Title
A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.

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Publication Date
2014-02-01

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BERKELEY NATIONAL LABORATORY

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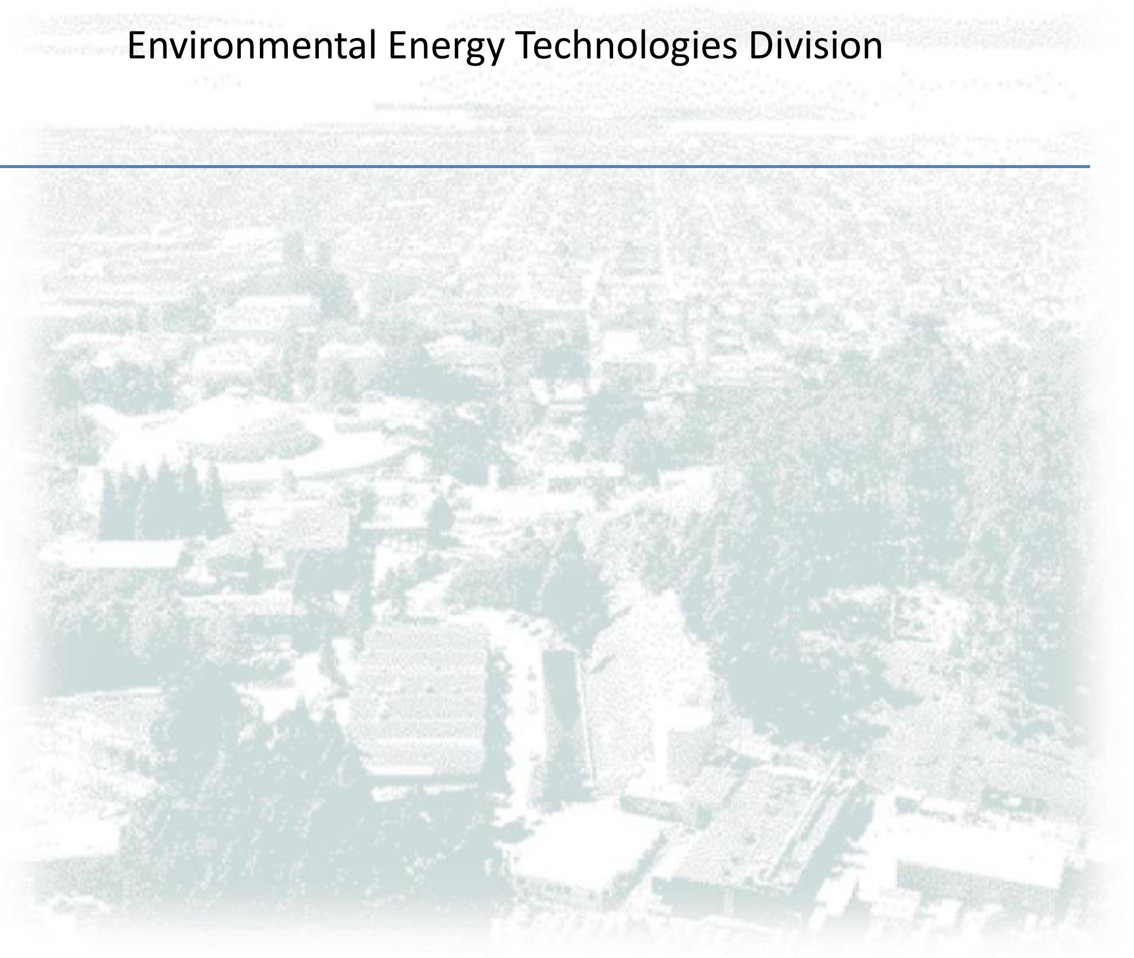
2014

Environmental Energy Technologies Division



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Acknowledgment

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. We would like to thank those who provided internal and external review. We would also like to thank all those whose hard work resulted in Deep Energy Retrofits that could be included in this meta-analysis.

Abstract

The current state of Deep Energy Retrofit (DER) performance in the U.S. has been assessed in 116 homes in the US, using data gathered from the available domestic literature. Substantial airtightness reductions averaging 63% (n=48) were reported (two- to three-times more than in conventional retrofits), with average post-retrofit airtightness of 4.7 Air Changes per House at 50 Pascal (ACH_{50}) (n=94). Yet, mechanical ventilation was not installed consistently. In order to avoid indoor air quality (IAQ) issues, all future DERs should comply with ASHRAE 62.2-2013 requirements or equivalent. Projects generally achieved good energy results, with average annual net-site and net-source energy savings of 47%±20% and 45%±24% (n=57 and n=35), respectively, and carbon emission reductions of 47%±22% (n=23). No significant difference was observed between reported actual energy savings and simulated energy savings. Net-energy reductions did not vary reliably with house age, airtightness, or reported project costs, but pre-retrofit energy usage was correlated with total reductions (MMBtu). Annual energy costs were reduced $1,283±$804 (n=31), from a pre-retrofit average of $2,738±$1,065 to $1,588±$561 post-retrofit (n=25 and n=39). The average reported incremental project cost was $40,420±$30,358 (n=59). When financed on a 30-year term, the median change in net-homeownership cost was only $1.00 per month, ranging from $149 in savings to an increase of $212 (mean=$15.67±$87.74; n=28), and almost half of the projects resulted in reductions in net-cost. The economic value of a DER may be much greater than is suggested by these net-costs, because DERs entail substantial non-energy benefits (NEBs), and retrofit measures may add value to a home at resale similarly to general remodeling, PV panel installation, and green/energy efficient home labels. These results provide estimates of the potential of DERs to address energy use in existing homes across climate zones that can be used in future estimates of the technical potential to reduce household energy use and greenhouse gas emissions through DERs.

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Executive Summary

Deep Energy Retrofits (DERs) are aggressive and comprehensive whole house renovations that target energy savings beyond those typically achieved in weatherization or utility retrofit programs. The feasibility of DERs has been demonstrated in various projects in the U.S. and the European Union, but no integrated analysis or summary of these projects has been published. This study summarizes the current state of DER performance in the U.S. using data gathered from 116 single-family residences documented in the domestic literature. Projects were included in the database if they self-identified as DERs, and if project scopes were aggressive and comprehensive. Project data reporting was broadly inconsistent, which led to most metrics having substantially fewer data points than the 116 total projects. The number of homes for each metric is shown in parentheses in this summary. Reported data includes both actual and simulated values. The States with the highest number of projects are California (n=24), Florida (n=20), and Massachusetts (n=19). The average age of the homes (from a 2013 baseline) is 78±41 years (n=64), and the average of the pre- and post-retrofit floor areas is 1,967±819 ft^2 (n=82) and 2,110±883 ft^2 (n=99), respectively.

The reviewed projects generally achieved good results that are summarized in Figure 1. Substantial airtightness reductions averaging 63% (n=48) were reported, with an average post-retrofit airtightness of 4.7 Air Changes per House at 50 Pascal (ACH_{50}) (n=94). One potential shortcoming in these homes was that mechanical ventilation was not installed consistently, particularly outside of Cold climate zones. The DERs demonstrated consistent energy reductions in the 30% to 70% range. Average annual net-site and net-source energy reductions were 47%±20% and 45%±24% (n=57 and n=35), respectively, with corresponding carbon emission reductions of 47%±22% (n=23). Reductions were generally lowest in Hot-Humid climates, where DERs were less aggressive. When these homes were removed from analysis, reductions across energy and carbon metrics increased to approximately 55%. Homes that increased electricity use (n=7) had source energy and carbon reductions 57% and 42% lower than their site energy reductions. Net-energy reductions did not vary reliably with house age, airtightness or reported project costs, but pre-retrofit usage was correlated with total reductions (MMBtu).

On average, when financed over a 30-year term (using the Freddie Mac average fixed-rate 30-year interest rate from 2009 to 2012), DER energy cost savings balanced out the increased mortgage costs. The median change in net-monthly homeownership cost was $1 (mean=$16±$88; n=28). Annual energy costs were reduced $1,280±$800 (n=31), from a pre-retrofit average of $2,740±$1,060 to $1,590±$560 post-retrofit (n=25 and n=39). The average reported incremental project cost was $40,400±$30,360 (n=59), which generally included only energy-related costs. This is lower than the popularized notion that DERs cost $100,000.

We identified the following issues that we feel may increase the market adoption of DERs: (1) increasing the financial desirability of DERs through a focus on their non-energy benefits, e.g., increased home value, lower default risk, and improved comfort, convenience, IAQ and durability, and lower maintenance, (2) using phased approaches that implement efficiency measures over time, as maintenance, equipment replacement, and funds allow, and (3) achieving reductions in DER costs, which we foresee as occurring broadly across the entire retrofit design and construction process, rather than in a single break-through technology or approach.

In the report, we provide a number of recommendations for program managers and designers that are based on our observations and experiences in this research:

- Adopt formal definition of a deep retrofit as 50% or greater savings.
- Adopt formal retrofit data reporting standards.
- Consider use of source energy or carbon performance metrics.
- Target DERs towards remodeling projects and existing equipment replacement/maintenance, where incremental costs are more easily justified.
- Consider the use of cost-effectiveness tests that incorporate NEBs.
- Consider basing allowable project costs on achievable cost savings.
- Ensure ability to respond to future changes in energy prices and rate structures, carbon emission regulation, and demand response scenarios.
- Require ASHRAE 62.2-2013 or equivalent compliance.
- The Weatherization Assistance Program should consider including an advanced option that allows more money to be spent for deeper savings.

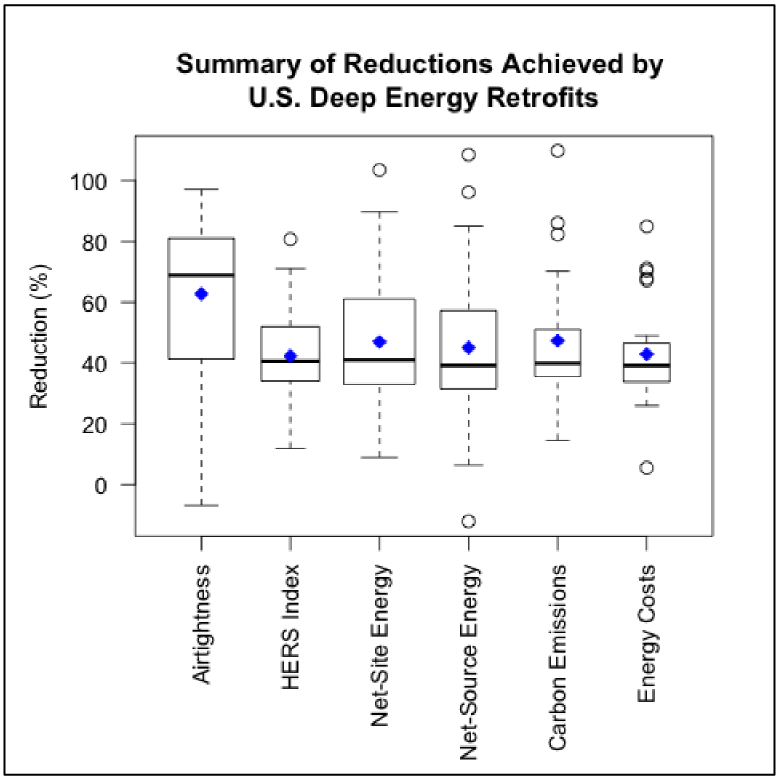

Figure 1 Summary DER Annual Reductions in Airtightness, HERS Index, Net-Site Energy, Net-Source Energy, Carbon Emissions, and Energy Cost (blue diamonds represent mean values and dark black bars the median)

1 Introduction

Energy retrofits of existing single-family homes represent by far the largest energy and carbon emissions reduction investment opportunity in the U.S. buildings sector. Integrated engineering, financial and policy assessments have suggested that it would be economically justifiable to cut energy use in existing single-family U.S. dwellings by approximately 30% (Fulton et al., 2012; Granade et al., 2009). Fulton et al. (2012) suggest that this effort would reduce energy consumption in U.S. homes by 1,497 trillion British Thermal Units (Btus) and reduce related carbon emissions by 302 million metric tons annually, while saving Americans an estimated $28.3 billion per year and creating 1.7 million cumulative U.S. job years. Granade et al. (2009) argue that these improvements have a net-present value (2009 dollars) of $166 billion, and that 71% of the opportunity is in the building shell and HVAC equipment of existing homes.

Yet, most analysts agree that meeting current 2050 carbon emissions reduction goals (e.g., 80% reductions below 1990 baselines in state of CA and the European Union by 2050 (European Commission, 2011; Schwarzenegger, 2005)) will require greater than 50% savings in existing homes, which is substantially higher than most U.S. retrofit programs currently achieve (Neme, Gottstein, & Hamilton, 2011). Previous studies have documented the methods of major energy retrofits in cold North American climates (Marshall & Argue, 1981) and demonstrated actual energy reductions greater than 50% in a small sample of existing California homes (Brohard et al., 1996). Presently, research and demonstration (R&D) projects outside the U.S. have proven the feasibility of deep energy reductions in existing homes, both through modeling exercises (Becchio, Corgnati, Ballarini, & Corrado, 2012; Henderson & Mattock, 2007) and through measured performance of actual retrofitted homes (Herkel & Kagerer, 2011; SuperHomes, 2013; The Technology Strategy Board, 2013). The Passive House Institute has also developed a building retrofit standard called EnerPHit, which specifies certification criteria including airtightness, primary energy demand, heating energy demand and component requirements for deeply retrofitted buildings (Passive House Institute, 2012). In the U.S., simulation optimization engines have been used to generate near-neutral-cost retrofit packages (on a cash-flow basis, assuming retrofit costs are financed) in varied U.S. climate zones, with average source energy savings varying from 43% to 74%, depending on the assumed interest rates for a 30-year loan (Fairey & Parker, 2012; Polly et al., 2011). Consistent with past research and current demonstration efforts, a 50% savings target represents a reasonable, achievable definition of the minimum requirements for a Deep Energy Retrofit (DER), though greater savings levels are desirable and have been used as a benchmark in some programs and studies (Affordable Comfort, Inc., 2010; Boudreaux, Hendrick, Christian, & Jackson, 2012; Less, Fisher, & Walker, 2012).

In terms of implementation in the U.S., DERs in existing homes have been targeted by the U.S. Department of Energy's (U.S. DOE) Building America R&D program (Bianchi, 2011), as well as by a number of electric and gas utilities and public utility agencies (Boudreaux et al., 2012; Chitwood & Harriman, 2012; CPUC, 2008; Keesee, 2012; National Grid, n.d.; NYSERDA, n.d.). Nonprofit organizations have also been involved in driving the demonstration and market development of U.S. DERs (Affordable Comfort, Inc., 2010; ASID & USGBC, n.d.).

Numerous DER projects have been implemented across the U.S. using a variety of methods, reporting metrics, and levels of project support (e.g., incentive-based funding of measures, as well as design and construction management services). This paper is an attempt to compile and report pertinent information about as many of these projects as possible, and to summarize the state of DER performance in the U.S. Our intention is to demonstrate the performance that can actually be expected of such projects. The summary statistics we provide should be useful as inputs for larger modeling assessments of the potential economic, energy and carbon impacts of DERs as they are progressively adopted in the market. They will also provide realistic estimates of performance and appropriate economic targets for future projects, on a climate zone-by-climate zone basis. The dataset is relatively small (116 homes), and is not necessarily representative of all existing or future DER performance. In particular, the climate zone-specific values are weakened in some cases by small sample sizes and inconsistent methods among projects. Nevertheless, this effort has included most single-family DER information currently available in the U.S. literature.

2 Methods

In order to create a summary database of existing deep retrofits in the United States, we performed an extensive review of available DER literature and case studies. Sources used for the search included U.S. DOE Building America research projects, the Affordable Comfort, Inc. Thousand Home Challenge case studies, publications from U.S. DOE national labs, utility retrofit programs (e.g. DER pilot programs at National Grid in Massachusetts and NYSERDA in New York state), and the U.S. Green Building Council's (USGBC) REGREEN website. Projects were included in the database if they self-identified as DERs, and if project scopes were aggressive and comprehensive (i.e., targeting all or nearly all building assemblies, services and end-uses). To be included, projects also had to provide at least one of the following—airtightness, energy use or cost data. Very few projects provided all the information required for a thorough and complete analysis across the sample. Both simulated/estimated and actual energy performance was used in our analysis. Our summaries include both the estimated and measured data combined, but we also provide a comparison between the two distributions. Data are reported as summaries of the entire sample, as well as subsets disaggregated by U.S. DOE Building America climate zone (Baechler et al., 2010).

There was substantial variation in reporting methods (e.g., site or source energy, carbon, and HERS indices), as well as in the definitions of "deep" used in each project. DER definitions included targeting Home Energy Ratings (HERS) indices of 70 post-retrofit (RESNET, 2006), 30% to 70% energy reductions, Passive House standards as well as green certification and/or Energy Star designation. Site and source energy were both used as metrics, but most projects did not report both. We used Building America source energy conversion factors of 3.16 for electricity and 1.02 for natural gas (Hendron et al., 2004)[1], and generated carbon dioxide equivalent (CO_2e) emissions for natural gas using the national average (0.399 pounds/kWh) and for electricity using state-by-state data for delivered electricity from the U.S. EPA's eGRID 2009 dataset (U.S. EPA, 2012). In cases where only total source energy or carbon were reported, we were not able to ensure that conversion factors were identical, which may be a source of error in this reporting. Similarly, total site energy (lacking electricity/gas breakdown) was sometimes reported alongside total source energy, and our source energy conversion factors were not used in such instances. All annual energy use is reported in million British Thermal Units (MMBtu) and CO_2e is reported in pounds. We report net-energy use (i.e., the total annual energy consumption minus the total renewable energy generation) wherever renewable energy systems were installed.

