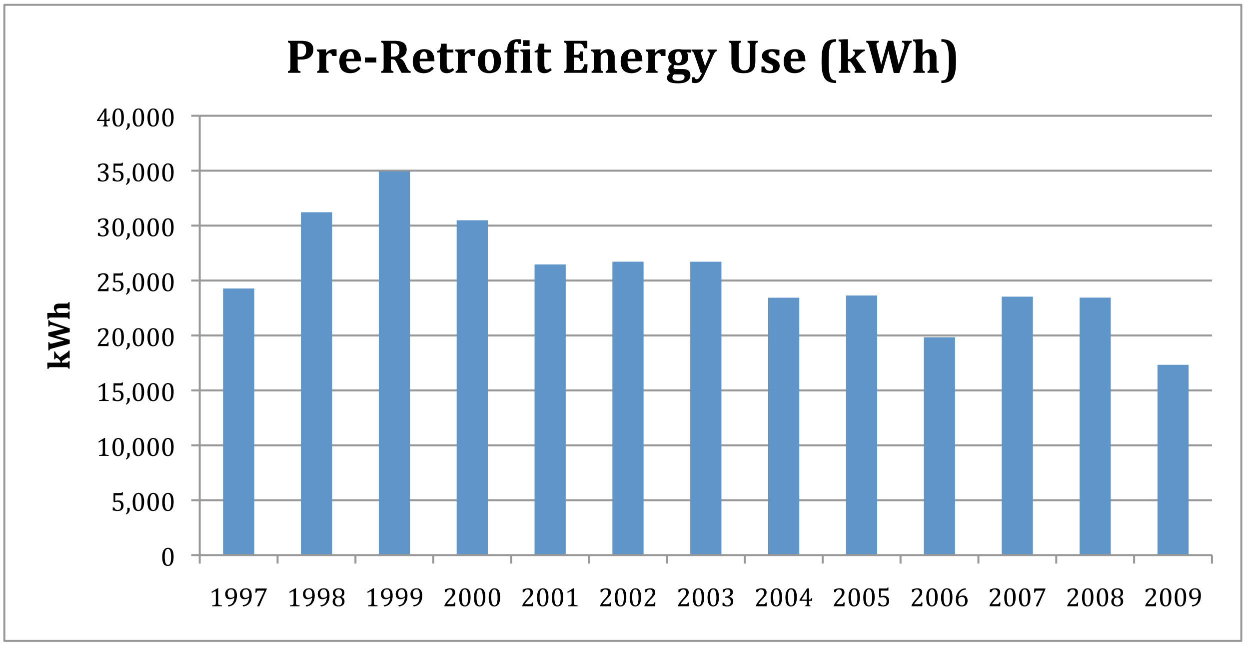


Figure 88 - P7 Pre-Retrofit Energy Use

The baseload at P7 is 172 Watts with 2,208 observations; less 15 Watts of monitoring equipment leaves a baseload of 157 Watts. Discretionary energy use is different in P7 as the decision to use an inefficient gas range is arguably discretionary. Figure 98 shows that if the gas range, lights and MELs are included, then 78% of the energy used to date is discretionary! Again, this will change when the heating season is included in the analysis, but the gas range is clearly overwhelming all other energy uses in the home thus far.

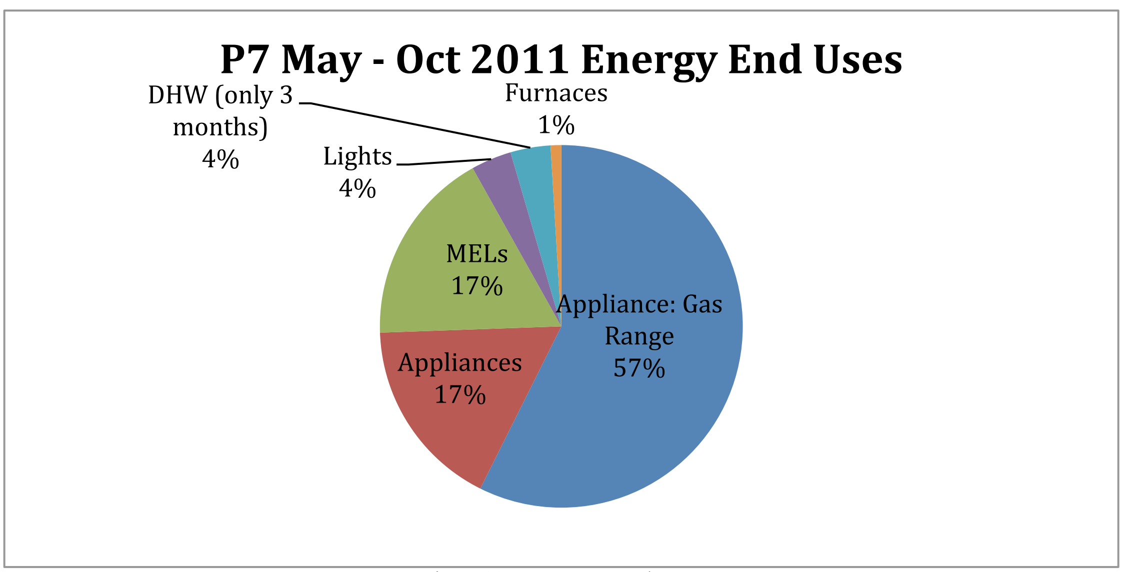


Figure 89 - P7 Energy End-uses

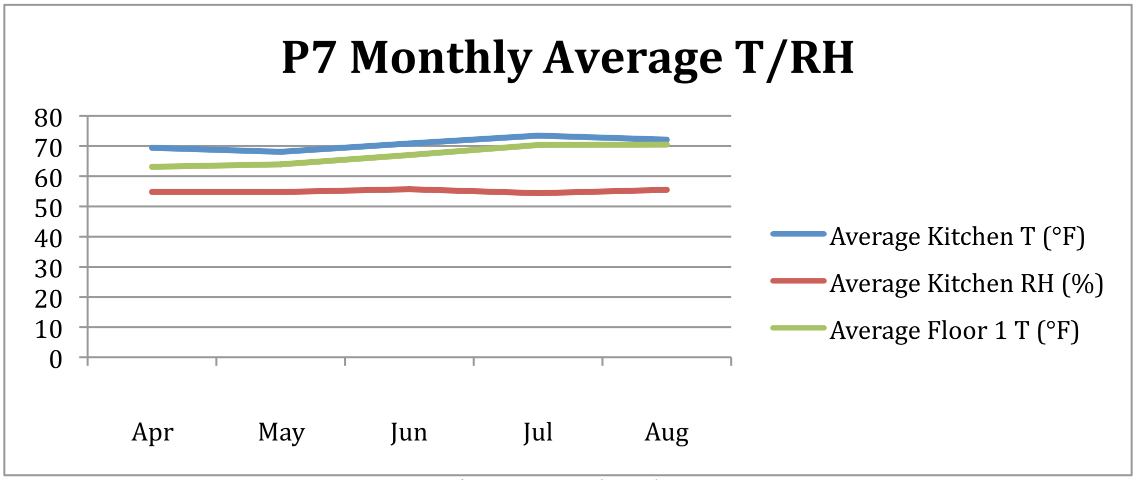


Figure 90 - P7 Indoor T/RH

Whole House Energy Use

Overall, energy use in P7 is fairly low, and due to the fact that the majority of the energy is natural gas, the CO_{2e} will be relatively low compared to other projects.

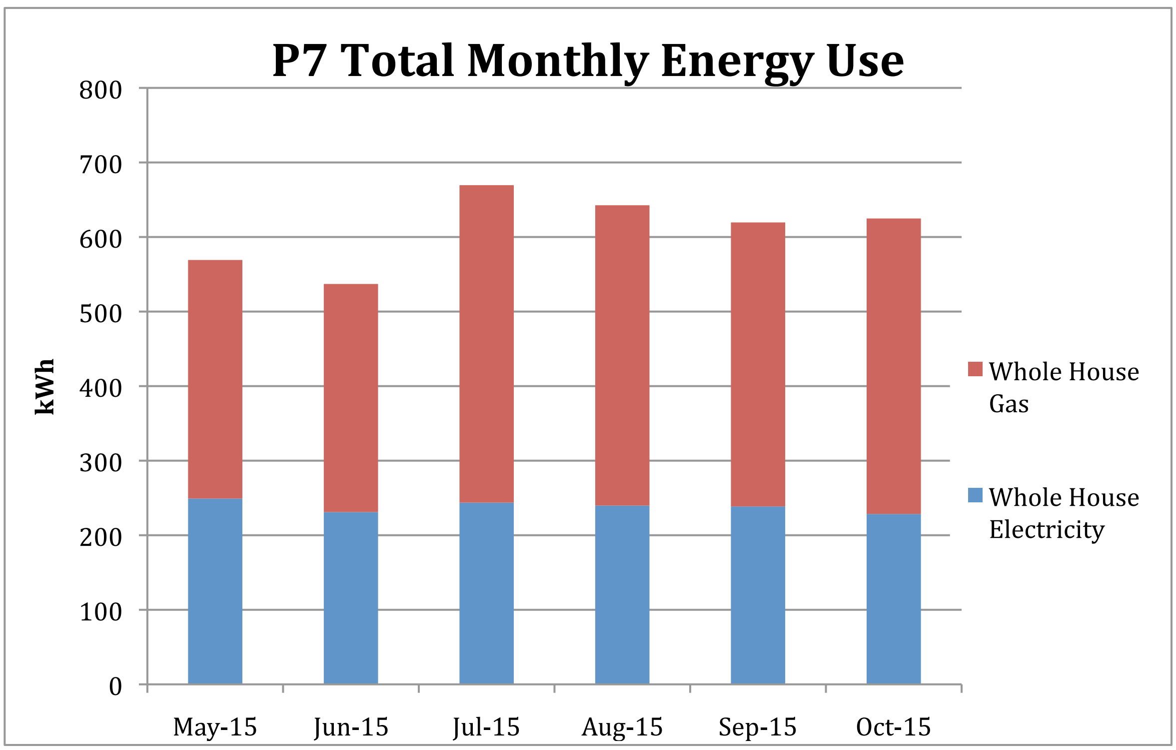


Figure 91 - P7 Total Monthly Energy Use

6.8 P8

Figure 92 - P8 Pre/Post-Retrofit

6.8.1 P8 Project Description

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, 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 net-zero 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.

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 square feet. A small 120 square foot 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. 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.

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. 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. 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.

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 cook top. The homeowners placed the old refrigerator in the garage for additional food storage.

Plug Loads

There are three televisions in the home, which appear to use a significant amount of energy. Besides that there are two laptops and a desktop, 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 net-zero energy 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 may 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 air tightness and the use of a high pumping energy greywater and rainwater system, as well as space conditioning and DHW system. P8 is a project that took deep energy reductions seriously, and achieved what it was supposed to. If air tightness and energy conservation were part of the original intentions, it is likely that these also would have been achieved.

6.8.2 Building Diagnostic Results

Blower Door

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH	SLA (ELA/ft^2_{FA})
P8	2397	9.3	0.48	1.5	131	0.63	0.00056

Figure 93 - P8 Blower door results

6.8.3 Monitored data results

Monthly End-uses

There appears to be something wrong with the solar thermal combisystem in P8. The monitored data suggests that the boiler is using far more gas than would be expected. The homeowner was notified but unfortunately the home was put up for sale in November 2011, as it was deemed too small for the family, and is now empty. Our hope is that the new tenants will also want to participate in the DER research project, but it is possible that we will not get a full year of monitored energy use from this home.

