Title
Deep Energy Retrofit Guidance for the Building America Solutions Center:

Authors
Less, Brennan
Walker, Iain

Publication Date
2015

Ernest Orlando Lawrence Berkeley National Laboratory

Deep Energy Retrofit Guidance for the Building America Solutions Center

Brennan Less & Iain Walker
2015

Environmental Energy Technologies Division

Disclaimer

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 acknowledge the efforts, feedback and support provided by our committee of expert reviewers, who each reviewed this guidance in-part, including:

- Chris Stratton (LBNL),
- Richard Diamond (LBNL),
- Linda Wigington (Linda M. Wigington Associates),
- Mike DuClos (DEAP Energy),
- Paul Francisco (University of Illinois at Urbana-Champaign),
- Gavin Healey (Balance Point Home Performance),
- Dan Perunko (Balance Point Home Performance),
- Mark Ternes (ORNL),
- Asa Foss (U.S. Green Building Council),
- Gregory Pedrick (NYSERDA),
- Tina Fawcett (University of Oxford),
- Eric Werling (U.S. DOE) and
- George Beeler (AIM Associates).

Abstract

The U.S. DOE Building America program has established a research agenda targeting market-relevant strategies to achieve 40% reductions in existing home energy use by 2030. Deep Energy Retrofits (DERs) are part of the strategy to meet and exceed this goal. DERs are projects that create new, valuable assets from existing residences, by bringing homes into alignment with the expectations of the 21st century. Ideally, high energy using, dated homes that are failing to provide adequate modern services to their owners and occupants (e.g., comfortable temperatures, acceptable humidity, clean, healthy), are transformed through comprehensive upgrades to the building envelope, services and miscellaneous loads into next generation high performance homes.

These guidance documents provide information to aid in the broader market adoption of DERs. They are intended for inclusion in the online resource the Building America Solutions Center (BASC). This document is an assemblage of multiple entries in the BASC, each of which addresses a specific aspect of Deep Energy Retrofit best practices for projects targeting at least 50% energy reductions. The contents are based upon a review of actual DERs in the U.S., as well as a mixture of engineering judgment, published guidance from DOE research in technologies and DERs, simulations of cost-optimal DERs, Energy Star and Consortium for Energy Efficiency (CEE) product criteria, and energy codes.

These guidance documents include specific recommendations for each Building America climate zone, as well as guidance on more general topics, including:

- Lessons learned on U.S. DERs
- Guidance for the overall DER process
- Controlling costs and increasing cost-effectiveness
- Fuel switching, adding energy uses and source energy/carbon emissions considerations
- Occupant behavior in planning, design and operations
- Over-time or phased approaches

Contents

List of Figures

List of Tables

Introduction

The U.S. DOE Building America program has established a research agenda targeting market-relevant strategies to achieve 40% reductions in existing home energy use by 2030. Deep Energy Retrofits (DERs) are part of the strategy to meet and exceed this goal. DERs are projects that create new, valuable assets from existing residences, by bringing homes into alignment with the expectations of the 21st century. Ideally, high energy using, dated homes that are failing to provide adequate modern services to their owners and occupants (e.g., comfortable temperatures, acceptable humidity, clean, healthy), are transformed through comprehensive upgrades to the building envelope, services and miscellaneous loads into next generation high performance homes. When done correctly, DERs provide a multitude of benefits to various parties. The home occupants may have an improved indoor environment and health, as well as reduced utility bills, environmental footprint, maintenance and repair issues. Evidence from other energy efficiency upgrades (e.g., solar PV and efficiency certifications) also suggests that a substantial portion of DER project costs might be recoverable through increased home resale value (Bloom, Nobe, & Nobe, 2011; Dastrup, Zivin, Costa, & Kahn, 2012; Kok & Kahn, 2012), though this has not been studied directly in DERs. Society benefits from DERs in terms of job creation and carbon emissions reductions.

A recent review of Deep Energy Retrofit performance in the U.S. provides substantial background on real-world projects, demonstrating that cost-effective deep retrofits are possible and have been constructed across the U.S. (Less & Walker, 2014). Airtightness reductions averaging 63% (n=48) were reported (two- to three-times more than the 20-30% in conventional retrofits), with average post-retrofit airtightness of 4.7 Air Changes per House at 50 Pascal (ACH_{50}) (n=94). 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). 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 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 monthly savings to a monthly increase of $212 (mean=$15.67±$87.74; n=28). Almost half of the projects resulted in reductions in net-cost.

Some international examples of DERs and guidance for successful projects have been developed, and can provide useful examples and information to building professionals in the U.S. The UK Technology Strategy Board has developed guidance for making DERs work, based upon 40 actual projects implemented as part of their Retrofit for the Future initiative (The Technology Strategy Board, 2013). Similarly, the SuperHomes database provides plenty of detailed, real-world case studies of UK homes. DERs have also been implemented across the European Union in International Energy Agency Task 37 - Advanced Housing Renovation, and the project produced useful performance summaries, case studies and project guidance documents (Herkel & Kagerer, 2011).

The DER guidance provided in this document was developed based upon the experience and performance of actual projects in the U.S. The following are some overarching guiding principles that can contribute to successful DER projects:

- Collaboration and communication
- Careful planning and integrated solutions
- Systems thinking

- Clear goals and objectives
- Integration with general remodeling, repair and replacement activities
- Comprehensively address all end-uses and building systems
- Reduce the load, then use efficient technologies
- Occupants are essential to the process and results
- User-centered design
- Non-energy benefits drive much of the decision making
- Use experienced and dedicated designers and contractors
- Simple, off-the-shelf, high-efficiency solutions
- 3rd party inspection, testing and verification
- Do no harm

For Building America guidance on deep energy retrofit topics that apply to projects in all locations, follow the links below:

1. Lessons learned on U.S. DERs
2. Guidance for the overall DER process
3. Controlling costs and increasing cost-effectiveness
4. Fuel switching, adding energy uses and source energy/carbon emissions considerations
5. Occupant behavior in planning, design and operations
6. Over-time or phased approaches

Building America has also developed DER guidance for specific climate zones (see map below), including climate descriptions, example DER specifications, an exemplar case study in that climate, lessons learned, and climate-specific resources. Use the interactive map below to find climate-specific guidance that you can use on your projects today!

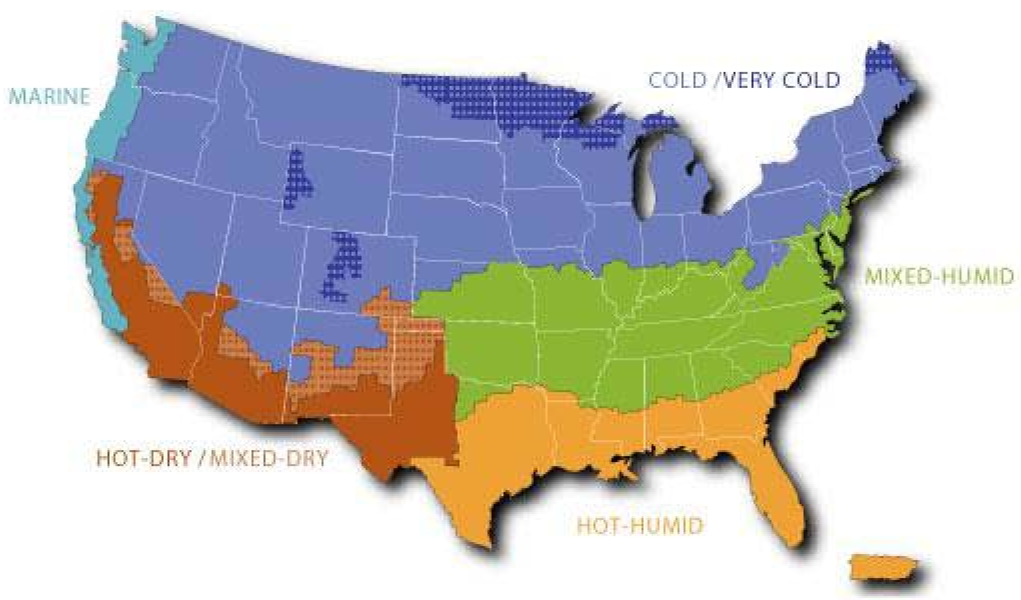


Figure 1 Map of the U.S. DOE Building America climate zones in the continental United States.

References

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.

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

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

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

Less, B., & Walker, I. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* (No. LBNL-6601E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/sites/all/files/a_meta-analysis_0.pdf

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

Lessons learned

Based upon a review of DERs in the U.S., successful projects did the following:

- Had lots of room for improvement
- Were in need of remodeling, repairs and maintenance
- Were high energy users
- Used a skilled design and construction team that planned carefully, involving everyone in decision-making
- Used simple, high-efficiency strategies
- Addressed all energy end-uses
- Employed building science best practices (moisture management, building control layers, ventilation, integrated design, etc.)
- Commissioned and verified work
- Used lower cost alternative strategies wherever possible
- Had engaged occupants
- Provided feedback and education to occupants

Below, we provide more detailed summaries of experiences and lessons learned for specific design approaches and systems.

As long as projects are comprehensive and aggressive, the specifics of the retrofit approach do not have significant impacts on project success. For example, in 36 northeastern DERs, specific retrofit strategies used in basements, attics and walls were associated with increased airtightness, but not with energy performance (Gates & Neuhauser, 2014). In Florida DERs, the most successful projects typically implemented more measures across a variety of end-uses, but with lots of variability in measure packages (McIlvaine, Sutherland, & Martin, 2013). In California DERs, both code-style and superinsulated projects achieved impressive energy performance, using a wide array of technologies and strategies (Walker & Less, 2013). These projects suggest that a flexible but comprehensive approach is acceptable, and that no single technology, material or strategy is required for a successful DER. For example, it is clear that a successful DER can be completed with or without window replacement, at 1.5, 3 or 5 ACH50, with or without use of spray foam, with or without a sealed crawlspace, with or without solar PV, etc. This freedom should liberate project teams to pursue those strategies that are lowest cost and most appropriate for the occupants, the specific conditions encountered in the home, and the experience/skills of local workers.

Do no harm. As is the case with standard remodeling projects, DERs have the potential to expose occupants and workers to hazards from legacy pollutants (e.g. lead paint, asbestos insulation), but free guidance exists to help those involved in remodeling to identify and remediate such issues. Lead or asbestos abatement, radon testing and mitigation, moisture managed construction and other issues should be addressed using the U.S. EPAs Healthy Indoor Environment Protocols for Home Energy Upgrades. Also, most DERs include airtightening the building envelope, and this can potentially increase levels of some indoor air pollutants in the home (Emmerich, Howard-Reed, & Gupte, 2005). The average DER in the U.S. reduced air leakage by 63%, which could have a substantial impact on indoor pollutants. In fact, airtightness in post-retrofit homes was roughly equivalent with that in new, energy efficient construction. Yet, approximately 30% of U.S. DERs failed to install mechanical ventilation, and when broken down by climate zone, installation rates varied from 10% to 90%. Resistance to the installation of mechanical ventilation was particularly apparent in developer projects (Keesee, 2012; McIlvaine et al., 2013). Mechanical ventilation in aggressively airtightened homes should not be seen as optional. At a minimum, we recommend compliance with ASHRAE 62.2-2013, which specifies airflows for continuous fans, as well as bathroom and kitchen exhaust fans. Notably, indoor air pollutants have been measured in deeply retrofitted homes in California, and the pollutant levels were similar to (or better than) those measured in non-retrofitted, existing homes and/or conventional new homes. This was because the projects followed best practices, including continuous and kitchen/bathroom ventilation, commissioning, filtration, occupant education and source control (e.g., eliminate unvented combustion or low-emitting building materials) (Less & Walker, 2013).

Numerous projects reported on performance issues and occupant complaints related to mechanical ventilation systems, namely heat and energy recovery ventilators, which made up 70% of all installed mechanical ventilation systems in DERs (Less & Walker, 2014). 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; faults were common in these systems (Less & Walker, 2013). This is of great concern in newly airtightened homes packed full of new construction and finish materials. Problematic issues reported by project teams included a lack of knowledgeable suppliers, capable installers and commissioning agents to verify system performance (Berges & Metcalf, 2013). Furthermore, occupants often did not understand the systems or their maintenance requirements. These factors led to comfort complaints, lack of system operation and a lack of required maintenance (Berges & Metcalf, 2013; Gates & Neuhauser, 2014; Less, Fisher, & Walker, 2012). We recommend that DER project teams make systems simpler and less costly (less ducting, simple user-controls), make them easier to commission (easily accessible inlets and outlets), and make their operation and maintenance needs obvious (clear labeling, documentation and discussion with occupants).