Given the variability in reporting, we made efforts to extract and translate as much useful information from each source as was feasible. For example, if site electricity and gas data were provided, we calculated source energy use and carbon emissions, even if they were not reported in the primary information source. We also used percent reductions and post-retrofit usage to calculate pre-retrofit usage. Nevertheless, while 116 DERs were identified and catalogued in this review—all of which met our criteria of self-identifying as a DER and being aggressive/comprehensive—most individual metrics we report have 50 or fewer data points (see Figure 2 for detailed summary of data completeness).

We gathered project cost data wherever it was provided. We identified substantial variability in project cost accounting methods, and as a result, we consider this to be the least reliable/consistent of the data assembled. We used whatever cost data was provided, and in the majority of cases, the costs represent either incremental DER costs for those features of the project that exceeded basic code requirements, or those costs for energy-related components. Many projects included whole house remodels, as well as substantial deferred maintenance (e.g., new roofing or siding), and non-energy-related components of total costs were excluded in those cases where such a breakdown was possible. For projects that were energy-only improvements, such as air sealing, new HVAC, etc. we included the full project cost.

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[1] Source energy accounting for PV production is sometimes handled differently from consumption (i.e., applying a source energy "credit" using a conversion factor of 1.0 rather than 3.16), but this is not the case in the Building America method we used. Furthermore, many projects did not separately report consumption and production, so more nuanced accounting was impossible.

It was not clear in most projects how and if design and consulting services were accounted for. No inflation adjustments were made to any cost data gathered—energy costs or project costs—because pre-retrofit utility bill dates were generally not provided, and project costs were nearly all incurred within the past few years.

In our economic analysis, we attribute all energy cost savings to the reported incremental DER costs and measures, which is not entirely accurate in all cases, because substantial cost savings can be realized by getting the home up to current energy performance levels that are sometimes required by code for extensive home renovations. Unfortunately, we do not have a reliable way to separate energy savings achieved by standard remodeling practices from those achieved by DER practices, and very few such efforts were reported in the literature. Berges & Metcalf (2013) provide a simulated example of 12 homes renovated to Energy Star and deep retrofit standards, and the DERs provided 40% energy cost savings over Energy Star retrofits (Berges & Metcalf, 2013). Market simulation assessments in four European countries (where energy codes are more stringent than in the US) have estimated that the energy savings for standard refurbishment practices are 40-65%, with best available (DER) technologies providing either substantial or minimal further reductions, depending on the building stock, refurbishment practices and house type (Becchio et al., 2012). However, standard refurbishment in the U.S. may not be equivalent with European practices. Another reason for not splitting out the fraction of energy saved by going beyond code is that, in many cases, bringing a home up to energy code would realize >50% energy savings, and the home may qualify as a DER simply by making it energy code compliant. The authors have suggested that energy code compliance (IECC 2012) itself is an acceptable path for many DERs in California, provided that other end-uses are addressed (Walker & Less, 2013). Sewalk & Throupe (2013) estimated the costs and benefits of implementing the IECC 2012 in existing residences, using a sample of 114 single-family homes located in Denver, CO, and they report an average estimated retrofit cost of $22,091 with average increase in efficiency of 40% (Sewalk & Throupe, 2013). While less than our 50% threshold, the analysis notably did not include appliances or HVAC equipment, which would increase both the costs and savings. Therefore, in this study we report the energy savings to the retrofit and do not attempt to disaggregate the fraction of energy saved by going beyond code. Where our results are used to develop stock-wide energy scenarios, this assumption is a realistic one as it reflects the total amount of energy reductions that could be anticipated.

Our primary financial metric is net-monthly cost of homeownership, where the balance is calculated between monthly energy cost savings and the monthly reported costs of a financed DER. For financing, we assume that the full reported costs are financed using a 30-year home-improvement loan with a 4.46% annual interest rate, which was the four-year U.S. average for fixed-rate mortgages from 2009 to 2012 (Freddie Mac, n.d.). We then account for mortgage interest tax deductions assuming a 25% tax rate, using the average of the first five years of interest deduction. Local or national financial incentives (e.g. tax credits or utility rebates) were not included. Negative net-costs mean that net-cost of homeownership is less after the retrofit, indicating net-savings. We believe a target of neutral net-monthly costs is appropriate to justify a DER on an economic basis, while recognizing that the decision to perform a DER is mostly non-economic. Other factors include a desire to make a home more comfortable, healthy, safe and durable, and to reduce environmental impacts.

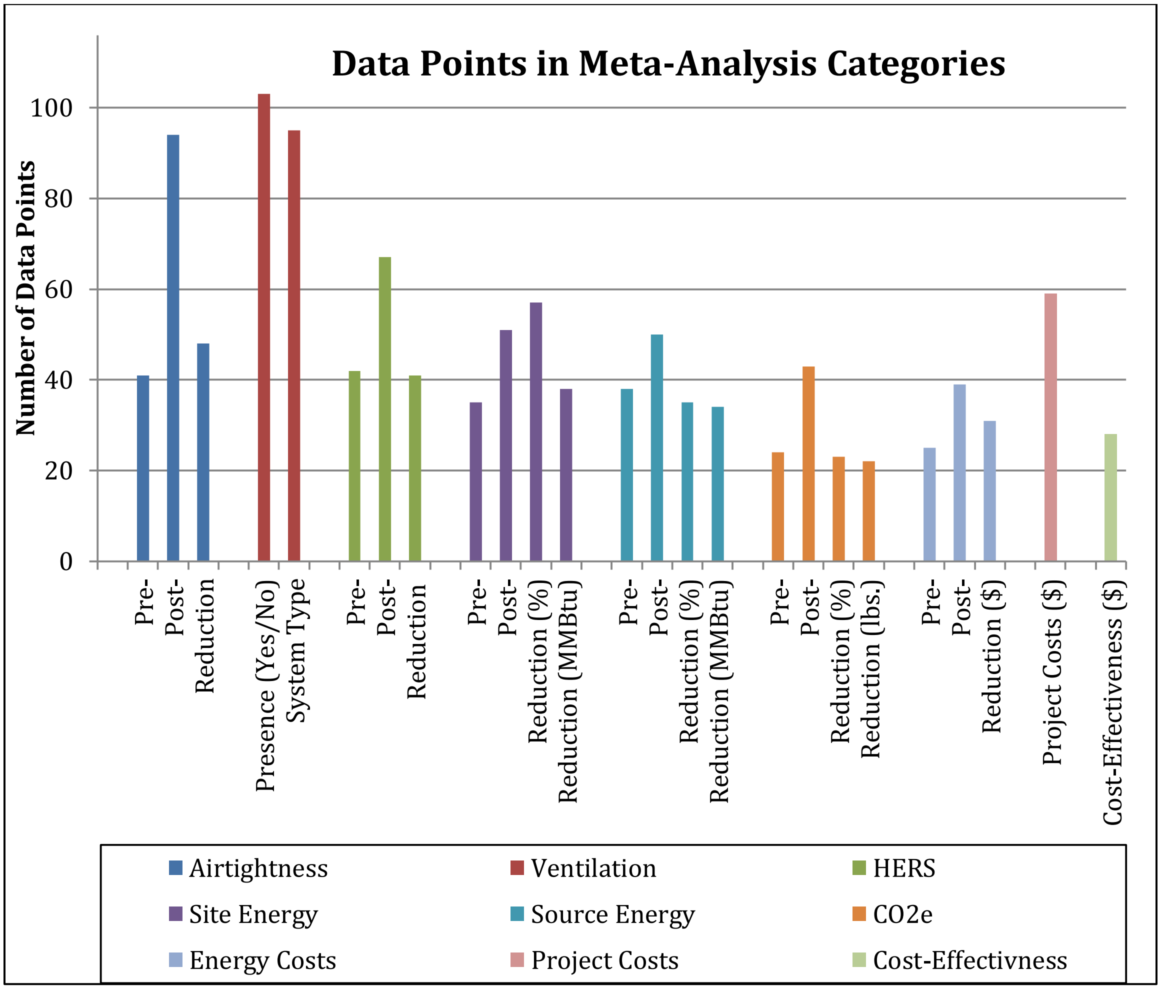

Figure 2 Summary of Available Data Points for Each Analysis Category

3 Summary of DER Characteristics and Performance

3.1 Sample Description

The locations of the 116 DER homes are summarized by U.S. state in Table 1. The average age of the DER homes (from a 2013 baseline) is 77.7±41.3 years (n=64), and the average pre- and post-retrofit floor areas were 1,967±819 ft^2 (n=82) and 2,110±883 ft^2 (n=99), respectively (floor areas are summarized by climate zone in Table 8 in

Appendix 2). Post-retrofit homes were similar in size to the median new home size built between 2005 and 2009 (2,100 ft^2) (Sarkar, 2011). Of the 82 projects with both pre- and post-retrofit floor areas, 20 (24%) of them increased floor area, by an average of 670±482 ft^2. While such additions could lead to increased energy use, they are also good examples of instances when DER measures can be incrementally incorporated into other planned renovation activities. Conversely, McIlvaine, Sutherland, & Martin (2013), which was published after completion of this review, summarized 46 unoccupied, foreclosed DER homes in Florida, where removal of conditioned floor area was reported in some retrofits (McIlvaine, Sutherland, & Martin, 2013). Approximately 10% of homes removed porches or garages from conditioned space, reducing floor area by an average 354 ft^2. This also led to an average decrease in window area of 45 ft^2. Other descriptive performance indicators (e.g., insulation levels and equipment types) were not gathered in this assessment, but such an effort may be part of future research.

State	Count	State	Count
CA	24	NY	9
Canada	1	OH	13
DC	1	OR	4
FL	20	PA	1
IL	1	TN	7
MA	19	TX	3
ME	1	VT	2
MI	2	WA	4
MT	1	WI	1
NH	1	N/A	1

Table 1 Summary of DER Locations by State

3.2 Airtightness

Airtightness was commonly reported for post-retrofit conditions (n=94), but was much less frequent for pre-retrofit (n=41) (see Table 2). Air leakage reductions were generally very impressive, averaging 63%. Chan et al. (2012) provide a summary of standard airtightness retrofits in the U.S. for non-Weatherization Assistance Program (WAP) retrofits and WAP retrofits, which achieved average percent reductions in ACH_{50} of 20% (n=9,999) and 30% (n=13,093), respectively (Chan, Joh, & Sherman, 2012). DERs are regularly doubling and tripling these average reductions. Ninety-fifth percentile reductions in WAP and non-WAP retrofits reported by Chan et al. (2012) were 50% and 61%, respectively, which makes these DERs amongst the most aggressive airtightening efforts in the U.S. Post-retrofit airtightness was lowest and leakage reductions were highest in cold climate DERs (see Table 9 in

Appendix 2 for airtightness summaries by climate zone). This is not surprising, as cold climate projects are more strongly driven by envelope loads, and a number of the projects were part of the National Grid Deep Retrofit Pilot project, which specified 0.1 CFM_{50}/ft^2 of thermal enclosure area (approximately 1.5 ACH_{50}) as a goal (Neuhauser, 2012). Simulation assessments of IAQ and residential retrofits have shown that air leakage reductions of 40% have a significant impact on levels of indoor contaminants (Emmerich, Howard-Reed, & Gupte, 2005). This highlights the importance of ventilation and IAQ provisions in DER projects that target aggressive air leakage reductions.

In addition to lowering average leakage levels, the DERs also showed less variability in air leakage post-retrofit, as characterized by smaller standard deviations (11.3 versus 2.9). This tighter control of envelope leakage means that DER homes are less likely to suffer from drafts and comfort issues.

	Min.	Median	Mean	Max.	SD	n
Pre-Retrofit (ACH_{50})	3.6	12.1	16.1	57.7	11.3	41
Post-Retrofit (ACH_{50})	0.4	4.6	4.7	16.8	2.9	94
Reduction (%)	-7	69	63	97	25	48

Table 2 Summary of Pre- and Post-Retrofit Air Leakage (ACH_{50})

3.3 Ventilation

Given the aggressive air leakage reductions being achieved in U.S. DERs, the provision of ventilation is of primary concern. Lacking actual pollutant and air exchange rate measurements, we use the reported presence of continuous mechanical ventilation as an indicator of minimum IAQ provision. A summary of continuous mechanical ventilation provision is provided in Table 3, and system types are summarized in Table 4. Finally, airtightness is compared between vented and unvented DERs in Figure 3.

Just over two-thirds of DERs installed continuous mechanical ventilation (71%), which is a reasonably good rate, given that a substantial portion of the homes remained more leaky than the current requirement for Energy Star homes (5 ACH_{50}). The new International Energy Conservation Code (IECC) requirements are 3 and 5 ACH_{50} depending on the climate zone (ICC, 2012), and the 70th percentile (aligning with ventilation saturation) of post-retrofit airtightness in these homes was approximately 6 ACH_{50}. Furthermore, unvented homes were much less airtight on average (6.8 versus 3.7 ACH_{50}), showing that most projects that achieved substantial airtightness also chose to install continuous ventilation. Yet, as is clear in Table 3, this trend was determined largely by Cold climate DERs, which installed ventilation in over 90% of projects—all other climate zones, except mixed-humid, had installation rates at or below 50%.

Installed ventilation systems (see Table 4) were dominated by energy or heat recovery units (n=52, 72%). Many of these systems could be termed “complex”, meaning they have one or more of the following: independent duct systems, humidity controllers, variable speeds, multiple points of occupant controls, filtration, etc. All of these added complexities add potential points of performance failure and risk of inadequate maintenance, which is troubling, given that performance errors are common even in "simple" mechanical ventilation systems (Stratton, Walker, & Wray, 2012). A variety of ventilation system performance faults have been reported in California DERs and new homes (Less et al., 2012; Less, 2012; Offermann, 2009). Faults including low airflow, noise, unclean systems, poor design and/or installation, insufficient maintenance, operational errors, blocked air intakes and recirculation in Energy Recovery Ventilators (ERVs) and Heat Recovery Ventilators (HRVs), have also been commonly reported in Canadian and Dutch homes (Balvers et al., 2012; Hill, 1998). DERs using complex ventilation systems as part of their retrofit strategy should include substantial system commissioning, occupant education efforts, and potentially either periodic re-commissioning or some form of automated fault-detection. These are important due to the near-total reliance of mechanical air exchange in very airtight projects.

We recommend that, at a minimum, DER projects comply with ASHRAE Standard 62.2-2013 ventilation requirements. ASHRAE 62.2 is a minimum standard and additional improvements in IAQ (such as low-emission materials or use of ventilation with heat recovery) should be a target of DERs, because better IAQ is a key part of home improvement. Another advantage of installing a ventilation system is that any future tightening of the envelope can be more easily accommodated. Recent studies have compared the cost and performance of various whole-house ventilation strategies in retrofitted homes (Aldrich & Arena, 2013; LBNL, 2012). To-date, the installation of continuous mechanical ventilation has mostly been at the discretion of DER project teams. The exception to this is from states and programs that require compliance with ASHRAE 62.2 in retrofitted homes. Organizations involved in home retrofits have begun to include mechanical ventilation provisions in their standards and protocols (referring to ASHRAE 62.2), including the Building Performance Institute, Residential Energy Services Network (RESNET) and the U.S. DOE Weatherization Assistance Program (Building Performance Institute, 2012; RESNET, 2006; U. S. DOE, 2011).

BA Climate Zone	No	Yes	N
Cold	5 (9%)	51 (91%)	56
Hot-Dry	8 (89%)	1 (11%)	9
Hot-Humid	6 (55%)	5 (45%)	11
Marine	9 (47%)	10 (53%)	19
Mixed-Humid	2 (25%)	6 (75%)	8
All	30 (29%)	73 (71%)	103

Table 3 Summary of Presence of Continuous Mechanical Ventilation

Ventilation System Type	Count	Percent
ERV	27	28%

HRV	24	25%
Central Fan Integrated Supply (CFIS)	9	9%
Exhaust	10	11%
Supply	2	2%
None	23	24%

Table 4 Summary of Continuous Ventilation System Types in DER Homes

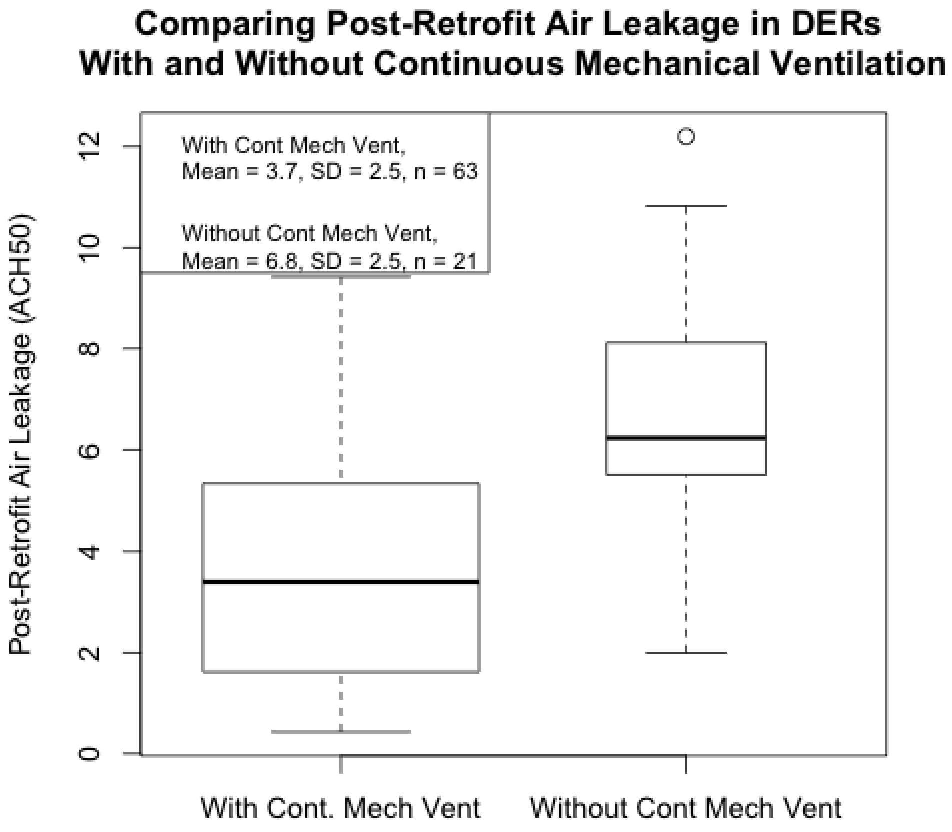

Figure 3 Comparing Airtightness in Continuously Vented and Unvented DERs

3.4 HERS Indices

HERS indices were calculated and presented by many projects, even those that provided no energy data. Pre- and post-retrofit HERS indices, as well as percent reductions in HERS Index are provided in Table 10 in

Appendix 2 (averaging 151±43, 68±24, and 45%±18%, respectively). The average DER was estimated to use 32% less energy than a new home built to comply with 2006 energy code. Notably the standard deviations in the post-retrofit homes were approximately half those in the pre-retrofit cases, suggesting that levels of performance were less variable and more tightly controlled in post-retrofit homes. The relationship between percent HERS index reduction and percent net-site energy reduction is depicted in Figure 4. There is a general trend towards higher net-site reductions when HERS reductions increase. The root mean square (RMS) of the percentage difference between HERS and net-site reductions was 11.8%, and the simple average error was 0.5%. Note that the RMS error was dominated by a few outliers where the predicted change in HERS index was much less than the reported energy savings. When these two data points are removed from analysis, the RMS error drops to 7.2% and the average error increases to 2.8%.