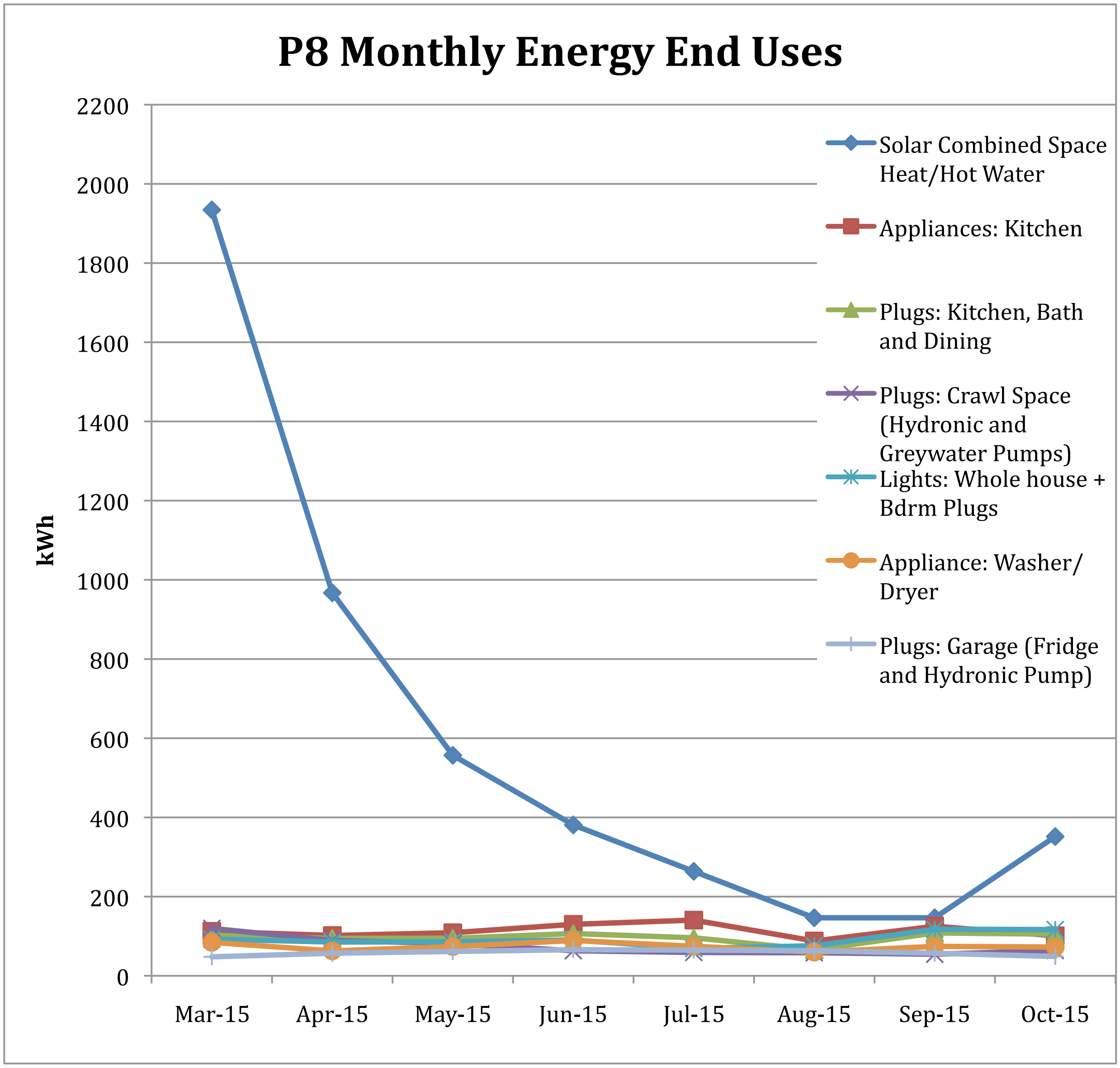


Figure 94 - P8 Monthly Energy End-uses

All other loads are fairly consistent and slightly higher than other homes. The hydronic pumps, as well as the greywater and rainwater pumps consume a significant amount of energy in this home.

User Behavior

The baseload in P8 is the third highest of all case studies, with 341 Watts, 3,696 observations, less 15 Watts of monitoring equipment leaves a baseload of 326 Watts. Discretionary energy use represents roughly 21% of the energy monitored to date. Overall, energy conservation was not a priority of the occupants in P8. The home has the potential to use very little energy, depending on how it is used. But issues with the solar combisystem and the excessive pumping energy would need to be assessed.

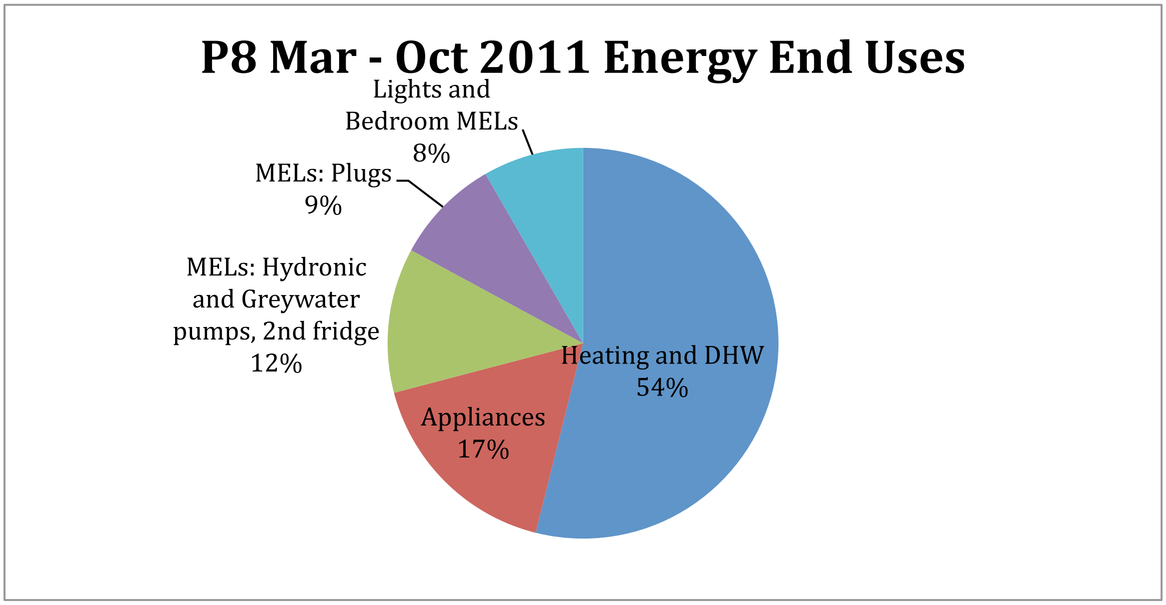


Figure 95 -P8 Energy End-uses

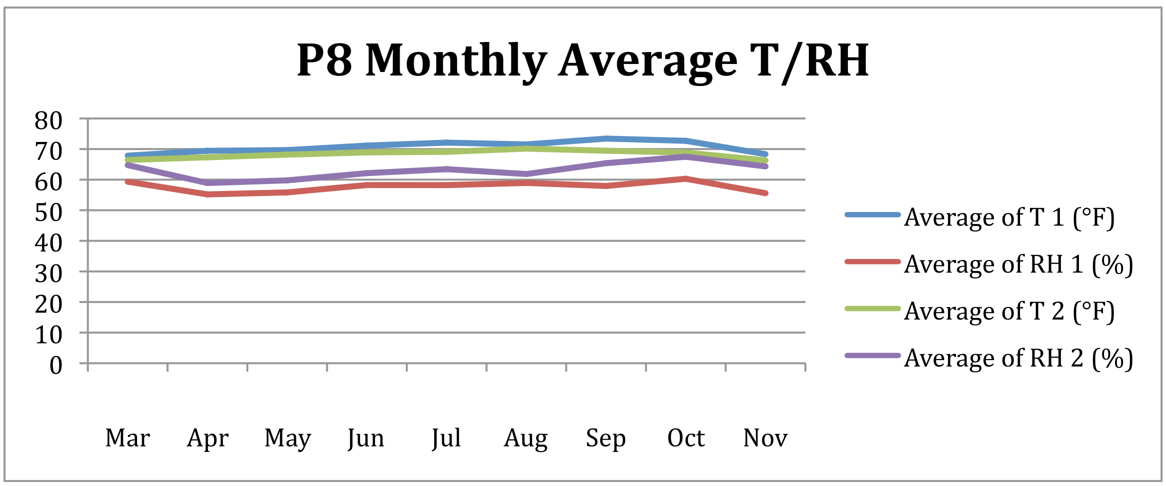


Figure 96 -P8 Indoor T/RH

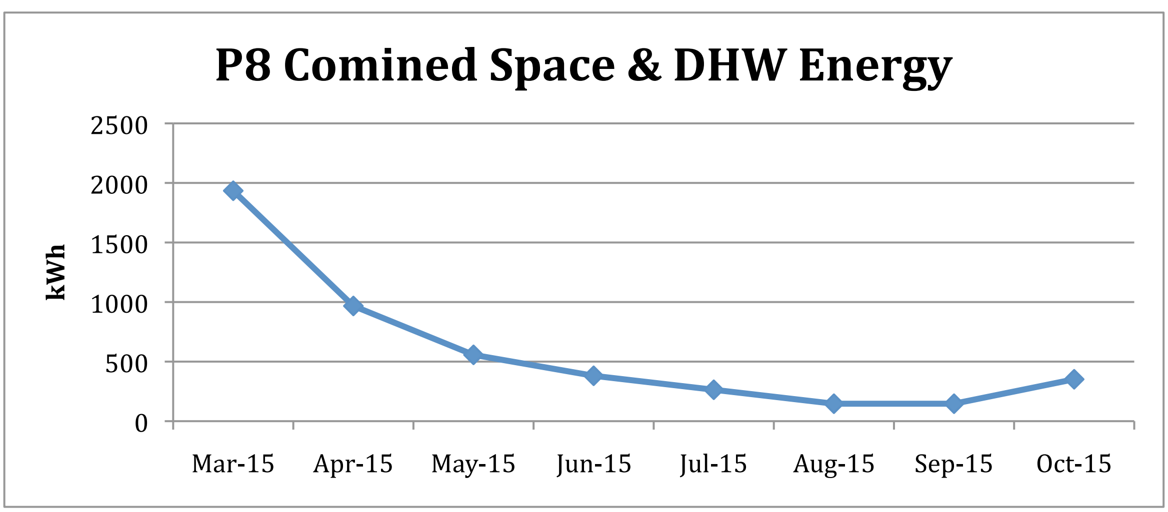


Figure 97 -P8 Heating/DHW Energy

Whole House Energy Use

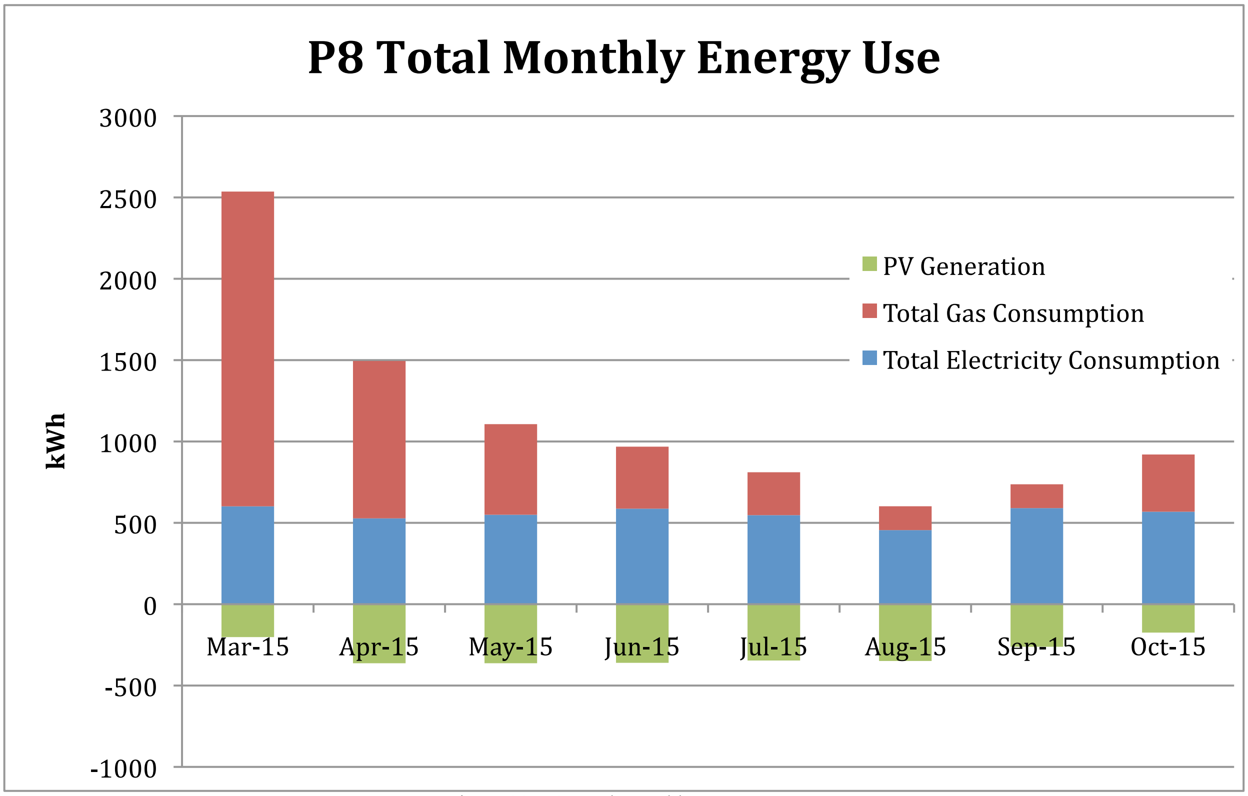


Figure 98 -P8 Total Monthly Energy Use

6.9 P9

Figure 99 - P9 Exterior

6.9.1 P9 Project Description

General Information
P9 is a 2,850 square foot production built home in Folsom, CA that was constructed in 1998 under the 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 62%. 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 discussing, 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 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 air tightness measurements revealed 1,879 CFM_{50} for the building envelope, and 103 CFM_{25} for duct leakage, amounting to 7.4% of the 1400 CFM nominal air handler flow. Both of these values are considered better than average.