Availability is limited of qualified and skilled contractors and design professionals. Many projects reported that finding adequately skilled and trained contractors with building science and energy efficiency experience was difficult, and that the questionable work of subcontractors often reduced project success (Berges & Metcalf, 2013; Phillip Boudreaux, Hendrick, Christian, & Jackson, 2012; Chandra et al., 2012; Gates & Neuhauser, 2014; McIlvaine et al., 2013). Code officials were also noted for lack of awareness and knowledge about energy efficiency upgrades. Issues including frustrations with badly coordinating scheduling, poor cost estimations, problematic building inspections and long lead times for specialty products. It is essential to avoid the low-cost bid mentality, and instead to invest in dedicated and experienced construction professionals. We recommend that a HERS rater or other building science specialist should provide support and guidance to a DER project from its inception until its completion. Also, as recommended elsewhere, choose technologies and strategies that that local suppliers and installers are familiar with.

Simple, high efficiency, off-the-shelf systems are often superior to advanced systems that look great on paper. The realities of complex system design, procurement, installation, commissioning, servicing and repair often means that these technologies cannot be justified. For example, combisystems were used to provide space and water heating in a number of DERs, and these systems often had high costs, with little obvious performance benefit over high efficiency off-the-shelf alternatives (e.g., 95 AFUE condensing gas furnace and heat pump water heater) (Less et al., 2012). The definition of a "complex" system varies by location. For example, DERs in Cleveland noted that ductless heat pumps were not supported by adequate local suppliers and installers (Berges & Metcalf, 2013). And while effective in Florida DERs, two-staged advanced heat pumps were not common for most installers and required extra attention (McIlvaine et al., 2013). We recommend avoidance of any systems that require substantial custom design and engineering services. Complex systems, whether they be mechanical or envelope systems, are most prone to failure, miscommunication and trades person errors. Base your decision on local market conditions and availability of experience professionals. If complex technologies are used, special care is needed to avoid problems, such as detailed training, oversight and inspection on the job site. See our Cost-Effectiveness guidance for more ideas on how to lower DER project costs.

Fuel switching in DERs (going from gas to electric heat) and adding energy using features can reduce or entirely eliminate source energy and carbon emissions reductions. Site energy reported on a utility bill does not always reflect the impact of household energy use on natural resources or on carbon emissions, mostly because a unit of electricity has a roughly three times the environmental impact of a unit of natural gas. Yet, some think that no matter what fuels are used (electricity or gas), a deep reduction project will almost certainly still reduce energy use and carbon emissions. But some actual case studies have shown otherwise (Less et al., 2012), and others have shown how site savings can be dramatically degraded when considering source energy and carbon emissions (Philip Boudreaux, Biswas, & Jackson, 2012; Gates & Neuhauser, 2014; Less & Walker, 2014). We recommend careful source energy and/or carbon assessment in DERs that are considering fuel switching and/or adding energy using features, particularly mechanical cooling. See our Source Energy and Carbon guidance for further details.

Occupants are an essential part of the DER design, construction and operations process. A number of projects reported on how occupant behavior affected retrofit performance. The success of mechanical ventilation systems was often contingent on occupant understanding and maintenance. Occupants were noted to not be familiar with "right-sized" HVAC systems, where pull-down time is long, and aggressive thermostat set-backs can cause problems. Occupants in DERs in Florida were noted to have disabled the smart functions of "smart" thermostats, because their needs were not being met (Parker, Sutherland, Chasar, Montemurno, & Kono, 2014). In a project at PNNL, homeowners were noted as being very finicky, in that they were resistant to actually carrying out retrofits (Chandra et al., 2012). They wanted cheap, silver-bullet solutions that used fancy new technologies, and were minimally disruptive. Careful, continuous support and engagement was required in order to get follow-through in these cases. DERs in Eastern Tennessee noted similar difficulty in engaging owners in this process (Phillip Boudreaux et al., 2012). We recommend broadly that DERs be designed according to the needs and abilities of the occupants (if they are present). But if occupants are not present, then DERs should be designed to be simple, well-documented, clearly labeled and insensitive to occupant behavior (e.g., super insulated, airtight homes have less variability in performance, no matter the thermostat setting). See our Occupant Behavior guidance for more details on this aspect of deep retrofits.

Deep retrofits can be cost-effective when financed improvements are incremental and aligned with other repairs, maintenance and equipment replacement. DERs can be most successful when integrated with remodeling activities that were already needed/desired, or at changes in ownership. Most homeowners who have done DERs in their homes do not focus intensely on cash-flow, and cost-effectiveness does not drive most of their decision making. Rather they are more interested in the numerous other benefits of DERs, including improved comfort, better health, durability, lower maintenance, increased home value, etc. Nevertheless, alignment with remodeling and other improvements reduces disruption and lowers the costs to occupants.

Addressing all end-uses comprehensively is crucial to success, rather than focusing solely on space conditioning. Pool pumps are a great example of huge energy wasters in many Florida homes, which can be cheaply addressed with substantial energy savings (Parker et al., 2014). DERs in California were noted for having highly variable base loads (continuous electricity demand), which contributed substantially to annual energy use (Keesee, 2012; Less et al., 2012). Such energy waste should be addressed intelligently in any DER that is investing heavily in other building elements in order to save energy.

References

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.

Boudreaux, P., Biswas, K., & Jackson, R. (2012). *Advancing Residential Retrofits in the Mixed-Humid Climate to Achieve Deep Energy Savings: Final Report on Knoxville, TN Homes* (No. ORNL-27 (4-00)). Oak Ridge, TN: Oak Ridge National Laboratory. Retrieved from http://inspire.ornl.gov/Document/View/be3b23ee-a47d-449d-ad62-5bb17299f99a?q=boudreaux

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://inspire.ornl.gov/Document/View/e89694bd-68c0-43fb-a6fa-3a17c6557a97?q=boudreaux

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

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

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

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

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

Less, B., & Walker, I. (2013). Indoor Air Quality and Ventilation in Residential Deep Energy Retrofits. Presented at the Environmental Health in Low Energy Buildings, Vancouver, Canada: ASHRAE.

Less, B., & Walker, I. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* (No. LBNL-6601E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/sites/all/files/a_meta-analysis_0.pdf

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

Parker, D., Sutherland, K., Chasar, D., Montemurno, J., & Kono, J. (2014). *Measured Results of Phased Shallow and Deep Retrofits in Existing Homes* (No. FSEC-PF-463-14). Cocoa, FL: Florida Solar Energy Center. Retrieved from http://www.fsec.ucf.edu/en/publications/pdf/FSEC-RR-510-14.pdf

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.

Design and Construction Process

Deep retrofit projects (DERs) have different phases, and how each phase is managed can impact the success of a project. Phases include: pre-planning, planning, construction, test-out and post-occupancy. Detailed guidance is provided for each phase below. Notably, we do not cover all of the major variations in project phases or types. For example, major distinctions in opportunities and limitations may exist between projects in homes that are occupied during renovations versus those that are empty. Or between those that are homeowner driven versus developer driven. Or those that are comprehensive renovations versus focused home performance upgrades. Furthermore, for projects not using an all-at-once approach, guidance and suggestions for over-time/phased DERs can be found here. Process guidance and suggestions provided below should be applied flexibly to projects depending on their needs, scope and the experience of those involved. We recommend reviewing some of the useful planning documents provided by the Thousand Home Challenge.

Pre-Planning Phase

The first step of a Deep Energy Retrofit is to **establish and clarify the project needs, opportunities, goals and objectives.** This will influence the overall scope of the project, as well as the strategies used throughout. Carefully assess the occupants' needs, desires and priorities (find a useful priorities planning tool here). Determine if the project will occur all-at-once or over-time, and decide if the home will be occupied during renovation activities. Also assess the existing performance of the home, and then tailor a retrofit plan based on these assessments. Find more on occupants and DERs here. This pre-planning phase may be best carried out by a home energy professional, with the experience necessary to inspect the home and help to develop performance baselines and overall project direction/strategy.

Establish a performance baseline

Perform home inspection and energy audit. Assess existing condition of the home, including all major systems. Perform building diagnostic tests to quantify air leakage, duct leakage, ventilation airflows, and HVAC system performance, where appropriate. Create specific performance targets for each test that will be achieved during retrofit and can be used to verify contractor performance. Note, not all projects need to measure of all these systems. Prioritize those diagnostic tests needed to obtain information that will impact project decisions. For example, it is not strictly necessary to test duct leakage if the project plan is to eliminate forced air ducts (but such testing may be useful in energy modeling and establishing an energy baseline, if desired).

Identify *Healthy Homes* health and safety issues that can be solved during retrofit, such as gas or water leaks, radon intrusion, improperly vented heating appliances, moisture or pest damage, lead paint, asbestos, structural inadequacy, etc. Identify paths to solving any issues, which can include either fixing a faulty gas appliance exhaust duct or eliminating the appliance entirely. For a useful tool in planning how to address Healthy Homes issues click here. For more detailed guidance on addressing health and safety issues, refer to the U.S. EPAs Healthy Indoor Environment Protocols for Home Energy Upgrades.

Establish energy baseline using utility bill analysis, preferably with minimum 12-month duration. Depending on fuel type, estimate heating, hot water, cooling and other energy categories. If bills are unavailable, a consumption or performance target may be more appropriate (see Figure 2 below). Also consider performing an electricity audit for miscellaneous devices in the home (find a useful tool here).

Use a plug-in electrical meter to estimate use of appliances, entertainment centers, computers/peripherals, etc.

Develop project goals and performance metrics

Establish an annual performance target or energy reduction goal. Setting specific goals for a project unites the project team, and ensures that priorities are clear to all parties. Many DER research efforts and programs have begun to prefer specifying a post-retrofit target, rather than reductions. This is because pre-retrofit data is often unavailable, and the assessment of reductions is often confused by changes in floor area, occupancy, and building services. In these cases, *Consumption Targets* or *Performance Targets* are appropriate (see Figure 2 below for examples of these goal types). If pre-retrofit energy use is either known (from utility bills) or estimated by simulation, then *% Reduction* and *Absolute Reduction* targets can be used, potentially in-addition to consumption/performance targets.

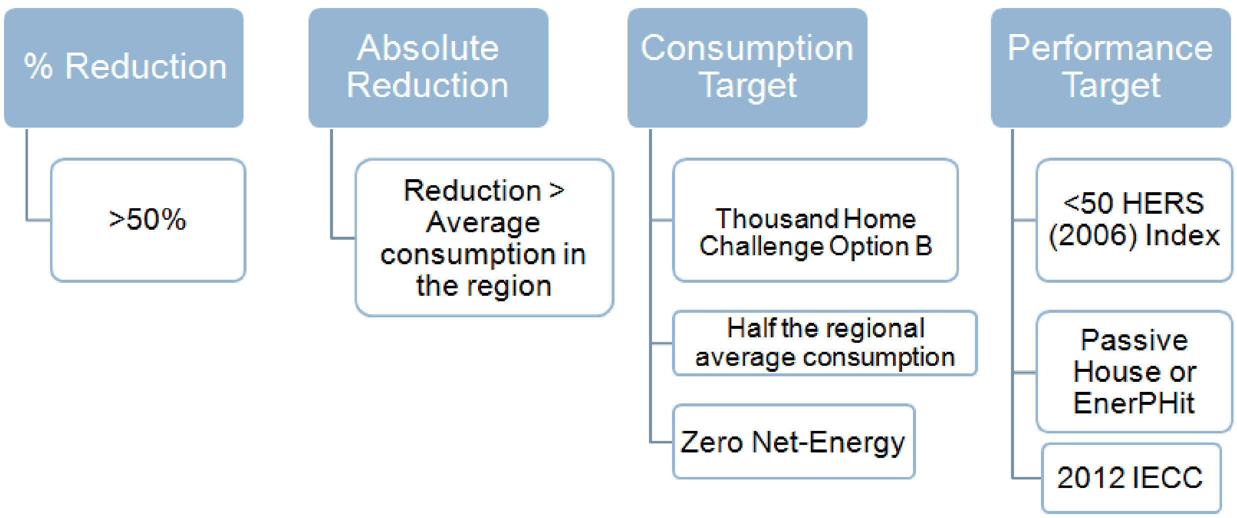


Figure 2 Example definitions of DERs that can be used in project planning and assessment.