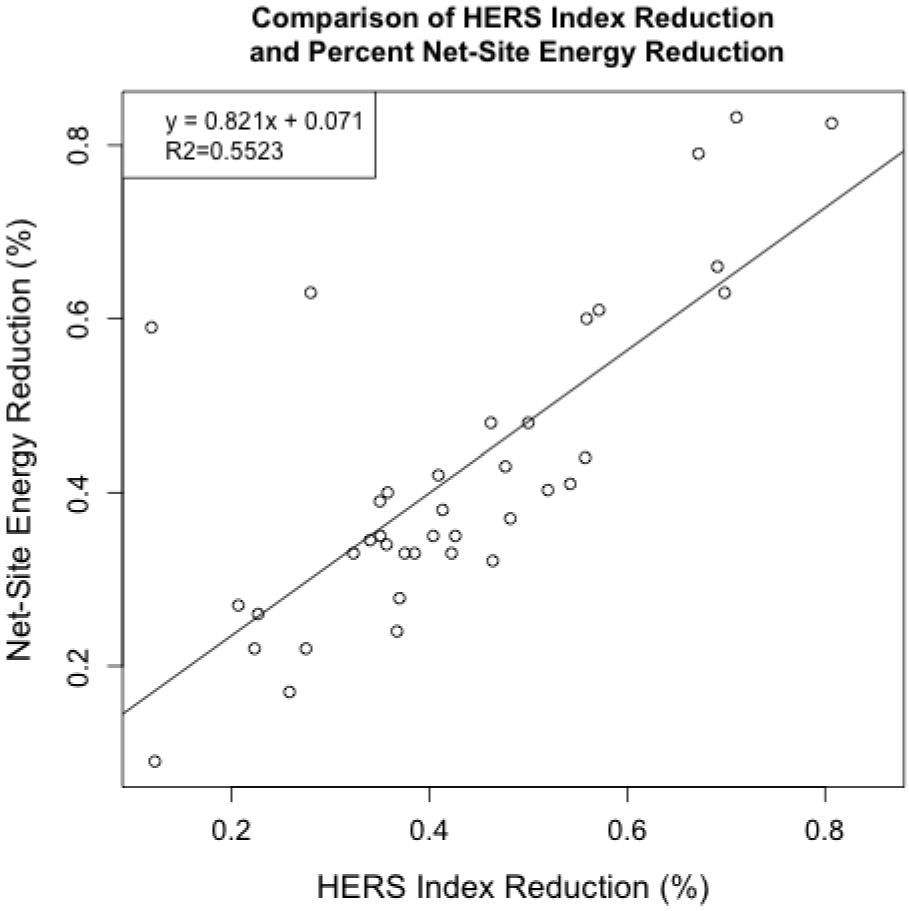

Figure 4 Relation of HERS Index Reduction to Net-Site Energy Reductions

3.5 Energy Performance

The ultimate justification for most DER projects is the energy use reduction achieved. Fisher, Less, & Walker (2012) discuss how multiple metrics may be required for adequate DER assessment, due to changes between pre- and post-retrofit conditions, including size, layout, fuel mix, etc. Consistent with this, we summarize site energy, source energy and carbon emissions data, and we compare absolute (MMBtu) and relative (%) energy reductions. Net-site energy and net-source energy usages and reductions are summarized in Table 11 and Table 12 in

Appendix 2 (floor-area-normalized site and source energy usages and reductions are provided in Table 16 and Table 17). Climate zone summaries are not intended to be definitive representations of regional DER potential, as data consistency and sample sizes vary substantially amongst climate zones.

3.5.1 Net-Site Energy

Pre- and post-retrofit net-site energy use averaged 127.1±89.6 kWh (n=35) and 47.7±30.2 kWh (n=51), respectively. Average net-site energy reductions were 47%±20% (n=57) (74.5±76.3 kWh (n=38)).

On average, pre-retrofit usage was 20% higher than the reported mean for single-family detached (SFD) residences in the 2009 Residential Energy Consumption Survey (127.1 versus 105.7 MMBtu) (U.S. Energy Information Administration, 2009). More variability was introduced when analyzed by Building America climate zone. Hot-humid and Marine climate pre-retrofit consumptions were similar to the national climate zone averages (5% lower and 6% higher, respectively), whereas all other climate zones varied from 55% to 86% more pre-retrofit energy use than their climate zone average[2]. This suggests that DER homes generally had higher than average energy consumption pre-retrofit, which could be the result of differing home sizes or the tendency for high-usage homes to have greater interest in pursuing reductions.

When compared to the consumption of an average U.S. home (105.7 MMBtu), the average DER used 55% less total net-site energy post-retrofit (average usage was 47.7). When normalized by floor area, the average absolute annual reduction for these DERs (39.8 kBtu/ft^2) was very similar to the total annual consumption of an average U.S. single-family detached home (42.6 kBtu/ft^2). So, each DER project effectively removed a "home" from the electrical and gas grids; one project effectively removed three average U.S. homes from the grid.

Percentage reductions were similar across climate zones, with the lowest average savings reported in Hot-Humid projects (36%±11%, n=23), where many homes were in programs with a lower bar to qualification as a DER (e.g., defining DERs as either 30% energy savings or HERS 70 (Chandra et al., 2012; McIlvaine, Sutherland, Schleith, & Chandra, 2010)). Due to the high number of projects in this zone (n=23), the average is drawn down, but only slightly—the average net-site reduction is 55% (n=34) when disregarding Hot-Humid projects. This is similar to the 58% average site energy reduction reported in a review of 27 DERs in a pilot community in Massachusetts and Rhode Island, which was published after completion of this review (Gates & Neuhauser, 2014). Unsurprisingly, absolute reductions had more variability, resulting from differing performance targets, varying pre-retrofit usages and floor areas, as well as analysis and reporting methods.

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[2] Climate zone data in RECS (2009) includes housing types other than SFD.

Figure 5 illustrates the relationship identified between pre-retrofit site energy usage and the absolute site energy reduction achieved. A clear correlation exists, showing that the more energy consumed pre-retrofit, the larger the savings. This indicates that energy savings programs may want to selectively target high energy users (as is done by some utility programs). Nevertheless, 14 of the 35 projects that provided pre-retrofit data used less than the average consumption in their climate zone. So, while the opportunity is greatest in high usage homes, those are not always the homes being retrofitted. This may be due to the tendency for households already conserving energy to be interested in further reducing consumption, and it may also result from the desire for improved comfort and convenience, irrespective of energy or cost savings. Consistent with this, several projects reviewed reported that homeowners considered non-cost saving benefits to be the most important in their choice to perform a DER (Boudreaux et al., 2012; Neuhauser, 2012).

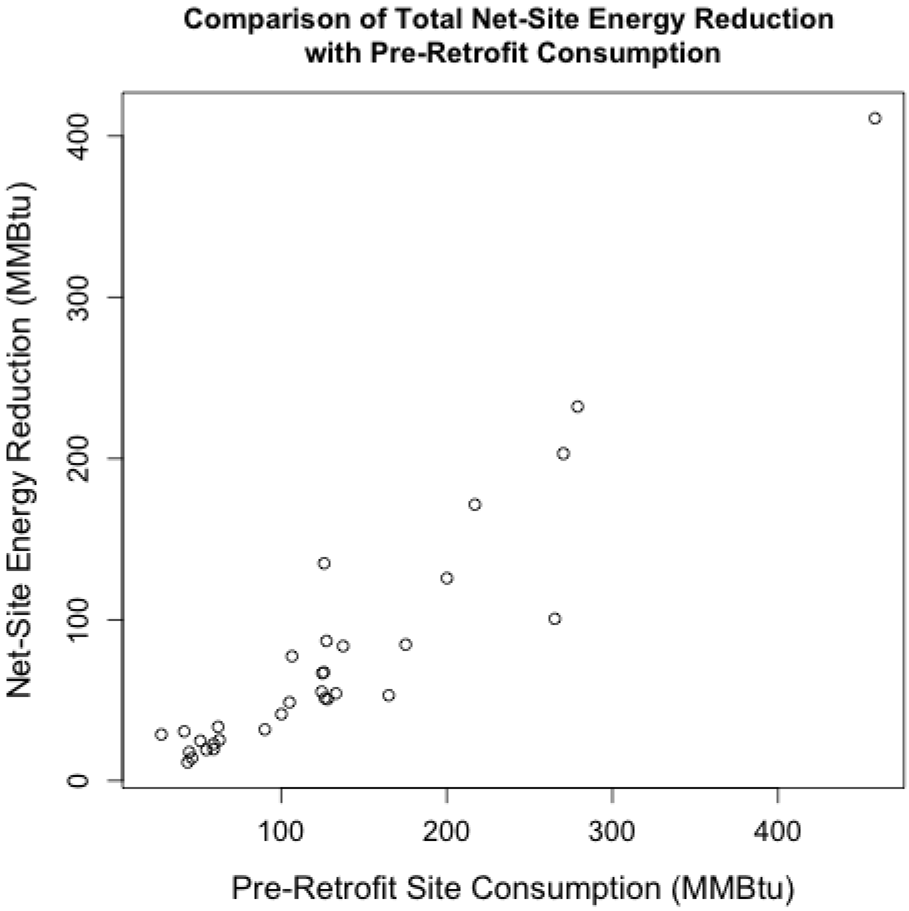

Figure 5 Relationship Between Net-Site Reduction and Pre-Retrofit Usage

No relationship was observed between house age and net-site energy reductions, suggesting that reduction opportunities are stable for homes of differing ages. Very few newer homes (1990s or later) were included in the dataset, but those four that were built after 1990 had average net-site reductions of 52% (above average). This finding contrasts with the reduced potential for energy reductions in newer homes reported by McIlvaine, Sutherland, & Martin (2013). The hot-humid DERs reported on by these authors were all targeting a post-retrofit HERS index of 70, so lower than average pre-retrofit HERS indices in the newer homes limited their overall reduction potentials. DERs that are not constrained by a lower limit of targeted performance should be able to achieve reductions commensurate with older homes.

The relation between post-retrofit airtightness and net-site energy savings is depicted in Figure 6. Airtightening is generally considered an essential element of most DERs, yet no relation with energy savings was observed in this sample (r^2=0.03). Similar results were obtained when comparing air leakage and net-site energy reductions (r^2=0.09). This is consistent with findings in DERs in the UK and in a Rhode Island and Massachusetts DER community (Gates & Neuhauser, 2014; The Technology Strategy Board, 2013). Airtightness improvements are still justified in DERs, because of their generally low cost (relative to other improvements, such as wall insulation) and accepted role in efficiency improvements, as well as potential IAQ and thermal comfort benefits. Yet, it is clear that no particular level of post-retrofit airtightness or airtightness reduction is required for success.

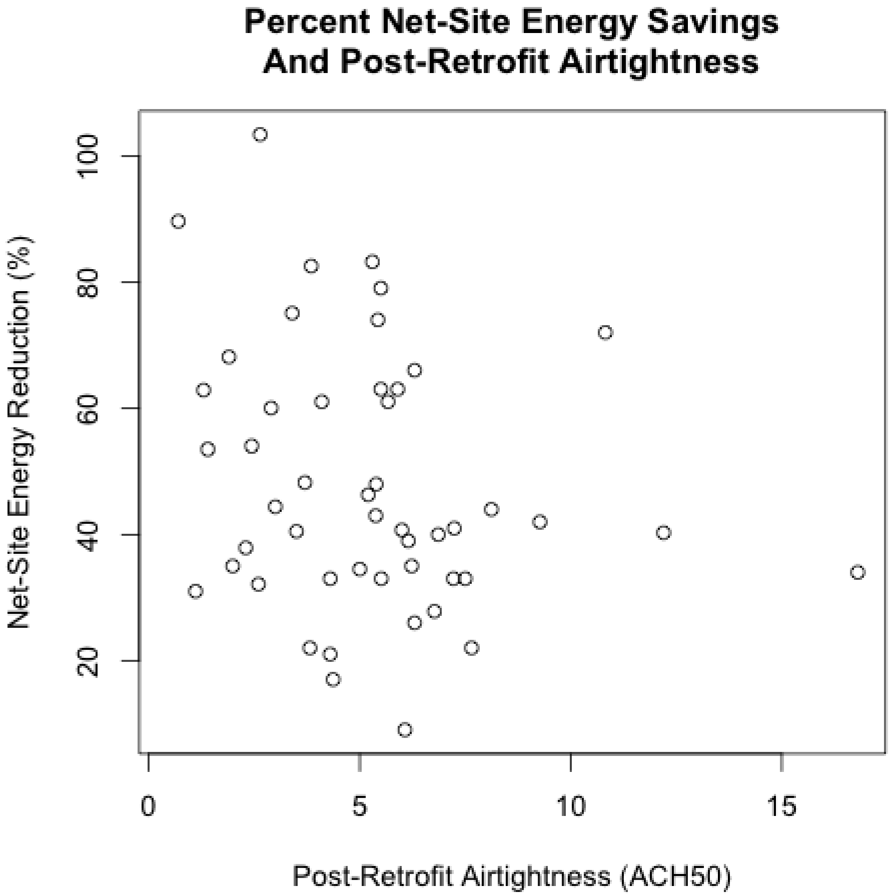

Figure 6 Relationship Between Net-Site Reduction and Post-Retrofit Airtightness

3.5.2 Net-Source Energy

Pre- and post-retrofit net-source energy use averaged 225.0±128.0 kWh (n=38) and 101.1±56.6 kWh (n=50), respectively. Average net-site energy reductions were 45%±24% (n=35) (103.8±103.0 kWh, n=34). Source energy reductions were similar to site reductions discussed above, with the exceptions of DERs that engaged in fuel switching (see Section 3.5.4 below). Absolute source energy reductions were highest in Cold climate projects.

The source energy use of post-retrofit homes is normalized by floor area and compared with the source energy requirement of the Passive House EnerPHit standard (12.3 kWh/ft^2-yr) in Figure 7. While meeting the source energy threshold is not by itself sufficient for EnerPHit certification, the fact that 31% (16 of 49 projects) of U.S. DERs met the requirement is impressive and suggests that these projects are comparable to the most aggressive renovations in the European Union. When assessed by climate zone, Cold, Hot-Dry, and Hot-Humid projects had similar average source energy use intensities (17.0, 20.5, 23.3 kWh/ft^2-yr, respectively (n=24, 8, and 9)), while Marine climate DERs had by far the lowest usage (10.3 kWh/ft^2-yr, n=8). Notably, Cold climate projects did not have the highest source energy use intensity, which would be expected based on outdoor temperatures. This suggests that envelope retrofits were more aggressive and effective in Cold climates, which is consistent with airtightness levels reported in Section 3.2. Why usage was so low in Marine climate homes is unknown, though it could be attributed to more aggressive retrofits, as well as lower cooling energy demand, which can have a substantial impact on source energy use.

