An Assessment of Envelope Measures in Mild-Climate Deep Energy Retrofits

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ABSTRACT

Energy end uses and interior comfort conditions were monitored in 11 deep energy retrofits (DERs) in a mild marine climate. Two broad categories of DER envelope were identified: first, bringing homes up to current code levels of insulation and airtightness, and second, enhanced retrofits that go beyond these code requirements. The efficacy of envelope measures in DERs was difficult to determine, due to the intermingled effects of enclosure improvements, HVAC system upgrades, and changes in interior comfort conditions. While energy reductions in these project homes could not be assigned to specific improvements, the combined effects of changes in enclosure, HVAC system, and comfort led to average heating energy reductions of 76% (12,937 kWh) in the five DERs with pre-retrofit data, or 80% (5.9 kWh/ft^2) when normalized by floor area. Overall, net site energy reductions averaged 58% (15,966 kWh; n=5*), and DERs with code-style envelopes achieved average net site energy reductions of 65% (18,923 kWh;* n=4*). In some homes, the heating energy reductions were actually larger than the whole-house reductions that were achieved, which suggests that substantial additional energy uses were added to the home during the retrofit that offset some heating savings.*

Heating system operation and energy use was shown to vary inconsistently with outdoor conditions, suggesting that most DERs were not thermostatically controlled and that occupants were engaged in managing the indoor environmental conditions. Indoor temperatures maintained in these DERs were highly variable, and no project home consistently provided conditions within the ASHRAE Standard 55-2010 heating season comfort zone. Thermal comfort and heating system operation had large impacts on performance and were found to depend upon the occupant activities, so DERs should be designed with the occupants' needs and patterns of consumption in mind. Beyond-code building envelopes were not found to be strictly necessary for the achievement of deep energy savings in existing uninsulated homes in mild marine climates, provided that other energy end uses were comprehensively reduced. We recommend that mild-climate DERs pursue envelopes in compliance with the 2012 International Energy Conservation Code *(*IECC*) and pair these with high-efficiency, off-the-shelf HVAC equipment. Enhanced building envelopes should be considered in cases where very low heating energy use (<1,000 kWh/year or <0.5 kWh/ft^2·year) and enhanced thermal comfort (ASHRAE Standard 55-2010) are required, as well as in those situations where substantial energy uses are added to the home, such as decorative lighting, cooling, or smart-home audio/visual and communication equipment.*

INTRODUCTION

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

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voltaics or solar hot water. These building upgrades are often combined in varying degrees with occupant conservation efforts.

While the exact definition of a DER is not yet clear, most working in the field consider energy reductions of 50% to 90% to be readily achievable with existing technologies, materials, and construction practices (Henderson and Mattock 2007; Wigington 2010). Published definitions of DERs range from 30% to 75% of annual energy use compared with a pre-retrofit baseline (ACI 2010a; Chandra et al. 2012). Given advances in minimum building codes and the general DER objective to make significant changes in energy use, we believe that the most appropriate DER definition should be on the high end of this scale, at the 70% level.

In this paper, we summarize the building envelope improvements, heating energy use, and thermal comfort in eleven case study homes in Northern California that have targeted energy reductions of 70% or more. All project homes were located in the San Francisco Bay Area and Sacramento regions. The retrofit measures and performance of each DER are documented in detail in Less et al. (2012). Each home was retrofitted by the homeowner prior to joining the research project, so the study had no influence on the retrofit measures taken. The project goals, strategies used, and results achieved represent actual results of the homeowners', designers', and contractors' approaches to a high-performance retrofit.

These DER case study homes were equipped with wireless energy monitoring equipment, providing one-minute resolution on each electrical and gas energy end use, as well as indoor temperature and relative humidity. This live data stream was made available to the home occupants and research team via a web application. Pre-retrofit utility billing data were available in only 5 of 11 projects. These pre-retrofit usages were weather-adjusted by heating degree-day regression for direct comparison to the monitoring year.

Project and Enclosure Descriptions

Table 1 provides basic descriptions for the 11 DER homes in this study, and retrofit measures are broadly summarized in Table 2. Significant diversity was observed between homes, which is likely to be true of DERs as they reach a wider audience because of the variability in existing home construction, location, and occupancy. The breadth of available paths to deep energy savings in even one climate zone is evident in Table 2. All DERs were constrained by the existing site, building, equipment, and fuel types, and all projects uncovered unforeseen obstacles during construction. This required flexibility throughout the process. Furthermore, homeowners and developers had different goals and reasons for performing the retrofits, which led them to different solutions. No particular technological or behavioral solution was required for success; rather, solutions had to be evaluated on a project-by-project basis for appropriateness and acceptability to occupants. The wide range of approaches is reflected in the range of Home Energy Rating System (HERS) indices (RESNET 2006) between projects for the retrofitted homes, ranging from 25 to 86. Despite this large range, these indices imply that these homes are all better than the HERS reference home. Pre-retrofit HERS indices were not calculated, because project teams were not able to consistently provide data on pre-retrofit conditions.

Insulation. Nearly all pre-retrofit homes were uninsulated structures, with occasional small amounts of insulation in the attic. Post-retrofit insulation levels varied from approximately code-compliant (termed *code-style*) to either 50% or 100% better than code (termed *highly* and *super* insulated, respectively). The code-style homes were consistent with the prescriptive requirements of the *California Building Energy Code* (Title 24) (CEC 2008).