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.

<u>Building Enclosure</u>
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.

<u>Air Leakage</u>
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.

<u>Ventilation</u>
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, and a variable speed kitchen exhaust fan.

<u>Heating</u>
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 and wasting energy. 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 pre-cooled outdoor condensing unit, which significantly increases energy performance at high outdoor temperatures. 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. 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.

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 air flow, 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.

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 61% reduction in electricity and 44% reduction in natural gas usage based on utility bills.

6.9.2 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	SLA (ELA/ft^2_{FA})
P9	1227	2.44	0.18	0.39	69.80	0.14	0.00016

Figure 100 - P9 Blower door results

6.9.3 Monitored Data Results

Monthly End-uses

Although there are only four months of monitored energy use, P9 is very impressive. The retrofit was relatively minor yet the energy end-uses are all very low. The natural gas tank water heater is the highest end-use, followed by lights and plugs. 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.

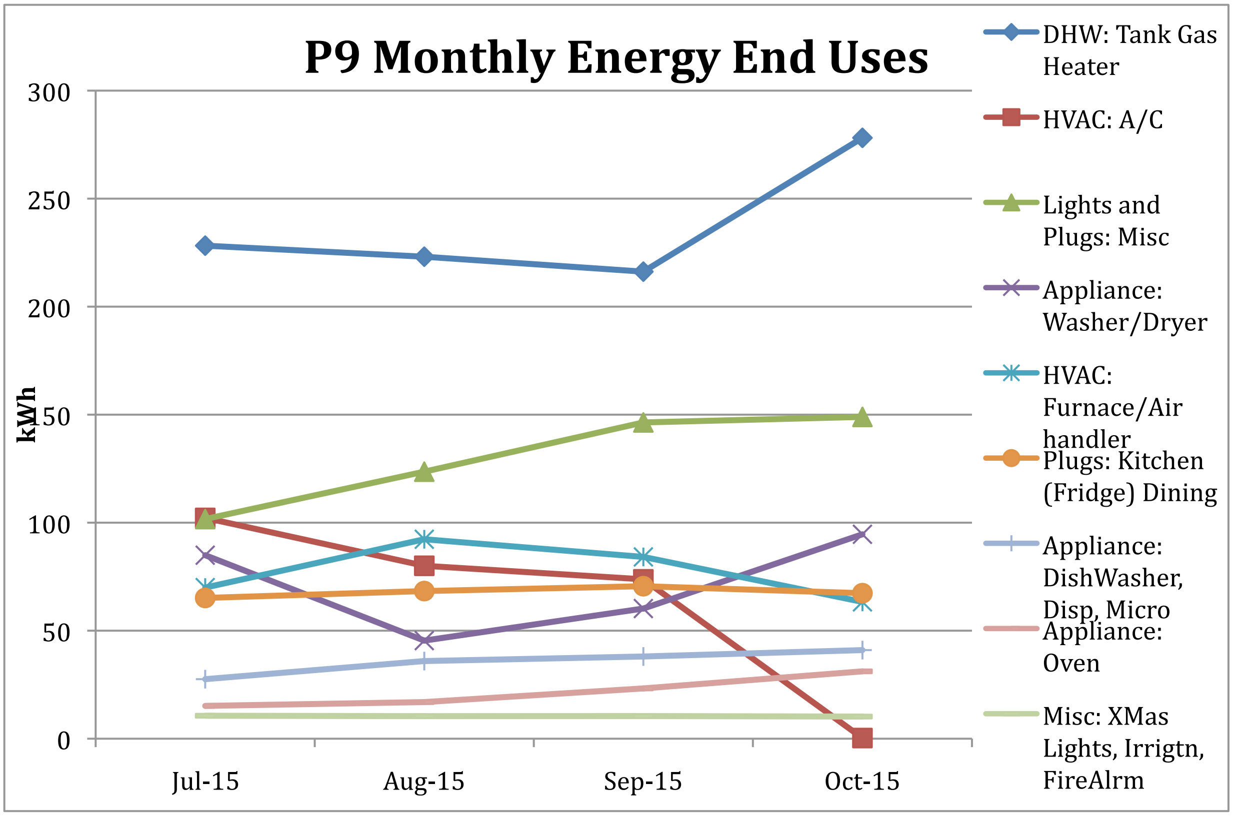


Figure 101 -P9 Monthly Energy End-uses

<u>User Behavior</u>

The baseload in P9 is 225 Watts with 3,637 observations; less 15 Watts for monitoring equipment leaves a baseload of 210 Watts. Discretionary energy use (shown in figure 102), including lights, makes up 25% of the energy used thus far.

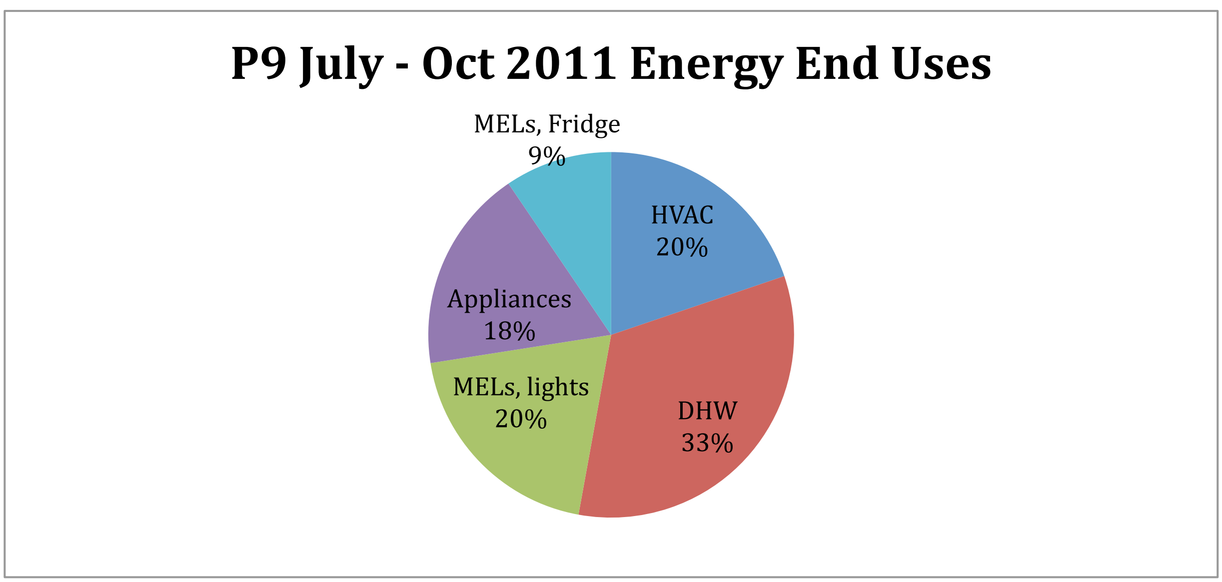


Figure 102 -P9 Energy End-uses

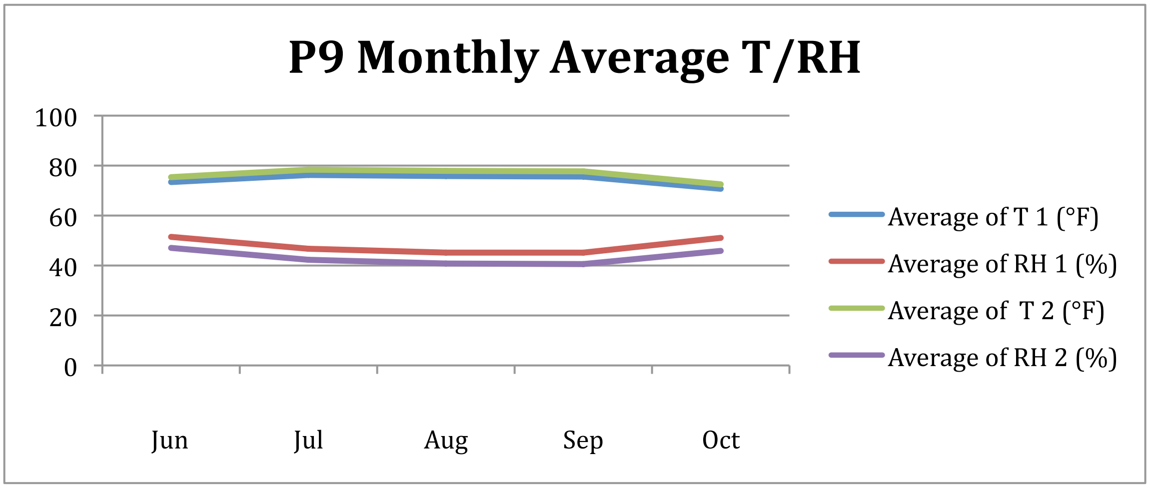


Figure 103 -P9 Indoor T/RH

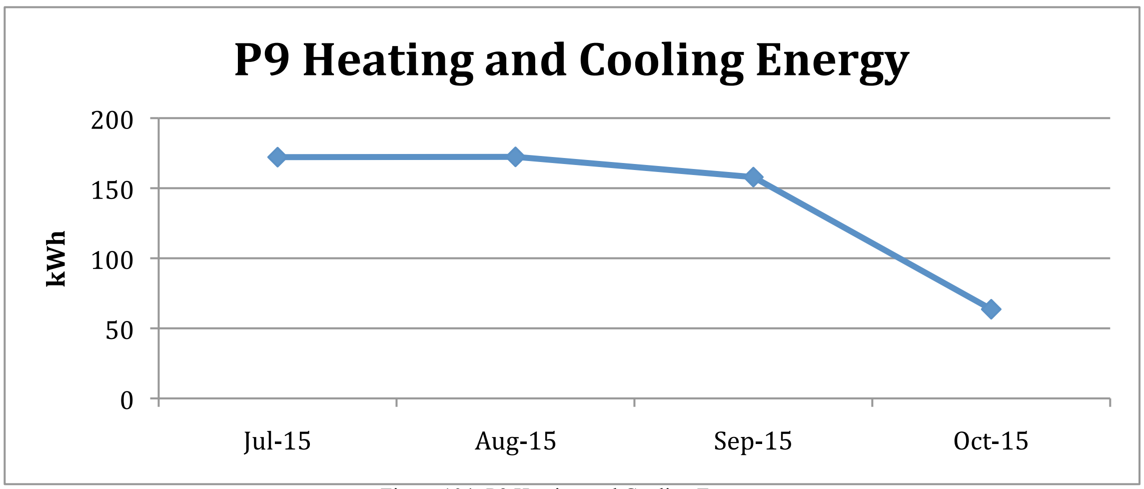


Figure 104 -P9 Heating and Cooling Energy

Whole House Energy Use

As shown in figure 105, the energy use at P9 is very consistent thus far, but the gas use will likely increase substantially throughout the heating season.