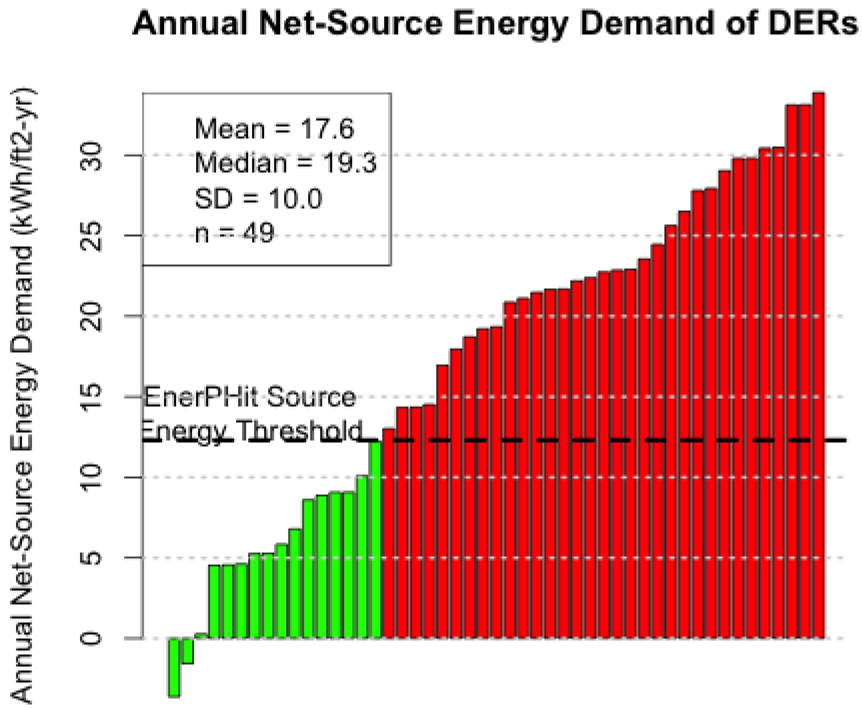

Figure 7 Summary of the Floor Area Normalized Source Energy Use of U.S. DERs and Comparison to EnerPHit Standard

3.5.3 Simulated Versus Actual Savings

Site energy reductions were also compared using a two-sided t-test between homes that reported actual energy usage and homes that estimated energy use (see Table 5). A significant difference ($p < 0.05$) was observed between the percentage reductions of all DERs, with average actual and estimated reductions of 56% and 44%, respectively. This difference is mainly because projects in the Hot-Humid climate zone targeted lower energy savings, and they only provided simulated results. When these Hot-Humid homes were removed from the analysis, no statistically significant difference remained between the two samples. These results suggest that estimated/simulated energy reductions may be comparable to those actually achieved, when averaged across a population of homes. Notably, some actual consumption values may have been weather-normalized, which may have reduced the difference between simulated and actual results. Significant simulation or prediction errors may still occur on a house-by-house basis, and must be considered by project design teams.

Projects	Data Type	Percent	n	p-value	Absolute	n	p-value

		Reduction			Reduction		
All DERs	Actual	56%	18	0.0297	69.2	15	0.5774
	Estimated	44%	27		59.4	20	
Non-Hot-Humid	Actual	56%	18	0.4485	69.2	15	0.4220
	Estimated	50%	12		88.5	11	

Table 5 Summary of Average Savings in Actual Usage and Estimated Usage DERs

3.5.4 Fuel Switching

Less, Fisher, & Walker (2012) noted the danger that fuel switching can pose to source energy performance in otherwise successful DERs. They highlighted several projects that chose to switch from natural gas to electricity for heating end-uses, and which incurred severe source energy penalties as a result. One project went from site savings of 31% to a source energy *increase* in usage of 12%, and another went from a 61% net-site reduction to only a 7% net-source reduction. The addition of energy-using features also contributed to these performance degradations. Seven projects were identified in this review that increased electricity use from pre- to post-retrofit (two of which derive from the Less, Fisher, & Walker (2012) results). All of these projects had lower net-source energy savings than net-site, with an average degradation in percent savings of 57% (median 37%) due to increases in electricity usage. This ignores those projects that provided no pre-retrofit data, but still went from gas to electric heating or hot water (Less, Fisher, & Walker (2012) discussed two such projects).

We did not evaluate fuel switching in which electric appliances were exchanged for gas appliances, though this is expected to occur less frequently. Because gas is generally less expensive than electricity on a per unit energy basis, those homes with existing gas service tend to already use gas appliances, and the addition of gas service can be very expensive. Furthermore, ample efficiency upgrades are available in electrical heating end-uses, namely high performance heat pumps, which do not necessitate the addition of gas service. The Florida phased DER reported on by Parker & Sherwin (2012) did switch from electrical to gas heating end-uses, with hopes of reducing source energy usage, but source energy use actually increased, as two children were born very soon after the change (Parker & Sherwin, 2012).

Overall, fuel switching appeared to be relatively infrequent in this literature search[3]. This may be the result of expert involvement in project planning, in particular, the use of source energy as the primary metric in Building America (BA) project assessment. We recommend this practice. It may also have resulted from unclear reporting of fuel-switching activity. Gates & Neuhauser (2014) reported similar source energy penalties in their assessment of a DER community in the Northeast, with average site reductions of 58% contrasted with source energy reductions of

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[3] The seven projects that increased electricity use from pre- to post-retrofit may not exhaustively document fuel-switching, as some homes may have fuel switched, but achieved drastic cuts in other electrical end-uses or produced sufficient PV energy to offset the increase. Fuel switching was not directly or consistently reported in most projects.

only 41%. They noted that several projects switched to all-electric homes, while some others switched from gas or oil for heating and hot water to heat pump systems. The DERs studied by Less, Fisher, & Walker (2012) were entirely homeowner, contractor, and designer driven. For this reason, they are more likely to reflect the retrofit decision-making process outside the BA methodology. Furthermore, many projects in this review provided only simulated data, which may not reflect the common practice of adding energy-using conveniences and features to the home, such as mechanical cooling, ventilation, decorative lighting, A/V equipment and the like (as documented by Less, Fisher and Walker (2012)).

3.6 Carbon Emissions

Carbon emissions pre- and post-retrofit averaged 20,73±8,125 (n=24) and 9,093±6,380 pounds CO_2e (n=43), respectively (see Table 13 in

Appendix 2 for detailed climate zone summaries). Carbon emissions reductions averaged 47%±22% (n=23) (9,152±5,309 pounds CO_2e, n=22), respectively. Fractional reductions averaged across all projects are nearly identical to net-site energy reductions. Yet, in terms of carbon performance, similar penalties were incurred by projects that increased electricity usage, with an average performance degradation of 42% (n=5). Carbon emissions reductions were consistent with results found for 37 DERs in the UK, which were designed with the goal of 80% carbon reductions relative to a 1990 average baseline. Twenty-three of 37 projects achieved between 50% and 80% emissions reductions and three exceeded the 80% goal (The Technology Strategy Board, 2013). On average, DERs are nearly achieving the 50% reduction in residential carbon emissions commonly thought to be required for acceptable climate mitigation (Neme et al., 2011). When Hot-Humid climate DERs are removed from analysis, average reduction are above 50%. This is consistent with the 50% to 85% reductions in global CO_2 emissions required for climate stabilization with respect to a year-2000 baseline (Intergovernmental Panel on Climate Change, 2007).

Unlike the national average source energy conversions, we have used state-by-state CO_2e carbon intensity factors for electricity (see Appendix 1), which are more variable. In 2009, these varied from a low of 0.006 pounds CO_2e /kWh in Vermont to 2.9 pounds CO_2e /kWh in the District of Columbia. States whose electricity has a "Low" carbon intensity were generally 0.6 to 0.7 pounds CO_2e /kWh, whereas "high" states were generally 2.0 to 2.5 pounds CO_2e /kWh. Natural gas converts at 0.399 pounds CO_2e /kWh, meaning that depending on the state (and ignoring outliers), CO_2e emissions from electricity can be from 50% to 600% higher than those from natural gas, per unit of site energy. To maximize emissions reductions, DERs in state's whose electricity has a "high" carbon intensity should preferentially target electricity reductions, potentially even at the expense of aggregate site and source energy savings.

Source energy and carbon conversions vary with changes in power generation fuel mixes, as the installed generation mix changes, and on shorter time scales, where the carbon content of generation is different for baseline and peak electricity demand. For example, The California Public Utilities Commission's Greenhouse Gas Calculator, predicts that the carbon intensity of PG&E's electricity supply will drop from 2009 levels of 0.58 pounds CO_2e per kWh to 0.29 by the year 2020—almost a 50% reduction ("Greenhouse Gas Emission Factors: Guidance for PG&E Customers," 2013). If this is achieved, electricity from PG&E in CA will be less carbon intensive than natural gas, and our warnings about fuel switching could transition to suggestions to aggressively switch fuels in that state and others with similarly low emissions factors. Consistent with this, modeling assessments have concluded that the de-carbonization of electricity, combined with the electrification of transportation and other services (including home heating and hot water) will be necessary to achieve desired carbon emission reductions (Williams et al., 2012). DER designers should consider these dynamics when choosing fuel types and systems in retrofit homes, with a focus on ensuring flexibility and adaptability in a changing cost and regulatory environment.

3.7 Energy Costs, Project Costs and Financing

3.7.1 Energy Costs

Annual average energy costs pre- and post-retrofit were $2,738±$1,065 (n=25) and $1,588±$561 (n=39), respectively. Average energy cost savings were $1,283±$804 (n=31) (see Table 14, in

Appendix 2 for detailed summaries by climate zone)[4]. For comparison, in 2009 the average U.S. single-family residence spent $2,354 annually on energy costs. These projects had slightly higher than average energy expenditures pre-retrofit. Average savings were similar across climate zones, with generally lower savings in Hot-Humid projects, due to less aggressive projects, as noted above. Some of the lower savings in milder climates may be the result of non-envelope, user-discretionary energy use being a larger fraction of the total energy use, which can be more difficult to address in a DER. The annual energy costs are not adjusted for changes in unit energy costs over time, because the dates of energy use are not always provided. For example, recent decreases in prices for natural gas could have significant impact on the reported costs and savings.

3.7.2 Project Costs

The cost of DERs is considered to be one of the key barriers to widespread adoption. Reported project costs averaged $40,420±$30,358 (n=59), which on a per square foot basis averaged $22.11±$17.70 per ft^2 (n=57) (detailed climate zone summaries are provided in Table 15 in

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[4] We were not able to ascertain the time periods for pre-retrofit costs, and as a result, have not performed inflation normalization, which would have corrected for energy costs from different time periods. This would only make a substantial difference if the time periods were spread far apart.

Appendix 2)[5]. For comparison, Sewalk & Throupe (2013) estimated an average cost of $22,091 to bring a sample of 114 Denver, CO homes to the IECC 2012, which excluded HVAC and appliance upgrades. It has been commonly reported on a popular green building blog, that a typical DER costs over $100,000 (Holladay, 2012); these data seem to resoundingly contradict that assertion, at least based on the reported incremental costs in this review.

Cold and Mixed-Humid climate projects reported the highest average costs ($57,480 and $42,160, respectively), while Hot-Humid were the lowest ($9,503), consistent with their lower performance targets and specific cost-effectiveness requirements. Despite the larger energy savings achieved in Cold climate projects (see Table 11), the high project costs noted above led to increased costs per unit energy savings, such that Cold climate projects averaged $815 per MMBtu net-site savings, whereas other climate zones averaged $447 per MMBtu.

A comparison of annual energy costs savings and reported project costs is provided in Figure 8. A slight positive correlation exists between the two variables, but in general, the relationship is weak in this dataset due to the variability caused by climate zones, construction costs, and pre-retrofit conditions. Similar results were found comparing reported project costs with percent net-site energy reductions. In other words, many retrofit costs are more or less fixed (e.g., installation of a new high-efficiency gas furnace), but the achievable energy costs savings are highly variable depending on pre-retrofit usage, climate, etc. Nevertheless, we believe that for any particular home, a higher investment will generally lead to higher savings, if decisions are based on cost-effectiveness, which is not always the case.

The average minimum project costs across climate zones (excluding Hot-Humid) was between $10,000 and $15,000. This range could be considered the minimum incremental cost reasonably capable of generating deep energy reductions in existing homes. For comparison, the maximum allowable expenditure for conventional retrofits on a single dwelling by the U.S. DOE Weatherization Assistance Program was increased from $2,500 to $6,500 by American Recovery and Reinvestment Act (ARRA) ("Weatherization Assistance Program - The American Recovery and Reinvestment Act of 2009 - wx_recovery_fact_sheet.pdf," n.d.). It appears that DERs need to at least double WAP spending per housing unit.

Caution in interpreting these project cost values is necessary, as a portion of the variability in this data is the result of different accounting and reporting methods, which were not consistent across projects, as noted in the methods section. Furthermore, both labor and hard construction costs vary regionally throughout the U.S. (e.g., RS Means remodeling location factors vary around the national average (1.0) from 0.67 to 1.37) (*RS Means, Contractor's Pricing Guide, Residential Repair and Remodeling Costs*, 2012), and no effort was made to account for such variability.

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[5] Values were not adjusted for inflation. All projects were recently retrofitted and reported on, so inflation issues should be minimal.

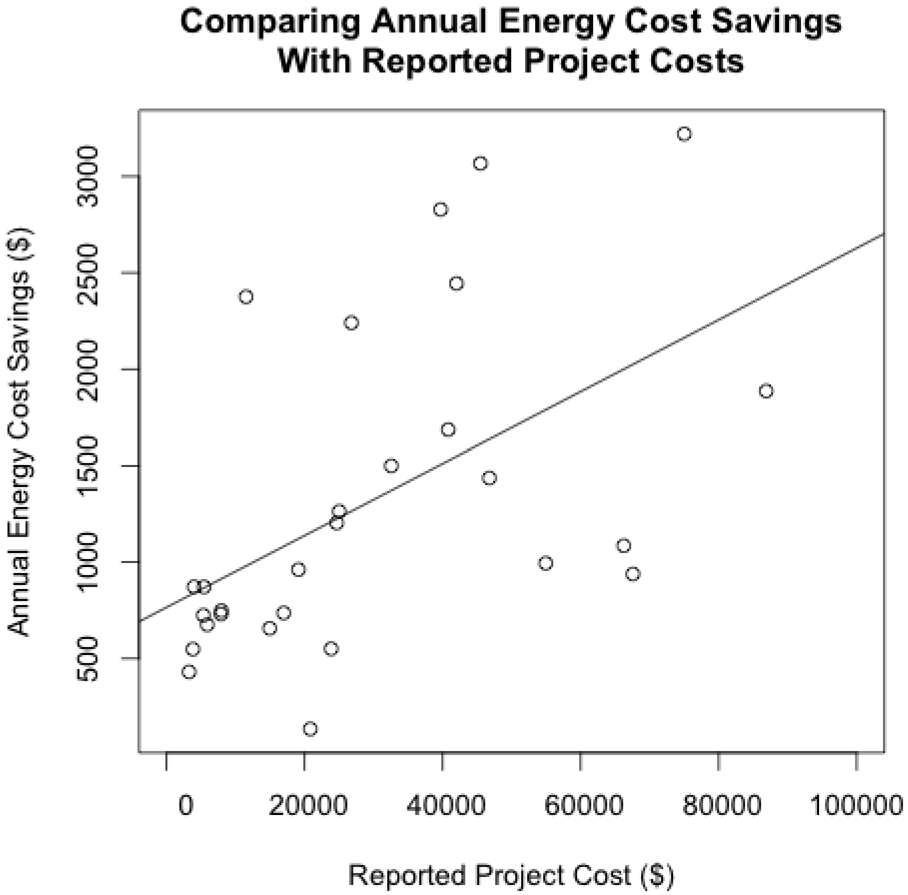

Figure 8 Comparison of Annual Energy Cost Savings With Reported Project Costs

3.7.3 Financed Costs

We estimated the net-monthly cost of homeownership for 28 DER homes (see Figure 9), which reported both energy costs savings and retrofit project costs. Net-monthly costs averaged $15.67±$87.74; median costs were $1.00. Of these 28 projects, 13 of them (48%) yielded positive cash flow (green color), meaning that energy cost savings balanced or exceeded financed incremental retrofit costs. Notably, the average reported project cost in these 28 homes was $29,460 (with average annual savings of $1,315)—approximately $10,000 less than the larger sample average of $40,420 (n=59). The average net-cost in the 28 DERs seems manageable for many American households, when compared to the cost of cable television or cellular telephone services. Of course, this only demonstrates the increased cost for pursuing a DER over a standard remodel; total project costs would be greater. Our finding of an average 45% net-source energy use reduction and median net-costs of $1 per month is consistent with the reports of source energy savings in near-neutral cost retrofits by Polly et al. (2011) and Fairey & Parker (2012).

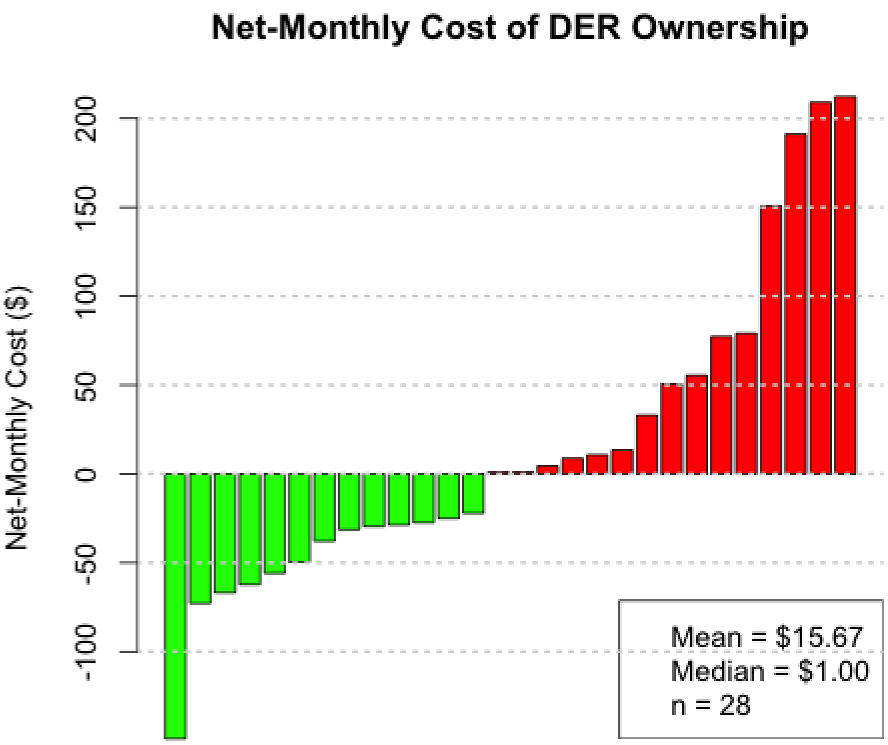

Figure 9 Summary of Net-Monthly Homeownership Costs, Assuming Incremental Efficiency Costs are Financed with a 30-Year Loan at 4.46% Interest, 25% Mortgage Interest Deduction

This finding only represents the 28 projects with both energy cost savings and project cost data, whereas many more DERs reported project costs alone. In order to have no net-change in homeownership cost for the average DER ($40,420, n=59), $2,062 in annual energy cost savings are required. Approximately 18% of the 31 DERs reporting energy cost savings in this sample exceeded this $2,062 threshold. So, such savings are achievable in aggressive retrofits, though not yet common. The feasibility of cost-justified DERs would be bolstered by a reduction in retrofit costs; the methods of doing so constitute future research needs. For example, a reduction in project costs and cost variability is likely to be achieved by standardizing retrofits for particular home styles and climates.