Table 1. Project Summaries

ID	Location	Year Built / Retrofitted	HDD_{65}	Floor Area Pre / Post	Occupants Pre / Post	HERS
P1	Berkeley, CA	1904 / 2008	2909	960 / 1630	2 / 4	72
P2	Palo Alto, CA	1936 / 2008	2563	2780 / 2780	NA / 2	55
P3	Sonoma, CA	1958 / 2010	2844	1937 / 2357	NA / 1	25
P4	Petaluma, CA	1940 / 2010	2844	1540 / 2510	2 / 2	36
P5	Point Reyes Station, CA	1920 / 2010	3770	800 / 905	NA / 3	86
P6-N	Davis, CA	1932 / 2011	2702	1179 / 1462	NA / 4	28
P6-S	Davis, CA	1934 / 2011	2702	1496 / 1496	NA / 4	37
P7	San Mateo, CA	1910 / 2011	3042	3288 / 3288	2 / 2	76
P8	Oakland, CA	1915 / 2008	2909	1440 / 1627	NA / 4	33
P9	Folsom, CA	1998 / 2006	2702	3114 / 3114	NA / 4	72
P10	Pacifica, CA	1934 / 2008	3770	1503 / 1706	2 / 2	25

Table 2. Project Retrofit Comparison

Project ID	P1	P2	P3	P4	P5	$P6_N$	$P6_S$	P7	P8	P9	P10
Building Enclosure											
Super Insulated (100% > CA Title 24)			X			X	X				
Highly Insulated (50% > CA Title 24)	X				X						
Insulated (Meets CA Title 24)		X		X				X	X	X	X
All Triple-Pane Glazing			X								
All Double-Pane Glazing	X	X		X	X	X	X			X	X
Airtightness: Passive House Standard (<0.6 ACH_{50})			X								
Airtightness: <3 ACH_{50} (recommended)	X		X		X					X	
Airtightness: ENERGY STAR® Ver. 3 (<5 ACH_{50})	X		X		X					X	
HVAC											
Heat/Energy Recovery Ventilation	X	X	X								
Electric Resistance Heating	X				X						
Heat Pump Heating and Cooling		X	X								
Air Conditioner with Evaporative Cooling										X	
Heat and Domestic Hot Water Combisystem		X	X						X		X
Night Ventilation Cooling				X		X	X			X	
Domestic Hot Water											
Electric Resistance					X						
Heat Pump		X									
On-Demand Condensing Natural Gas	X		X	X		X	X	X			
Atmospheric Draft Natural Gas Tank										X	
Solar Thermal Tank with Condensing Natural Gas Backup			X			X	X		X		X
User Behavior											
24/7 Electric Baseload <200 Watts	X			X	X	X	X	X		X	X
24/7 Electric Baseload >200 Watts		X	X						X		
Solar Technology											
Photovoltaics		X	X	X		X	X		X		X
Solar Thermal			X			X	X		X		X

A variety of methods were used to insulate above-grade walls, and multiple assemblies were often employed on a single home due to varying envelope constructions. Three homes exclusively drilled and filled using dense packed cellulose (P2, P4, and P8). A number of other projects exposed wall framing cavities from either the interior or exterior, then filled them with cellulose, fiberglass, or spray foam insulation. Often these homes also added continuous exterior foam insulation of thickness ranging from 1 to 5 in. (P1, P3, and P5). P3 provided the most exterior foam insulation, with those assemblies constructed from 2 × 4 framing, adding 5 in. of foam, and those using new 2 × 6 framing, adding 2.5 in. P1 used a mixed approach, resulting from the lifting of the home and rebuilding of the ground floor, using 2 × 6 framing. This 2 × 6 frame was insulated with blown cellulose, and the existing 2 × 4 framed wall on the second floor was insulated with blown cellulose; a continuous layer of exterior foam was added on the second floor only. Mixed assemblies such as this were seen on P1, P3, P7, and P10. P7 used a unique "house within a house" approach that sought to fully insulate a portion of the first floor with respect to inside and outside using a fiberglass insulation blow-in blanket system (BIBS),[1] providing a central zone that could be kept more comfortable while the rest of the home was not directly conditioned and whose temperature was allowed to vary over a wide range (50°F–75°F). The two P6 homes are notable for their construction of an additional stud wall to the interior, which was spaced 1/2 in. from the existing framed wall. Both assemblies were filled with sprayed cellulose insulation. P9 was a newer home that already had fiberglass batts in all walls. Finally, some homes left portions of their above-grade walls uninsulated (P2, P7, and P8), which was usually due to existing historical/decorative elements that could not to be disturbed. The overall R-values for all these alternatives are summarized in Table 3.

Attic or roof insulation was upgraded in all homes. Six projects used the ceiling plane as the thermal barrier, and five projects moved the thermal barrier to the slope of the roof, producing an unvented attic. For those homes that created unvented attic assemblies, two approaches were used: (1) spray polyurethane foam (SPF) insulation on the undersides of rafters (P2, P8, and P10), and (2) a combination of blown insulation in rafters and continuous foam insulation on either the underside of rafters (P7) or on top of roof decking (P3). Both approaches create conditioned space in the attic, which can reduce distribution losses for attic HVAC systems, though two homes used this approach with no mechanical services in the attic whatsoever. SPF installed beneath the roof deck tended to produce the lowest R-values in the range of only 25 to 30, usually due to a combination of the project team's decision to install only one lift of SPF and the manufacturer's depth limits on single-lift applications (CPI 2012). High R-values were achieved in attics that added blown cellulose insulation to the attic floor, ranging between approximately 40 and 60. These were the lowest-cost attic retrofits by a large margin. P9 used this approach to bury HVAC ductwork in the attic to reduce distribution losses.

Foundations were a mixture of slab-on-grade, crawlspace, and basement types, with a number of homes combining types. Slabs were treated in Passive House (PH) style homes (P1 and P3) with both perimeter foam insulation and continuous foam on top of the slab. P3 consisted of two structures joined together during the renovation, with the slabs at slightly different heights. A continuously level floor and sufficient insulation were achieved using solely expanded polystyrene (EPS) foam on one slab and a mixture of foam and aeorgel on the other. P1 installed a new perimeter foundation and slab during the renovation. The other slab homes (P4 and P9) added no insulation. A number of homes insulated the framed floor of the basement or crawlspace, using either SPF (P2 and P8), fiberglass batts (P8), foam board beneath floor joists (P7), or dense packed cellulose in floor joists using oriented strand board as an air barrier beneath the joists (P5). The two P6 homes created sealed crawlspaces, installing 2 in. of extruded polystyrene (XPS) foam board on the interior of new poured foundation stem walls and 6 in. of SPF in the rim joists. Neither home directly conditioned, dehumidified, or vented the crawlspaces, in contradiction to current best practices (Dastur et al. 2005). Several potential problems were observed with the sealed crawlspace homes. Cupping of hardwood floors was observed in one P6 house after sealing of the crawlspace, suggesting a potential moisture issue. During the removal of monitoring equipment at P5, a puddle of water was observed on top of the ground vapor barrier installed as part of the sealed crawlspace, and the seal of the vapor barrier to the foundation wall had failed in numerous locations. The puddle of water was most likely due to water intrusion from beneath, as the puddle was in the lowest part of the crawlspace and