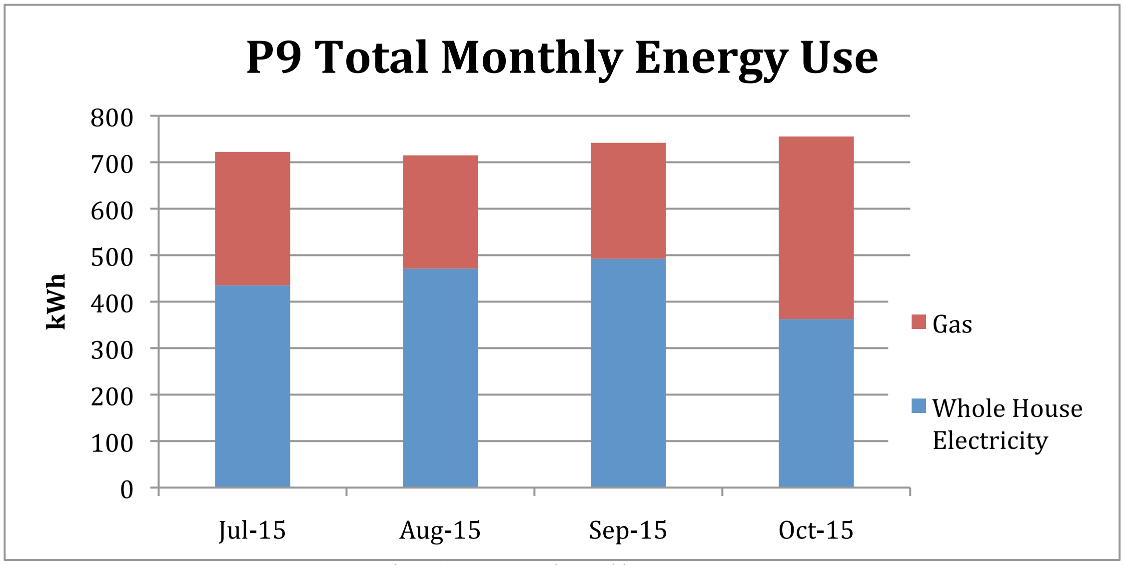


Figure 105 -P9 Total Monthly Energy Use

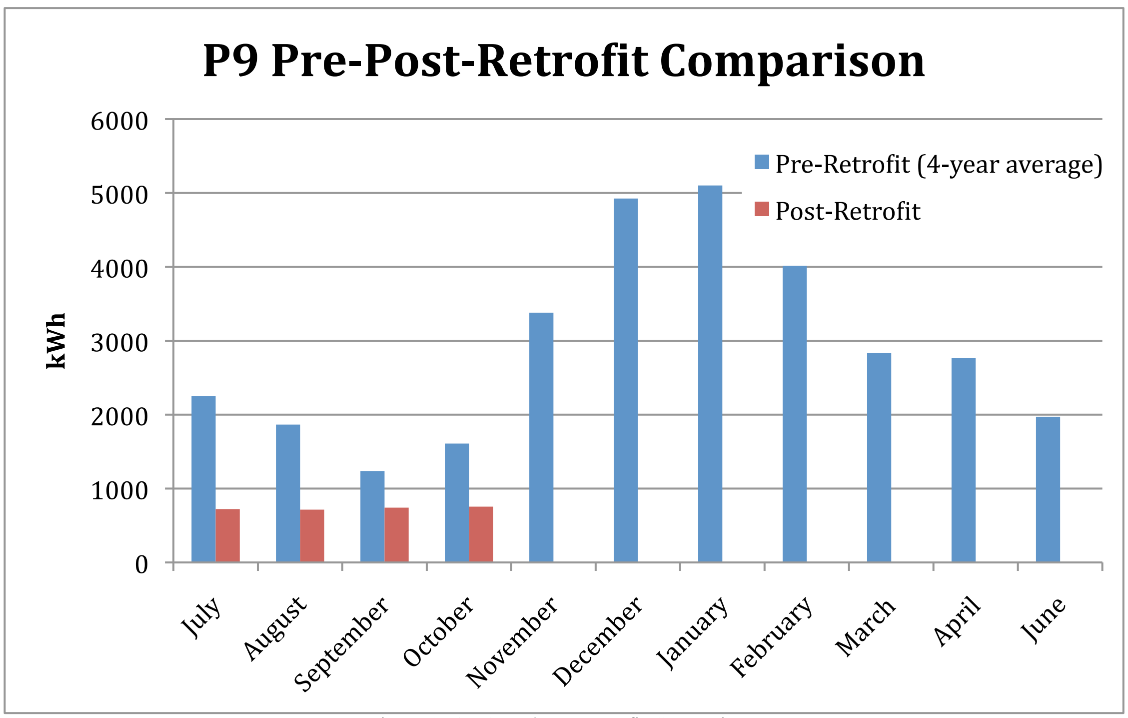


Figure 106 -P9 Pre/Post-Retrofit Comparison

6.10 P10


Figure 107 - P10 Pre/Post-Retrofit

6.10.1 P10 Project Description

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 and before the retrofit was 1,503 square feet. 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.

Building Enclosure

As an uninsulated structure, P10 required a comprehensive insulation and air tightness 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

Despite the use of spray foam insulation throughout the house, the structure remained relatively leaky, achieving an air tightness level 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. Eighty CFM Energy Star, low-sone (a measurement of sound volume) bathroom exhaust fans were installed in each bathroom. A 380 CFM kitchen down draft exhaust fan was also installed. 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. 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.

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. 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 Fahrenheit), 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 passively light the house passively using the sun. This effort included installation of numerous skylights, solar tubes and translucent interior doors, 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.

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.

6.10.2 Building Diagnostic Results

Blower Door

ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2_{SA}	CFM/ft^2_{FA}	ELA (in^2)	nACH	SLA (ELA/ft^2_{FA})
P10	1455	6.1	0.29	0.85	75.4	0.28	0.00031

Figure 108 - P10 Blower Door Results

6.10.3 Monitored Data Results

Monthly End-uses

The homeowners of P10 were away for half of July, and took several other trips, which should be considered when analyzing the energy use. However, this is somewhat irrelevant as they still only consumed the amount of energy that was monitored, and we want to know how people use their homes over the course of a year, which includes vacations and other time away from the home. To date the PV has actually produced 139 kWh more energy than they have consumed since the monitoring period began. So far the plug loads are the highest end-use in the home, but there has not yet been significant heating loads, and the upward trajectory of the water heater is visible in October, so the gas use is going to increase steadily along with the heating demand.

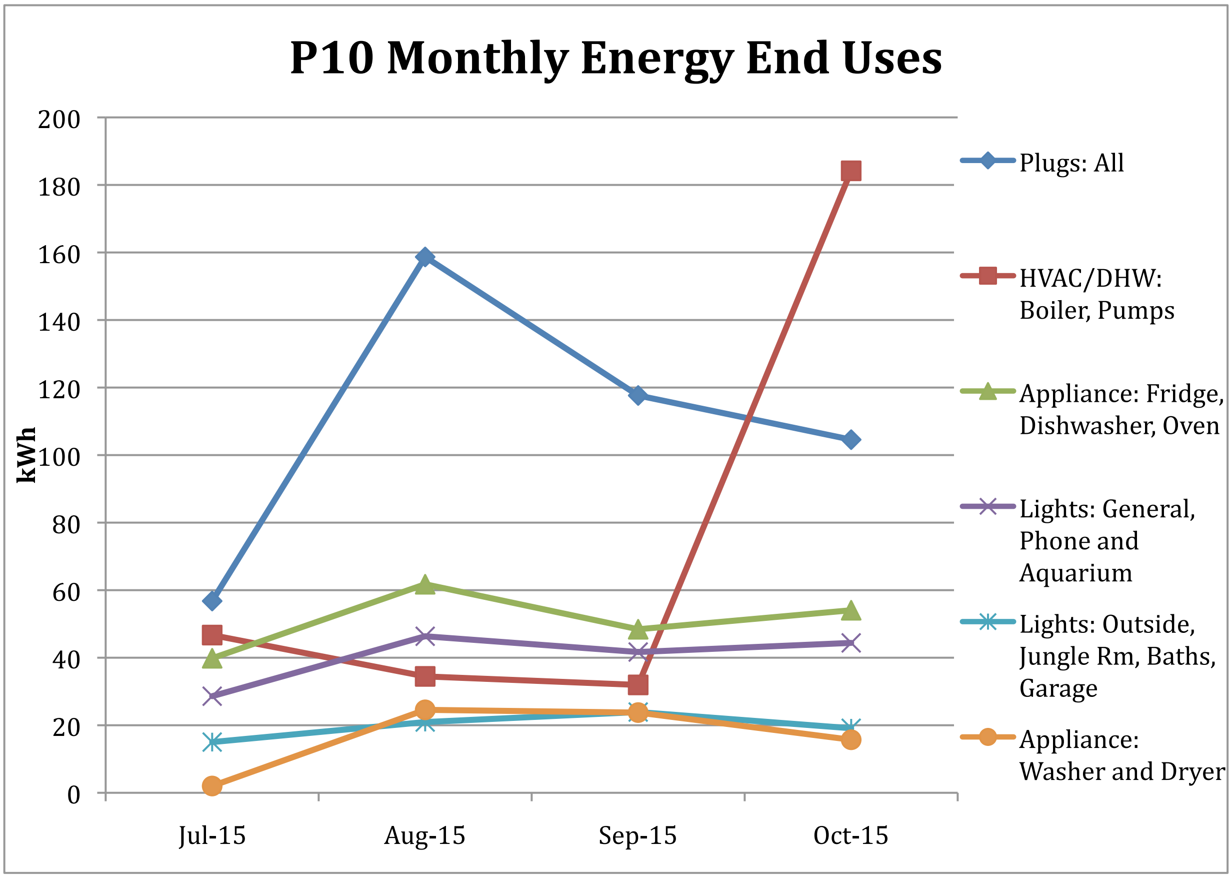


Figure 109 -P10 Monthly energy End-uses

<u>User Behavior</u>

The baseload in P10 thus far is 203 with 2,592 observations; less 15 Watts for the monitoring equipment leaves a baseload of 188 Watts. 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.

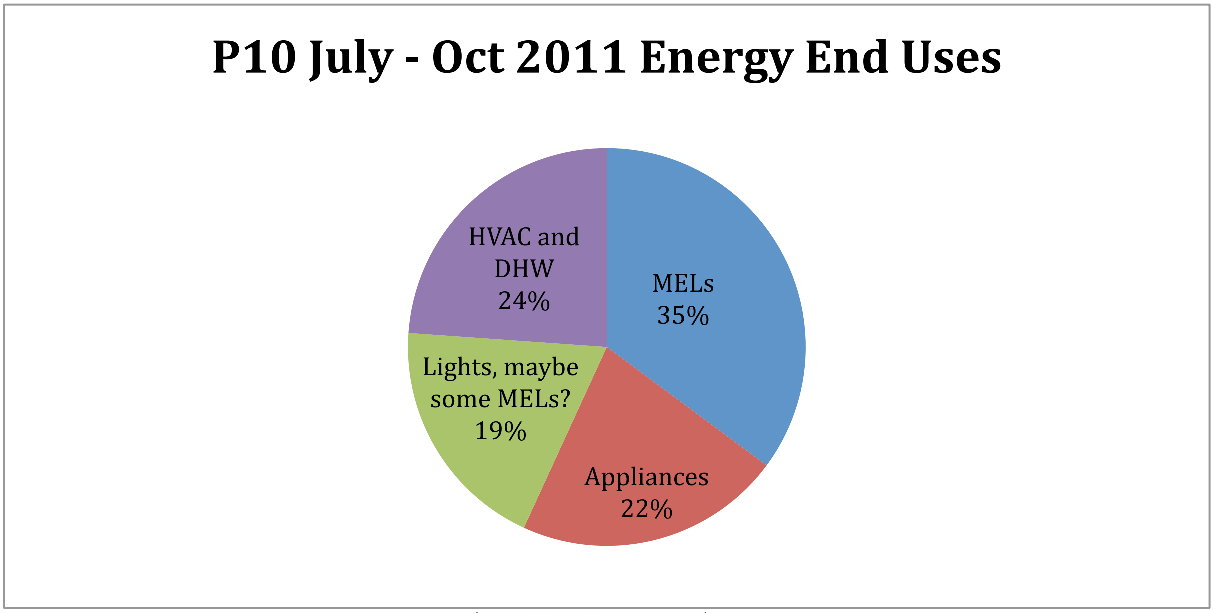


Figure 110 -P10 Energy End-uses

Whole House Energy Use

As shown in figure 111, the home is so far performing better than ZNE. However, this is going to change as the heating demand increases and the solar fraction decreases.