This is a limited economic analysis, covering only a subset of the 116 homes. The intention is not to be strictly rigorous, but rather to demonstrate value and feasibility in the minds of consumers. The limitations of this assessment include assumptions that retrofit measures endure or are valued over the 30-year loan term, and maintenance costs are ignored. It also assumes that energy savings persist and do not degrade, and it does not provide a time-varying assessment of how much energy the non-retrofitted home would have used with standard equipment replacement, addition of new devices, changes in energy prices, inflation, etc. Imperfect as they are, we feel these results are valuable, because they show a DER's monthly cost implications in a format that is accessible and meaningful for the average consumer.

Bearing in mind the limitations of this analysis, project teams can use the values provided in Table 6 in order to better-estimate the annual energy cost savings required to offset financed project costs in a DER. These values are intended to provide a "gut-check" for project teams, indicating whether they are on-track for a cost-effective retrofit or are missing the mark.

	Loan Amount ($)					
	$5,000	$10,000	$15,000	$20,000	$50,000	$100,000
Interest Rate (%)	Annual Cost Savings Required to Neutralize Monthly Loan Costs					
3.00%	$204	$408	$612	$817	$2,041	$4,083
3.50%	$221	$442	$663	$884	$2,211	$4,421
4.00%	$239	$477	$716	$954	$2,386	$4,771
4.50%	$257	$513	$770	$1,026	$2,566	$5,132
5.00%	$275	$550	$826	$1,101	$2,752	$5,503
5.50%	$275	$550	$826	$1,101	$2,752	$5,503

Table 6 Summary of Required Annual Energy Cost Savings for Retrofit Loan Amounts at Varying Interest Rates, assuming mortgage interest deduction at 25% tax rate

4 Interpreting the Cost-Effectiveness of DERs in a Wider Context

While on average we have reported that DERs can be cost-effective, half of projects had increased monthly costs post-retrofit, which is likely undesirable for those investing in a DER. More consistency in cost and savings, as well as lower overall retrofit costs, are desirable, and may be required to extend DERs out of their current early-adopters market segment. A number of DER research reports have reflected on the poor cost-effectiveness of DER homes (Boudreaux et al., 2012; Chandra et al., 2012), while others have aggressively targeted traditional cost-effectiveness (McIlvaine et al., 2010). It is also clear that reasons other than utility bill savings motivate some DERs (Boudreaux et al., 2012; Neuhauser, 2012). We argue that the value of a DER greatly exceeds the net-balance between its design and construction costs, and its energy cost savings. Going forward beyond early adopters it is likely that this will continue to be true. DERs are financially and socially justified due to a combination of utility bill savings and non-energy benefits (NEBs) (e.g., increased home value, and improved comfort, convenience, IAQ and durability, as well as lower maintenance). First, we will show that reported DER incremental costs are similar in magnitude to routine renovation expenditures reported by American homeowners. Second, we will explore how the costs of typical remodeling activities, solar PV installation, and having an energy or green label, are estimated to be recouped through increased home value at resale. Finally, we will explore how substantial NEBs can add value ranging from 50% to 300% of annual utility bill savings. These include improved thermal comfort, IAQ and health, reduced maintenance, loan default risk, moisture problems, and noise. When properly accounted for and marketed, these can all contribute significantly to the desirability of DERs and to the building owner's willingness to invest in the home.

The costs of DERs should be considered in the larger context of American household expenditures on remodeling. In general, DER costs, which averaged \$40,420±\$30,358 in this sample, are in line with those of other medium-sized remodeling projects. In 2009, 15.3 million American households reported professional remodeling expenditures averaging \$9,605 (JCHS, 2011). Room additions or alterations were reported in 1,035,000 residences, and average values varied from \$16,432 to \$38,979, depending on the room type. Of the 15.3 million households, 921,000 reported remodeling activities with costs greater than \$35,000, and the average expenditure in those 552,000 homes reporting the highest remodeling costs was \$95,865. Similarly, the average aggregated remodel cost (across a variety of project types) from the Remodeling 2012–13 Cost vs. Value Report (www.costvsvalue.com) was \$36,725 (Remodeling Magazine, 2013). DER costs are lower than the remodeling expenditures of a substantial minority of American households each year, and it is in the current higher-cost remodels that DER features can be best and most cost-effectively integrated.

Furthermore, the costs of any remodeling activity or home upgrade are generally recouped, to some extent, in increased home value and resale price. While it is not yet clear exactly how the costs of a DER contribute to increased home value (as few DERS have yet been resold), we can use general remodeling activities, energy efficiency, solar panel installation, and home certification as useful points of comparison. The Remodeling 2012–13 Cost vs. Value Report (www.costvsvalue.com) also provides estimates of the increased resale value attributed to various remodeling activities, with an average across all midrange project types of 66% (\$23,297) of the total expenditure (i.e., approximately two-thirds of total costs are recouped in increased resale value). If reported DER costs were similarly capitalized, the average project (\$40,420) would increase in value by \$26,677. Laquatra et al. (2002) provide a review of the literature published between 1980 and 2000 assessing the capitalization of energy efficiency in the housing market, and they found efficiency was positively capitalized to some degree (consistent with expectations based on economic theory), but the limitations of the published studies made definitive conclusions impossible. They recommended future assembly of a large data set with a clear, consistent definition of "energy efficient" (Laquatra, Dacquisto, Emrath, & Laitner, 2002). Some current studies have done just that, and have demonstrated significant increases in resale value. The capitalization of solar panels during resale has also been investigated by Dastrup et al. (2012), who examined sales records of single-family homes in Sacramento and San Diego counties in California. They found that solar panels added a 3.6% premium to the sale price in San Diego (a \$22,554 premium to the average sales price in 2010 U.S. dollars) and 4% in Sacramento (Dastrup, Zivin, Costa, & Kahn, 2012). In San Diego, the premium was greater, on average, than the net-cost (post-rebate) of the system itself. The capitalization rates varied with neighborhood characteristics, such as education level, political affiliation and Prius concentration (these variables were controlled for), so value may not accrue to all DERs equally. Finally, Nok & Kahn (2012) reported an average 9% ($34,800) resale price premium for energy efficient or green labeled homes over that of nearby comparable homes in the 1.6 million California homes sold from 2007-2012 (Kok & Kahn, 2012). Similarly, Bloom, Nobe, & Nobe (2011) found an $8.66 per ft^2 price premium for Energy Star certified versus conventional new homes (n=300) in Fort Collins, CO (Bloom, Nobe, & Nobe, 2011). Those retrofitted homes that attain energy or green labels may realize similar resale value increases.

We do not expect resale value to accrue to DER measures exactly as it does to general remodeling or solar panel installation, nor do we expect that it will accrue to all homes equally, irrespective of location, demographics, average income, etc. Nevertheless, these estimates do indicate that the net-costs of DERs may be substantially less than others and we have reported, when increased property values are quantified and included in calculations. Of course, realization of increased property values requires that consumers, real estate agents, and appraisers become aware of a home's energy efficient and sustainable features, which requires documentation, certification and careful record keeping. While not yet common practice, the issues, knowledge and approaches appropriate for valuing energy efficient and/or green homes are being recognized in appraisal trainings and the real estate valuation literature (Adomatis, 2010; Austin, 2012).

Finally, substantial non-energy benefits are thought to accrue from whole house retrofits, including benefits to the utility provider, society and participants. While these benefits are not accounted for in traditional cost-effectiveness tests, there is reason to think they are a primary driver of homeowner retrofit decision-making behavior. Mills & Rosenfeld (1996) provide a fairly comprehensive cataloguing of NEBs derived from efficiency activities in buildings, and they argue that the value of NEBs for end-users can equal or exceed avoided energy costs (Mills & Rosenfeld, 1996). Amann (2006) provides probably the most comprehensive, modern review of NEB valuation in residential retrofits, drawing on both Weatherization and Home Performance with Energy Star (HPwES) assessments (Amann, 2006). Amann's review of HPwES assessments suggests an average of $425 in annual participant benefits per household. A review of U.S. weatherization activities reported that the economic value of greenhouse gas and job creation benefits to society alone equaled or exceeded energy cost savings (Imbierowicz & Skumatz, 2004). Knight et al. (2006) presented NEB findings from a survey of California HPwES program participants, and they attributed only approximately one quarter of participant motivation to energy cost savings. Extrapolating from past research, Knight et al. estimated that NEBs had value possible exceeding 300% of the utility bill savings (Knight, Lutzenhiser, & Lutzenhiser, 2006). Finally, while not directly related to retrofits, evidence exists that those energy efficient homes with HERS ratings on average present a 32% lower risk of home loan default—a strong societal benefit in the wake of the 2008 housing crisis (Quercia, Sahadi, & Stellberg, 2013). Clearly, any assessment of DER projects based solely on energy and project costs will almost necessarily undervalue the retrofits undertaken.

While there is no current DER-specific research into NEBs or capitalization of retrofit costs at time of resale, the arguments above suggests that in all likelihood the value of a DER—both to society and occupants—can greatly outstrip the traditional balance between project costs and energy savings. If DERs are to be expanded to the larger population, research and marketing efforts are required that will not only establish the energy performance, but also the varied NEBs of projects.

5 Policy Implications for Deep Home Retrofits

It is clear from this review and analysis of the U.S. domestic DER literature that cost-justified retrofits are feasible in existing homes, with the energy use and carbon emissions reductions necessary to reduce our homes' contribution to global climate change (Neme et al., 2011). Unfortunately, it has historically been very difficult to drive market demand for comprehensive home energy improvements when customers have been asked to pay the majority of improvement costs (Fuller et al., 2010). Based on a review of 14 existing U.S. home efficiency programs, Fuller et al. characterize retrofits as a "tough sell", and they suggest that providing information and financing have been insufficient to incentivize widespread retrofitting. Rather, they suggest marketing the NEBs of retrofits, namely comfort, practical investment, self-reliance, health, community and social norms. Yet, even such marketing assumes a basic level of awareness, which a recent survey of California households suggests may not be trivial. A 2011-2012 general household population study in California revealed that less than 25% of respondents were even aware of the statewide whole house retrofit program—Energy Upgrade California—and its generous incentives, even in those market segments most positively disposed towards awareness and concern for energy efficiency and usage (Peters, Spahic, Dunn, & Randazzo, 2012).

The issue then becomes, how can and/or should governments, utilities, etc. encourage the broader implementation of deep retrofits? The California Energy Commission's Draft Action Plan for comprehensively addressing energy efficiency in existing buildings presents a multi-pronged, holistic approach to answering this question; it includes actions related to: (1) workforce development, (2) public marketing, education, and outreach, (3) code compliance and enforcement, (4) innovative financing mechanisms, (5) energy efficiency in property valuation, and (6) use of mandatory measures and performance disclosure (California Energy Commission, 2013). Below, we offer some additional insight and review of phased retrofit approaches, reducing project costs, and specific program design considerations.

5.1 Phased Approaches

Staged or "over time" deep retrofits may provide an accessible means for aggressive energy upgrades to be deployed across a market which has been historically reluctant to adopt whole house energy upgrades without massive direct subsidy (Fuller et al., 2010). Staged retrofits have been argued to be potentially less disruptive, less costly, and more oriented towards integration with standard repair, maintenance and renovation activities. Consistent with this, the state of California's Draft Action Plan for Comprehensive Energy Efficiency in Existing Buildings has called for multiple, flexible pathways for increasing energy efficiency in residences, including encouragement of both whole-home and incremental upgrades at key decision points (e.g., equipment replacement, maintenance, and home sale), as well as flexible program participation options ranging from single- and multi-measure installs to deep upgrades and self-generation projects (California Energy Commission, 2013).

The theoretical feasibility, appropriateness, and potential for phased deep retrofits has been explored by authors in both the U.K. and the U.S. (Fawcett, 2013; Wigington, 2010). Fawcett (2013) highlights the benefits of a phased approach—spreading costs out over time, alignment with normal upgrades, and introducing occupants to retrofit benefits—as well as the deficits—increasing the number of disruptions, lack of a knowledgeable integrator[6], and lower expected energy savings. Fawcett also provides some overall validation for the approach, citing 18 phased projects from the U.K. SuperHomes database with 60% carbon savings. She concludes there is a need for operational metrics for over time upgrades that allow projects to track advancement towards DER goals, as well as a need for additional industry training and development of specific over time retrofit plans. Wigington (2010) explored the phased approach in U.S. markets, as well as treated specific building technologies and strategies in greater detail. Her paper focused on the need to create, rather than block future options and opportunities for energy reductions (e.g., air sealing *before* insulating in attics), as well as striving to minimize negative unintended consequences (e.g., combustion safety issue created by air sealing), noting that the ability to fully deal with existing hazards will be limited in a phased approach. The author argued for the importance of transitionally appropriate technologies, namely those with multiple co-benefits and an ability to perform well at both full- and part-load (e.g., ductless heat pumps or combisystems), in order to align with progressive building improvements. Avoidance of sub-optimal investment and reworking was also stressed. The need for development of phased packages was also stressed by Wigington, with a focus on leveraging co-benefits such as increased flood, fire or earthquake resistance, as appropriate. She argued that approval-stamped packages (i.e., expert-designed retrofit packages with

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[6] Such an "integrator" would act over time as the centralized source for retrofit planning and implementation, as individual repairs and retrofit activities arise. This actor would replace the general contractor or energy rater that serves as integrator across building trades when retrofits are carried out at a single point in time.

validated performance and costs) could increase consumer confidence and be linked to financing and reduced risk.

The EuroPHit program is aimed at developing the methods, tools and case studies necessary for the deployment of phased retrofits across Europe, using the EnerPHit standard as a performance goal. This is seen as a key aspect of bringing existing buildings in the EU to net-zero energy by 2020, as stipulated by the Energy Performance of Buildings Directive. Key outcomes of the project are to include the following innovations tailored to the phased retrofit approach: (1) criteria and certification schemes, (2) financing models and market incentives, (3) design concepts and guidelines, (4) simulation tools, and (5) training materials (Werdenich, 2013). Programs that recognize the need to have flexible pathways to deep energy reductions as an essential element to reaching meaningful scale can serve as a model for deployment in the U.S.

The following are some examples of phased retrofit programs and successful case studies that can act as examples and guides moving forward. The Massachusetts and Rhode Island National Grid electric and gas utility has experimented with a phased approach to incentivizing deep retrofits by providing $2.00 to $3.50 per square foot of subsidies for treatment of roof/attic assemblies (R-60), exterior walls (R-40), and basements (R-20 and 10 for walls and floor, respectively), in order to align with home maintenance upgrades, as well as an airtightness incentive; incentives can be pursued either individually or as a bundle ("2013 Deep Energy Retrofit Measure Guidelines," 2013). The effectiveness of this approach has not been reported. As noted above, a number of successful phased deep retrofits have been identified in U.K. project databases, but no information was provided that would validate claims of phased benefits, such as lower costs or less disruption. Finally, one of 11 California DER projects reported on by Less, Fisher, & Walker (2012) was a three-phase retrofit implemented over approximately ten years, and it ultimately achieved net-site and net-source energy reductions of 74% and 96%, respectively (Less et al., 2012). While this was a highly successful project, the homeowner did report wishing that a comprehensive plan had been developed to guide the process, yet the iterative nature of the project also allowed the occupants to learn and implement new strategies in response to their experiences in the various phases. Fawcett (2013) suggested that such iterative feedback loops might encourage occupants to become more ambitious over time.

Parker and Sherwin (2012) provide unquestionably the most highly detailed and instrumented report of any phased retrofit we have identified (Parker & Sherwin, 2012). The author's Florida home was retrofitted over a 23-year period, with several retrofit phases, and extensive energy and performance measurement. The retrofits were implemented based on convenience, available funds, and the breakdown of conventional equipment, and they were not done in any optimal order or based on economic criteria. Nevertheless, the project now operates as a zero net-electricity home, with an estimated $4,000 in annual energy cost savings, when the PV production for the home and electric car[7] are combined. The phased retrofit experienced additions to the family (2 children), a 660 ft^2 addition, and a variety of other changes, including the addition of energy-using devices, such as adding a freezer, a 2nd refrigerator, flat-screen TV with DVR, and an electric car. This phased retrofit demonstrates how a home, family, and energy saving measures can grow and develop over time in a dynamic and ultimately successful process.

The purported benefits and effectiveness of phased retrofits still require validation, as do the potential downsides. Are projects able to successfully avoid re-work or sub-optimal investment, as urged by Wigington (2010)? Are deep savings still achieved, and if so, over what timeframe? Furthermore, does an extended timeframe that can span decades delay reductions in carbon emissions past some climatological tipping point? Does the lack of currently operational metrics and defining criteria mean that projects are not able to sufficiently track their progress towards a goal of deep reductions?