Establish metrics to be used in assessing progress towards project goals. The metric used to assess performance will drive the results. In the case, of performance targets, fulfillment of some 3rd party standard is an appropriate metric. All metrics are useful in some way, but the appropriate metric to use in a given case depends on project priorities and who(m) is responsible for the retrofits (i.e., homeowner vs. utility). Nevertheless, for energy-based goals, we recommend:

- **Whole house assessment**, rather than floor area normalization.
- **Site energy**, if fuel sources are not changing for heating end-uses and if substantial additional energy using features are not added.
- **Source energy and/or carbon emissions**, if fuel sources are changing and/or end-uses are being added. See our Source Energy and Carbon guidance.
- Warning, the HERS rating methods will not adequately reflect whole house energy and environmental performance when the project includes occupant behavior modification, changes in

floor area or fuel mix, or innovative strategies/technologies that cannot be modeled in HERS software.

- In these cases, we recommend that alternative modeling and assessment methods be used in addition to HERS assessments.

Establish non-energy goals of the project, including improvements in aesthetics, comfort, disaster resistance, water efficiency, IAQ, health, durability, structural integrity, home resale value, accessibility, etc. It is also essential to determine if traditional cost-effectiveness is a project goal. Metrics are also important for assessing achievement of non-energy goals. These can be informally assessed by occupants/designers, or here are some specific examples:

- IAQ - ASHRAE Standard 62.2-2013 compliance
- Environmental Health – Use of the Healthy Indoor Environment Protocols for Home Energy Upgrades
- Comfort - ASHRAE Standard 55
- Accessibility - Use of Certified Aging-In-Place Specialist
- Cost-effectiveness - positive monthly cash-flow when energy upgrades are financed
- Structural integrity – compliance with current seismic guidance or local requirements
- Water efficiency – U.S. EPA WaterSense certification

Project Planning Phase

The design team

Assemble qualified and trusted team. A DER team will likely include an energy consultant/home performance professional, a contractor, engineers and a designer, though the composition of the project team can depend heavily on the project scope and goals. Project costs may be reduced by not hiring an extensive team. Some high performance homes contractors provide much of this varied expertise in-house, and our guidance is an attempt to convey some expert knowledge which is otherwise only available from consultants and other for-hire experts. Smaller teams may be ideal for projects that do not include major general remodeling, structural improvements and architectural design. Ideally, the chosen professionals will have knowledge and experience in energy efficient construction techniques and building science principles. Team members should read this guidance, so that they all have some basic background as to the goals and methods of DERs. Strategies:

- Hire the best professionals you can find locally.
- Avoid lowest-bidder mentality. Inexperienced construction professionals were repeatedly noted as limitations in DER projects.

Planning approaches

Plan all aspects of the project as if it were new construction. Be as thorough as possible. Do not leave major decisions to the last minute, where cost, lead-times and convenience can result in bad decisions. But be aware that projects in existing homes always have surprises (e.g., hidden moisture damage, radon infiltration, structural problems), which requires flexibility and an openness to changes in the project and recalibration if necessary. Careful attention to detail by team members through all phases of design and construction is essential for successful implementation.

Systems integrated approaches allow for creative problem solving and synergistic measures. For example, existing duct work can often be extensively air sealed, or can be brought inside the building envelope, or could be eliminated entirely.
Design to the energy reduction goal or target. Be specific about the energy reductions that are targeted for each end use, account for everything that will get you to your target/goal.

An integrated project delivery method is advisable in a DER. Include the occupants, architect, engineers, contractor and subcontractors from the beginning in order to holistically address all aspects of the project.

Use energy models to test retrofit approaches but with caution. A thorough understanding of the limitations of these models is necessary, as is an experienced modeler. Many advanced system types cannot be modeled using commercial software (e.g., combisystems). Also, occupant behavior can be challenging or impossible to model.

Construction Phase

Plan product procurement for a DER as you would any remodel, allowing lots of lead time and ensuring flexibility for change orders. Many DER project teams have complained about long lead times and retailers who were poorly equipped to answer questions and provide service on advanced equipment/materials. In particular, plan ahead for:

- Advanced windows, namely triple-pane, imported units
- Advanced HVAC, such as mini-split heat pumps, combisystems, etc.

Be prepared for unexpected issues to arise, such as hidden structural issues or pest/moisture damage. Expect that these unanticipated obstacles will have costs in terms of time, money and the scope of other improvements. Early in project development, the creation of contingency plans and priority lists will help in making decisions during these challenging periods.

Provide quality assurance wherever possible. Always have a trusted and knowledgeable representative overseeing the work of insulation, HVAC and other subcontractors. Due to reported problems with contractor quality in DERs, it is a best practice to have the work of any contractor verified by a third party inspector, such as HERS rater, energy auditor or other knowledgeable project team member. Where feasible, use diagnostic testing equipment, such as a blower door, to track progress and fulfillment of project goals during construction.

Test Out

Verify installation and performance of retrofit measures. The same diagnostic tests that were performed prior to the retrofit should be performed post-retrofit, in order to evaluate whether the goals were achieved or not. Blower door tests should ideally be performed prior to finishes in order to allow for additional air sealing if needed.

Commission all building systems. This includes measurement of airflows for ventilation and forced air space conditioning systems (e.g., room-by-room measurements and total system flow), heat pump and air conditioner diagnostics (e.g., refrigerant charge, superheat, subcooling), and confirmation of correct operation of controls (e.g., thermostats, ventilation controllers, etc.).

Post-Occupancy Evaluation

Provide post-occupancy performance feedback to occupants. A DER is not complete once the building is occupied, but in many ways is only beginning. The energy savings are the main focus of a DER, therefore, the energy use must be monitored and compared to the baseline in order to evaluate progress. More detailed levels of metering allow occupants and energy professionals to identify problems or anomalies linked to equipment or behavior. Monitoring can occur at three levels:

- *Minimum:* consumption through utility billing data should be used.
- *Better:* install whole house electricity meter and provide continuous feedback/access to occupant and potentially contractor.
- *Best:* install end-use metering, with a focus on biggest energy consumers.

Encourage occupants to make acceptable behavioral adjustments based on feedback from monitoring.

An electricity audit of miscellaneous equipment can be just as valuable after the retrofit is complete, as DERs often include new equipment, new home offices and a variety of miscellaneous energy draws.

Guide occupants using short-term usage targets that are easier to track and achieve. Have weekly or even monthly energy use targets, rather than an annual target. This allows for tracking of progress and earlier discovery of trends.

Reducing Deep Retrofits Costs and Increasing Cost-Effectiveness

This document begins by providing suggestions for controlling deep retrofit costs and increasing cost-effectiveness, including both Do's and Don'ts. This is followed by a brief discussion of the larger context for thinking about the economic value of deep energy retrofits. Finally, estimates are provided (based on actual U.S. projects) of average DER project costs, energy cost savings and cost-effectiveness.

Guidance for reducing costs and increasing cost-effectiveness

DERs will be most cost-effective for developers or home owners when the costs are financed, and the monthly utility bill savings can be used to offset monthly loan increases. Ideally, the improvements are aligned with existing equipment replacement, maintenance and remodeling activities. This means that deep retrofit measures are incrementally added to other remodeling activities that were already planned to occur. When properly balanced, the annual energy cost savings can equal or exceed the annual loan costs—these are referred to as having neutral net-monthly costs. A number of studies have used building energy simulations to generate optimal cost-neutral DER packages, which can be useful for reference (Fairey & Parker, 2012; Polly et al., 2011), but their results are highly dependent on assumptions for the pre-retrofit home, interest rates, loan terms, discount rates, etc. Building energy professionals can use BEopt (free energy simulation software developed by Building America program) to generate a cost-optimized retrofit solution based on a specific project, if desired.

As a rough guide, DER designers can use the table below to estimate how much annual utility bill savings are required to have neutral net-monthly costs, when the project is financed for a 30-year term at various interest rates and loan amounts. This approach does not tell project teams what specific upgrades to do, but rather provides a very basic financial structure for project planning. For example, if you are targeting a $1,100 annual cost reduction, and you are targeting net-neutral monthly costs, then your target energy upgrade costs should not be more than ~$20,000, depending on available interest rates. This is not intended to be a precise guide for project cost planning, but rather to provide a gut-check for the overall feasibility of a cost-effective DER in any given scenario.

Interest Rate	Energy Upgrade Costs ($)					
	$5,000	**$10,000**	**$15,000**	**$20,000**	**$50,000**	**$100,000**
	Required Annual Savings for Neutral Net-Costs					
3.0%	$204	$408	$612	$817	$2,041	$4,083
3.5%	$221	$442	$663	$884	$2,211	$4,421
4.0%	$239	$477	$716	$954	$2,386	$4,771
4.5%	$257	$513	$770	$1,026	$2,566	$5,132
5.0%	$275	$550	$826	$1,101	$2,752	$5,503

Table 1 Quick guide to determining the necessary energy cost savings for a cost-neutral retrofit, for a variety of project costs and interest rates. This table assumes a 30-year loan term, no down payment and a 25% mortgage interest deduction.

The following guidance is based upon the most and least cost-effective projects in a review of U.S. DERs (Less & Walker, 2014).

- **The most cost-effective projects were** generally in poor condition with little or no insulation and had low-efficiency equipment throughout. They also generally had higher than average utility bill savings, and in one case, heating energy made up a large majority (~75%) of annual energy costs. These homes had lots of potential, high utility bills, and generally did not pursue extremely expensive retrofits.
- **The least cost-effective projects were** generally very-aggressive, super-insulation retrofits, but they also had lower pre-retrofit energy bills, and in some cases pre-retrofit conditions were better than average (i.e., considered insulated but not to DER levels, had double pane windows, with modern HVAC equipment, etc.). In combination, these factors led to low overall cost-effectiveness. It should be noted that these projects are not be seen as “failures”, because cost-effectiveness may not have been a project goal.

What works well for cost-effective DERs?

- Begin by **comprehensively addressing low- and no-cost efficiency solutions**, such as behavior, controls, window operation, lighting, hot water fixture upgrades, etc.
- **Select simple, off-the-shelf, high-efficiency systems**. In addition to lower up-front costs, this also makes it much easier to find capable suppliers, installers and service providers.
- When facing decisions among equivalent strategies/products, **select the lower-cost options** (e.g., blown cellulose versus spray polyurethane foam, air-source mini-split heat pump versus ground-source heat pump). The perceived benefits of the higher-costs alternatives rarely lead to substantially better energy performance.
- **Target homes with high pre-retrofit energy use and costs**.
- **Target homes that lack intermediary efficiency measures** (e.g., single-pane window homes versus existing double-pane windows, uninsulated walls versus those you think are “poorly” insulated, existing SEER 8 A/C versus existing SEER 13).
- **Target existing remodeling projects and equipment replacement** for incremental DER measures. These projects will typically already be engaging design and construction professionals, as well as code officials, and the added DER energy upgrade measures are reduced in cost. For example, if replacing a furnace or air conditioner, use the highest efficiency model, as the additional cost of a high efficiency unit are typically justified relative to a code-minimum unit. Or when re-siding a home, install insulation in the wall cavity and consider exterior continuous insulation, as the cost of the re-siding is already being spent.
- **Address all building systems and end-uses** without an obsessive focus on any one use (e.g., space heating). For example, during an aggressive envelope upgrade, very low-cost improvements, such as upgraded lighting, appliances, low-flow hot water fixtures, or plug-controls can often be overlooked.
- **Engage the home occupants** (if willing and available) early and often in the planning process. How the home is used and what owners expect will provide strong insight into where investments are appropriate and what outcomes are desirable and reasonable. This engagement also provides opportunities to better match outcomes to owner expectations.

- **Be sure to assess the impacts of DER measures on energy costs**, rather than relying solely on site energy reductions. Some improvements (e.g., heat pumps) can increase the use of more costly energy sources, while appearing to provide site energy reductions.
- Where applicable, **aggressively target peak load reductions**, so as to avoid increased electricity rates at those times. This includes passive measures, such as solar shading and selective glazing applications for different faces of the home, or HVAC controls that pre-cool a home prior to the peak period.
- If a cost-effective retrofit is desired, it is useful to **have estimates of pre-retrofit energy costs**, so as to provide some sense of what possible gains can be provided by the efficiency measures. Pre-retrofit billing data from the home is best, but other estimates could be from regional averages, simulations, or the occupants' current usage (if in another property), adjusted for home size if applicable. For example, if the current usage (or estimated pre-usage) is $1,100 per year, then a retrofit >$15,000 is not likely to be cost-effective, based on cash-flow alone (see table above).