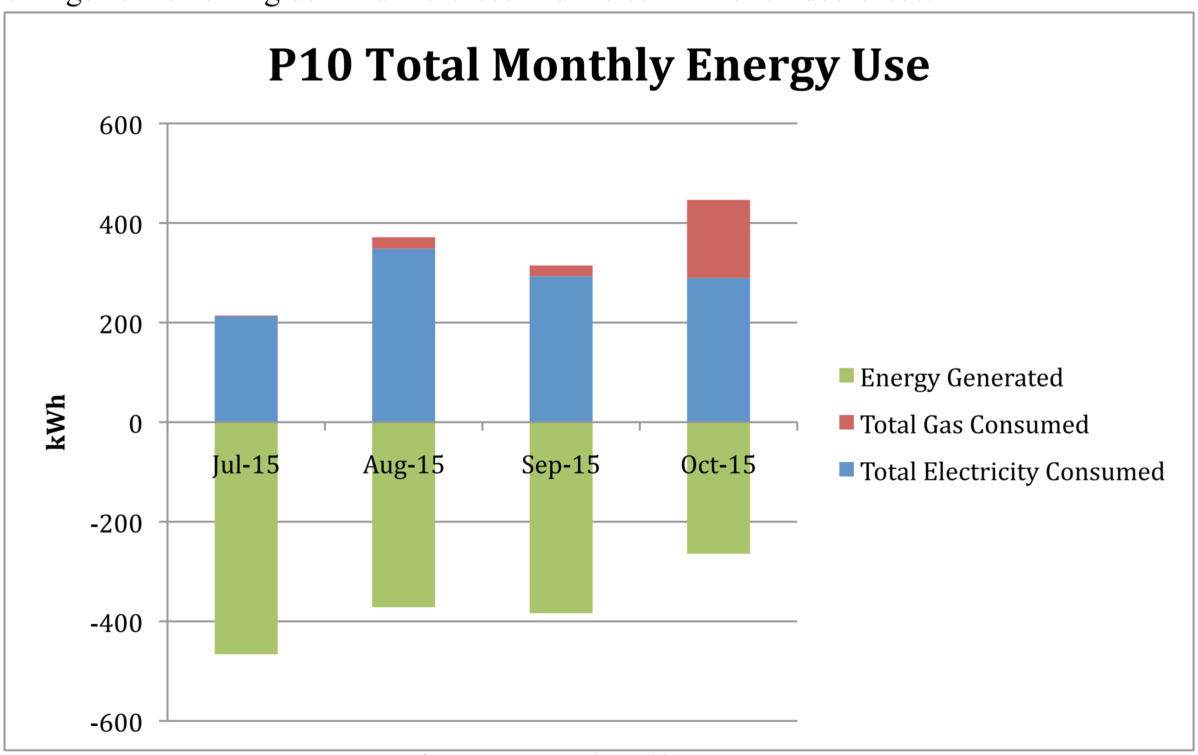


Figure 111 -P10 Total Monthly Energy Use

7 DISCUSSION

7.1 Overview of Results

Each case study is unique, offering different insights and important lessons learned that can be used to implement successful DERs in the future. A summary of the retrofit measures in each case study, and possible explanations of performance is discussed below. This is followed by the main takeaways from the case studies, and the broader implications of how this research could lead to deeper energy savings in our existing homes.

Monitoring end-use energy has been extremely valuable, helping create a detailed understanding of how much energy is being used in these DERs, and where. The data and online energy dashboard has also helped homeowners better understand their own energy use, and certain malfunctioning or unnecessary energy issues have been 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.

Through this combination of detailed performance data and project descriptions, homeowners, contractors and researchers can extract pertinent information from each case study in order to fit their own unique projects and interests in our collective push towards deep energy savings.

7.1.1 P1 Overview

P1	Pre-Retrofit	Post-Retrofit
ENVELOPE		
Wall Insulation	None	1st floor: 5.5” cellulose – R19 2nd floor: 3.5” cellulose, 2” XPS – R23
Attic/Roof Insulation	Some fiberglass	10” 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
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

Figure 112 - P1 Retrofit Summary Table

The final results of 28% site and 5% 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. Additionally, the question of which metric to use in the evaluation of these case studies becomes a topic of concern when evaluating P1. At 28%, 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 are less impressive at 5%. However, if the post-retrofit CO_{2e} is evaluated on a per person basis (See figure 126), then the ranking is significantly different, showing that higher density results in lower GHG emissions. Each different metric tells a different story, a range of metric comparisons are shown below in figures 126 – 127 in order to highlight this problem.

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 (IS Walker and MH Sherman 2007).

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 (in California the energy code is often referred to as “Title 24”). While the temperature data (See figure 13) 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.

7.1.2 P2 Overview

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

Figure 113 - P2 Retrofit Summary Table

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 50% 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 31% of all site energy used, not including lights, compared to the California average of 10-15% (CPUC 2008). Figure 124 shows that post-retrofit, P2 is barely performing better than the typical California single-family home (KEMA, Inc. 2010). The CO_{2e} results however, show a 63% decrease in GHG emissions. Thanks to the low carbon fuel mix of the Palo Alto Utility provider, the carbon output is close to half of that of the typical California single-family home. This clearly demonstrates the need for low carbon electricity, a subject that will be further discussed below.

So far, P2 is the highest energy consumer of the study, by at least a factor of two (also shown in figure 124). One factor is the high baseload of 617 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.

7.1.3 P3 Overview

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

Figure 114 - P3 Retrofit Summary Table

The lost data from the changes made in monitoring equipment after the addition of the PV, as well as the issues associated with the original placement of the heatpump, both amount to an overall biased performance analysis of P3 during the first year of operation. However, many important lessons can still be drawn from the current results. The heatpump issue described in detail in the findings again shows that even in a Passive House, well-distributed heating systems are necessary for optimum comfort. Admittedly, the indoor temperatures were kept higher than all other case study homes in P3; since this project demonstrates the highest construction quality observed, and the layout of the structure is particularly challenging, it is feasible that a point source heater could provide sufficient comfort with a modified building layout.

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 the combination of efficiency and conservation are necessary if we are to significantly lower GHG emissions through retrofitting our existing buildings.

Several issues were found through the energy monitoring of P3; the ERV was stuck on high for over a week, which was caused by a clogged air filter, and was later resolved by the contractor. The problem was encountered again 6 months later and the reason for rapid reoccurrence should be further investigated. The excessive energy use by the heatpump helped uncover the problem of the original location of the head, which in turn increased comfort and saved significant energy.

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 regardless of user behavior.

7.1.4 P4 Overview

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

Figure 115 - P4 Retrofit Summary Table

P4 is overall the most exemplary DER to date. The most impressive part about the project is that it is unknown how much energy was saved since before the initial retrofit, and even without including these initial savings; it has saved 90% of the site energy and 63% of the CO_{2e}.

The formula for success has been the combination of optimized energy efficiency and extreme energy conservation. The homeowners of P4 are models of low energy user behavior. The advantages that the homeowner has over other projects are that he is an experienced architect with a focus on energy efficiency, and was able to carry out the retrofit in stages, learning from the results of each subsequent retrofit, and adjusting the building accordingly.

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, will result in a successful DER.

7.1.5 P5 Overview

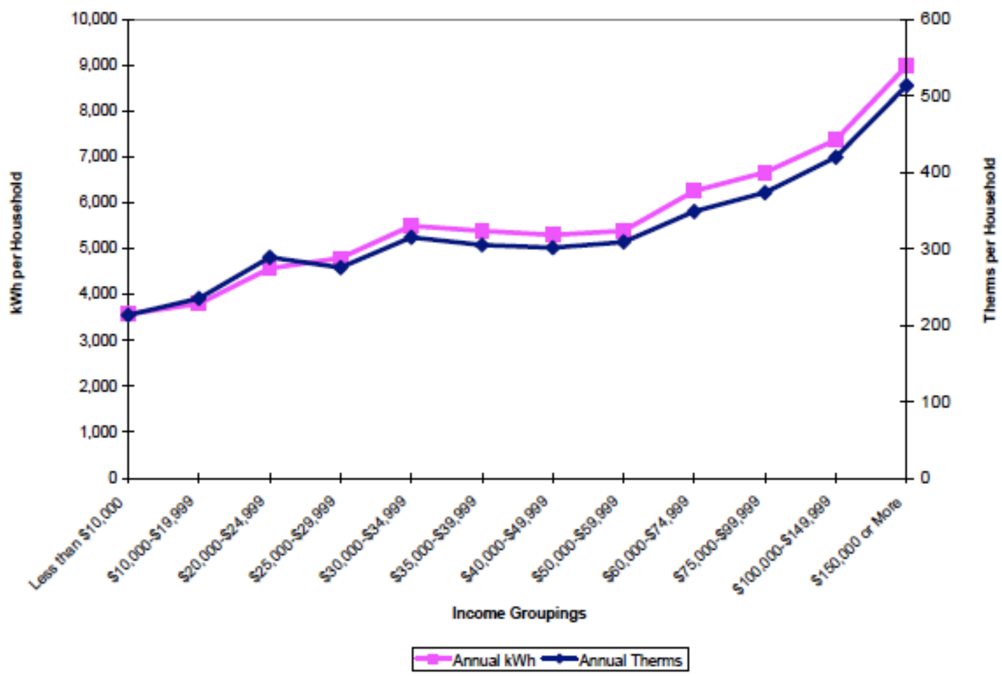
P5	Pre-Retrofit	Post-Retrofit
ENVELOPE		
Wall Insulation	2X4 fiberglass batts	3.5” cellulose, 1” XPS – R18
Attic/Roof Insulation	Some fiberglass batts	16” loose fill cellulose – R57
Foundation Insulation	R-19 fiberglass batts	Sealed crawlspace, 11.5” blown cellulose – R41
Windows	Single pane aluminum 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

Figure 116 - P5 Retrofit Summary Table

A full year of monitored data has not been collected for P5; therefore, overall performance results are inconclusive. It is apparent that the water heater and the appliances are the dominant loads to date. Very little heating energy has been used, but is expected to rise in the coming months. As P5 is an all electric home, the CO_{2e} is going to be an important (and likely high) measure of performance for P5.

The most commendable aspect of this home is the user behavior represented in the low baseload and discretionary energy use. P5 is a low-income home, and there are not a lot of plug loads or extra appliances and gadgets that are found in the other homes. 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 Residential Appliance Saturation Survey (KEMA, Inc. 2010) shows a parallel relationship between income level and energy consumption.

Figure ES-34: Average Electricity and Natural Gas Consumption by Income



Source: *2010 California Residential Appliance Saturation Survey*

The monitored energy data shows very little propane used for cooking, and also very infrequent ERV use, which raises the question of; "Are the residents getting enough fresh air supply?" Based on the ASHRAE 62.2 Standard (ASHRAE 2007), and since it is a relatively tight home, it appears that they are not.

7.1.6 P6 Overview

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		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		100% CFL, Energy Star ref, very low MELs
RENEWABLES		Planned 4 kW PV, 8 flat plate solar thermal panels

Figure 117 - P6 Retrofit Summary Table

Very little data has been collected at P6 thus far; therefore any evaluation of performance is premature. All residents are committed to a low energy lifestyle; their baseload is the lowest seen in this research. Additionally, it is an affordable housing cooperative, which may lead to a similar conclusion to the low baseload in P5. The fact that eight people are living here makes it the highest density case study. The low baseload and the fact that no heating energy has been used to date (Mid December) shows very low energy user behavior, and leaves great expectations for the data to come.

7.1.7 P7 Overview

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

Figure 118 - P7 Retrofit Summary Table

In addition to P4, P7 is likely to be another exemplary project. 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 88, the pre-retrofit energy analysis of P7. The fact that 50% of their site energy could be saved through austerity measures 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 before beginning the retrofit of the home 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, Fairey, and Hendron 2010). P7 has used over 2,100 kWh after only 6 months of monitoring. The energy monitoring helped discover the extremely high amount of gas used for the pilot lights of the stove, which were then reduced by extinguishing all of the range pilots. 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 over 57% of the energy used in the home thus far.

7.1.8 P8 Overview

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

Figure 119 - P8 Retrofit Summary Table

The most unfortunate news about P8 is that the homeowners moved out in November 2011, therefore a full year of monitored energy use will not be completed for at least another year, and only if the new homeowners decide to participate in the research. Additionally, the problems with the combined solar space and hot water heating system that were discovered through our energy monitoring will likely go unresolved. It is likely that the solar hot water controls are recirculating the hot water at night, resulting in high heat losses, especially noticeable in the winter when the solar fraction is far less and the heating demand is far higher. However, this is only speculation and no commissioning of the system was ever performed, despite notification of the homeowner. P10 has the same system installed and is also experiencing problems and higher heating energy than expected. No conclusions have yet been made but caution should be used if these systems are to be used in the future, as they do not appear to be performing as well as expected.

The data that was collected shows fairly high energy user behavior, nominal construction quality, and far higher gas use than expected for the solar combisystem. Additionally, the pumping energy for the greywater, rainwater and hydronic heating systems were significant, amounting to nearly 10% of the whole house energy use. Further research on pumping energy in these systems is needed. 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 a certain percentage of energy savings. However, similar to P1, there are 4 occupants in the home, and if the performance metrics are evaluated on a per person basis, then P8 is performing very well.

7.1.9 P9 Overview

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, 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

Figure 120 - P9 Retrofit Summary Table

P9 is another unique DER as it demonstrates a low cost solution for deep energy savings in a relatively new, and already efficient home. Minimal data has been collected to date, but so far it is most impressive for the significant energy savings given the fact that the original construction was built to 1998 Title 24 requirements, a relatively energy efficient building code. The retrofit of P9 was more similar to an energy performance upgrade rather than a typical DER, with added insulation, air sealing and HVAC improvements. The majority of the energy savings seem to come from the HVAC upgrades. The whole house fan for night cooling and the evaporative cooling unit have proven to be very effective at reducing the air conditioning load 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.