5.2 Lowering Retrofit Costs

The cost of a DER, whether it is $100,000 or only $40,000, is a very substantial barrier to widespread adoption. Lowering deep retrofit design and construction costs is clearly desirable, even in the context of the economic factors (i.e., NEBs, increased home value) explored in Section 4. Providing direct incentives is one way to lower project costs, but most programs will have a difficult time justifying the expenses without adjusting cost-effectiveness tests and criteria from those that are currently used. We predict that cost reductions will need to occur incrementally across the whole retrofit delivery process, without reliance on measures that disrupt a current construction paradigm, and as a result dramatically impact prices for labor and materials (i.e., disruptive technology).

By their nature, renovations are expensive propositions, and whole house energy retrofits are multifaceted and labor intensive. This makes the likelihood of a dramatic drop in price seem unlikely. The need to address most if not all building systems in an aggressive whole-house retrofit to some extent precludes dramatic lowering of costs resulting from a single technological or process breakthrough. Single-system innovations could drop costs, such as dramatically lower-cost solar PV systems, but such all-PV retrofits would lack the numerous co-benefits typically valued by homeowners. Other innovations are possible, such as whole-house envelope sealing methods that adopt technologies currently used in other applications (e.g., aerosol duct sealing, whose current feasibility in existing, occupied homes is questionable).

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[7] We are unaware of any other DERs included in this review study that added an electric car. The only exception is one project highlighted in Less, Fisher, & Walker (2012), but the electric car was sub-metered and not included in the analysis.

Incremental cost reductions across the entire retrofit construction process—design, retrofit measures, and workforce—may be more feasible, and in combination, could substantially reduce costs. Construction processes and equipment could become less costly on an item-by-item basis, such as low-cost, self-commissioning ductless heat pumps or easily retrofitable exterior insulation with integrated cladding. While construction options seem limited, it may be possible to dramatically cut design and engineering costs through the use of standardized retrofit packages, which would only need slight adjustment, rather than ground-up, consultant-intensive development for each home. No clear reports have been provided in the literature on the magnitude, relative or absolute, of design costs. In fact, most R&D projects have provided such services free of charge. Similarly, standardized DER contract language could enable retrofits, mostly by reducing risk associated with performance guarantees. Finally, a better trained workforce, more accustomed to delivering high performance retrofits, would no doubt be able to provide them at somewhat lower cost, and possibly with better performance, but cost reductions cannot be expected to be substantial. Labor costs, job safety and security are low and lacking effective regulation in the residential remodeling industry (Zabin et al., 2011), and as a result, large cuts in labor costs seem unlikely. This is particularly the case when higher performance and verification standards are put in place, necessitating a better trained and tested workforce. A number of DER research reports have suggested that contractor quality was poor and represented a substantial barrier to success (Boudreaux et al., 2012; Chandra et al., 2012; McIlvaine et al., 2010). Developing and streamlining project delivery methods appropriate to DERs could also reduce project costs and improve contractor profitability, all while improving performance (Janet McIlvaine et al., 2013).

This whole-retrofit process, incremental-cost reduction vision could make DERs feasible across a wider audience, but it will require an investment in R&D, workforce training, and careful determination of where the costs lie in owner-conducted DERs that are not supported by research projects.

5.3 Recommendations for Program Design and Requirements

As DERs are rolled out across the U.S., numerous organizations will be involved in their development, including the U.S. DOE, U.S. EPA, Housing and Urban Development (HUD), the Weatherization Assistance Program (WAP), utility companies, nonprofits, and state energy code bodies. How might they change and form their policies based on the results of this meta-performance analysis?

- Formally adopt the definition of a deep retrofit to be 50% or greater savings. This level is achievable across a variety of project types, locations and costs, and this would facilitate some level of consistency amongst programs.
- Adopt formal retrofit data reporting standards, so that information about DERs can be made more accessible and to facilitate development of a larger, more usable dataset in the future. The Building Performance Institute's Standards for Home Performance-Related Data Collection and Transfer (BPI-

2200 and BPI-2100, respectively) are suitable. Their HPXML protocols have already been adopted by programs in four states and are being considered in three others. The U.S. DOE-supported Building America Field Data Repository uses HPXML to compile building and performance information, and it represent one example of a potentially powerful, future source of information (Neymark & Roberts, 2013).

- Consider use of source energy or carbon performance metrics, so that fuel switching and increased miscellaneous electrical uses do not inadvertently sabotage societal goals of retrofit. We found that in homes with clear fuel switching from gas to electricity, average source energy and carbon reductions were 57% and 42% less than those reported for site energy.
- Consistent project cost reporting methods should be developed that will make published data intercomparable and transparent in meaning.
- Target DERs towards remodeling projects and existing equipment replacement and/or maintenance activities, where incremental costs are more easily justified. Total project costs are generally not justifiable based on energy cost savings over the measure life (Boudreaux et al., 2012; Herkel & Kagerer, 2011; McIlvaine et al., 2013).
- Consider the use of cost-effectiveness tests that incorporate non-energy occupant and societal benefits, both of which are likely to be large in aggressive whole-house retrofits.
- If simple economic justification is desired, consider basing allowable project costs on achievable savings. For example, in this work, we found that the average energy cost savings ($1,283), when financed, could justify a project cost of approximately $25,150, assuming unchanging interest rates, energy costs, inflation, etc.
- Ensure that projects are able to respond to future changes in energy prices and rate structures, carbon emission regulation, and demand response scenarios. For example, we recommend that DERs be "all-electric ready". This means installing the infrastructure (e.g., wiring, sockets, and high-amperage service) required for an all-electric home, which is relatively low-cost at the time of retrofit, but much higher cost later.
- Building codes need to require ASHRAE 62.2 or equivalent compliance in home renovations that include substantial efficiency improvements, namely airtightening. For example, the California Energy Code Title 24 (2008) requires 62.2 compliance in new homes and retrofits, but only if they add more than 1,000 ft^2 of floor area.
- While DERs were demonstrated to be less expensive than previously reported, a substantial portion of the population will never be able to afford an aggressive home retrofit. In light of this, the Weatherization Assistance Program should consider including two tiers—with an advanced option that allows more money to be spent for deeper savings. While weatherization crews might not be suitable for generating >50% savings, the model provided by McIlvaine et al. (2010) might be suitable, with a HERS target score of 70 and approximately 30% energy savings (McIlvaine et al., 2010).

6 Summary

The current state of DER performance in the U.S. has been assessed in 116 homes across climate zones, using performance data gathered from the available domestic literature. The value of the analysis for some metrics is hindered by data gaps and inconsistent reporting. So, future analyses are needed using a larger, more fully developed dataset, which could be facilitated by a centralized, standard database of high performance home projects, as envisioned in the U.S. DOE supported Building America Field Data Repository (Neymark & Roberts, 2013).

Projects generally achieved good results, with average annual net-site, net-source and carbon reductions of 47%±20%, 45%±24%, and 47%±22%, respectively (74.5±76.3 MMBtu, 103.8±103.0 MMBtu, and 9,152±5,309 pounds; n=57, n=35, and 23). While net-site energy savings averaged approximately 50%, it was possible to achieve higher savings. Approximately the top 16% of DERs achieved 70% or greater savings. For most of the cases where 70% was not met, the targeted reduction was also below 70%, so this is indicative of varying project goals, not necessarily project failure. While average performance was consistent across the reporting metrics, those homes (n=7) that increased electricity use achieved source energy and carbon reductions that were 57% and 42% lower than their net-site energy reductions. Reliance solely on site energy performance is insufficient for some policy goals, because of the potential impacts of fuel switching and of regional variation in the environmental (CO_2e) impacts of electrical generation. No significant difference was observed between reported actual energy savings and simulated energy savings, suggesting that simulation methods, such as HERS or Building America simulation protocols (Engebrecht & Hendron, 2010), may be appropriate for predicting average DER performance for a single home within approximately ±12%. Net-energy reductions did not vary reliably with house age, airtightness or reported project costs, but pre-retrofit usage was correlated with total reductions (MMBtu).

Substantial airtightness reductions averaging 63%±25% were reported (n=48), yet mechanical ventilation was not installed consistently in airtight post-retrofit homes (4.7±2.9 ACH_{50}, n=94), with approximately 30% of homes not installing mechanical venting (<50% when excluding Cold climate projects). All future DERs should comply with ASHRAE 62.2-2013 requirements, given their potential to worsen IAQ.

Annual energy costs went from a pre-retrofit average of $2,738±$1,065 to $1,588±$561 post-retrofit (n=25 and n=39), with average annual energy cost savings of $1,283±$804 (n=31). The average reported incremental project cost was $40,420±$30,358 (n=59), which when financed using a 30-year mortgage at 4.46% interest, increased average net-homeownership costs $15.67±$87.74 per month (median of $1 per month) (n=28)—48% of projects realized net-savings. The average cost per MMBtu net-site savings was $603, but this was approximately 45% lower in non-Cold climate projects. Yet, the economic value of a DER may be much greater than is suggested by these net-costs, because DERs entail substantial NEBs, and retrofit measures may have capitalization rates similar to those in general remodeling.

To increase retrofit energy and cost reductions will require broader scopes of work, which will only become common when the risks and benefits of DERs are better characterized for all actors involved—homeowners, contractors, lenders, buyers, etc. Risk can be reduced through standardized retrofit packages and contract language, which can both reduce design costs and ensure that an effective, validated systems approach is employed. Risk can also be reduced through a better-trained workforce capable of delivering the quality of workmanship required in aggressive retrofits. The varied benefits of DERs also need better characterization, particularly since demand has proven to be a greater barrier to home energy retrofits than cost (Borgeson, Zimring, & Goldman, 2012). Nearly all DER research has focused on building improvements, energy, and economic performance, with only cursory efforts made to document thermal comfort improvements, changes in IAQ or health, convenience, and durability. Yet, these factors likely play a role that is at least as important in homeowner decision-making and market demand as those of energy and environmental performance. We also need to develop a transparent, consistent format and method for reporting project costs, which would support a better understanding of DER costs, including consultants and designers. This will inform our estimates of what cost reductions are feasible in DERs at-scale, and also may contribute to efficiency valuation efforts. Finally, we need to establish the outcomes of DER investments at time of resale, as well as the loan performance of financed retrofit projects.

7 References

2013 Deep Energy Retrofit Measure Guidelines. (2013). National Grid. Retrieved from https://www1.nationalgridus.com/Files/AddedPDF/POA/2013%20Deep%20Energy%20Retrofit%20Measure%20Guidelines%2020130212.pdf

Adomatis, S. K. (2010). Valuing High Performance Houses. *The Appraisal Journal*, *Spring*, 195–201.

Affordable Comfort, Inc. (2010). Transforming America's Housing Stock | Thousand Home Challenge. Retrieved January 22, 2013, from http://thousandhomechallenge.com/

Aldrich, R., & Arena, L. (2013). *Evaluating Ventilation Systems for Existing Homes*. Norwalk, Connecticut: Consortium for Advanced Residential Buildings. Retrieved from http://dx.doi.org/10.2172/1064546

Amann, J. T. (2006). *Valuation of Non-Energy Benefits to Determine Cost-Effectiveness of Whole House Retrofit Programs: A Literature Review* (No. A061). American Council for an Energy-Efficient Economy. Retrieved from psb.vermont.gov/sites/psb/files/projects/EEU/screening/Amann_ValuationOfNon-energy.pdf

ASID & USGBC. (n.d.). Case Studies | REGREEN Residential Remodeling. Retrieved June 28, 2013, from http://www.regreenprogram.org/case-studies

Austin, G. W. (2012). Sustainability and Income-Producing Property Valuation: North American Status and Recommended Procedures. *Journal of Sustainable Real Estate*, *4*(1), 78–122.

Baechler, M. C., Williamson, J., Gilbride, T., Cole, P., Hefty, M., & Love, P. M. (2010). *Guide to Determining Climate Regions by County* (No. PNNL-17211). Richland, WA: Pacific Northwest National Laboratory. Retrieved from http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/ba_climateguide_7_1.pdf

Balvers, J., Bogers, R., Jongeneel, R., van Kamp, I., Boerstra, A., & van Dijken, F. (2012). Mechanical Ventilation in Recently Bulit Dutch Homes: Technical Shortcomings, Possibilities for Improvement, Perceived Indoor Environment and Health Effects. *Architectural Science Review*, *55*(1), 4–14. doi:10.1080/00038628.2011.641736

Becchio, C., Corgnati, S. P., Ballarini, I., & Corrado, V. (2012). Energy Savings Potential by Retrofitting Residential Buildings in Europe - Full Version. *REHVA Journal*, 34–38.

Berges, M., & Metcalf, M. (2013). Lessons Learned on Energy-Efficient Affordable Housing: Practical insights on combining deep energy retrofits with affordable housing for 12 Cleveland homes. *Journal of Light Construction*, (February), 55–63.

Bianchi, M. V. A. (2011). *Challenges and Opportunities to Achieve 50% Energy Savings in Homes: National Laboratory White Papers*. Golden, CO: National Renewable Energy Laboratory. Retrieved from http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/ba_tech_roadmap.pdf

Bloom, B., Nobe, M. C., & Nobe, M. D. (2011). Valuing Green Home Design: A Study of Energy Star Homes. *Journal of Sustainable Real Estate*, *3*(1), 109–126.

Borgeson, M., Zimring, M., & Goldman, C. (2012). The Limits of Financing for Energy Efficiency. In *Summer Study for Energy Efficiency in Buildings-Fueling Our Future With Efficiency*. Pacific Grove, CA: American Council for an Energy-Efficient Economy. Retrieved from http://eetd.lbl.gov/sites/all/files/publications/lbnl-limits-of-financing-aceee-ss2012-final2.pdf

Boudreaux, P., Hendrick, T., Christian, J., & Jackson, R. (2012). *Deep Residential Retrofits in East Tennessee* (No. ORNL/TM-2012/109). Oak Ridge, TN: Oak Ridge National Laboratory. Retrieved from http://info.ornl.gov/sites/publications/files/Pub35498.pdf

Brohard, G., Brown, M., Cavanagh, R., Elberling, L., Hernandez, G., Lovins, A., & Rosenfeld, A. (1996). *Advanced Customer Technology Test for Maximum Energy Efficiency (ACT2) Project: The Final Report*. Pacific Gas and Electric Company. Department of Research and Development.

Building Performance Institute. (2012). BPI to Reference ASHRAE Standard 62.2-2010. Retrieved March 29, 2013, from http://www.bpi.org/news_expansion.aspx?selectedID=964

California Energy Commission. (2013). *Draft Action Plan for the Comprehensive Energy Efficiency Program for Existing Buildings* (No. CEC-400-2013-006-D). Sacramento, CA. Retrieved from http://www.energy.ca.gov/2013publications/CEC-400-2013-006/CEC-400-2013-006-D.pdf

Chan, W. R., Joh, J., & Sherman, M. (2012). *Analysis of Air Leakage Measurements from Residential Diagnostics Database* (No. LBNL-5967E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://homes.lbl.gov/sites/all/files/lbnl-5967e.pdf

Chandra, S., Widder, S., Parker, G., Sande, S., Blanchard, J., Stroer, D., … Sutherland, K. (2012). *Pilot Residential Deep Energy Retrofits and the PNNL Lab Homes* (No. PNNL-21116). Richland, WA: Pacific Northwest National Laboratory. Retrieved from http://www.pnl.gov/main/publications/external/technical_reports/PNNL-21116.pdf

Chitwood, R., & Harriman, L. G. (2012). Measured Home Performance: Best Practices for Home Energy Retrofits. *ASHRAE Journal*, (January), 16–26.

CPUC. (2008). California Long Term Energy Efficiency Strategic Plan: Achieving Maximum Energy Savings in California for 2009 and Beyond. California Public Utilities Commission. Retrieved from http://www.cpuc.ca.gov/NR/rdonlyres/D4321448-208C-48F9-9F62-1BBB14A8D717/0/EEStrategicPlan.pdf

Dastrup, S. R., Zivin, J. G., Costa, D. L., & Kahn, M. E. (2012). Understanding the Solar Home price premium: Electricity generation and “Green” social status.