What are the problems to look out for in cost-effective DERs?

- **Avoid custom-engineered, complex systems**. Rarely do these perform as intended/expected/advertised, and commissioning, repairs and maintenance can become highly burdensome, as can simply identifying a contractor who is capable of working on the system.
- **Budget for unanticipated needs.** These emerge in all projects, and these contingencies need to be both accommodated and budgeted for. Identify potential contingencies and unknowns, and then attempt to develop plans for dealing with these. Or prioritize the various elements of a project early on, so that trade-offs can be made in an informed and careful manner.
- **Be flexible about performance targets.** Be wary of aggressive performance targets that mandate precise levels of performance, and which may lead a project down a high-cost path. It has been demonstrated that many paths to successful deep retrofits are available, and there is no one-size-fits-all approach that will guarantee either success or failure in every circumstance.
- **Beware the perceived performance benefit of higher cost systems and strategies.** For example, while spray foam (SPF) insulation is costly, it is often seen as the best way to establish an air barrier. Nevertheless, SPF provided no benefits in terms of airtightness relative to other air sealing strategies in a community of DERs in Massachusetts and Rhode Island.
- **Be aware that the addition of energy consuming features** is common in a DER project, and these have the potential to offset savings or even increase usage, most commonly of electricity.
- **Fuel switching** from gas to electricity may seem to provide great site energy savings, but energy costs may increase, because electricity is on average three to four times more expensive than natural gas per unit of delivered energy (and it also often has higher carbon emissions).
- **Homes with low pre-retrofit utility bills do not have as much potential for cost-effective savings**. There may be other reasons to deeply retrofit these properties, but strong cost-effectiveness should not be anticipated, unless project costs are kept on the lower end.

The context for DER costs and cost-effectiveness

A number of DER research reports have reflected on the poor cost-effectiveness of DER homes (Boudreaux, Hendrick, Christian, & Jackson, 2012; Chandra et al., 2012), while others have aggressively targeted and achieved traditional cost-effectiveness (McIlvaine, Sutherland, Schleith, & Chandra, 2010).

It is also clear that reasons other than utility bill savings motivate many DERs and home energy upgrades (Boudreaux et al., 2012; Fuller et al., 2010; Neuhauser, 2012). Furthermore, developer driven DERs (such as in low-income housing and redevelopment projects) may have very different goals and approaches to economic value. Either way, high project costs and questionable cost-effectiveness are often seen as some of the most important barriers to widespread DERs. Yet, reported project costs for U.S. DERs are similar in magnitude to those reported every year by tens of thousands of Americans for conventional home renovation activities (Less & Walker, 2014). Clearly, there is a subset of the U.S. population who have the financial resources to deeply retrofit their home.

There is a traditional view of cost-effectiveness that tabulates all project costs and balances them against only some of the project benefits. But the value of a DER greatly exceeds the traditional balance between design/construction costs and energy cost savings. DERs are financially and socially justified due to a combination of utility bill savings and non-energy benefits (NEBs) (e.g., increased home value, economic stimulation, and improved comfort, convenience, disaster resistance, IAQ and durability, as well as lower maintenance).

These additional benefits are real. Research by economists on standard renovations and other home efficiency upgrades (e.g., solar PV and efficiency certification) suggests that DER costs may be at least partially recouped by homeowners through increases in their property value (Dastrup, Zivin, Costa, & Kahn, 2012; Kok & Kahn, 2012). Similarly, assessments of the economic value of home energy upgrades have estimated that the value of non-energy benefits ranges from 50% to 300% of the utility bill savings (Amann, 2006; Imbierowicz & Skumatz, 2004; Knight, Lutzenhiser, & Lutzenhiser, 2006). 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.

Actual project costs, savings and cost-effectiveness for U.S. DERs

While motivations and the need for cost-effectiveness (traditional or more nuanced, as discussed above) will vary by project and by developer type, it is a rare project where money is totally disregarded and where controlling costs is not seen as beneficial. Below we provide average estimates of DER project costs, average energy cost savings, and the cost-effectiveness of DERs based on 30-year financing. These should provide some context for those beginning on the DER path.

An LBNL review of U.S. DERs suggests that an average project will cost approximately $40,000 ($22 per ft^2) (Less & Walker, 2014). There was lots of variability in project costs, which was driven by mostly by project scope, performance targets and choices in materials and technologies. Total project costs were always greater than those costs associated with energy efficiency improvements, because DERs nearly all included other home upgrades, including new finishes, deferred maintenance, and overall repairs. Energy measure costs varied from 25% to 75% of the total costs in the few cases where this level of detail was provided (Gates & Neuhauser, 2014; Keesee, 2012; McIlvaine et al., 2010). Projects in cold climate regions were more expensive on average, because they often targeted extreme airtightness (<2 ACH_{50}) and super-insulated envelopes. Most projects in more mild climates had overall lower average costs, but very aggressive projects in these mild climates also had high costs. Costs were lowest in hot-humid projects, where performance targets were generally lowest.

Utility bill savings averaged $1,300 per year in U.S. DERs, with little variability with climate. Energy costs in pre-retrofit homes in the review were slightly above average for the U.S., and post-retrofit bills were approximately 30% below the U.S. average. Notably, some aggressive retrofits were documented in low-usage homes and energy cost savings were low. Presumably these projects were driven not by a desire for cost-effective improvement, but rather by the common desire, noted above, to update the home, increase comfort, durability, etc.

On average, the U.S. DERs were cash-flow neutral on a monthly basis. However, variability was large, with some projects substantially reducing net-monthly costs and others substantially increasing net-costs.

References

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

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://inspire.ornl.gov/Document/View/e89694bd-68c0-43fb-a6fa-3a17c6557a97?q=boudreaux

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

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

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

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

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

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

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

Less, B., & Walker, I. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* (No. LBNL-6601E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/sites/all/files/a_meta-analysis_0.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

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

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

Source Energy and Carbon Decisions in DERs

The Problem: DERs are projects that create new, valuable assets from aging residences, and part of that process is bringing the home into alignment with the expectations of the 21st century. Some changes we make while upgrading a home can lead to an offsetting of other reductions or even increased electricity use, which can reduce the project's utility bill savings and beneficial environmental impact.

When Is It Important?

1. When switching from gas to electric for heating end-uses, such as space heating, water heating, cooking or clothes drying;
2. When adding energy-using features, such as mechanical cooling, mechanical ventilation, decorative lighting, audio-visual equipment, smart home features or appliances.

The Solutions:

1. In cases highlighted above, carefully assess the impacts of switching from gas to electricity for heating end-uses, using source energy and/or carbon emissions assessments;
2. Only implement those changes in fuel use that can provide a net-environmental benefit;
3. Attempt to include changes in home features (e.g., lighting, smart home features, mechanical cooling, etc.) in your assessments and energy calculations. For example, in BEopt, the user can input a carbon factor for each fuel type specified in the model. If you know the carbon content of your local electricity, use that, otherwise, we recommend the use of local averages, such as those provided on a state-by-state basis in Table 3.
4. Carefully weigh the benefits and consequences of adding features to a home, to ensure they are "worth" the reduction in environmental performance that comes with them. In other words, inspire a conscientious, conservative and aware attitude in the project team and home occupants.

Background and Further Details

The U.S. DOE Building America program already uses source energy as its primary metric in home performance assessment. This is done in order to account for the approximately three-fold increase in primary fuel requirements (e.g., natural gas, coal, oil, hydro, nuclear, etc.) for delivered electricity compared with natural gas (see Table 2). Nevertheless, utility bills (e.g., site energy) are the most familiar to both homeowners and contractors, and they are therefore a useful tool for thinking about deep energy reductions in homes. Yet, site energy does not always reflect the impact of household energy use on natural resources or on carbon emissions. As a society, we have an interest in reducing these negative consequences, and many homeowners engage in the deep energy reduction process in order to specifically reduce their "environmental footprint". When appropriate, using source energy and carbon metrics can ensure that you do not accidently limit the impact of your deep renovation project on these larger, environmental goals.

Energy Type	Natural Gas	Electricity
Site Energy	1 kWh	1 kWh
Source Energy	1.02 kWh	3.16 kWh
Carbon Emissions	0.399 lbs/kWh	1.32 lbs/kWh

Table 2 Conversion factors between site and source energy, as well as carbon emissions.

You may be thinking that no matter what fuels are used, a deep reduction project will almost certainly still reduce energy use and carbon emissions, but some actual case studies have shown otherwise. The ratio of gas use to electricity use can change even in aggressive deep reductions projects. This can have substantial negative impacts. For example, two DERs in Northern California incurred severe source energy penalties as a result of electricity use increases (Less, Fisher, & Walker, 2012). 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 (e.g., cooling, home office, home networking) also contributed to these performance degradations. Similarly, two DERs in eastern Tennessee increased electricity use post-retrofit, and their site savings went from 32% and 61%, down to 8% and 33%, respectively (Boudreaux, Biswas, & Jackson, 2012). In a review of U.S. DERs, seven projects were identified that increased electricity use, and their average site savings went from 52% to 34% for source energy (Less & Walker, 2014). Similarly, in a community of DERs in Massachusetts and Rhode Island the average site savings of 58% was reduced to 41% for source energy (Gates & Neuhauser, 2014).

To illustrate more clearly what can happen, Figure 3 below shows site and source energy before and after an ***imaginary*** deep reduction project. Site energy reductions were 90% for heating, 45% for hot water, 50% for lights and 25% for appliances (an overall 60% savings). But the home's space and water heating switched to electricity, and mechanical cooling was added, as were some modest plug loads increases. So, a site energy reduction of 60% translates to a 0% source energy reduction! Carbon emissions reductions would be similar, with some variability by location as noted elsewhere in this summary. This is what DER designers and homeowners should try to avoid.

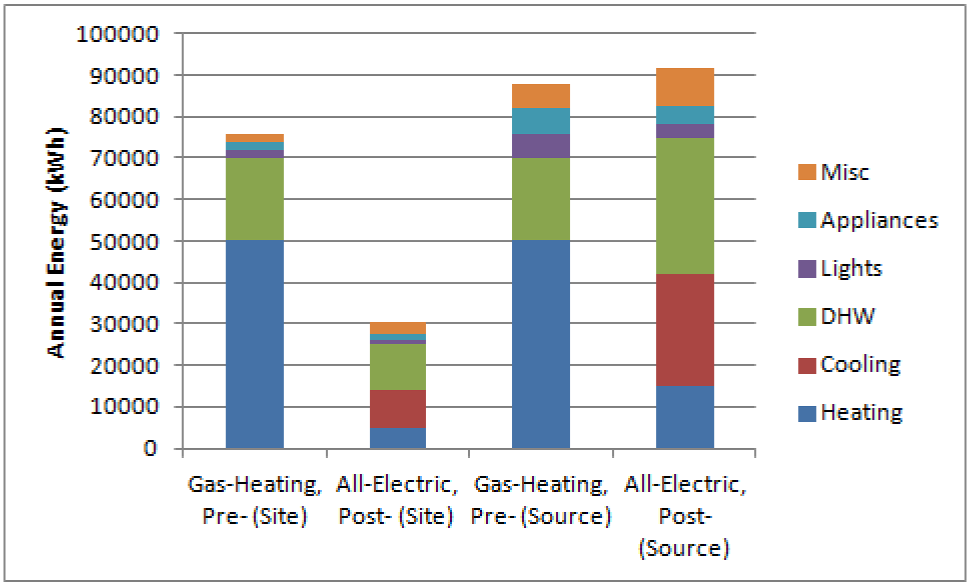


Figure 3 Example energy use of an *imaginary* deep retrofit project whose fuel switching and other choices eliminate all source energy savings and environmental benefit.

So, what leads to electricity increases in deeply retrofitted homes?

1. Switching from gas to electric for heating end-uses, such as space heating, water heating, cooking or clothes drying.
2. Addition of energy-using features, such as mechanical cooling, mechanical ventilation, decorative lighting, audio-visual equipment, smart home features or appliances.

Features added to a home have great value to homeowners, and they may be some of the primary drivers of the decision to do a deep energy retrofit. For example, indoor temperatures and humidity in the summer may be extremely uncomfortable, and the addition of mechanical cooling (along with improvements to the building envelope) are an obvious choice for any homeowner. Other similar improvements are required to modernize any older home that has not had substantial updates. DERs are projects that create new, valuable assets from aging residences, and part of that process is bringing the home into alignment with the expectations of the 21st century.