7.1.10 P10 Overview

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

Figure 121 - P10 Retrofit Summary Table

So far, P10 is performing extremely well, producing slightly more energy than it has used. However this is due to change as the heating demand increases and the solar fraction decreases. The homeowners have reported problems with the solar combisystem and similar to P8, historical utility bills indicate higher gas use than expected, but not enough data has been collected to evaluate the problem.

The monitored energy data at P10 is being used to minimize phantom loads and trouble shoot the operation of the heating system. MELs are thus far a significant load in the home, totaling 35% of the energy consumed over the summer. P10 hopes to achieve the Thousand Home Challenge and it will be interesting to see if the heating system can be resolved and the MELs can be reduced sufficiently to achieve the goal of 75% energy reduction.

7.2 Takeaways

<u>Diversity</u>
Figure 122 compares the ten case studies, and shows the wide range of attempted solutions, building characteristics, and occupant behavior found in our study. This is likely to be true of DERs as they reach a wider audience because of the variability in existing home construction, location and occupancy. It also shows that there are many different paths to deep energy savings; its more than just adding PV, and does not require particular technology specifications, but must instead allow for flexibility.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Building Enclosure										
Super Insulated (100% > T-24)			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
Passive House Standard <0.6 ACH_{50}			X							
R-2000 Standard <1.5 ACH_{50}	X									
Energy Star V. 3 <5 ACH_{50}					X				X	
HVAC										
Heat/Energy Recovery Ventilation	X	X	X		X					
Electric Resistance Heating	X				X					
Heatpump Heating and Cooling		X	X							
A/C with Evaporative Cooling									X	
Solar Thermal Combisystem			X					X		X
Night Ventilation Cooling				X		X			X	
DHW										
Electric Resistance					X					
Heatpump		X								
On Demand Condensing Natural Gas	X			X			X			
Tank Natural Gas									X	
Solar Thermal w/ Condensing N. Gas Backup			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
Solar Thermal			X			X		X		X

Figure 122 - P1-P10 Retrofit Comparison

One unexpected result is that not a single case study used the traditional "passive solar" approach to reducing energy use. Since these were all retrofits, the proper orientation and fenestration location was in many instances already established before the retrofit. However, it also represents an important shift in the industry that relies far more on high performance building enclosures and technology as opposed to southern exposure and thermal mass to achieve deep energy reductions.

The extensive retrofit approach of the Passive House standard in P3 (using superinsulation, triple pane windows and extreme air tightness) is unnecessary in our climate in order to achieve deep energy savings. P3 is the only home in this research that achieved Passive House certification, although P1 and P5 were also guided by the same principles. However, using the Passive House metric described in the literature review of 120 $kWh/m^2/yr$ EUI, we can see in figure 123 that all four of the projects that have a full year of monitored energy data have met the performance requirements. In fact, the EUI is far below the Passive House requirement in all four homes.

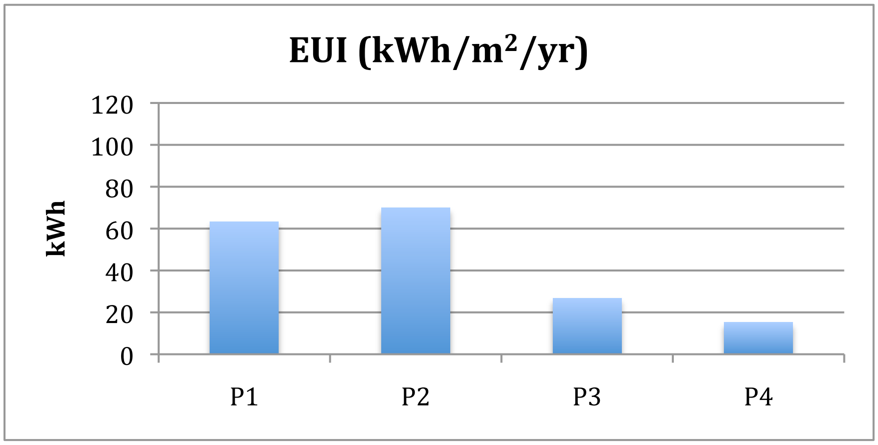


Figure 123 - P1-P4 Passive House Performance Metric Comparison

CO_{2e}

Based on the monitored energy data to date, there is a misunderstanding in the industry about the relationship between site energy savings and green house gas emissions. The tendency is for retrofit programs and homeowners to rely on site energy savings as the measure of success. In this research, several DERs switched fuels to all electric space and hot water heating. The reasons for this switch was different in each case, ranging from affordability and an assumption that the electric baseboard heaters would not be used often in P1, to the belief that all energy would be offset with onsite PV in P2, as well as not having access to natural gas in P5. The problem is that this change is prone to negatively effect green house gas emissions, even when site energy savings are significantly increased. In order to counterbalance this, as is the case in P2, the fuel mixture of electricity supplied by the utility company must incorporate a high percentage of renewable energy and low carbon fuels. Figure 124 shows that the site energy use of P2 is double that of P1, yet the CO_{2e} is the same.

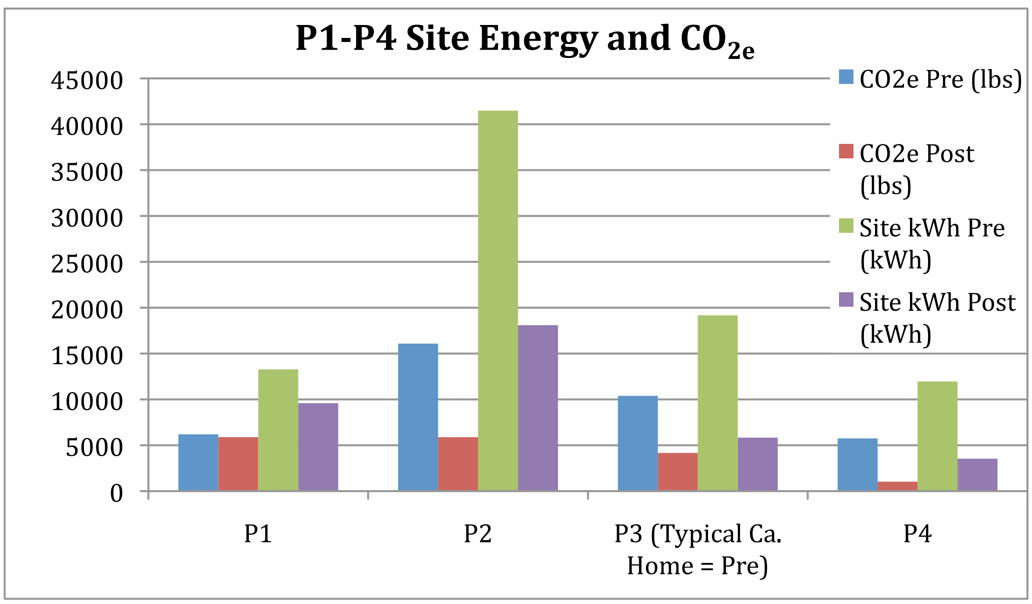


Figure 124 -P1-P4 Site Energy and CO_{2e} Pre/Post-Retrofit Comparison

However, this low carbon fuel mixture is not immediately available from most utility providers. Therefore, an awareness of the local utility fuel mix is necessary when planning DERs and making these fuel and equipment choices. This is a very important point; it means that technology selection depends not just on climate and efficiency, but also on how your utility operates. The AEC industry must understand the carbon implications of the type of equipment used in their energy saving strategies. Heatpump technology, condensing gas furnaces and hot water heaters are more efficient than electric resistance, ultimately resulting in smaller loads. However, all of this must be considered along with the carbon content of the fuel mix in order to adequately assess GHG emission reductions.

<u>Efficiency + Conservation</u>

Several of the case study homeowners show a high level of energy literacy; they understand their own energy use and the greater implications of that energy use. This level of understanding is very important, as it is through the combination of energy efficiency and energy conservation that will allow us to save more energy in our retrofits than is typically achieved, and for much lower costs. P7 demonstrated this point perfectly, with 50% energy savings prior to beginning the retrofit. Additionally, current research indicates that behavioral changes could save 20% of our national GHG emissions (Janda 2011). As previously stated in the background, the fundamental problem is the consumption of goods, rather than how efficiently they are consumed.

MELs become a larger portion of whole house energy use with the installation of more efficient heating and hot water equipment. Sanchez et al. (1998) found that 20% of MELs electrical consumption was due to phantom loads, or "consumed while in stand-by mode." Elimination of these phantom loads is key to achieving a low baseload, and a low baseload is key to reducing MELs. Therefore, the cross comparison of each case study's baseload in figure 125 reveals a great deal about user behavior and energy literacy. The lowest baseload homes have eliminated all unnecessary phantom loads, and therefore have lower MELs; demonstrating behavior adjustments to reduce their energy consumption.

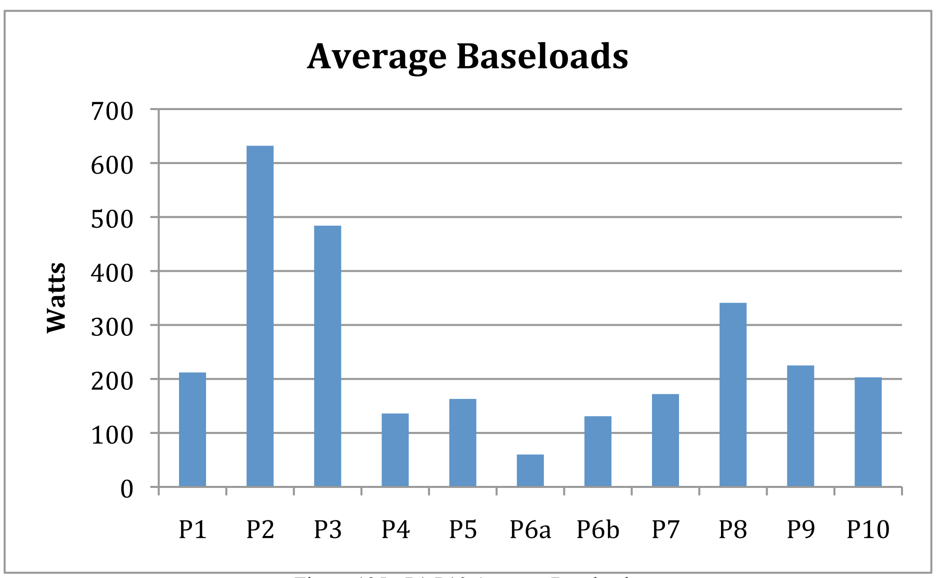


Figure 125 - P1-P10 Average Baseloads

Construction Quality

The influence of construction quality on overall energy performance is not obvious based on the analyses to date. Comparing P3 and P4 are perhaps the best examples of this. P3 has the highest observed construction quality and due to a combination of factors including user behavior, lighting design and the presence of a home office with a large server; the overall energy performance does not reflect the construction quality based on the achieved air tightness and superinsulation. For example, in order to meet the THC of 70% energy reduction, P3 would have to meet the option B threshold discussed in the literature review since pre-retrofit utility bills are unavailable. The threshold for P3 is 3,553 kWh/yr. In the first year, P3 consumed 5,832 kWh. Therefore an additional 40% reduction in energy use is required for P3 to meet the THC option B threshold. P4 on the other hand demonstrates excellent energy performance even though the construction quality is not as good as P3. P4 has already achieved the THC certification, and is an important demonstration of combined energy efficiency and conservation to achieve deep energy savings.

Based on the analysis of air and thermal leakage, there is plenty of room for improvement in the construction quality of most all of the homes observed. But, surprisingly, the overall performance does not seem to be heavily impacted by this. Therefore, once a certain level of air and thermal leakage are achieved (such as Title-24 plus 50% insulation levels, and Energy Star Version 3 air leakage of < 5 ACH_{50}), along with the installation of the most efficient HVAC and DHW equipment, it is the user behavior that will ultimately lead to deep energy savings in our climate. Construction quality obviously helps improve the efficiency; meaning it provides a higher level of comfort using less energy, but has little influence on how the building is ultimately used. The results of P3 do show however, that meeting the Passive House standard allows for greater variability in user behavior while still achieving deep energy savings.

Metrics

As discussed in the literature review, choosing which metric to use when reporting energy performance is a recurring problem (Deru and Torcellini 2005). On a per household basis, figure 126 shows that P1 is producing the same amount of CO_{2e} as P2, and significantly more than P3 and P4. However, when the CO_{2e} is measured on a per person basis, P1 is shown to significantly outperform both P2 and P3.