Table 3. Summary of Above-Grade Wall Insulation Methods

ID	Wall Insulation Method	R-Value Cavity Insulation*
P1	First floor: 5.5 in. dense pack (dp) cellulose	19
	Second floor: 3.5 in. dp cellulose, 2 in. polyiso exterior	23
P2	3.5 in. dp cellulose	13
P3	1: 3.5 in. dp fiberglass, 5 in. EPS exterior	38
	2: 5.5 in. dp fiberglass, 2.5 in. EPS exterior	33
P4	1: 5.5 in. dp cellulose	19
	2: 3.5 in. dp cellulose	13
P5	3.5 in. cellulose, 1 in. XPS exterior	18
P6-N	7 in. cellulose	25
P6-S	7 in. cellulose	25
P7	Rear zone: 5.5 in. BIBS, 1 in. polyiso	23
	Upstairs: 3.5 in. blown fiberglass	13
	Downstairs: None	—
P8	3.5 in. dp cellulose	13
P9	Fiberglass batts, improved installation and air sealed in kitchen and under stairs, insulated attic knee wall	13
P10	3.5 in. low-density SPF	13
	5.5 in. low-density SPF in garden room	19

* Values do not account for thermal bridging in framing members.

1. BIBS involves attaching a vapor- and air-permeable material to the rough framing members, with insulation then blown into the resulting cavity.

moisture was observed trapped between the two vapor barrier layers throughout the crawlspace. Failure to follow best practices, including improper use of sealants and mechanical attachment at the ground-to-wall interface, likely contributed to this moisture issue.

Windows. Most homes began with single-pane windows with either wood or steel frames. Windows were replaced in most homes; the other homes rehabilitated their windows through air sealing and use of storm windows. Most new windows were double-pane gas-filled units with U-factors ranging from 0.29 to 0.34 and SHGCs from 0.18 to 0.35. P3 used triple-pane windows imported from Europe with a U-factor of 0.125 and an SHGC of 0.53. In the P6 homes, one structure replaced all windows with high-performance[2] units, and the other structure's windows were rehabbed, adding new weather-stripping and an additional glass pane to the wood frame. Windows in P2 were historically significant, so a custom interior double-pane low-e storm window was installed that attached magnetically to the existing steel frames. Unfortunately, a number of these storm windows were observed to be uninstalled or broken. P7 used a mixed approach, with new windows in the "house within a house" zone and existing windows elsewhere. A number of homes that replaced windows left intact individual units that were particularly large and costly or otherwise unavailable (P4, P8, and P10). A complete discussion of existing window retrofit options is provided by Baker (2012).

2. Compliant with current ENERGY STAR South-Central regional requirement (U-factor <0.35 and SHGC <0.3) (EPA 2011).

Airtightness. Enclosure airtightness averaged 4.8 ACH_{50} but varied from relatively loose (10.8 ACH_{50}) to extremely airtight (0.48 ACH_{50}). Envelope airtightness for each project is summarized in Table 4. Consistent with the PH emphasis on superinsulation and airtightness, the projects inspired by the PH standard were substantially more airtight. Average airtightness in PH style projects was 1.3 ACH_{50}, whereas other DERs averaged 6.3 ACH_{50}. PH style projects approached air sealing systematically and methodically, with a specific goal in hand. All other project homes did not necessarily prioritize airtightness, and their results leave much room for cost-effective improvement. The only airtight non-PH style home was P9 at 2.4 ACH_{50}, which was constructed using modern materials in the 1990s. Despite the touted air-sealing capabilities of spray foam insulation, those homes that used SPF did not achieve good airtightness. They averaged 7.0 ACH_{50}, making them amongst the leakiest homes in the sample. Only two projects were assessed for air leakage prior to beginning the retrofit, P7 and P9, and they achieved reductions of 37% and 35%, respectively.

Average levels in this study can be compared to those summarized in Table 5 from the DER literature (ACI 2010b; BA-PIRC 2012; Berges and Metcalf 2013; Blanchard et al. 2012; Christian et al. 2011; McIlvaine 2010; Keesee 2012; Less 2012; McIlvaine et al. 2010; Neuhauser 2012; Osser et al. 2012; Chandra et al. 2012). Airtightness levels in this project were similar to those measured in DERs located in hot-dry, mixed-humid, and marine climates, whereas hot-humid DERs have been more leaky and cold-climate DERs have been much more airtight, on average. Cold-climate DERs have achieved

Table 4. Summary of Blower Door Airtightness Testing

Project ID	CFM_{50}	ACH_{50}	CFM_{50}/ft^2, Surface Area	CFM/ft^2 Floor Area	Effective Leakage Area, in^2	nACH	Specific Leakage Area (ELA/ft^2 Floor Area)
P1	271	1.1	0.063	0.166	10.3	0.05	0.00004
P2	2260	5.7	0.325	0.588	124.6	0.27	0.00031
P3	151	0.4	0.019	0.064	8.3	0.02	0.00002
P4	1983	5.4	0.322	0.790	110.0	0.26	0.00028
P5	292	2.4	0.097	0.323	14.0	0.10	0.00011
P6-N	991	5.1	0.222	0.678	49.4	0.18	0.00023
P6-S	1114	5.6	0.247	0.745	55.9	0.20	0.00026
P7	5336	10.8	0.790	1.623	300.6	0.72	0.00064
P8	2397	9.3	0.476	1.474	130.6	0.63	0.00056
P9	1227	2.4	0.183	0.394	69.8	0.14	0.00016
P10	1455	6.1	0.288	0.853	75.4	0.28	0.00031
Average	1588	4.9	0.276	0.700	86.3	0.26	0.00027

Table 5. Summary of Average Airtightness Levels (ACH_{50}) in DER Literature by DOE Building America Climate Zone