These additional features will always increase energy usage, unless they are replacing some less-efficient pre-retrofit alternative. A project may still save electricity, but those reductions will be less than they would have been without the added feature(s). As a result, these additional features should be weighed carefully, and in full consideration of their impact of environmental performance.

Some electricity use increases are reflected in common building energy models. For example, switching from a gas furnace to an electric heat pump can be easily modeled, as can changing fuel/system type for water heating (thought these will not be adequately reflected in outputs such as HERS indices). Other elements can be included in a model, but are often not included as part of the typical “asset” performance assessment. For example, lighting density can be modeled, but accurately reflecting the before and after change is not common. The same goes for miscellaneous plug loads, security systems, A/V equipment, etc. The DER designer should be aware that these changes in usage patterns and in-home fuel mix can have a substantial impact on environmental performance. They should:

1. Make a concerted effort to reflect these changes in any building simulation model.
2. In these situations where environmental performance is potentially degraded, designers should assess source energy and carbon reductions, alongside site energy
3. Explain to homeowners that some of their decisions will cut into energy savings they are paying to achieve elsewhere. This will hopefully inspire a conscientious attitude.

Carbon Emissions in U.S. Electricity and Retrofit Decisions

The following is an example of a nuanced carbon emissions/source energy assessment that is based on the variability in the carbon intensity of electricity from state-to-state. Table 3 lists the 2010 carbon emissions per unit of delivered electricity (lbs./kWh) for each state in the U.S. These emissions are compared with those of a 95% efficient, on-site gas heater (gas emissions are 0.399 lbs./kWh) in order to assess the heat pump equipment efficiencies required to break-even with natural gas in terms of carbon emissions. Holding all else constant (e.g., insulation levels, airtightness, ducts), in those states highlighted in green, a high performance air-source heat pump can at least break-even with a 95% efficient gas heater (and often do better). Yellow states require best-in-class heat pumps (such as those listed in the Energy Star Most Efficient list) in order to break-even. In red states, no currently available air-source heat pump can break-even with a 95% efficient gas heater, given federal performance ratings.

These values are not meant to suggest that one should never install a heat pump in a red state nor that one should always install a heat pump in a green state. Rather, these are indicators to **Pay Attention** and assess the impacts in greater detail. There are also other good reasons that one technology is chosen over another, including energy prices, equipment prices, availability of electricity and gas at heating appliance location, performance at part-load, utility service connection fees, etc. Also, think about equipment choice in the context of the house as a system. For example, in a DER, heating loads may be reduced 70-90%, so even a heat pump in a red state would reduce carbon emissions, but emission reductions would be less than they would have been if gas heat were used. This may be acceptable, given the overall environmental benefit; this is for the homeowner and the project team to decide.

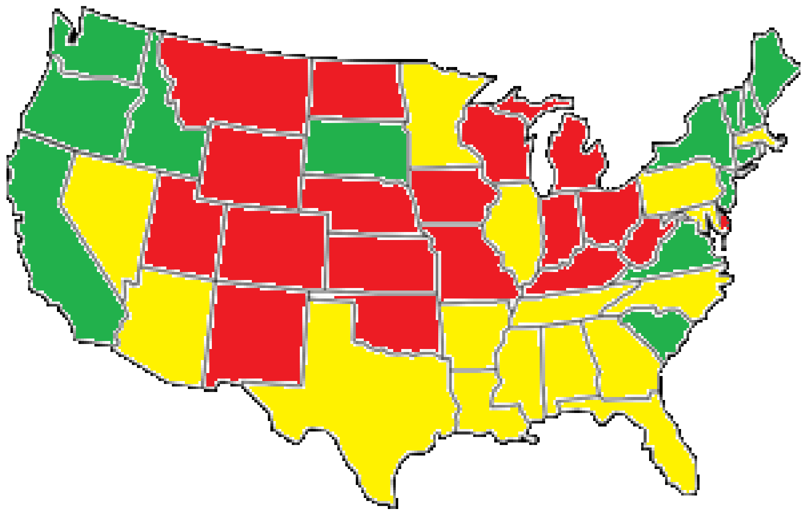


Figure 4 Map of the United States color-coded by carbon emissions for delivered electricity

U.S. State	CO_2e Emission Factor for Delivered Electricity (lb/kWh)	*Break-Even* Heat Pump COP	*Break-Even* Heat Pump HSPF
AK	1.280	3.0	10.4
AL	1.330	3.2	10.8
AR	1.400	3.3	11.4
AZ	1.290	3.1	10.5
CA	0.603	1.4	4.9
CO	2.147	5.1	17.5
CT	0.728	1.7	5.9
DC	2.671	6.4	21.7
DE	1.815	4.3	14.8
FL	1.449	3.5	11.8
GA	1.518	3.6	12.3
HI	1.822	4.3	14.8
IA	1.919	4.6	15.6
ID	0.156	0.4	1.3
IL	1.267	3.0	10.3
IN	2.364	5.6	19.2
KS	1.964	4.7	16.0
KY	2.448	5.8	19.9
LA	1.320	3.1	10.7
MA	1.255	3.0	10.2
MD	1.595	3.8	13.0
ME	0.578	1.4	4.7
MI	1.659	3.9	13.5
MN	1.541	3.7	12.5
MO	2.166	5.2	17.6

MS	1.325	3.2	10.8
MT	1.767	4.2	14.4
NC	1.395	3.3	11.3
ND	2.309	5.5	18.8
NE	1.719	4.1	14.0
NH	0.661	1.6	5.4
NJ	0.728	1.7	5.9
NM	2.136	5.1	17.4
NV	1.243	3.0	10.1
NY	0.745	1.8	6.1
OH	2.083	5.0	16.9
OK	1.744	4.2	14.2
OR	0.476	1.1	3.9
PA	1.385	3.3	11.3
RI	1.071	2.6	8.7
SC	1.034	2.5	8.4
SD	0.916	2.2	7.4
TN	1.350	3.2	11.0
TX	1.501	3.6	12.2
UT	2.162	5.1	17.6
VA	1.227	2.9	10.0
VT	0.008	0.0	0.1
WA	0.355	0.8	2.9
WI	1.841	4.4	15.0
WV	2.325	5.5	18.9
WY	2.468	5.9	20.1
US	1.320	3.2	10.8

Table 3 CO_2e emission factors for delivered electricity in all 50 states, based upon U.S. EPA eGRID 2010 data.

Future Carbon and Electricity

Most long-term carbon reduction scenarios recommend that domestic heating end-uses will need to be converted to electricity. Yet, in many U.S. locations, pursuing this path presently will result in a carbon penalty (as noted above). The expected life-time of HVAC equipment is approximately 15 years, so a choice for gas heating now does not necessarily lock you out of electric heating in the future. But care should be taken to ensure flexibility and maintain the potential for a future switch to electricity in 15-years time. Projects might install a gas forced air heater today, but leave room for future installation of a heat pump heat exchange coil. Or projects could ensure that sufficient electrical service is installed that can meet the demand of future electrical heating appliances (e.g., heating, cooling and hot water).

References

Boudreaux, P., Biswas, K., & Jackson, R. (2012). *Advancing Residential Retrofits in the Mixed-Humid Climate to Achieve Deep Energy Savings: Final Report on Knoxville, TN Homes* (No. ORNL-27 (4-00)). Oak Ridge, TN: Oak Ridge National Laboratory. Retrieved from http://inspire.ornl.gov/Document/View/be3b23ee-a47d-449d-ad62-5bb17299f99a?q=boudreaux

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

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

Less, B., & Walker, I. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* (No. LBNL-6601E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/sites/all/files/a_meta-analysis_0.pdf

Occupant Behavior in Deep Retrofit Phases

Given our training as building performance professionals, designers, engineers or construction professionals, it is easy to think of a deep energy remodeling project as a purely technical matter. All of the important decisions and factors affecting performance before and after the project are those we've been taught to consider—HVAC, hot water system type, airtightness, cellulose versus fiberglass, foam board versus spray polyurethane foam, etc. This is an asset-based approach, which ignores the occupants. But the real rule of home performance and home energy use is variability. If we hold all of the building's technical features constant and place different occupants in those buildings, very different energy uses can result. In most cases, who occupies the home is more important than what type of insulation you use, or whether the walls are R 23 vs. R30, or whether the home is 3 vs. 2 ACH_{50}. Controlling for variable behaviors is exactly what we try to do when performing an asset rating of a home, such as a HERS assessment or Passive House certification. Yet unsurprisingly, evidence suggests that our building simulation models can become more accurate for a given house when we include actual operational information, such as thermostat set-points, appliance usage, etc (Ingle et al., 2012). Contrary to the common asset-based approach, experience shows that a deep retrofit guided by the home occupants' behavior, needs, patterns, and desires will be the most successful, in terms of actual performance, cost-effectiveness, willingness to progress from a design to an actual implementation, and customer satisfaction. This equals more business for you, the contractor.

How can thinking about behavior and occupants make you and your DER projects more successful? Here are some basic tips to improve homeowner engagement and decision making:

- Engage with your clients to find what might motivate them to undergo a DER—is it comfort, control, health, security, energy savings or a combination of factors?
- Design your DER strategy around your client's needs and wants.
- Leverage existing behavior patterns to reduce energy use and discuss new patterns that could have a significant impact.
- Attain better estimates of energy and cost reductions and where energy is going in their specific home. Some people use lots of hot water because they have children, or have many plug loads because they operate a home server and have multiple TVs/gaming systems and large lighting demand due to outdoor security lighting or a basement. Addressing these individual end-uses can make or break a project.

Below, we provide an outline of the DER process—recruitment, planning, use—and some concrete examples and guidance as to how to advantageously incorporate occupant behavior into your projects.

Occupants during project recruitment

Sell the benefits that customers value. Large reviews of U.S. home retrofit programs have suggested that occupants are generally more interested in improved comfort and IAQ, or less noise, maintenance, etc (Fuller et al., 2010). But some are highly motivated by cost savings, and it is important to identify these cases (see below).

Know your market, so that you can sell most effectively. Try to identify the following in your locale:

- What sells?
- What are the drivers of closing a deal (going from talk to work)?
- How can you couple DER upgrades with other home improvements?
- How can you portray your other retrofit projects in a real-life, social contexts for future marketing purposes (this can include open-house events)?
- What competing desires does energy retrofitting have to be negotiated against? You have to be aware of what people are otherwise spending their remodeling money, and some of it needs to be redirected into energy upgrades. For example, if homeowners are set on replacing windows for aesthetic, maintenance and comfort reasons, ensure that they install climate-appropriate, energy efficient units.

Target the homes most likely to engage in DERs, including **dedicated environmentalists** and **high-usage homes.** Dedicated environmentalists *may* already have low energy use or you can help them achieve that goal. Either way, they are motivated to perform a DER, either because of their dedication to reducing environmental impact or their desire for a better performing home. High-usage homes have the greatest potential for cost-effective energy savings and carbon emissions reductions. These can be identified as homes with substantially higher energy consumption than the regional average.

Occupants during project planning

Understand the occupant's interest, needs, wants and expectations. Ranking occupants on the following categories will help you generate insight as to how best to meet their needs and create a successful project.

- Social and personal background
    - Familiarity with home ownership, maintenance, upkeep?
    - Any past experience with remodeling?
    - Cultural notion of what a "good home" is?
    - Multiple decision-makers and styles/approaches?
    - Husband vs. wife team?
    - Trust in professionals
- Resources
    - Budget
    - Time/availability
    - Competencies/skills
    - DIY contributions, including design and/or construction
- Tolerance for disruption
    - This could suggest things like an exterior insulation retrofit to minimize interior disruption
    - Could also lead to recommendations for over-time deep upgrades
- Hunger for information or curiosity
    - Level of engagement in planning and eventual energy management
    - Active vs. passive
- Knowledgeable about home and its systems, or interested in becoming so?
- Ranking of priorities—saving the planet, energy savings, comfort, noise, lighting quality, aesthetics, costs, cost savings, payback, historical preservation/detailing.

- Remember, some priorities are overlapping and linked. For example, wall insulation can reduce energy use and noise from outside, as well as improve comfort. Try to identify retrofit strategies that provide as much benefit to the homeowner across as many priorities as possible.
- A careful ranking of priorities will help in making tough choices during construction that often arise as unanticipated issues are revealed, such as mold or structural damage. For a useful homeowner priorities planning tool click here.