European Economic Review, *56*(5), 961–773. doi:http://dx.doi.org/10.1016/j.euroecorev.2012.02.006

Emmerich, S. J., Howard-Reed, C., & Gupte, A. (2005). *Modeling the IAQ Impact of HHI Interventions in Inner-city Housing* (No. NISTIR 7212). Gaithersburg, MD: National Institute of Standards and Technology. Retrieved from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&ved=0CDcQFjAA&url=http%3A%2F%2Ffire.nist.gov%2Fbfrlpubs%2Fbuild05%2FPDF%2Fb05054.pdf&ei=9itCUdfCGceSyQH4-4GoAw&usg=AFQjCNF46Z_hBEN2IMZ7Do02YSZY2a5y5g&bvm=bv.43287494,d.aWc

Engebrecht, C., & Hendron, B. (2010). *Building America Simulation Protocols* (No. DOE/GO-102010-3141). U.S. Department of Energy. Retrieved from http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&ved=0CDYQFjAA&url=http%3A%2F%2Fwww.nrel.gov%2Fdocs%2Ffy11osti%2F49246.pdf&ei=Sg3_UIXBKMvliwLfzoCAAg&usg=AFQjCNFmX2z9pAOxdKzU68jvn3UV2Yn-9Q&bvm=bv.41248874,d.cGE

European Commission. (2011). *A Roadmap for Moving to a Competitive Low Carbon Economy in 2050* (Communication from the Commission to the European Parliament, the Council, the European Economic). Brussels, Belgium. Retrieved from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0112:FIN:EN:PDF

Fairey, P., & Parker, D. (2012). *Cost Effectiveness of Home Energy Retrofits in Pre-Code Vintage Homes in the United States* (No. NREL Contract No. DE-AC36-08GO28308). Golden, CO: National Renewable Energy Laboratory. Retrieved from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&ved=0CDUQFjAA&url=http%3A%2F%2Fwww.fsec.ucf.edu%2Fen%2Fpublications%2Fpdf%2FFSEC-CR-1939-12.pdf&ei=asoKUZ-qL8KKjALbxoD4Ag&usg=AFQjCNHCdUoNEm2sXTIs9JCe2hu5nKHLQA&sig2=un8xwZcmrUSsz6pHqcoGcA&bvm=bv.41642243,d.cGE

Fawcett, T. (2013). Exploring the time dimension of low carbon retrofit: owner-occupied housing. *Building Research & Information*. doi:10.1080/09613218.2013.804769

Freddie Mac. (n.d.). Primary Mortgage Market Survey Archives - 30 Year Fixed Rate Mortgages - Freddie Mac. Retrieved August 15, 2013, from http://www.freddiemac.com/pmms/pmms30.htm

Fuller, M. C., Kunkel, C., Zimring, M., Hoffman, I., Soroye, K. L., & Goldman, C. (2010). *Driving Demand for Home Energy Improvements - Motivating Residential Customers to Invest in Comprehensive Upgrades that Eliminate Energy Waste, Avoid High Bills, and Spur the Economy* (No. LBNL-3960E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://emp.lbl.gov/sites/all/files/REPORT%20low%20res%20bnl-3960e.pdf

Fulton, M., Baker, J., Brandenburg, M., Herbst, R., Cleveland, J., Rogers, J., & Onyeagoro, C. (2012). *United States Building Energy Efficiency Retrofits-Market Sizing and Financing Models*. The Rockefeller Foundation & Deutsche

Bank Group. Retrieved from http://www.stateinnovation.org/Uploaded-Documents/ee-retrofits.aspx

Gates, C., & Neuhauser, K. (2014). *Perforance Results for Massachusetts & Rhode Island DER Pilot Community* (No. Building America Research Report - 1401). Somerville, MA: Building Science Corporation. Retrieved from http://www.buildingscience.com/documents/bareports/ba-1401-performance-results-massachusetts-rhode-island-der-pilot-community

Granade, H. C., Creyts, J., Derkach, A., Farese, P., Nyquist, S., & Ostrowski, K. (2009). *Unlocking Energy Efficiency in the U.S. Economy*. McKinsey & Company. Retrieved from http://www.mckinsey.com/client_service/electric_power_and_natural_gas/latest_thinking/~/media/204463A4D27A419BA8D05A6C280A97DC.ashx

Greenhouse Gas Emission Factors: Guidance for PG&E Customers. (2013, April). Pacific Gas and Electric. Retrieved from http://www.pge.com/includes/docs/pdfs/shared/environment/calculator/pge_ghg_emission_factor_info_sheet.pdf

Henderson, S., & Mattock, C. (2007). *Approaching Net-Zero Energy in Existing Housing*. Canada Mortgage and Housing Corporation.

Hendron, R., Anderson, R., Judkoff, R., Christensen, C., Eastment, M., Norton, P., … Hancock, E. (2004). *Building America Performance Analysis Procedures* (No. NREL/TP-550-35567). National Renewable Energy Laboratory. Retrieved from http://www.nrel.gov/docs/fy04osti/35567.pdf

Herkel, S., & Kagerer, F. (2011). Energy Performance and Cross-Analysis of Demonstration Buildings. In *Advances in Housing Retrofit: Processes, Concepts and Technologies, IEA SHC Task 37* (pp. 8–1 to 8–6). Freiburg, Germany: Fraunhofer Institute. Retrieved from http://archive.iea-shc.org/publications/downloads/Advances_in_Housing_Retrofit.pdf

Hill, D. (1998). *Field Survey of Heat Recovery Ventilation Systems* (Technical Series No. 96-215). Ottawa, Ontario: Canada Mortgage and Housing Corporation: Research Division. Retrieved from http://publications.gc.ca/collections/collection_2011/schl-cmhc/nh18-1/NH18-1-90-1998-eng.pdf

Holladay, M. (2012). The High Cost of Deep-Energy Retrofits | GreenBuildingAdvisor.com. Retrieved August 21, 2013, from http://www.greenbuildingadvisor.com/blogs/dept/musings/high-cost-deep-energy-retrofits

ICC. (2012). International Energy Conservation Code. International Code Council.

Imbierowicz, K., & Skumatz, L. A. (2004). The Most Volatile Non-Energy Benefits (NEBs): New Research Results “Homing In” on Environmental and Economic Impacts (pp. 8–156 to 8–167). Presented at the Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA: American Council for an Energy-Efficient Economy. Retrieved from http://www.eceee.org/library/conference_proceedings/ACEEE_buildings/2004/Panel_8/p8_14/paper

Intergovernmental Panel on Climate Change. (2007). *Climate Change 2007: Synthesis Report*. Geneva, Switzerland. Retrieved from http://www.ipcc.ch/publications_and_data/ar4/syr/en/spms5.html

Janet McIlvaine, Saunders, S., Bordelon, E., Baden, S., Elam, L., & Martin, E. (2013). *The Next Step Toward Widespread Residential Deep Energy Retrofits*. Golden, CO: National Renewable Energy Laboratory. Retrieved from http://www.nrel.gov/docs/fy13osti/57978.pdf

JCHS. (2011). A New Decade of Growth for Remodeling: Improving America's Housing, 2011, Appendix Tables. Joint Center for Housing Studies of Harvard University. Retrieved from http://www.jchs.harvard.edu/sites/jchs.harvard.edu/files/2011_remodeling_color.pdf

Keesee, M. (2012). Deep Energy Retrofits: Six Real World Examples and Lessons Learned. In *2012 ACEEE Summer Study for Energy Efficiency in Buildings-Fueling Our Future with Efficiency* (Vol. 1, pp. 141–152). Pacific Grove, CA: American Council for an Energy-Efficient Economy. Retrieved from http://www.aceee.org/files/proceedings/2012/data/papers/0193-000006.pdf

Knight, R. L., Lutzenhiser, L., & Lutzenhiser, S. (2006). Why Comprehensive Residential Energy Efficiency Retrofits Are Undervalued (pp. 7–141 to 7–150). Presented at the ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA: ACEEE. Retrieved from http://www.aceee.org/sites/default/files/publications/proceedings/SS06_Panel7_Paper12.pdf

Kok, N., & Kahn, M. E. (2012). The Value of Green Labels in the California Housing Market: An Economic Analysis of the Impact of Green Labeling on the Sales Price of a Home. Retrieved from http://www.builditgreen.org/_files/Marketing/ValueofGreenHomeLabelsStudy_July2012.pdf

Laquatra, J., Dacquisto, D. J., Emrath, P., & Laitner, J. A. (2002). Housing Market Capitalization of Energy Efficiency Revisited. In *Teaming for Efficiency*. Pacific Grove, CA: American Council for an Energy-Efficient Economy. Retrieved from http://aceee.org/files/proceedings/2002/data/papers/SS02_Panel8_Paper12.pdf

LBNL. (2012). Ventilate Right | Ventilation Guide for New and Existing California Homes. Retrieved September 19, 2013, from http://resaveguide.lbl.gov/

Less, B. (2012). *Indoor Air Quality in 24 California Residences Designed as High Performance Green Homes*. University of California, Berkeley, Berkeley, CA. Retrieved from http://escholarship.org/uc/item/25x5j8w6

Less, B., Fisher, J., & Walker, I. (2012). *Deep Energy Retrofits-11 California Case Studies* (No. LBNL-6166E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/publications/deep-energy-retrofits-eleven-california-case-studies

Marshall, B., & Argue, R. (1981). *The super-insulated retrofit book: a homeowner's guide to energy-efficient renovation*. Renewable Energy in Canada.

McIlvaine, J., Sutherland, K., & Martin, E. (2013). *Energy Retrofit Field Study and Best Practices in a Hot-Humid Climate*. Cocoa, FL: BA-PIRC/Florida Solar Energy Center. Retrieved from http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/energy_retrofit_study_hothumid.pdf

McIlvaine, J., Sutherland, K., Schleith, K., & Chandra, S. (2010). *Exploring Cost-Effective High Performance Residential Retrofits for Affordable Housing in Hot Humid Climate* (No. FSEC-PF-448-10). Cocoa, FL: Florida Solar Energy Center. Retrieved from http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CDYQFjAA&url=http%3A%2F%2Fwww.fsec.ucf.edu%2Fen%2Fpublications%2Fpdf%2FFSEC-PF-448-10.pdf&ei=YLomUY7YKs_figKNu4CwAQ&usg=AFQjCNHqQHNf2tFci4C6j-Gjpg1vv6RZLg&bvm=bv.42768644,d.cGE&cad=rja

Mills, E., & Rosenfeld, A. (1996). Consumer non-energy benefits as a motivation for making energy-efficiency improvements. *Energy*, *21*(7-8), 707–720.

National Grid. (n.d.). Super Insulation Upgrades. Retrieved July 3, 2013, from https://www1.nationalgridus.com/DeepEnergyRetrofit-MA-RES

Neme, C., Gottstein, M., & Hamilton, B. (2011). *Residential Efficiency Retrofits: A Roadmap for the Future*. The Regulatory Assistance Project. Retrieved from http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CDcQFjAA&url=http%3A%2F%2Fwww.raponline.org%2Fdocs%2FRAP_Neme_ResidentialEfficiencyRetrofits_2011_05.pdf&ei=NzdnUa_-H4rBigK62ICwBg&usg=AFQjCNGurh4Kdo_ym75PBQ1hftbrVX0Qgw&sig2=AVmIZXtACVWx7rPugiNKJA&bvm=bv.45175338,d.cGE&cad=rja

Neuhauser, K. (2012). *National Grid Deep Energy Retrofit Pilot* (No. KNDJ-0-40337-00). Golden, CO: NREL. Retrieved from http://www.nrel.gov/docs/fy12osti/53684.pdf

Neymark, J., & Roberts, D. (2013). *Deep in Data: Empirical Data Based Software Accuracy Testing Using the Building America Field Data Repository* (Conference Paper No. NREL/CP-5500-58893). Golden, CO. Retrieved from http://www.nrel.gov/docs/fy13osti/58893.pdf

NYSERDA. (n.d.). Advanced Residential Buildings - NYSERDA. Retrieved July 3, 2013, from http://www.nyserda.ny.gov/BusinessAreas/Energy-Innovation-and-Business-Development/Research-and-Development/Buildings-Research/Advanced-Residential-Buildings.aspx

Offermann, F. (2009). *Ventilation and Indoor Air Quality in New Homes* (No. CEC-500-2009-085). California Energy Commission. Retrieved from http://www.energy.ca.gov/2009publications/CEC-500-2009-085/CEC-500-2009-085.PDF

Parker, D., & Sherwin, J. (2012). *Achieving Very High Efficiency and Net Zero Energy in an Existing Home in a Hot-Humid Climate: Long-Term Utility and Monitoring Data*. Cocoa, FL: BA-PIRC/Florida Solar Energy Center. Retrieved from http://www.fsec.ucf.edu/en/publications/pdf/FSEC-RR-383-12.pdf

Passive House Institute. (2012). EnerPHit and EnerPHit+i - Certification Criteria for Energy Retrofits with Passive House Components. Passive House Institute.

Retrieved from http://www.passiv.de/downloads/03_certification_criteria_enerphit_en.pdf

Peters, J. S., Spahic, M., Dunn, A., & Randazzo, K. (2012). *2011-2012 General Households Population Study in California* (No. SCE0321). Research Into Action. Retrieved from http://energycenter.org/sites/default/files/docs/nav/programs/swmeo/GPS_Report_08302012_FINAL.pdf

Polly, B., Gestwick, M., Bianchi, M. V. A., Anderson, R., Horowitz, S., Christensen, C., & Judkoff, R. (2011). *A Method for Determining Optimal Residential Energy Efficiency Retrofit Packages*. Golden, CO: National Renewable Energy Laboratory. Retrieved from http://www.nrel.gov/docs/fy11osti/50572.pdf

Quercia, R., Sahadi, R., & Stellberg, S. (2013). *Home Energy Efficiency and Mortgage Risks*. Chapel Hill, NC: UNC Center for Community Capital and Institute for Market Transformation. Retrieved from http://ccc.unc.edu/documents/HomeEEReport.pdf

Remodeling Magazine. (2013). Remodeling 2012–13 Cost vs. Value Report. Retrieved September 20, 2013, from http://www.remodeling.hw.net/2013/costvsvalue/national.aspx

RESNET. (2006). 2006 Mortgage Industry National Home Energy Rating Systems Standards. Residential Energy Services Network. Retrieved from http://www.resnet.us/professional/standards/mortgage

RS Means, Contractor's Pricing Guide, Residential Repair and Remodeling Costs. (2012) (2012th ed.). Norwell, MA: Reed Construction Data.

Sarkar, M. (2011). *How American Homes Vary by the Year They Were Built* (Working Paper No. No. 2011-18). Washington, D.C.: U.S. Census Bureau. Retrieved from http://www.census.gov/hhes/www/housing/housing_patterns/pdf/Housing%20by%20Year%20Built.pdf

Schwarzenegger, A. (2005, June 1). Executive Order S-3-05. State of California. Retrieved from http://gov.ca.gov/news.php?id=1861

Sewalk, S., & Throupe, R. (2013). The Feasibility of Reducing Greenhouse Gas Emissions in Residential Buildings. *Journal of Sustainable Real Estate*, *5*(1). Retrieved from http://www.josre.org/wp-content/uploads/2013/09/Sewalk-and-Throupe-Final.pdf

Stratton, C., Walker, I., & Wray, C. P. (2012). *Measuring Residential Ventilation System Airflows: Part 2 - Field Evaluation of Airflow Meter Devices and System Flow Verification* (No. LBNL-5982E). Berkeley, CA: Lawrence Berkeley National Lab. Retrieved from http://homes.lbl.gov/sites/all/files/lbnl-5982e.pdf

SuperHomes. (2013). SuperHomes - Openining Doors to Low Energy Refurbishment. Retrieved October 18, 2013, from http://www.superhomes.org.uk/

The Technology Strategy Board. (2013). *Retrofit Revealed: The Retrofit for the Future projects - data analysis report* (p. 30). Swindon, UK. Retrieved from http://www.retrofitanalysis.org/retrofit-revealed-by-technology-strategy-board.pdf

U. S. DOE. (2011). *ASHRAE 62.2 for WAP*. Presented at the Weatherization Assistance Program Standardized Curriculum. Retrieved from http://www.builditgreenutility.org/sites/default/files/ASHRAE%2062.2ForWeatherizationAssistanceProgram%28WAP%29.pdf

U.S. Energy Information Administration. (2009). Residential Energy Consumption Survey (RECS) - Data - U.S. Energy Information Administration (EIA). Retrieved August 13, 2013, from http://www.eia.gov/consumption/residential/data/2009/

U.S. EPA. (2012). *eGrid2012 Version 1.0 Year 2009 Summary Tables* (Vol. 2012).

Walker, I., & Less, B. (2013). An Assessment of Envelope Measures in Mild Climate Deep Energy Retrofits. Presented at the Thermal Performance of the Exterior Envelopes of Whole Buildings XII International Conference, Clearwater Beach, FL: ASHRAE.