DOE Building America Climate Zone	Pre-Retrofit Mean (n)	Post-Retrofit Mean (n)	% Mean Reduction
Cold	20.7 (14)	3.3 (32)	80% (15)
Hot-Dry	15.3 (3)	5.2 (6)	65% (3)
Hot-Humid	24.7 (3)	7.0 (12)	59% (3)
Marine	6.6 (1)	5.1 (7)	35% (1)
Mixed-Humid	16.7 (2)	5.3 (3)	62% (2)
All	19.8 (23)	4.5 (60)	72% (24)

tighter homes because airtightness was a project priority due to the extreme climate. Many participated in the National Grid Deep Retrofit Pilot project, which specified approximately 1.5 ACH_{50} as a goal (Neuhauser 2012). Hot-humid homes likely achieved leakier post-retrofit results due to the definition by programs operating in that region of a DER as 30% or greater energy savings, which is the lowest published value in the U.S. Air leakage reductions averaged 72% from the pre-retrofit baseline. Chan and Sherman (2013) provide a summary of standard airtightness retrofits in the U.S. for Weatherization Assistance Program (WAP) retrofits and non-WAP retrofits, which achieved average percent reductions in ACH_{50} of 30% (n=13,093) and 20% (n=9,999), respectively (Chan and Sherman 2013). DERs have regularly doubled and tripled these average reductions. Ninety-fifth percentile reductions reported by Chan and Sherman were 47% and 61%, respectively, which makes these DERs amongst the most aggressive airtightening efforts in the U.S.

Some general similarities existed between observations from this project and the reports in the literature. As in our study, Eldenkamp and DuClos (2013) found that the major difficulty in getting to lower airtightness levels was details at interfaces. The construction and air-sealing details around eaves, rim joists, plumbing stacks, chases, and top interior partitions can be difficult to address depending on the construction details of each particular home. In other words, some homes are easier to seal than others. Also, it was evident that DERs targeting aggressive leakage reductions were able to achieve impressive results, consistent with high-performance new homes. Very airtight homes (<3 ACH_{50}) were nearly solely achieved in DERs that completely redid the exterior finish of the above-grade walls, including new continuous air barriers and exterior foam insulation.

New construction literature and standards are also relevant for comparison. The 2009 *International Energy Conservation Code* (*IECC*) target (7 ACH_{50}) was met by all but two homes in this study, and the 2012 *IECC* target (3 ACH_{50}) was met by only four homes in this study (see Table 4) (ICC 2009, 2012). On average, DER project homes were more leaky than California single-family homes built between 2001 and 2011 (mean 3.9) (Chan 2012). Similarly, Offermann (2009) reported a median airtightness of 4.8 ACH_{50} in 106 new California homes (ranging from 3.6 to approximately 8 ACH_{50}).

Thermal Distribution. The thermal distribution systems installed in these DERs included a range of solutions. Five homes used no thermal distribution, providing either point-source (P3, P6-N, and P6-S) or electric baseboard (P1 and P5) heat. Four homes used full forced-air systems, with three of the four installing new ductwork throughout (P2, P4, and P7). Effort was made to include ducts in conditioned spaces, but only P4 was able to fully achieve this. Both P2 and P7 created conditioned attics but insulated them at the framed floor so that the upstairs systems were inside conditioned space and the downstairs systems were outside. P9 buried ducting in several inches of attic insulation to achieve lower distribution losses. For P2, the post-retrofit duct air leakage to outside was indistinguishable from zero. Duct systems were tested before and after retrofit at P7, and it was revealed that total supply and return leakages to outside were reduced by 25% (from 115 to 86 cfm) and 46% (from 124 to 67 cfm), respectively. Total leakage of the duct system in P9 was reduced 61% (from 103 to 40 cfm). Testing of post-retrofit leakage to outside for the system revealed only 10 cfm of supply and 15 cfm of return leakage. Two homes used hydronic radiant heat, with in-floor heat used in P10 and wall radiators in P8. Thermal distribution in P8 was particularly troubling, as the solar storage tank with integrated boiler was located in an unconditioned, detached garage. This required an underground supply line to the unconditioned crawlspace, where a manifold system created lots of water pipe surface area; they used R-2 pipe wrap insulation.

Durability. DERs provide an opportunity to increase the durability of building envelopes through correction of moisture management issues, such as roof leaks, improper or missing flashing, door pans, etc. When the building control layers for air, heat, and moisture are exposed, significant improvements are possible. Rain screen systems were used in P1, P3, and P5, where exterior cladding was installed over a ventilated air space, which allows the building assembly to drain. Fully adhered weather-resistive barriers and meticulously detailed flashing can also be incorporated into project design. The P3 remodel took this strategy the furthest, using a REMOTE/PERSIST system, with a fully adhered membrane tying together the foundation, walls, and roof (Benesh 2009). The P4 remodelers installed new roof overhangs to protect the walls and the foundation from rain and for solar control. The North P6 home added awnings over each window opening, which, in addition to providing shade, provide protection from rain. Most projects installed gutters to remove bulk rainwater, but P8 built a rainwater harvesting system to retain water for other uses. Even in those homes that did not provide rain-screen systems, new cladding was common. Some projects did not incorporate these kinds of improvements, which may have been a lost opportunity for improved building durability.

Envelope and Energy Performance

Heating Energy Savings. Post-retrofit heating energy consumptions are presented in Table 6 (whole house) and Table 7 (per ft^2); these are compared with estimated pre-retrofit consumptions for those five homes where usage was known. The estimated pre-retrofit heating energy consumptions were obtained from billing data that was adjusted for post-retrofit weather conditions. Post-retrofit heating consumptions were determined from submetered data or by weather regression in P2 due to use of a combined heating and hot-water system. Data are not included for P8 and P10, because both homes used solar combined heating and hot-water systems, which were not disaggregated by our submetering. Homes using forced air include air-handler energy use. Absolute heating energy reductions averaged 12,937 kWh (76%), with reductions per square foot averaging 5.9 kWh/ft^2 (80%). Not surprisingly, those homes with relatively little pre-retrofit heating energy usage did not achieve dramatic savings (P1 and P4) despite substantial envelope improvements, nearly to the Passive House standard in the case of P1. These heating savings can in general be attributed to three sources: (1) envelope improvements, (2) HVAC equipment changes, and (3) changes in indoor temperature. In a number of cases, floor area was added to the homes (see Table 1), so heating energy reductions had to overcome these increases.