Try to identify the occupant's persona. These categories and rankings may help you better understand the occupants' persona (type), which can help you to understand their motivations, actions and goals. Homeowners vary in terms of their level of engagement (e.g., active vs. passive), their priorities (e.g., money, climate change, pollution, comfort), and the extent to which their behaviors actually reflect their priorities (e.g., stumbling vs. effective proponents of conservation). BC Hydro produced the following helpful list of persona types based upon analysis of customer survey and energy usage data:

- Tuned-out and carefree
- Stumbling proponents
- Comfort seekers
- Entrenched libertarians
- Cost-conscious practitioners
- Devoted Conservationists

Use the persona to inform project strategy. One way in which such persona typing could be useful is for targeting homeowners for a DER. This is illustrated by the *Stumbling Proponent* type. They are interested in conservation in the abstract, but their behaviors are "poor" and metered energy use often high. For example, they identify with environmental causes, but they do not consistently turn lights off when leaving a room. This is a great segment to target for a DER, because they have high energy usage (and lots of cost-effective potential), as well as well-intentioned attitudes and opinions, and you can help them fulfill those values through a DER project.

Another way this type of occupant characterization could be useful would be in system design and controls. An engaged and effective occupant may respond best to systems and controls that give them lots of feedback and opportunity to interact and learn. For example, they can be relied upon to engage in passive cooling strategies, such as window and whole house fan operation, or they can reliably keep interior doors open to facilitate air-mixing in a home with ductless heat pumps. They might also use whole house electricity monitoring to help them diagnose and eliminate energy vampires in their home. In contrast, dis-engaged, set-it-and-forget-it types might benefit more from systems where controls are not in the occupants' hands. This could include a smart thermostat-controlled nighttime ventilative cooling system or a ducted forced air system, and instead of electricity monitoring and feedback, they may benefit more from a post-retrofit electricity audit by a professional and installation of smart power strips.

E**ngage occupants in technical planning early and often.** There is rarely a system whose performance does not vary with behavior. For example, a water heating system may seem like a straightforward decisions based on Energy Factors, but the performance benefit of tankless water heaters is highly variable depending on piping layout and use patterns. For example, some occupants use more hot water when there is no tank constraining the available amount of hot water. Similarly, a ductless mini-split heat pump can seem like a great option that eliminates ducts and has fabulous energy performance. But occupants can tell you if they are willing/able to keep doors open between rooms or have jump ducts added to ensure more even temperature distribution. Some also have strong opinions about the non-traditional-looking interior heat pump head unit. Furthermore, any measures that are included in a project must be understood and accepted by the occupants. For example, several cases of very airtight DERs have been documented with mechanical ventilation systems that are simply turned off or otherwise "defeated" by occupants, whether due to noise, confusion, or discomfort (Berges & Metcalf, 2013). Similar occupant "defeat" efforts have also been documented with high efficiency clothes dryers (and their very long cycle times), as well as with smart, learning thermostats, where occupants have disabled their energy saving features, such as temperature setbacks (Parker, Sutherland, Chasar, Montemurno, & Kono, 2014). Finally, an occupant's willingness/ability to engage in appropriate maintenance is important. For example, an ERV/HRV ventilation system needs periodic maintenance, including filter replacement/cleaning and service of heat exchanger elements.

Use iterative feedback loops of proposed designs. When occupants are engaged in the modeling/design process, it can both illuminate their own behaviors/patterns to themselves, as well as make them more conscious of the energy and environmental impacts of their otherwise baseline behaviors. Energy models can also be useful tools as part of the sales process, in which occupants get a sense of the opportunity in their home, which can reinforce their decision to invest in an energy upgrade.

Strategies for absent occupants. What to do when occupants are not available for the process, such as during affordable housing or other professional development efforts?

- Educate occupants on building systems, operations, maintenance, etc. post-occupancy (see Occupants during use section below).
- Develop best guess as to future-occupants' persona and other aspects listed above. For example, developing an affordable housing DER may take a different direction than developing a market rate, high-end, green certified DER project. Occupant density, cultural attitudes, available resources, and experience with home ownership and maintenance may vary between these two project types; use your local experience as a guide in this matter. For example, if low-income households commonly have large extended families living under one roof in your local community, DER ventilation and hot water systems should be designed to accommodate.
- Given occupant unknowns, simple, robust systems will almost always maintain superior performance over the long term, in the face of neglect.
- Prioritize the use of systems whose performance is relatively independent of occupant behavior.
    - For example, DERs with high levels of insulation and airtightness will be less sensitive to variations in temperature set points.
    - Variable capacity equipment can meet loads, whether they are small or large.

Occupants during use

Educate occupants about a home's systems, design, etc. Provide a *Home Guide*, similar to those required by most green home certifications. Occupants often defeat "smart" or "advanced" systems that do not fill their needs (e.g., smart thermostats, heat pump water heaters that switch to resistance heating, or efficient clothes dryers with unacceptably long runtimes). Education on the purposes, functions and operations/maintenance requirements are especially important for such items. Provide a summary of the estimated energy uses in the home, to provide an enhanced understanding of what drives consumption in the renovated home. Also provide guidance on future decisions, including the basics of energy efficient and healthy purchasing for items such as appliances, cleaning supplies, etc.

Continue engagement and feedback. Develop a post-project relationship where you can help with energy management, including tracking progress on DER goals, and helping to troubleshoot if performance is not what was anticipated. This continued engagement can also lead to more "word of mouth" advocacy in the owner's social network for deep retrofits and a contractor's services.

References

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.

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

Ingle, A., Moezzi, M., Lutzenhiser, L., Hathaway, Z., Lutzenhiser, S., Van Clock, J., … Diamond, R. (2012). *Behavioral Perspectives on Home Energy Audits: The Role of Auditors, Labels, Reports, and Audit Tools on Homeowner Decision-Makingq* (No. LBNL-5712E). Berkeley, CA: Lawrence Berkeley National Lab.

Parker, D., Sutherland, K., Chasar, D., Montemurno, J., & Kono, J. (2014). *Measured Results of Phased Shallow and Deep Retrofits in Existing Homes* (No. FSEC-PF-463-14). Cocoa, FL: Florida Solar Energy Center. Retrieved from http://www.fsec.ucf.edu/en/publications/pdf/FSEC-RR-510-14.pdf

Over-Time Retrofits Guidance

Overview

Completing a deep green upgrade over-time may be an attractive alternative to an all-at-once approach, which can be seen as too costly, disruptive and simply overwhelming. Research in the United Kingdom has demonstrated that retrofits carried out over-time can achieve levels of home performance equal to those achieved by all-at-once DERs (Fawcett, 2013; Fawcett, Killip, & Janda, 2014), and select projects have been successful in the U.S. (Less & Walker, 2014). Over-time home energy upgrades can occur either with careful planning from the outset, or in a piece-meal fashion as time progresses. Both strategies have been shown to produce effective retrofits in the UK, and both paths have their own benefits and liabilities. The guidance we provide below is intended to capture the benefits (and limit the risks) of both approaches.

The following ***potential benefits*** may exist with an over-time approach:

1. Less perceived disruption, because it is spread out over-time.
2. More likely that occupants can continue to inhabit their home continuously, without any need for alternative accommodations.
3. Costs are spread over-time, allowing owners to build up savings between phases.
4. Introduce occupants to the benefits of energy upgrades, thus feeding their desire for further improvements and refinements.
5. More aligned with making incremental deep green improvements, as maintenance and equipment replacement require.
6. Over-time process can inform occupants of the effects of their behaviors, and the potential for behavior modification to reduce both energy use and project costs (through use of human effort rather than technology to achieve savings)

There are also some ***potential downsides*** to an over-time approach:

1. More numerous small disruptions.
2. Difficult to finance traditionally.
3. Costs may be higher, due to repeated fees and fixed costs, such as permitting, inspection and construction labor.
4. Possible need to reinvest in measures that are inadequately addressed, due to a lack of careful and detailed planning.
5. Lower aggregate energy savings and reduction in environmental footprint.
6. Difficult for occupants to delay the gratification of investing in glamorous efficiency measures (such as solar PV or windows), by first investing in the invisibles (insulation and airsealing).

We anticipate the following ***potential challenges*** in over-time projects:

1. Create rather than block future options and flexibility. Insulating an attic prior to air sealing it is the classic example of this. But a more deep retrofit example would be spending $3,000 on duct system repairs, which might later discourage the use of non-ducted space conditioning, or ducts might be brought into conditioned space later, making the initial investment wasteful.

2. Minimizing negative unintended consequences of the over-time approach. For example, aggressive air sealing could introduce substantial IAQ risks, if NOT pursued in parallel with upgrades to ventilation systems, as well as to combustion appliances.
3. Lack of tools to design and track progress on over-time DERs.
4. Project planning may be difficult over an extended time frame (e.g., substantially >5-years). An extended timeframe may mean that best practices in energy retrofit measures change, as might available equipment types/efficiencies, local codes and applicable standards (e.g., ASHRAE 62.2).
5. It will be challenging to implement a technical and complex project over an extended time period without a consistent and knowledgeable integrator, who can tie the phases and plans together, as well as help adjust plans according to changes in energy use, as well as in technology, materials and best practices.

It is important to note that some of the benefits and challenges are in tension with one another. For example, occupant needs (financial, social, etc.) may stipulate an over-time approach, but this might be more costly and has the potential to be technically sub-optimal. It is not always possible to have one's cake and eat it too. Here we provide guidance that hopefully helps to leverage the benefits and limit the downsides of over-time approaches, making such projects mostly 'win-wins'.

Guidance and strategies to address challenges and increase success

Use detailed and careful planning from the outset. To the extent possible, an over-time retrofit should be planned from the beginning with as much detail as an all-at-once project would be, even though all the work is not to be completed at that time. Project goals and performance metrics should be identified, and upgrade plans for each element of the project should be developed and carefully documented using a systems approach. Some additional effort is also required on: (1) anticipating future changing needs, such as aging-in-place, added floor area, new electronics, etc., (2) developing a timeline for required deferred maintenance, equipment replacement, and other upgrades, so as to be aligned with efficiency measures, and (3) developing contingency plans that anticipate some of the ways in which changes in codes/standards, technologies and best practices might affect upgrade plans.

Use iterative, post-occupancy evaluations at each stage of work, in order to inform changes or adjustments required in future stages. This is essentially equivalent to performing an energy audit between each stage of the over-time retrofit. In order to generate valuable feedback and to develop important new insights for an over-time upgrade, two things are required:

- An assessment of how installed efficiency measures compare with their intended performance and specifications (e.g., commissioning and potentially monitoring), as well as comparing measured energy use with predictions and objectives.
- An assessment of the home occupants' experience and needs in the upgraded home, likely by unstructured interview (e.g., issues or successes with comfort, controls, maintenance, etc.).

Actual over-time deep energy upgrade projects have shown that design and occupant experience in prior phases can usefully inform future decisions and plans, as well as to formulate new goals and objectives. For example, solar gain and afternoon overheating might prove to be an issue after the first phase of a retrofit, and this could spur inclusion in future phases of mechanical cooling or passive strategies, such as shading, thermal mass, or cross-ventilation.

Identify a home energy specialist who is willing to act as an over-time integrator for your project from start to finish, contributing when necessary and possibly providing services such as post-occupancy evaluation, utility bill analysis and feedback during interim periods.

Use transitionally appropriate technologies. These are those technologies that will be able to respond to future changes brought about by the retrofit. For example, variable capacity/multi-speed heat pumps have widely varying outputs and good efficiency at part-load, which means that if the home is insulated and air sealed in the future, the appliance can still provide perfectly adequate heating and cooling services.

Avoid sub-optimal investment and required re-work. It is best to fully address items when the fixed costs of design, permitting, disruption, on-site labor, and quality assurance (home performance specialist) are already engaged. Elements of the project that are addressed in any given retrofit stage should be done so fully, using current best practices for high performance homes, or explicit future plans to do so should be developed. This should help to limit the future obsolescence of any given measure. For example, if you install a variable capacity, ductless heat pump with SEER rating >20, it is unlikely that future changes in minimum federal standards will make that technology obsolete anytime soon. On the other hand, rework may be required if one insulates an attic, but only to a minimum level, such as R25, and not using best practices to avoid wind-washing along eaves and ensuring no compression at the roof perimeter and missing the access hatch. Of course, it is important to understand that with a long enough timeframe (and the associated changes in fuel prices and other associated costs), all projects will implement some upgrades that appear "suboptimal" in retrospect; following this guidance should help limit this.