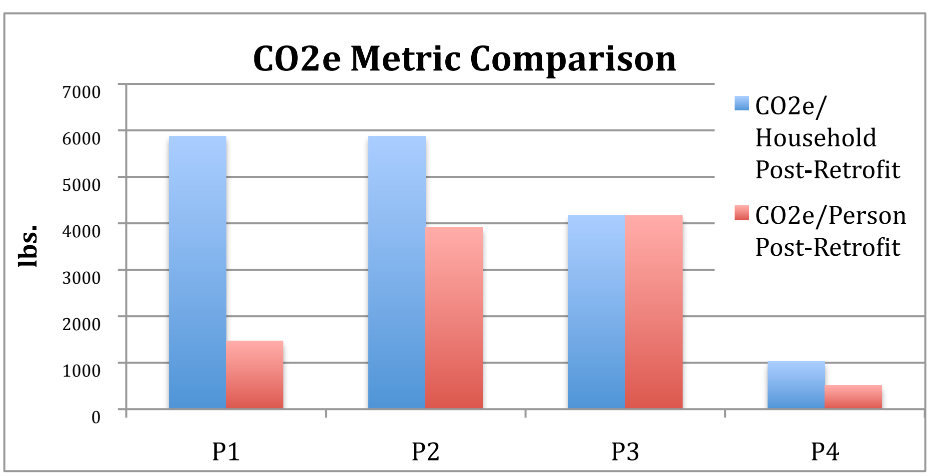


Figure 126 - CO_{2e} Metric Comparison

Similar to P1, P8 also had 4 occupants, and if evaluated by energy or carbon per person, would also reveal exceptional performance.

Additionally, the common metric of EUI, or kWh/ft^2/yr tells an even different story. Figure 127 compares the total site energy with the EUI, and although the ranking remains similar for this small sample (due to very similar floor areas), the relative differences are most notable between P1 and P2.

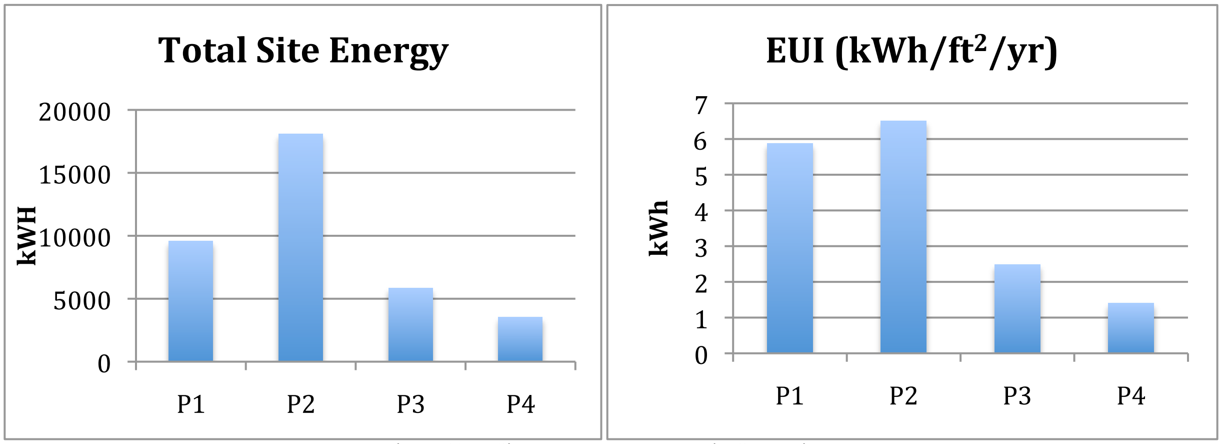


Figure 127 - Site Energy vs. EUI Metric Comparison

Although these may seem like trivial differences, they are extremely important to understand, as each metric used presents a different set of problems and solutions for the designers and contractors. Therefore, the performance metrics, along with the project goals must be carefully understood and evaluated by the project team, including the homeowner, if a DER is to be considered "successful."

7.3 Broader Implications

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 California's GHG reduction goals became an integral aspect of the research, the most important metric became CO_{2e}. 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 in the future to help meet the goals of AB 32. The tendency to switch fuels to electric space and hot water heating results in higher GHG emissions with the current typical fuel mixes used to generate electricity. The approach taken by P4 and P7, 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.

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. Natural gas is not the answer to reducing our GHG emissions; in fact, methane has 23 times the GWP as carbon (Deru and Torcellini 2007).

The primary focus of a DER is to significantly reduce the heating and DHW load through building enclosure upgrades and the simplest and most efficient natural gas or heatpump 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. According to experts in the sociology of consumption, our home is the synthesis of our consumption; the many layers of our social, economic and environmental realities are brought together to create a principal component of our identity (Shove 2007). America is proud to represent the ideal of becoming a devoted consumer; our economic and political system is based on economic growth fueled by ever-increasing consumption. Consumption has been marketed as a mode of self-expression (Ewen 1998), while conservation has a negative connotation of having less (Diamond 2003). Therefore, conservation requires a change in behavior, and there are very few Americans who are willing to do this. Yet, it is far more cost-effective than efficiency (Parker, Fairey, and Hendron 2010), and necessary if we are to achieve our energy and GHG reduction goals.

So what are these goals again? 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, cost effectiveness 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. Greater funding mechanisms for DERs are needed. But also, we have reached a point where society should internalize the external costs of energy production. Oil subsidies, both direct and indirect, are obfuscating the true costs of energy. Therefore, we need to change the conversation of cost-effectiveness in order to include the positive and negative impacts on ecosystem services, resource depletion, climate change, and future generations. It is in this holistic understanding of our world that DERs become very cost effective, and seemingly necessary in our current economic and ecological state. Wigington (2010) points out, “The only thing that appears to be certain regarding energy availability, costs, environmental impact, and the increased need for adaptability is increased uncertainty.” She adds, “Knowledgeable and motivated energy professionals and occupants are critical resources. The change agents who are embarking on deep energy reduction projects can help to inform and educate, to lead and serve those in their communities. Mobilizing a cadre of individuals who are willing to test emerging technology in their homes could be a valuable resource for accelerating the refinement and deployment of new systems and products." It is with this in mind that the monitored results of these ten case studies are made available, providing references and motivation for a deeper level of energy retrofits.

7.4 Future Research

Although this research has been very extensive in depth and breadth, there are various directions that it could be taken in the future. Significant time has gone into analyzing the hourly averaged data, but the depth of information that could be gathered from the high-resolution (10 second) end-use data has not yet been fully explored, and will be the topic of future papers. Additionally, many questions have been raised in regards to ventilation systems in these homes. First, how effective are ERVs and HRVs in our climate? Second, what are the effects of indoor air quality in tight and well-insulated homes? This includes issues such as using the ERV as kitchen exhaust, combustion safety in tight homes, and the effects of high RH levels over extended periods of time.

As more DERs are built, similar case studies could be assembled into a database, including monitored energy data, detailed project specifications, and even cost data and contact information, if the homeowners were willing to share. Using this database, designers, contractors and homeowners could compare the pre-retrofit energy 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.

Finally, this research needs to be expanded to other climate zones to include both hot and humid, as well as cold climates. 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.

8 CONCLUSION

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 ecological climate, it is suggested that GHG emission reductions should be one of the goals of DERs. 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.

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 literacy. The energy monitoring data and graphic user interface of the energy dashboard helped interested homeowners understand and make decisions about their energy use. Superinsulation and extreme air tightness, 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%. However, this strategy was shown to significantly reduce the heating energy, therefore allowing for greater variability in user behavior while still achieving deep energy savings.

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10 APPENDIX A

10.1 Monitoring Equipment Specifications

10.1.1 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 128 - ECM 1240 Energy Monitor

Figure 129 - 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

10.1.2 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")

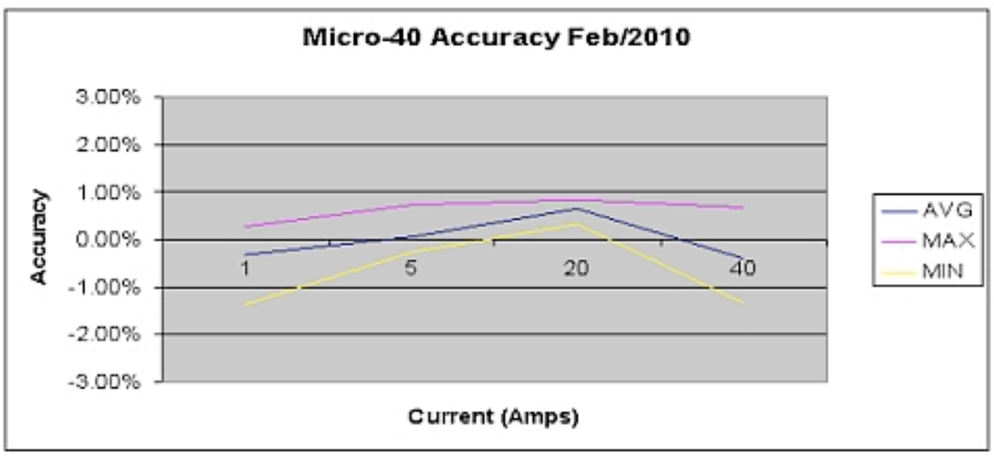
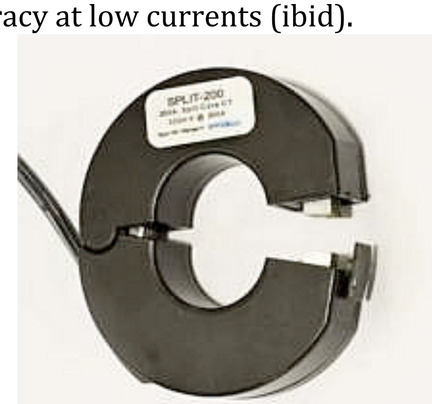
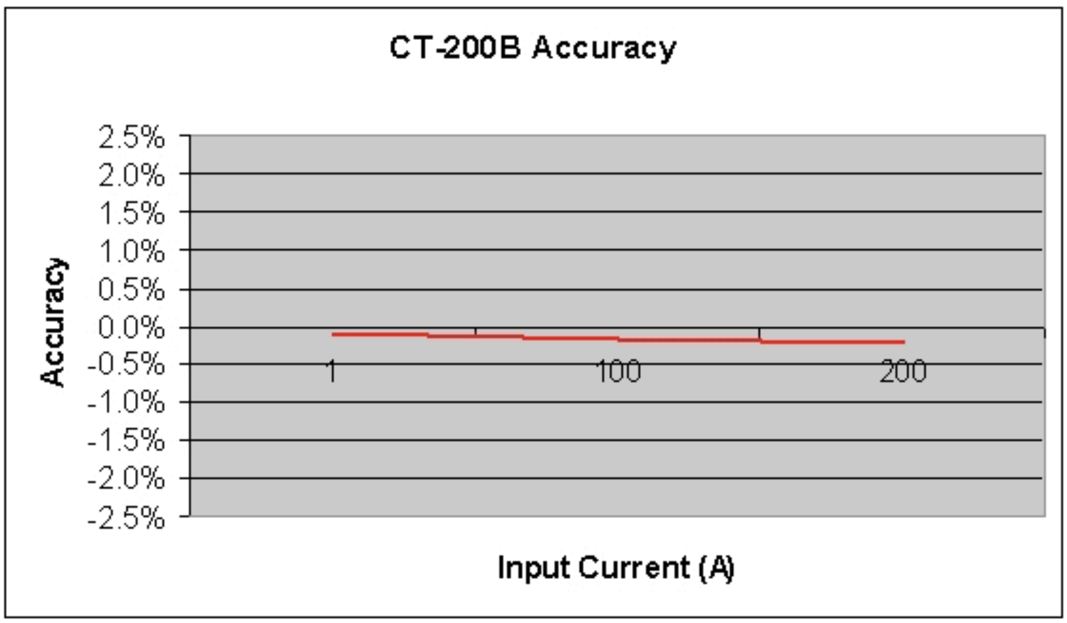


Chart from batch measurement displaying range of samples.