Table 6. Summary of Post-Retrofit Heating Energy Consumptions and Estimated Heating Energy Reductions, per House

Project ID	Pre-Retrofit Heating Consumption, kWh	Post-Retrofit Heating Consumption, kWh	Heating Energy Reduction, kWh	Heating Energy Reduction, %
P1	8,939	2,182	6,757	76%
P2	27,641	3,205	24,436	88%
P3	NA	576	NA	NA
P4	8,348	2,834	5,514	66%
P5	NA	415	NA	NA
P6-N	NA	489	NA	NA
P6-S	NA	1,781	NA	NA
P7	19,324	688	18,636	96%
P9	18,013	8,668	9,345	52%
Average	16,453	2,315	12,938	76%

Table 7. Summary of Post-Retrofit Heating Energy Consumptions and Estimated Heating Energy Reductions, per Square Foot Floor Area

Project ID	Pre-Retrofit Heating Consumption, kWh/ft^2	Post-Retrofit Heating Consumption, kWh/ft^2	Heating Energy Reduction, kWh/ft^2	Heating Energy Reduction, %
P1	9.3	1.3	8.0	86%
P2	9.9	1.2	8.8	88%
P3	NA	0.2	NA	NA
P4	5.4	1.1	4.3	79%
P5	NA	0.5	NA	NA
6-N	NA	0.3	NA	NA
P6-S	NA	1.2	NA	NA
P7	5.9	0.2	5.7	96%
P9	5.8	2.8	3.0	52%
Average	7.3	1.0	6.0	80%

When annual heating energy consumptions are compared between groups of highly or super insulated and code-style DERs (see Table 2), major differences are observed. The superior insulated homes averaged 1089 kWh (0.7 kWh/ft^2) in annual heating energy, whereas code-style homes averaged 3753 kWh (1.3 kWh/ft^2). The extreme examples in these groups can illustrate the true variability. P3, the first certified Passive House retrofit in the U.S., used only 576 kWh (0.24 kWh/ft^2), whereas code-style P9 used 7954 kWh (2.55 kWh/ft^2).[3] The difference between these two is greater than the total annual consumption of three of the project homes (P4, P5, and P6-N). Yet, as discussed in Less et al. (2012), low post-retrofit energy use did not always lead to large absolute energy reductions. In fact, P9 was the largest single reducer of net-source energy, despite having the highest post-retrofit heating energy use of any project home. This indicates that possibly more than one metric needs to be used when assessing DERs: percent savings, final energy use, energy use per square foot, code compliance as a target, etc. It also shows that other things significantly contribute to mild-climate energy performance and that a holistic approach to DER assessment is crucial rather than a simplistic focus on space-conditioning energy reductions.

Comparing Heating and Total Reductions. In order to assess the overall contributions of envelope and HVAC improvements to DER energy savings, the estimated heating energy savings are compared with total net site energy savings and envelope insulation designations in Table 8. The ratios of estimated heating energy savings to total net site savings varied from just below 50% to over 150%, with an average of 91%. Overall, heating energy reductions averaged 76%, whereas total net site reductions were only 58% for the same homes. Notably, four of the five homes in Table 8 had code-style envelopes, and they achieved an average net site energy reduction of 65%, which suggests that beyond-code envelopes are not strictly required in mild-climate DERs.

Those homes that achieved heating energy savings greater than total net site energy savings increased energy usage in other end-use areas, which offset their impressive heating reductions. For example, P1—the only highly insulated home with pre-retrofit data—reduced heating energy by 76%, but its total savings were only 31%. P1 nearly doubled its finished floor area (from 960 to 1630 ft^2) during the renovation by creating a full-height, livable ground floor, and its occupancy doubled from two to four. The fact that 76% heating energy reduction was achievable while nearly doubling the floor area is a testament to the value of the Passive House style approach used in this DER. Yet, increases in hot-water energy use and in other electrical end uses wiped out more than half of these savings.[4] Similarly, P2 reduced estimated heating energy by 88%, but its total net site savings were only 61%. No expansion of floor area occurred in P2, but it had the highest electrical baseload of any project home (562 W continuous power, estimated at 4926 kWh annually) and the highest combined usage of lights, appliances, and plugs (8875 kWh/yr). While baseload and miscellaneous electrical usage could not be assessed in the pre-retrofit home, P2 most likely substantially increased its miscellaneous power demand during renovation due to installation of mechanical cooling, large communication and A/V systems (see Figure 1), decorative lighting, etc. Nevertheless, P2's total net site reductions were the largest of any project home.[5]

Table 8. Summary Comparison of Total Net Site and Heating Energy Reductions and Insulation Designation

Project ID	Net Site Energy Reduction, kWh (%)	Estimated Heating Energy Reduction, kWh	Proportion of Heating-to-Total Reduction, %	Insulation Designation (from Table 2)
P1	4,138 (31%)	6,757	163%	Highly Insulated
P2	24,492 (61%)	24,436	100%	Code-style
P4	8,955 (74%)	5,514	62%	Code-style
P7	22,653 (72%)	18,636	82%	Code-style
P9	19,592 (54%)	9,345	48%	Code-style
Average	15,966 (58%)	12,938	91%	NA

These two projects highlight the importance of including all energy end uses in analyses of DERs as well as an awareness of how increases in other end uses can offset heating energy savings. This offsetting can be challenging, as many DERs include the addition of much needed or wanted services, such as additional appliances, enhanced lighting, and smart-home features. Yet these additions can offset costly heating and cooling energy savings. If no other changes are made to the home, a strictly heating and cooling DER is possible, though it is not necessarily the most cost-effective or valuable to the occupants, who often reap substantial benefits in aesthetics and convenience from non-space-conditioning DER measures.