Cluster upgrade projects by building trade, in order to limit transaction costs. For example, address all plumbing related measures at the same time, such as changes to distribution piping, pipe insulation, new piping for HVAC, low-flow fixtures and a new water heater. There may be some practical limitations on this, such as the need to use multiple trades persons for a given project/repair (e.g., needing to hire a carpenter or plasterer to make livable any damages caused by the primary plumbing work).

Whenever possible, address the building envelope and passive design elements (e.g., shading, cross-ventilation, daylighting) prior to making major HVAC and technology investments. The common argument for this approach is that it will allow you to properly select and size your HVAC system according to the loads of the upgraded home, which can save upfront costs and increase efficiency and performance. We argue further that in the over-time paradigm, innovation and change occur most dramatically in the realm of technology, so investments in the elements most subject to technological advances should be preferentially implemented later in the process, so as to capture as much of the innovative advantage as possible. Advances in heating and cooling technologies and household appliances are rapid, and they are driven by intense market competition, large R&D budgets and ever-increasing federal minimum efficiency standards. Other project elements, such as passive conditioning strategies, insulation and air sealing, experience much lower levels of innovation and change (i.e., we are still anxiously awaiting the cheap and effective 0.25" thick R30 wall sheathing).

Track and benchmark home performance over-time. Tracking performance from utility bills, or even better from Smart Meter data or other feedback devices, will help in assessing project performance over-time. This can greatly help any iterative post-occupancy evaluation that is engaged in. The use of real progress and data will help to calibrate expectations along the way. Always expect that energy consumption will vary year-to-year due to random factors, such as weather.

References

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

Fawcett, T., Killip, G., & Janda, K. B. (2014). Innovative Practices in Low Carbon Retrofit: Time, Scale and Business Models. In *Paradigm Shift: From Energy Efficiency to Energy Reduction Through Social Change*. Oxford, England. Retrieved from http://behaveconference.com/wp-content/uploads/2014/08/F_Tina_Fawcett_University_of_Oxford.pdf

Less, B., & Walker, I. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* (No. LBNL-6601E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/sites/all/files/a_meta-analysis_0.pdf

Climate Zone Guidance Packages

Method justification for DER specification recommendations

In the climate zone DER guidance documents, we provide specific guidance for insulation levels, basic approaches and technical equipment in DERs targeting energy reductions from 50% to zero net-energy. These were generated using a multifaceted and flexible approach. We performed no modeling or economic analysis in order to generate these recommendations, but we used others' results. These are not guaranteed to provide any given level of energy savings or cost-effectiveness. Rather, they represent a distillation of strategies that are currently available and have a demonstrated track record in deep retrofits. They are based on the following sources:

1. Engineering judgment, based upon an extensive review of over one hundred DER projects.
2. Specific published guidance given by researchers pursuant to their real-life research in DERs, such as efficiency measure specifications, best practices and lessons learned.
3. Simulation efforts (for more) that have targeted cost-optimal energy retrofits of existing U.S. homes, using representative measure cost data and different financing schemes.
4. U.S. EPA Energy Star product criteria and specifications, including ENERGY STAR Most Efficient designation.
5. Consortium for Energy Efficiency Tiers initiative for Super Efficient Home Appliances.
6. Published research findings and recommendations on specific technologies (e.g., heat pump water heaters, ductless mini-split heat pumps).
7. International Energy Conservation Code (2012) requirements.

Cold Climate

There are 34 states that are wholly or partially in the cold or very cold Building America climates. Conditions vary widely across these climate zones, which stretch from Alaska to Arizona and California to Rhode Island. Building professionals in the cold climate must be able to address solar gains in the summer and extreme, prolonged low temperatures and snow accumulation in the winter, along with torrential downpours, high winds, and, especially in areas east of the Mississippi, high humidity. The extreme temperature variations, forces of driving wind and rain, snow accumulation and melting can take their toll on buildings and contribute to premature aging. In addition, the cold climate housing stock of the Northeast includes some of the oldest homes in the U.S., some dating back to the 18th century.

Successful deep energy retrofits have been performed on existing homes in every climate zone in the U.S. A recent review of U.S. DERs reported on the performance of cold climate deep energy retrofits, and average energy use before and after the retrofits is pictured in Figure 5, in comparison with regional averages (Less & Walker, 2014). The average project cost was $57,000 ($31/ft^2), with average annual energy cost savings of $1,341. Further reporting on 36 Massachusetts and Rhode Island projects was published after the LBNL review (Gates & Neuhauser, 2014). These DERs had average site energy reductions of 55%, with average project costs for energy measures of $100,000 ($35/ft^2) ($79,000 for envelope improvements and $21,000 for HVAC and hot water improvements).

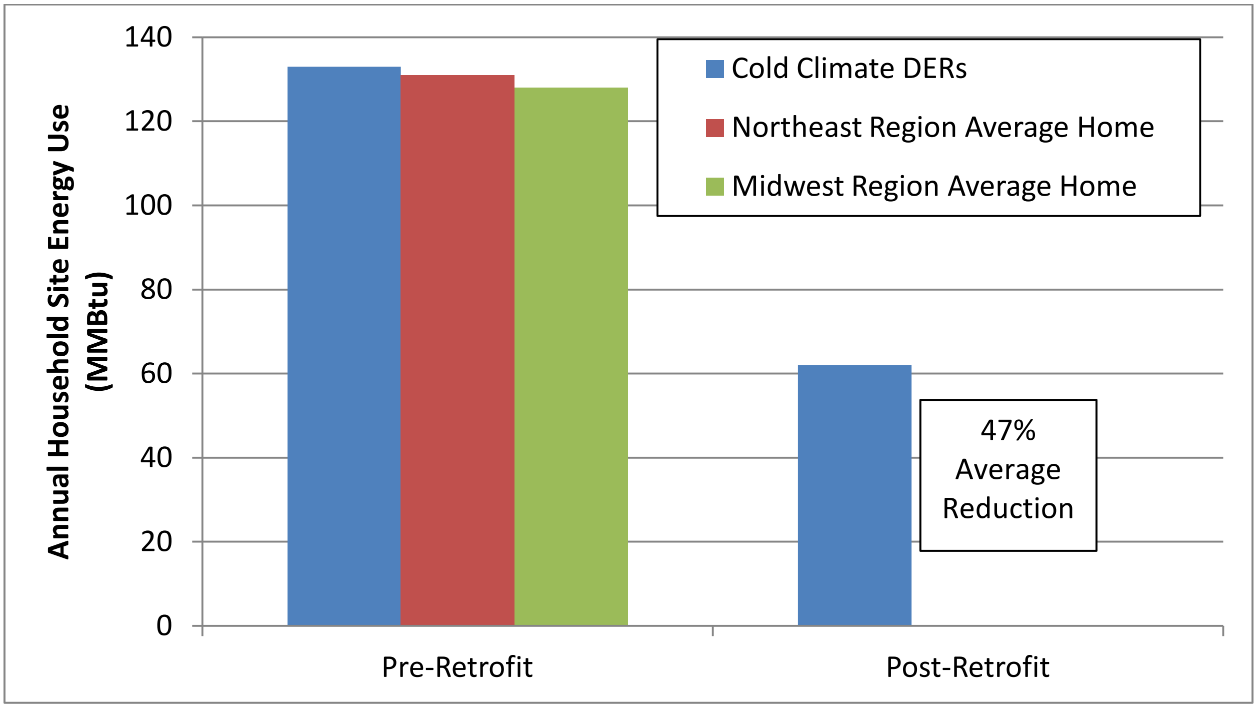


Figure 5 Average site energy use before and after deep retrofits in Cold climate homes, compared with regional averages from the 2009 Residential Energy Consumption Survey (U.S. Energy Information Administration, 2009).

Our analysis of financial return on investment for cold climate DERs suggests that project costs were generally too high to be justified by energy cost savings (though many other benefits may support these projects, including improved comfort, IAQ, home value, durability, etc.). Given this finding and given the aggressive envelope measures considered necessary for a cold climate DER, we suggest finding lower cost solutions (with similar performance) across the spectrum of retrofit measures. For example, while unvented attics conferred some airtightness benefit to DERs in Gates and Neuhauser, no obvious energy benefit was observed, so we might recommend the lower cost solution of insulating the attic floor. Or rather than a fully ducted and distributed heat recovery ventilation system, with its high costs, a much smaller distribution system could be provided with lower costs.

DER Specifications

This Building America Optimized Solution describes a set of building practices necessary to achieve the next step in energy performance for existing homes. Any home that follows the specifications listed below can be considered a high performance existing home. There is a high likelihood that the energy use, utility bills and environmental footprint of the home will be substantially less than either the pre-retrofit home or other similar homes in the region. The home will also most likely have lower maintenance, as well as improved comfort, air quality, humidity control, durability and resale value. The specifications and case studies below reflect only a few examples of the hundreds of ways that existing homes can be transformed into high performance homes through deep energy retrofits.

Below we provide specific guidance for insulation levels, basic approaches and technical equipment in deep retrofits. This guidance was generated using a multifaceted and flexible approach. These recommendations are not guaranteed to provide any given level of energy savings or cost-effectiveness, because existing homes and their occupants are so varied. Rather, they represent strategies that are currently available on the market and have a demonstrated track record in deep retrofit projects. They are based on a mixture of engineering judgment, published guidance from DOE research in technologies and DERs, simulations of cost-optimal DERs, Energy Star and Consortium for Energy Efficiency (CEE) product criteria, and the International Energy Conservation Code (2012).

All deep retrofits will be unique projects that vary depending on the existing conditions of the home and the owners' goals and budget. Projects that deviate from this guidance can still be successful. Always comply with local codes and regulations, and use local design and engineering expertise (as well as common sense) wherever appropriate. And as always, do no harm.

Component	**Deep Energy Retrofit Specification**
Envelope	

Foundation/Framed Floor	Address any bulk water issues through perimeter drains and site grading
	
	Basement:
	• Include basement in conditioned space
	    o Interior walls – R20 continuous interior insulation (preferably closed cell spray polyurethane foam, with ignition barrier--either ½" gypsum board or intumescent paint)
	    o Exterior walls - consider exterior insulation approaches if exposing foundation walls from exterior
	    o Slab - R10 continuous insulation
	• Unconditioned space
	    o Framed floor – Air seal all subfloor penetrations. Fill framed floor cavity with insulation (~R19 to R30), ensuring no compression and full alignment with the air barrier (subfloor)
	    o Ground – continuous vapor barrier
	    o *Note:* May be most appropriate if crawlspace has no mechanical equipment located in it and framed floor is relatively clear of obstructions, such as plumbing, ducting and bracing
	
	Crawlspace:
	• Vented, unconditioned crawl
	    o See unconditioned basement specification
	• Convert to unvented, conditioned crawlspace
	    o Walls - continuous R20 or greater, after sealing walls and existing vents
	    o Ground – continuous vapor barrier
	    o Install HVAC supply vent to condition

<table>
<tr><td></td><td>Slab:
Slab, R10 continuous insulation;</td></tr>
<tr><td>Above Grade Wall</td><td>Address any bulk water leakage through weather resistive barrier;

Wall cavity:
If cavity is not insulated, fill to R13
If removing sheetrock, ensure continuous air barrier at exterior sheathing, fill to R13
Consider additional interior insulation (targeting R30 total) using furring strips or 2nd framed wall
Exterior Insulation:
If replacing siding,
Ensure continuous drainage plane using Weather Resistive Barrier on exterior of sheathing
Add R15 continuous
Or R30 continuous insulation (and no cavity insulation)</td></tr>
<tr><td>Windows</td><td>Replacing existing windows:
Replace existing windows if there is surrounding water damage, lead-based paint or other issues
Replace with U-value <0.2, SHGC >0.35
Rehab existing windows;
Air seal with caulk and weather-stripping
Add storm window units or additional panes
Apply solar control window film or exterior shading</td></tr>
<tr><td>Attic</td><td>Address any bulk water intrusion through roof leaks;