Weatherization Assistance Program - The American Recovery and Reinvestment Act of 2009 - wx_recovery_fact_sheet.pdf. (n.d.). Retrieved August 21, 2013, from http://www1.eere.energy.gov/wip/pdfs/wx_recovery_fact_sheet.pdf

Werdenich, A. (2013). *EuroPHit - Retrofitting for the Energy Revolution One Step at a Time*. Retrieved from http://europhit.eu/sites/europhit.eu/files/D6.4_EuroPHit_presentation_EN.pdf

Wigington, L. (2010). Staged Approaches for Deep Energy Reductions in Existing Homes. American Council for an Energy-Efficient Economy. Retrieved from eec.ucdavis.edu/ACEEE/2010/data/papers/2299.pdf

Williams, J. H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow, W. R. I., … Torn, M. S. (2012). The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. *Science*, *335*(6064), 53–59. doi:10.1126/science.1208365

Zabin, C., Chapple, K., Avis, E., Halpern-Finnerty, J., Lester, T. W., Montero, S., … Freely, J. (2011). California Workforce Education and Training Needs Assessment for Energy Efficiency, Distributed Generation, and Demand Response. Institute for Research on Labor and Employment. Retrieved from http://www.irle.berkeley.edu/vial/publications/WET_Part1.pdf

Appendix 1

State	2009 CO_2e Emission Factor for Delivered Electricity (lbs./kWh)	State	2009 CO_2e Emission Factor for Delivered Electricity (lbs./kWh)
Alaska	1.321	Montana	1.693
Alabama	1.224	North Carolina	1.361
Arkansas	1.309	North Dakota	2.421
Arizona	1.275	Nebraska	1.880
California	0.654	New Hampshire	0.710
Colorado	2.042	New Jersey	0.646
Connecticut	0.680	New Mexico	2.142
District of Columbia	2.919	Nevada	1.245
Delaware	2.110	New York	0.685
Florida	1.401	Ohio	2.096
Georgia	1.513	Oklahoma	1.757
Hawaii	1.797	Oregon	0.427
Iowa	1.912	Pennsylvania	1.342
Idaho	0.141	Rhode island	1.049
Illinois	1.256	South Carolina	0.970
Indiana	2.393	South Dakota	1.076
Kansas	1.969	Tennessee	1.261
Kentucky	2.408	Texas	1.461
Louisiana	1.326	Utah	2.182
Massachusetts	1.312	Virginia	1.171
Maryland	1.451	Vermont	0.006
Maine	0.597	Washington	0.337
Michigan	1.794	Wisconsin	1.782
Minnesota	1.646	West Virginia	2.366
Missouri	2.127	Wyoming	2.490
Mississippi	1.296	Average	1.459

Table 7 2009 Carbon Dioxide Equivalent Emissions Factors for Delivered Electricity, by State

Appendix 2

BA Climate Zone	Pre-Retrofit		Post-Retrofit	
	Floor Area ± SD (ft^2)	n	Floor Area ± SD (ft^2)	n
Cold	2213 ± 688	41	2331 ± 838	56
Hot-Dry	1504 ± 672	8	1452 ± 671	9
Hot-Humid	1305 ± 358	15	1312 ± 351	15
Marine	1851 ± 780	13	2165 ±654	13
Mixed-Humid	2966 ± 1342	5	2905 ± 1210	6
All	1967 ± 819	82	2110 ± 883	99

Table 8 Summaries and Pre- and Post-Retrofit DER Floor Area

BA Climate Zone	Pre-Retrofit (ACH50) (mean ± SD (n))	Post-Retrofit (ACH50) (mean ± SD (n))	Reduction (%) (mean ± SD (n))
Cold	17.0 ± 12.7 (22)	3.3 ± 2.2 (43)	71 ± 20 (28)
Hot-Dry	12.4 ± 7.4 (4)	5.0 ± 1.6 (9)	58 ± 30 (4)
Hot-Humid	20.5 ± 12.4 (7)	7.0 ± 3.1 (20)	54 ± 30 (7)
Marine	11.9 ± 7.4 (2)	5.1 ± 3.6 (15)	32 ± 10 (4)
Mixed-Humid	11.7 ± 6.2 (6)	5.2 ± 1.0 (7)	55 ± 20 (5)
All	16.1 ± 11.3 (41)	4.7 ± 2.9 (94)	63 ± 25 (48)

Table 9 Summary of DER Airtightness, Pre-, Post-ACH$_{50}$ and % Reduction

	Pre-Retrofit HERS Indices					
BA Climate Zone	Min	Median	Mean	Max	SD	N
Cold	125	137	156	216	24.7	4
Hot-Dry	174	194.5	207.5	259	34.3	6
Hot-Humid	97	132	135.3	189	27.6	23
Marine	87	166	140.3	168	46.2	3
Mixed-Humid	100	119	156.6	259	65.9	5
All	87	146.5	151	259	43.1	42
	Post-Retrofit HERS Indices					
Cold	34	67	59.2	112	21.8	19
Hot-Dry	28	78	67	107	28.5	9
Hot-Humid	57	79	79.1	93	9.4	23
Marine	25	68	62.5	148	35.4	11
Mixed-Humid	23	66	60	75	21.5	5
All	23	71	67.7	148	23.5	67
	Relative Reduction in HERS Index (%)					
Cold	28%	46%	47%	78%	19%	5
Hot-Dry	39%	61%	62%	85%	15%	6
Hot-Humid	12%	40%	39%	70%	13%	23
Marine	12%	16%	16%	21%	6%	2
Mixed-Humid	34%	67%	58%	81%	21%	5
All	12%	41%	45%	85%	18%	41

Table 10 Summary of HERS Indices in DERs

BA Climate Zone	Min	Median	Mean	Max	SD	N
	Pre-Retrofit Net-Site Usage (MMBtu)					
Cold	27.8	133.1	172.8	458.5	100.3	15
Hot-Dry	124.9	124.9	124.9	124.9	NA	1
Hot-Humid	43.6	59.3	62.9	100.2	19.6	9
Marine	21.8	46.3	70.7	137.4	48.9	5
Mixed-Humid	62.0	128.0	162.4	279.0	85.4	5
All	21.8	124.5	127.1	458.5	89.6	35
	Post-Retrofit Net-Site Usage (MMBtu)					
Cold	-5.9	62.4	62.3	164.7	38.0	19
Hot-Dry	14.7	38.3	44.6	90.7	24.5	9
Hot-Humid	26.5	36.5	39.1	58.9	11.9	9
Marine	6.7	22.5	27.9	58.3	18.0	9
Mixed-Humid	22.0	45.5	49.5	92.4	26.0	5
All	-5.9	40.6	47.7	164.7	30.2	51
	Relative Net-Site Energy Reduction (%)					
Cold	24%	47%	54%	103%	22%	16
Hot-Dry	33%	60%	55%	66%	13%	5
Hot-Humid	9%	35%	36%	63%	11%	23
Marine	21%	60%	51%	74%	21%	8
Mixed-Humid	28%	79%	61%	83%	28%	5
All	9%	41%	47%	103%	20%	57
	Absolute Net-Site Reduction (MMBtu)					
Cold	21.8	61.3	95.1	411	95.3	16
Hot-Dry	66.8	66.8	66.8	66.8	NA	1
Hot-Humid	11.4	22.8	23.8	41.3	8.7	9
Marine	14.1	67.0	57.9	101.8	32.8	7
Mixed-Humid	33.5	135	124.5	232	83.1	5
All	11.4	52.1	74.5	411	76.3	38

Table 11 Summary of Net-Site Energy Usage and Energy Reductions

BA Climate Zone	Min	Median	Mean	Max	SD	N
	Pre-Retrofit Source Energy Usage (MMBtu)					
Cold	84.4	197.7	267.3	616.3	150.3	22
Hot-Dry	215.0	215.0	215.0	215.0	NA	1
Hot-Humid	137.7	185.9	176.2	235.5	32.5	9
Marine	60.4	109.3	115.2	182.0	62.0	4
Mixed-Humid	174.6	202.9	202.9	231.2	40.0	2
All	60.4	190.2	225.0	616.3	128.0	38
	Post-Retrofit Net-Source Energy Usage (MMBtu)					
Cold	-18.1	116.0	114.2	311.2	67.0	24
Hot-Dry	29.1	91.3	89.6	155.7	44.5	9
Hot-Humid	83.6	112.7	110.4	152.2	21.3	9
Marine	2.3	60.5	64.3	170.3	50.0	8
All	-18.1	100.7	101.1	311.2	56.6	50
	Relative Net-Source Energy Reduction (%)					
Cold	23%	39%	49%	108%	23%	21
Hot-Dry	58%	58%	58%	58%	NA	1
Hot-Humid	26%	39%	37%	46%	6%	9
Marine	-12%	36%	39%	96%	51%	4
All	-12%	39%	45%	108%	24%	35
	Absolute Net-Source Energy Reduction (MMBtu)					
Cold	44.0	85.2	132.5	486.0	124.6	20
Hot-Dry	123.7	123.7	123.7	123.7	NA	1
Hot-Humid	36.1	62.1	65.8	86.09	16.1	9
Marine	-7.8	34.9	41.1	102.2	49.2	4
All	-7.8	74.0	103.8	486.0	103.0	34

Table 12 Summary of Net-Source Energy Usage and Energy Reductions

BA Climate Zone	Min	Median	Mean	Max	SD	N
	Pre-Retrofit CO_2e Emissions (pounds)					
Cold	13,540	22,080	23,980	41,360	10,785	7
Hot-Dry	17,660	17,660	17,660	17,660	NA	1
Hot-Humid	16,400	23,210	22,170	30,250	4,417	10
Marine	5,487	10,040	10,780	17,550	5,978	4
Mixed-Humid	20,420	23,630	23,630	26,850	4,545	2
All	5,487	19,360	20,730	41,360	8,125	24
	Post-Retrofit CO_2e Emissions (pounds)					
Cold	-3,861	12,880	9,917	24,870	8,512	15
Hot-Dry	2,213	6,205	6,555	12,810	3,308	10
Hot-Humid	10,480	13,920	13,910	19,550	2,848	10
Marine	974	4,218	4,702	10,320	2,996	8
All	-3,861	9,782	9,093	24,870	6,380	43
	Relative Carbon Emission Reduction (%)					
Cold	32%	43%	57%	110%	28%	8
Hot-Dry	55%	55%	55%	55%	NA	1
Hot-Humid	26%	37%	37%	47%	5%	10
Marine	15%	56%	52%	82%	30%	4
All	15%	40%	47%	110%	22%	23
	Absolute Carbon Emissions Reduction (pounds)					
Cold	6,061	9,148	12,350	27,760	7,922	7
Hot-Dry	9,752	9,752	9,752	9,752	NA	1
Hot-Humid	4,697	7,977	8,265	11,220	2,140	10
Marine	881	5,869	5,621	9,865	3,842	4
All	881	7,996	9,152	27,760	5,309	22

Table 13 Summary of Carbon Emissions and Reductions

BA Climate Zone	Min	Median	Mean	Max	SD	n
	Annual Energy Costs ($)					
Pre-Retrofit	$1,521	$2,417	$2,738	$5,818	$1,065	25
Post-Retrofit	$337	$1,431	$1,588	$2,794	$561	39
	Annual Energy Cost Savings ($)					
Cold	$135	$995	$1,341	$3,220	$917	9
Hot-Dry	$737	$1,475	$1,596	$2,444	$655	6
Hot-Humid	$431	$749	$831	$1,500	$286	11
Mixed-Humid	$551	$1,886	$1,798	$3,067	$1,176	5
All	$135	$962	$1,283	$3,220	$804	31

Table 14 Summary of Annual Energy Costs and Cost Savings

BA Climate Zone	Min	Median	Mean	Max	SD	n
	Incremental Project Cost ($)					
Cold	$11,500	$56,640	$57,480	$155,200	$31,027	29
Hot-Dry	$16,960	$25,000	$28,350	$42,000	$9,447	7
Hot-Humid	$3,246	$5,638	$9,503	$32,550	$9,300	10
Marine	$10,200	$21,970	$26,710	$57,120	$14,912	8
Mixed-Humid	$14,930	$39,700	$42,160	$86,870	$27,810	5
All	$3,246	$30,440	$40,420	$155,200	$30,358	59
	Incremental Project Cost per Square Foot Floor Area ($/ft^2)					
Cold	$ 4.36	$ 28.80	$ 30.78	$ 78.42	$ 19.44	29
Hot-Dry	$ 7.16	$ 19.91	$ 19.96	$ 39.23	$ 11.10	6
Hot-Humid	$ 2.36	$ 4.95	$ 6.55	$ 17.94	$ 5.43	10
Marine	$ 8.72	$ 11.27	$ 14.27	$ 33.48	$ 8.78	7
Mixed-Humid	$ 2.87	$ 19.81	$ 16.56	$ 27.93	$ 10.11	5
All	$ 2.36	$ 17.40	$ 22.11	$ 78.42	$ 17.70	57

Table 15 Summary of Incremental Project Costs

Time Period	BA Climate Zone	Min	Median	Mean	Max	SD	n
		Site Energy Usage (MMBtu/ft^2-yr)					
Pre	Cold	0.041	0.096	0.092	0.157	0.035	15
Pre	Hot-Dry	0.040	0.040	0.040	0.040	NA	1
Pre	Hot-Humid	0.032	0.038	0.048	0.106	0.023	9
Pre	Marine	0.014	0.032	0.034	0.049	0.015	5
Pre	Mixed-Humid	0.025	0.041	0.069	0.158	0.057	5
Pre	All	0.014	0.049	0.068	0.158	0.040	35
Post	Cold	-0.002	0.027	0.031	0.062	0.021	19
Post	Hot-Dry	0.010	0.032	0.035	0.060	0.017	8
Post	Hot-Humid	0.023	0.025	0.029	0.056	0.011	9
Post	Marine	0.004	0.013	0.015	0.036	0.011	9
Post	Mixed-Humid	0.007	0.018	0.018	0.026	0.007	5
Post	All	-0.002	0.023	0.027	0.062	0.017	50
		Source Energy Usage (MMBtu/ft^2-yr)					
Pre	Cold	0.047	0.137	0.139	0.292	0.058	22
Pre	Hot-Dry	0.069	0.069	0.069	0.069	NA	1
Pre	Hot-Humid	0.100	0.120	0.131	0.197	0.030	9
Pre	Marine	0.039	0.056	0.055	0.067	0.014	4
Pre	Mixed-Humid	0.044	0.058	0.058	0.071	0.019	2
Pre	All	0.039	0.118	0.122	0.292	0.056	38
Post	Cold	-0.012	0.065	0.058	0.113	0.036	24
Post	Hot-Dry	0.020	0.068	0.070	0.116	0.039	8
Post	Hot-Humid	0.071	0.078	0.080	0.095	0.009	9
Post	Marine	0.001	0.031	0.035	0.076	0.026	8
Post	All	-0.012	0.066	0.060	0.116	0.034	49
		Carbon Emissions (Pounds CO_2e/ft^2-yr)					
Pre	Cold	7.1	14.2	16.0	28.3	6.6	7
Pre	Hot-Dry	5.7	5.7	5.7	5.7	NA	1
Pre	Hot-Humid	13.0	15.5	16.6	25.4	3.8	10
Pre	Marine	3.6	5.3	5.1	6.3	1.4	4
Pre	Mixed-Humid	5.2	6.7	6.7	8.3	2.3	2
Pre	All	3.6	14.2	13.2	28.3	6.5	24
Post	Cold	-2.8	3.8	4.2	9.0	3.8	15
Post	Hot-Dry	1.5	3.8	5.1	8.5	2.6	9
Post	Hot-Humid	8.6	9.8	10.1	12.3	1.2	10
Post	Marine	0.4	2.3	2.6	4.7	1.7	8
Post	All	-2.8	4.7	5.5	12.3	3.8	42
		Energy Costs (Dollars ($)/ft^2-yr)					
Pre	Cold	0.99	1.34	1.43	2.22	0.39	10
Pre	Hot-Humid	1.21	1.44	1.49	1.91	0.22	10
Pre	Mixed-Humid	0.49	0.71	1.22	2.28	0.84	5
Pre	All	0.49	1.41	1.41	2.28	0.45	25
Post	Cold	0.36	0.75	0.80	1.27	0.25	22
Post	Hot-Humid	0.80	0.91	0.93	1.15	0.10	10
Post	Marine	0.58	0.58	0.58	0.58	NA	1
Post	Mixed-Humid	0.11	0.41	0.44	0.68	0.21	6
Post	All	0.11	0.79	0.77	1.27	0.26	39

Table 16 Summary of Site and Source Energy, Carbon, and Energy Costs, Normalized by Floor Area

BA Climate Zone	Min	Median	Mean	Max	SD	n
	Relative Site Energy Savings (%)					
Cold	32%	55%	63%	103%	22%	13
Hot-Dry	54%	54%	54%	54%	NA	1
Hot-Humid	26%	38%	38%	48%	7%	9
Marine	59%	72%	70%	84%	10%	5
Mixed-Humid	28%	79%	61%	83%	28%	5
All	26%	54%	57%	103%	21%	33
	Absolute Site Energy Savings (MMBtu/ft^2-yr)					
Cold	0.022	0.050	0.060	0.124	0.034	13
Hot-Dry	0.021	0.021	0.021	0.021	NA	1
Hot-Humid	0.008	0.015	0.019	0.050	0.012	9
Marine	0.010	0.024	0.023	0.030	0.008	5
Mixed-Humid	0.007	0.033	0.051	0.131	0.053	5
All	0.007	0.028	0.041	0.131	0.034	33
	Relative Source Energy Savings (%)					
Cold	18%	39%	49%	108%	26%	21
Hot-Dry	58%	58%	58%	58%	NA	1
Hot-Humid	26%	39%	38%	52%	7%	9
Marine	6%	50%	51%	98%	40%	4
All	6%	39%	47%	108%	24%	35
	Absolute Source Energy Savings (MMBtu/ft^2-yr)					
Cold	0.013	0.044	0.070	0.190	0.054	21
Hot-Dry	0.040	0.040	0.040	0.040	NA	1
Hot-Humid	0.026	0.046	0.051	0.102	0.022	9
Marine	0.004	0.027	0.024	0.038	0.015	4
All	0.004	0.042	0.059	0.190	0.046	35
	Relative Carbon Emissions Reduction (%)					
Cold	32%	45%	57%	110%	28%	7.00
Hot-Dry	55%	55%	55%	55%	NA	1.00
Hot-Humid	26%	37%	38%	52%	7%	10.00
Marine	41%	60%	63%	89%	21%	4.00
All	26%	41%	49%	110%	21%	22.00
	Absolute Carbon Emissions Reduction (CO_2e (pounds)/ft^2-yr)					
Cold	3.7	6.0	10.5	31.0	10.1	7.00
Hot-Dry	3.1	3.1	3.1	3.1	NA	1.00
Hot-Humid	3.4	5.7	6.4	13.3	2.7	10.00
Marine	2.6	3.1	3.0	3.2	0.3	4.00
All	2.6	5.2	6.9	31.0	6.3	22.00
	Relative Energy Cost Savings (%)					
Cold	6%	46%	44%	84%	22%	8
Hot-Humid	26%	37%	37%	44%	5%	10
Mixed-Humid	26%	67%	57%	85%	25%	5
All	6%	40%	44%	85%	18%	23
	Absolute Energy Cost Savings (Cost ($)/ft^2-yr)					
Cold	$0.07	$0.50	$0.67	$1.86	$0.54	8
Hot-Humid	$0.31	$0.55	$0.56	$0.77	$0.14	10
Mixed-Humid	$0.13	$0.61	$0.78	$1.60	$0.66	5
All	$0.07	$0.55	$0.64	$1.86	$0.43	23

Table 17 Summary of Reductions in Site and Source Energy, Carbon, and Energy Costs, Normalized by Floor Area