In contrast to these two homes, P4, P7, and P9 (all DERs with code-style envelopes) most likely reduced most other household energy uses as part of their DER, resulting in heat-

3. Some of this is certainly attributable to use of a mini-split heat pump in P3 versus a gas furnace in P9.

4. Net-source energy performance in P1 was quite bad (consumption increased by 12%) due to changes from natural gas for heating to electric resistance baseboard heat. When combined with increased miscellaneous electrical uses (home office, two additional occupants, etc.), this shift to electric heat led to source energy increases, despite the aggressive Passive House approach.

5. The net-source energy performance in P2 was degraded similarly to P1 through a switch to an all-electric home, where previously gas was used for cooking, heating, hot water, and clothes drying. As a result, P2's net site savings of 61% were reduced to only a 7% reduction in net-source energy.

ing energy savings that were only fractions of total net reduction. P9 was particularly successful at targeting energy reductions equally towards heating and other uses such as cooling, lighting, and miscellaneous electrical loads. In homes that have already achieved insulation levels near code, non-heating end-uses provide what may be the most cost-effective energy reductions in the home. Lighting retrofits and appliance upgrades are almost certainly less costly than super insulation of walls or extreme airtightness.

A holistic assessment of whole-house energy use is essential in determining the impacts of DER projects. The examples above clearly illustrate the distortions that can be introduced by offsetting space-conditioning savings with increases in other end uses. Enhanced whole-house savings were demonstrated in homes that did not increase other uses, showing a very effective mixed approach to deep savings in residences.

Heating System Response to Weather Conditions. We explored the thermal responses of the DERs by using sub-metered heating system energy data and site-specific weather data to create linear regression models. Daily average energy use and weather data were used to assess the variability of heating system energy use with indoor-outdoor temperature difference and with outdoor temperature alone. Homes P1, P2, P4, and P9 showed relatively consistent correlation between heating consumption and indoor-outdoor temperature difference, all of which had coefficients of determination (R^2) greater than 0.4. Figure 2 shows the relationship between daily average heating power consumption and daily average indoor-outdoor temperature difference for P9. A number of other homes had highly erratic relationships between weather conditions and heating system energy use; these homes were characterized by R^2 values less than 0.3 (P3, P5, P6-N, P6-S, P7, and P10). These less consistent results are illustrated in Figure 3 for project P6-N. Relationships were also poor in these erratic homes on a monthly basis, with an average R^2 of 0.52 versus 0.76 in the other projects. These results show that factors other than temperature difference can dominate heating consumption in low-load homes in mild climates. These

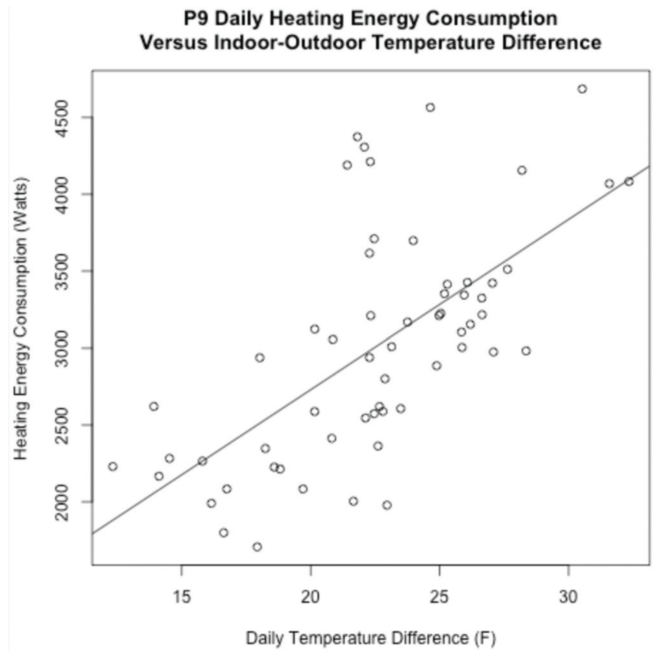

Figure 2 *P9 comparison of hourly and daily heating energy methods.*

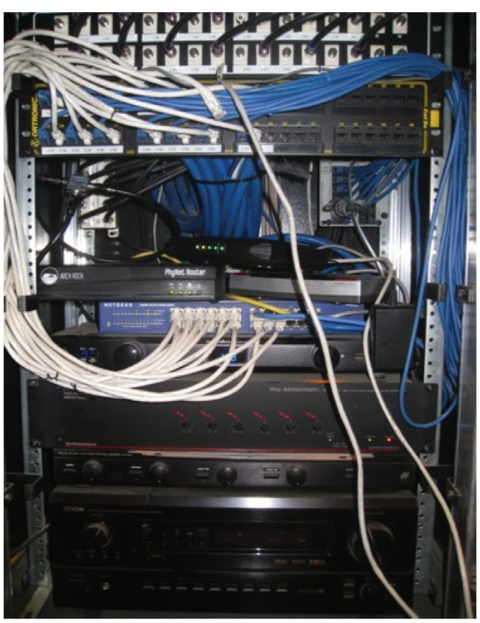

Figure 1 *P2 audio/visual and data equipment in basement cabinet.*

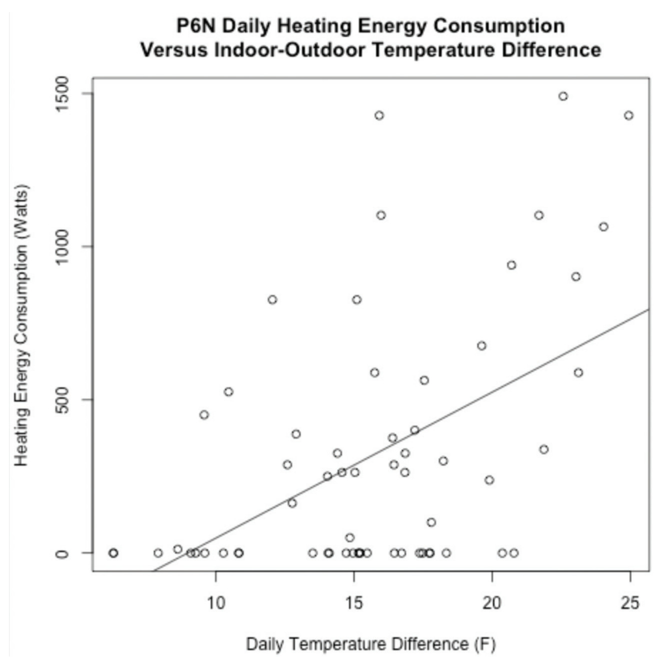

Figure 3 *P6 North, illustration of erratic daily plot.*

other factors include occupant temperature control, solar gain, and internal gains. This makes the prediction of heating energy use in such low-energy homes challenging, because weather data cannot be used exclusively to successfully predict usage.