<u>Split-200</u>
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



10.1.3 Gas Meters

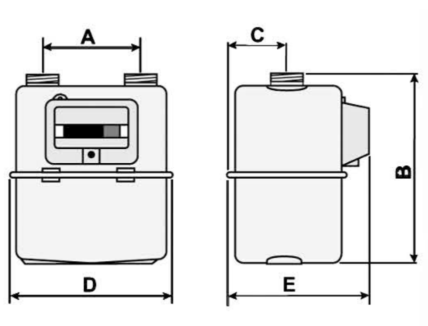
Technical Specifications

AMCO G4 200 CFH Gas Meter

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

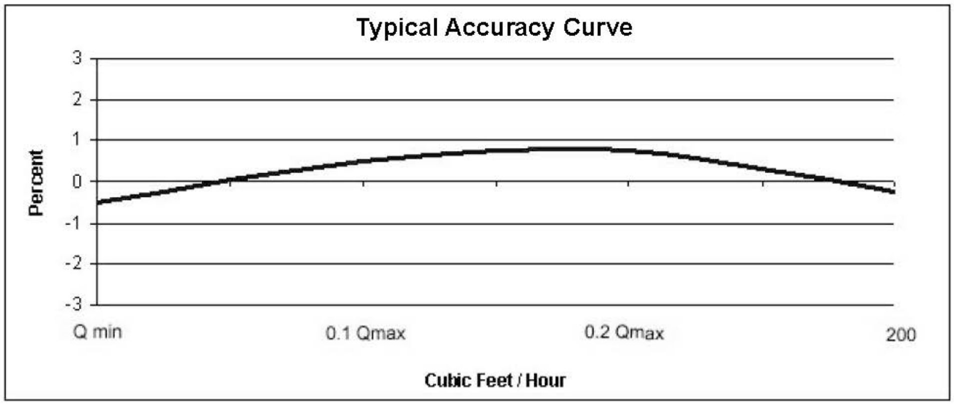
Performance:	
Max Flow Rate (cfh)	200
Min Flow Rate (cfh)	1.4
Max Working Pressure (psi)	5
Operating Temperature	-4ºF - 122ºF
Register Capacity (ft^3)	9999999.9
Contact Closure:	
Pulses/ft^3	1/1
Electrical Ratings:	
Maximum Voltage	12 VDC
Maximum Current	10 mA
Resistor	None
Duty Cycle	10% On
Physical:	
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)

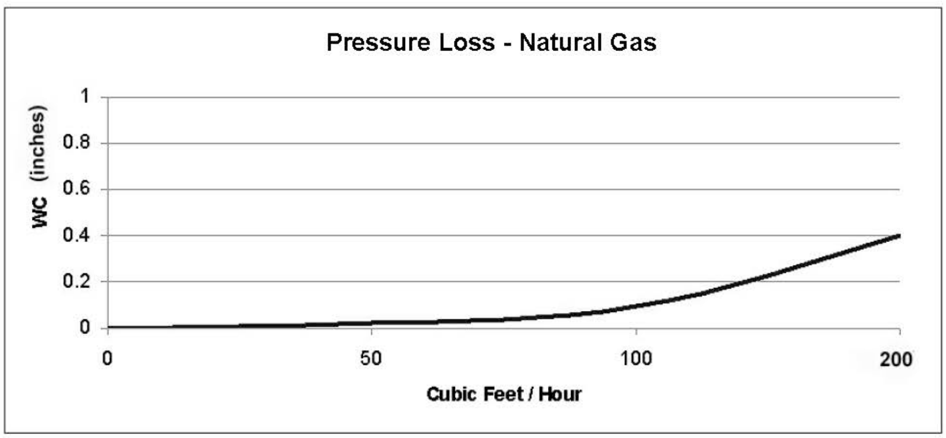
Dimensions

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

ELSTER AMCO

AMCO





AMCO

The company's policy is one of continuous product improvement and the right is reserved to modify the specifications contained herein without notice.

AMCO Water Metering Systems Inc.
www.amcowater.com

United States - ISO 9002 Registered
AMCO Water Metering Systems
P. O. Box 1852
Ocala, FL 34478-1852
352-732-4670 FAX 352-368-1950
Outside Florida: 800-874-0890
Inside Florida: 800-356-6829
e-mail:
watermeters@amcowater.com

Canada
Elster Water
3450 Harvester Road
Burlington, Ontario L7N 3W5
866-703-7582
905-634-4895
FAX 905-634-6705
e-mail:
watermeters@ca.elster.com

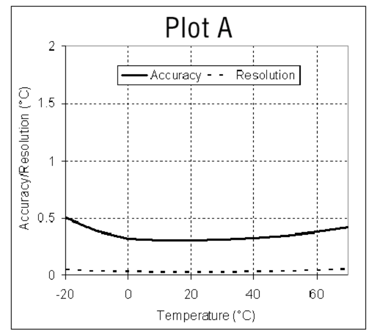
Caribbean
AMCO Water Metering Systems
P. O. Box 225
Carretera 112 KM 2.3
Isabela, PR 00662
787-872-2006
FAX 787-872-5427
e-mail:
prwatermeters@amcowater.com

Mexico
Elster Medidores
Lago Onega #281
Col. Modelo Pensil.
Del. Miguel Hidalgo
C P 11460
525 55 203 8002
FAX 525 55 203 8270
e-mail:
amcowater@prodigy.net.mx

SM-G4/11-02

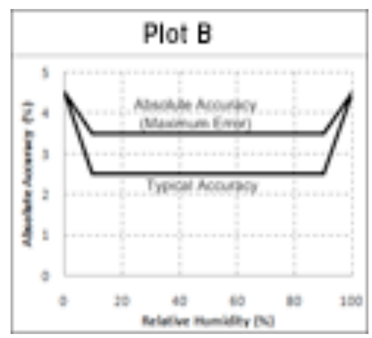
10.1.4 Temperature/Relative Humidity Sensors

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
http://www.onsetcomp.com/files/u10/u12012PlotB.gifExternal input channel (see sensor manual): ± 2 mV ± 2.5% of absolute reading

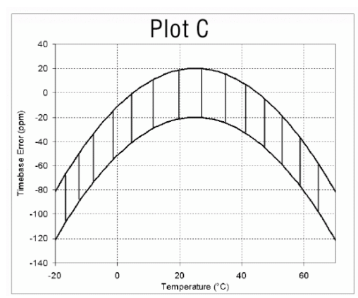
Resolution:
Temperature: 0.03°C at 25°C (0.05°F at 77°F), see Plot A
RH: 0.03% RH



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

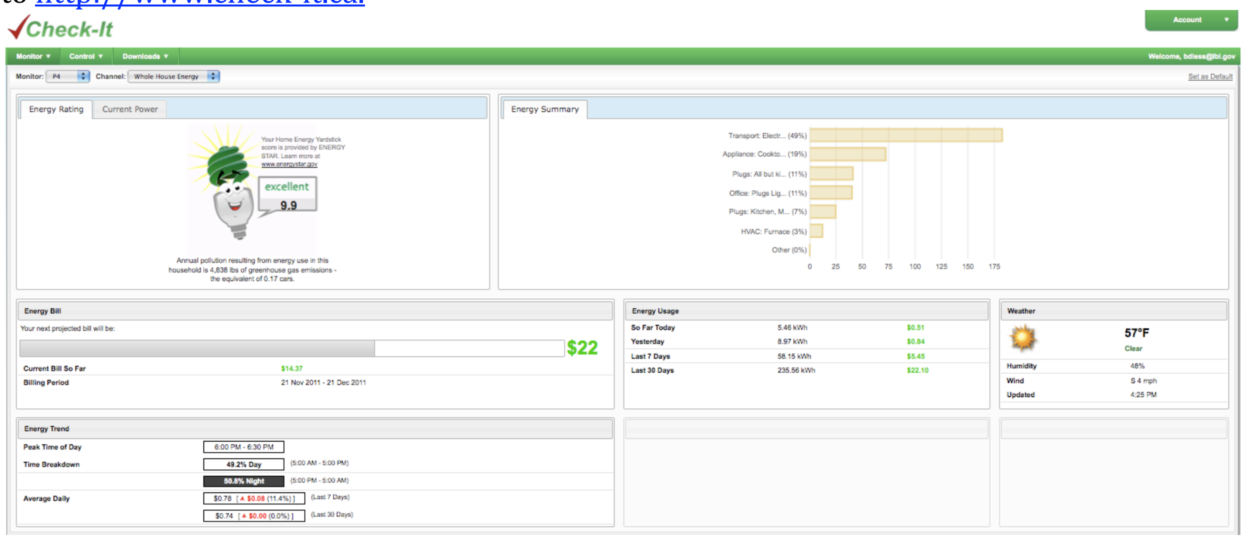
Memory:
64K bytes (43,000 12-bit measurements)

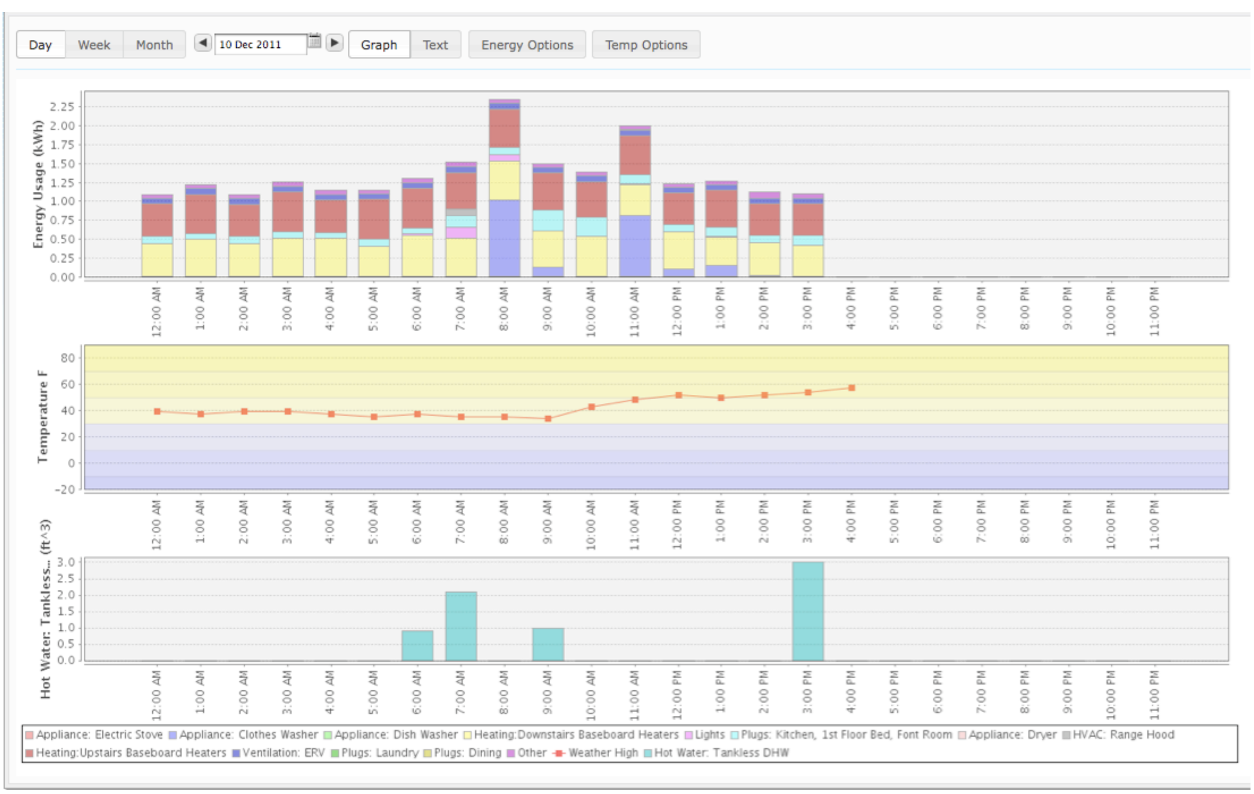
Weight:
46 g (1.6 oz)

Dimensions:
58 x 74 x 22 mm (2.3 x 2.9 x 0.9 inches)

10.2 Online Dashboard

At the beginning of the research the online dashboard “Google Powermeter” was used. Google cancelled the application in September 2011. Since then, we have been using 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.](http://www.check-it.ca)





11 APPENDIX B

Interview Guide

1. How many DER's have you been involved in?
2. What was the extent of your role in the project?
3. When did this retrofit begin, and how was the decision made to make such drastic energy reductions?
4. What were the main challenges during the design phase?
5. How was the Contractor selected?
6. Was the Contractor involved during the design phase? Was this helpful?
7. What were the main challenges during the construction phase?
8. Was air leakage addressed in the design? Was the desired air leakage attained?
9. Was thermal bridging addressed in the design, and was it implemented as designed?
10. Were passive systems part of the design?
11. What percentage of annual energy savings was actually achieved vs. what was modeled?
12. What aspect of the retrofit gave the greatest energy savings?
13. What was the greatest learning experience during this project?
14. What might you do differently next time?

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 Pascal 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	Green House 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