In addition, many of these DER project homes are not strictly controlled by a thermostat; rather, the heat is controlled by the occupants on an as-needed basis. This is illustrated in Figure 3 on those days where substantial temperature differences existed but average daily heating power varied from 0 to 1500 W. So, on equally cold days, sometimes the system was operated regularly and on other such days not at all. Occupant behavior, comfort, and preference drive this phenomenon. It may be that this behavior is the result of particularly engaged building occupants who elected to invest in deeply retrofitting their home for environmental reasons. Yet, even without occupant manipulation, the variation in internal loads and solar gains can have similar impacts, particularly in homes where the heating load is comparable to these gains. For example, it is recommended in Passive Houses that the winter heating load not exceed 3.17 Btu/hr·ft^2·°F (Schnieders 2003), which can be met in a 1000 ft^2 home by less than 1 kW of miscellaneous electrical equipment or solar gain.

The balance point temperature[6] of a home is an indicator of building envelope performance that is independent of the heating system but is still dependent on occupant temperature control as well as solar and internal gains. In an attempt to determine balance point temperature, heating system consumption was also compared directly to outdoor temperature. A mix of well-behaved and erratic results was obtained. Yet, even for the best fitted model (P4), a single standard deviation confidence interval for the balance point of 57°F was 46 to 70 degrees. All other models produced even poorer results. This suggests it may not be possible to generate valid balance points for low-energy homes from weather regressions.

Despite the limitations of weather regression in DERs, the heating energy regressions still demonstrated an obvious difference between homes that were highly or super insulated and code-type homes. Highly or super insulated homes had an average heating energy use per degree of daily average outdoor temperature of –24 W/°F (–0.016 W/°F·ft^2), compared with –85 W/°F (–0.035 W/°F·ft^2) in code-style homes. These suggest that enhanced building enclosures in mild-climate DERs still provided reduced heating loads—approximately 50% lower than code-style DERs by square foot of floor area.

6. By balance point temperature we are referring to the outdoor temperature at which heating input is required to maintain indoor conditions. This is not the same as the balance point temperature of a heat pump, with capacity that varies with outdoor temperature.

Thermal Comfort

Among the many non-energy benefits of DERs, improvements in thermal comfort may be a primary driver for homeowners investing in improvements. The hourly temperature profiles for the months of December and January are compared for each DER in Figure 4. Thermal comfort is highly variable in these DER homes, with indoor average hourly temperatures varying by up to 10°F between homes. The heating season thermostat setpoint used in all Building America simulation assessments is 71°F and is indicated for reference as a bold dotted line in Figure 4 (Engebrecht and Hendron 2010). All DER project homes, even those providing the warmest and most consistent indoor conditions (P1 and P3), did not quite meet the Building America setpoint requirement, which is based upon the "optimum seasonal temperature for human comfort as defined in ASHRAE Standard 55-2004" (Engebrecht and Hendron 2010, p. 49).[7] In fact, only P1, P2, and P3 provided any average hour within the Standard 55-2010 acceptable range of thermal comfort (ASHRAE 2010). The lower temperatures maintained in these DERs may be the result of occupant thermal preferences, efforts to reduce heating energy consumption, or both. It is also possible that lower setpoints were maintained due to reductions in drafts due to airtightening and a better radiant environment due to improved windows and wall insulation.

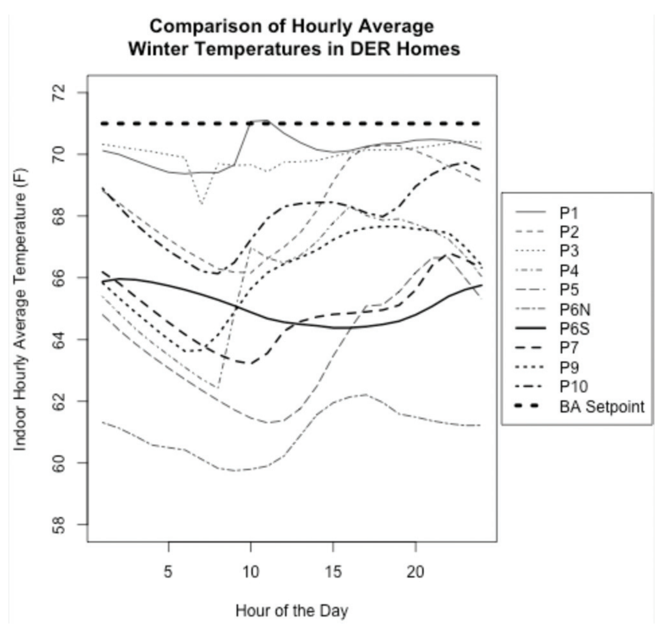

Figure 4 *Indoor hourly temperature profiles in DER homes for December and January.*

7. It is not clear that ASHRAE Standard 55 stipulates an "optimum" temperature; rather, a range of acceptable temperatures are provided that will result in an 80% acceptance level by building occupants.

Thermal comfort surveys were not distributed to occupants, but comfort complaints were not reported, with the exception of P10 and P7. Occupants in P10 complained that the heating system was not able to properly recover to a comfortable temperature after a nighttime set-back in their living room. In an energy-efficient home, the energy savings that can be obtained via setback are reduced and may not be worth the comfort trade-off when equipment is sized to meet the very small steady-state load. Research in super insulated cold-climate homes has shown that daytime setbacks may not be beneficial and may increase energy use (CARB 2010). Occupants in P7, while not directly admitting discomfort, did mention the need to heat to higher temperatures during visits by guests.

The impacts of building envelope and interior temperature can be compared by examining interior temperatures in DERs that used very little heating energy—P3, P5, P6-N, and P7. P3 used only 576 kWh for annual heating, and the other three homes averaged 531 kWh. P3 maintained average hourly winter temperatures at 70°F with very little variability from hour to hour. It was by far the most airtight and best insulated home in this research. Indoor conditions were much less consistent and cooler in the other three homes. Average hourly temperatures for P5, P6-N, and P7 were 64°F, 61°F, and 65°F, respectively.

Comparing these four homes allows us to understand some of the variables involved in DER thermal comfort. Similar to P3, P5 was built in a Passive House style, but it used electric resistance heaters. As a result, P5 required much more energy to produce equivalent indoor temperatures to those in P3, which used a high-efficiency ductless heat pump. Had P5 used such a heat pump, its interior conditions could have been greatly improved without sacrificing energy performance. P6-N was a super insulated home, but it lacked substantial airtightness (5.1 ACH_{50}) and its occupants were willing to accept very cool winter temperatures. With increased airtightness, much warmer conditions could likely have been achieved with little heating energy increase. P6-S did achieve better comfort (average of 65°F), but its heating energy was a little over 3.5 times the North house (1781 kWh). Airtightness was clearly overlooked in these super insulated homes to the detriment of indoor comfort. Finally, a home like P7, with an envelope only partially brought to code, achieved very low heating energy by using its "house within a house" approach, providing comfort in only one of three house zones. The P7 temperatures in Figure 4 are for the insulated kitchen zone, whereas the other house zones were substantially colder on average (55°F and 60°F in the non-kitchen first floor and second floor zones, respectively). This temperature manipulation was occurring alongside envelope improvements and high-efficiency HVAC, leading to heating energy reductions of nearly 19,000 kWh.

Similar heating energy usages were attained by these four homes, but significantly different indoor comfort conditions were necessary to do this. Both P3 and P6-N were super insulated and P5 was highly insulated, yet indoor comfort conditions were widely variable. Enhanced insulation did not necessarily lead to higher interior temperatures, though it was clearly related to very low heating energy use. DERs that are targeting consistent, high heating season temperatures and very low heating energy use will need to employ very high-performance envelopes (insulation and airtightness) and HVAC equipment. Code-style homes can still be comfortable and have highly successful whole-house energy reductions (P2, P4, and P9), but their heating energy use will remain high, which will need to be accounted for by reductions elsewhere.

DER Building Envelope Recommendations

The type of thermal envelope that is targeted in a mild-climate DER project will depend upon the project goals, the comfort demands of the occupants, and the existing condition and energy use of the home. This research demonstrates that enhanced insulation and high levels of airtightness are not necessarily required to achieve deep energy reductions. In the authors' opinion, most existing uninsulated homes in mild climates can achieve deep energy reductions by getting to new building code levels of envelope performance, provided that all energy end uses are comprehensively addressed. Enhanced building envelopes can contribute to increased thermal comfort and result in very low heating energy usage (<1000 kWh/yr or <0.5 kWh/ft^2·yr). Furthermore, an enhanced envelope allows leeway for the potential increases in select other end uses that can occur in DER projects—decorative lighting, cooling, and miscellaneous electric loads, for example—as well as increases in floor area and/or comfort. The occupant should always be considered directly in project planning because of the substantial impact that behavior and comfort requirements have been shown to have on heating and whole-house energy use, as well as HVAC system operation and indoor environmental conditions.

It is our recommendation for mild-climate DERs to pursue building envelopes compliant with current energy codes for the region, namely the 2012 *IECC*. The 2012 *IECC* airtightness requirement of 3 ACH_{50} should be targeted by all DERs. This target may be excessively difficult to meet in homes where neither the interior nor exterior claddings are removed. In such cases, the ENERGY STAR Version 3 target of 5 ACH_{50} for Climate Zone 3 can be used (EPA 2011). Insulation in excess of energy code requirements should be considered when other retrofit activities (such as re-siding) make it easier and cheaper to do so. For example, if exterior siding must be replaced during a DER, then continuous exterior insulation should be considered along with the required new sheathing and weather-resistive barrier.

High-efficiency, off-the-shelf HVAC equipment should be combined with these code-compliant envelopes to achieve the best results. Electric resistance heaters as primary heat should be avoided, even in super insulated projects, particularly for source energy and carbon emissions reasons, as discussed in footnotes 4 and 5.

CONCLUSION

Assessing the impacts of building envelope improvements in DERs is complicated by the intermingled effects of enclosure improvements, HVAC system upgrades, and changes in interior comfort conditions. Yet, beyond-code building envelope assemblies have been shown to be unnecessary to achieve deep energy reductions in existing uninsulated homes in a mild marine climate, provided that other energy end uses are comprehensively addressed. In this research, DERs with code-style envelopes averaged a 65% net site energy reduction. Nevertheless, the benefits of an enhanced beyond-code envelope include (1) the potential to increase indoor comfort conditions, (2) the ability to maintain enhanced comfort while minimizing heating energy use (<1000 kWh/yr or <0.5 kWh/ft^2·yr), and (3) to compensate for energy usage increases in other end-use categories, which has been observed to occur in many owner-conducted DERs. The building occupants have been shown to have substantial impact on indoor comfort conditions, heating system operation, and miscellaneous energy use, all of which can dramatically affect DER performance. While beyond-code envelope improvements can play a key role in deep energy reductions, we recommend that mild-climate DERs target envelope compliance with the 2012 *IECC* code requirements.

Ultimately, the decision to pursue a DER building envelope beyond prescriptive energy code requirements is at the discretion of the project designer and the occupant and by no means is it required in order for deep reductions to be realized. In our opinion, it is more important that deep retrofit strategies be tailored toward the needs and wants of the occupant and to current patterns of energy use. If high levels of thermal comfort are required and if substantial additional energy usages are to be added as part of the project, then an enhanced envelope may be prudent. On the other hand, a much less disruptive and lower-cost retrofit may be possible if comfort requirements are somewhat lower or if comprehensive energy reductions are achieved across all end uses.

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