Attic floor:
Ensure continuous air barrier at attic floor
Bring insulation up to R60 or greater
Cathedral attic:
Vented assembly
Establish continuous air barrier at ceiling
Add baffles providing ventilation airspace beneath roof sheathing
Fill remaining space with insulation, according to available rafter depth
Unvented assembly
Use air impermeable insulation to fill cavity
If using air permeable cavity insulation, must provide</td></tr>
</table>

	continuous air impermeable insulation (spf or foam board) above or below roof sheathing
Roof	
Airtightness	Interior/exterior gut-rehab: <= 1.5 ACH_{50}; Not gut-rehab: <= 3 ACH_{50}
Mechanicals	
Heating	If replacing central heating system: • Size according to ACCA Manuals J and S o *Gas:* Sealed combustion, modulating, variable speed, gas furnace, >= 0.95 AFUE o *Electric:* traditional or ductless heat pump with HSPF >9; • Consider combined space and water heating (more info) If not replacing heating system: • *Gas:* system tune-up • *Electric:* heat pump tune-up (refrigerant charge using superheat/sub cooling methods, ensure correct air flow, etc.)
Cooling	If replacing air conditioner: • Size according to ACCA Manuals J and S • Air conditioner or heat pump with SEER >16 If not replacing: • Perform tune-up (refrigerant charge using superheat/sub cooling methods, ensure correct air flow, etc.) Consider eliminating need for compressor cooling
Ventilation	Conform to ASHRAE 62.2-2013: whole house, kitchen and bathroom fans exhausted to outside and sized per the standard (for further guidance); Continuous whole house ventilation provided by HRV/ERV (possibly also providing local bathroom exhaust), with sensible recovery efficiency (SRE) >0.75.
Domestic Hot Water	Identify and fix any leaking distribution pipes; Replace all water fixtures with low-flow versions (<=1.5 gpm); Insulate all exposed hot water distribution pipes to >=R2; Consider lowering hot water set point; Consider demand pump for hot water delivery (due to increased wait

	times for hot water with low-flow fixtures); *If replacing domestic water heater:* • *Gas:* Condensing gas tankless water heater, EF >=0.95, Gas storage water heater, EF >0.7, avoid use of atmospheric draft water heaters in airtightened homes;; • *Electric:* Heat pump water heater, EF >2.0 (recommended ONLY if replacing electric resistance water heater) *If not replacing domestic water heater:* • Verify presence of or install heat trap on inlet/outlet ; • Insulate hot water tank to R5;
Air distribution	*Gut rehab:* • Move forced air ducts to conditioned space (unvented attic or crawlspace/basement) *Otherwise:* • Seal ducts so that duct leakage is <3% of nominal system airflow or 70% duct leakage is achieved • Bring duct insulation up to R8 with radiant barrier or bury & encapsulate ducts Consider eliminating the need for forced air ducting (e.g., ductless heat pump or point source gas heater); As necessary, address distribution, comfort and noise issues by adding support to sagging ducts, eliminating sharp bends and kinks, adding jump ducts, adding return area, addressing room air delivery issues, etc. Use ACCA Manual D for duct system re-design.
Other	
Lights	100% CFL or LED
Appliances	*Clothes washer and refrigerator:* • CEE Tier 2 or 3 (15-20% better than 2014 federal standards) *Dishwasher:* • CEE Tier 1 (10% better than 2014 federal standards)
Plugs/MELs	Specifically target for control or replacement the highest-consumption MELs or perform an MELs audit; Use smart receptacles or smart power strips, switched power outlets, whole house off switch, occupancy- or timer-based controls

Renewables	5 kW PV system (consider local weather and electricity rates, as well as PV financials (e.g., feed-in tariffs, net-generation issues))

Table 4 Cold climate DER specifications table.

Case Study Home—Belchertown, MA

Figure 6 Front facade of the Belchertown DER. ***Image courtesy of the Building Science Corporation.***

The Belchertown, MA DER from the National Grid DER pilot program is a great example of a cold climate DER with measured 74% energy savings, reasonable project costs of $52,000 ($27/ft2), and solid building science-guided design and construction. The home was built in 1760, and it was a great candidate for a DER, as it had above average pre-retrofit energy use and was otherwise in need of a substantial renovation. The home was thoroughly uncomfortable (occupants heated only one zone of the home and allowed the rest of the house to drop below freezing), and it had substantial water management issues (standing water in basement). The comprehensive DER addressed these comfort, durability and IAQ issues, while providing stellar energy performance 60% below the regional average and below the Passive House primary energy intensity requirement.

The home's envelope, systems, appliances and lighting were comprehensively upgraded to high performance standards. Some of the energy upgrades are pictured below in Figure 7 (for full details, see documents linked above). The existing 2x8 attic rafters were furred down with addition 2x3 purlins and the space was insulated spray polyurethane foam insulation. Similarly, the interior gut rehab of the post-and-beam framed home allowed for construction of an interior 2x4 stud wall spaced 1" from the post-and-beam structure, which when filled with spray foam was thermally broken and insulated to R32. The project implemented other best practices, such as bringing HVAC ducts into conditioned space through creation of an unvented attic, and the comfort of the home was dramatically improved with installation of a very-high efficiency propane furnace. A good example of future project planning was the inclusion of a condenser coil in the air handler to facilitate future heat pump installation. A heat recovery ventilator was connected with the ducted heating system, in order to provide tempered outdoor air, which is essential in a post-retrofit 1.9 ACH_{50} residence.

We recommend that DERs be planned to coincide with other planned renovations, as well as maintenance and equipment replacement activities. This home's existing need for a comprehensive renovation illustrates how this strategy can reduce both the costs and the disruption to the occupants. For example, the renovation already intended to trench around the interior perimeter of the basement and to install drains to address the moisture problems, and this allowed the DER measure (spray polyurethane foam and rigid sub-slab insulation) to be easily added. Similarly, previously installed and relatively new double pane low-e windows were upgraded with high performance exterior storm windows, which was much cheaper and less resource intensive than outright replacement of modern units. The window flashing did require repair and replacement throughout, which provides an example of the potential issues encountered in a DER when prior work has been done poorly and without consideration of the future super-insulated envelope.

Figure 7 Images from Belchertown DER (clockwise from top left), including sealed and insulated attic, high efficiency forced air gas furnace, new stud wall built to interior of old structure, and HVAC ducting insulated and in conditioned space. ***Images courtesy of the Building Science Corporation.***

What would we have done differently to improve performance and/or cost-effectiveness?

- DER research in cold climates has demonstrated that improved airtightness can be achieved without using spray polyurethane foam insulation. Furthermore, depending on the blowing agents used, the embodied energy and global warming potential of spray foam insulation materials can dramatically outweigh the benefits of reduced energy consumption. We might use the spf where it confers substantial other benefits (e.g., foundation walls), but avoid its

widespread use in the above grade walls, where blown fiber insulation could be paired with another air barrier option.
- We would also recommend a higher efficiency propane tankless water heater, as many such units are available on the market.

Special Considerations Based on Climate

- **Design building assemblies that manage moisture.** The extreme temperatures of cold climates can potentially lead to moisture damage and degradation in building assemblies, particularly in highly insulated homes with low drying potential. During the heating season, house pressurization can force warm inside air into building assemblies, where it can condense if it encounters cold surfaces near the exterior of the assembly. If mechanical cooling is provided, then condensation can also occur at interior surfaces, particularly those that are not vapor permeable.
    - Manage bulk water from wind driven rain using a continuous weather resistive barrier.
    - Ensure a continuous air barrier at interior surfaces (i.e., sheetrock, subflooring, etc.).
    - Prefer an assembly with drying potential to the exterior (and interior, if mechanically cooling). No interior vapor barrier. Any exterior vapor barrier must be insulated to the outside, so that its interior surface is above the dew point of inside air.
    - Control indoor humidity during heating season, target 40% relative humidity.
    - Use balanced mechanical ventilation, to avoid forcing moist interior or exterior air into building assemblies.

- **Temper ventilation air.** Due to very cold outside air temperatures, ventilation air should be tempered in cold climate homes, otherwise occupants may be uncomfortable. Air can be tempered by either mixing with heated inside air (as in a central fan integrated system), or through use of a heat or energy recovery ventilation system (which we recommend in cold climate deep retrofits).

- **Be careful when fuel switching.** Some states in the cold climate region have high carbon emissions in their delivered electricity, such as Montana, North Dakota, Wyoming, Wisconsin, Nebraska, Iowa, Indiana, Ohio, among others. Special care should be taken in these states when fuel switching in retrofits and when adding energy using features to a project, such as cooling, entertainment systems, etc. For a state-by-state estimate of electricity carbon intensity, see our guidance on Source Energy and Carbon Decisions.

Lessons Learned from Existing DER Projects in this Climate Zone

The following lessons are based on DERs in Massachusetts and Rhode Island (Gates & Neuhauser, 2014). DERs using heat pump space conditioning systems had 20% higher energy use and the space conditioning energy use was more variable between these projects than between natural gas heated projects. While it did not have an obvious impact on energy performance, the best airtightness was achieved with basement included in conditioned space, unvented attic assemblies using the “chainsaw” retrofit approach with fully adhered roofing membrane, and walls with exterior panels with taped seams. Homes with SPF in walls and attic had poorer airtightness than other insulation/air sealing approaches. Energy recovery ventilation systems with low sensible effectiveness led to comfort complaints by occupants in closed bedrooms with cold outside air being delivered continuously.

Climate-Specific Resources/Case Studies

Builder's Guide Cold Climates

Performance Results for Massachusetts and Rhode Island Deep Energy Retrofit Pilot Community (Gates & Neuhauser, 2014)

Proven Performance of 7 Cold Climate Deep Energy Retrofits (Osser, Neuhauser, & Ueno, 2012)

National Grid Deep Energy Retrofit Pilot (Neuhauser, 2012)

MASS SAVE Deep Energy Retrofit Builder Guide (Pettit, Neuhauser, & Gates, 2013)

Lessons Learned on Energy-Efficient Affordable Housing: Practical Insights on Combining Deep Energy Retrofits with Affordable Housing for 12 Cleveland Homes (Berges & Metcalf, 2013)

References

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.

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

Less, B., & Walker, I. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* (No. LBNL-6601E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/sites/all/files/a_meta-analysis_0.pdf

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

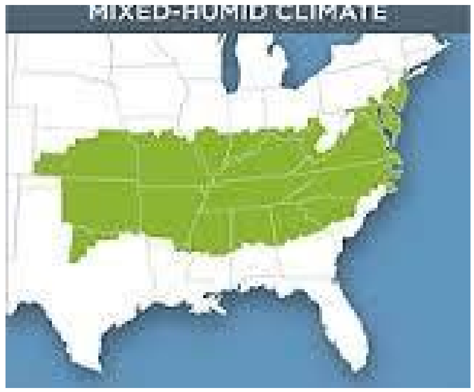
Osser, R., Neuhauser, K., & Ueno, K. (2012). *Proven Performance of Seven Cold Climate Deep Retrofit Homes* (No. KNDJ-0-40337-00). Somerville, MA: Building Science Corporation. Retrieved from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&ved=0CDIQFjAA&url=http%3A%2F%2Fwww.nrel.gov%2Fdocs%2Ffy12osti%2F54205.pdf&ei=Ys1UUenfO86ujALSqYDwCQ&usg=AFQjCNF01ZPHswARIvhfC-1Zh7TUBHCzUQ&sig2=jZ2ECKO5NOSpfDBd7otfmQ&bvm=bv.44442042,d.cGE

Pettit, B., Neuhauser, K., & Gates, C. (2013). MASS Save Deep Energy Retrofit Builder Guide. Building Science Corporation. Retrieved from http://www.buildingscience.com/documents/guides-and-manuals/gm-mass-save-der-builder-guide

U.S. Energy Information Administration. (2009). Residential Energy Consumption Survey (RECS) - Data - U.S. Energy Information Administration (EIA). Retrieved October 16, 2014, from http://www.eia.gov/consumption/residential/data/2009/

Mixed-Humid Climate

There are 22 states that are wholly or partially in the Building America mixed-humid climate. Conditions vary across this climate zone, which stretches from New York to South Carolina and from the Mid-Atlantic states to the Midwest as far as Kansas, Oklahoma, and northern Texas. Building professionals in the mixed-humid climate must be able to address solar gains in the summer, medium to high humidity, mild to cold temperatures in the winter, high annual rainfall and torrential downpours, high winds, and tornadoes, especially in the midwestern and southern states.



Successful deep energy retrofits have been performed on existing homes in every climate zone in the U.S. A recent review of U.S. deep energy retrofits (DERs) reported on the performance of mixed humid climate deep energy retrofits (Less & Walker, 2014), and average energy use before and after the retrofits is pictured in Figure 8, in comparison with regional averages. The average project cost was \$42,000 (\$17/ft^2), with average annual energy cost savings of \$1,800.

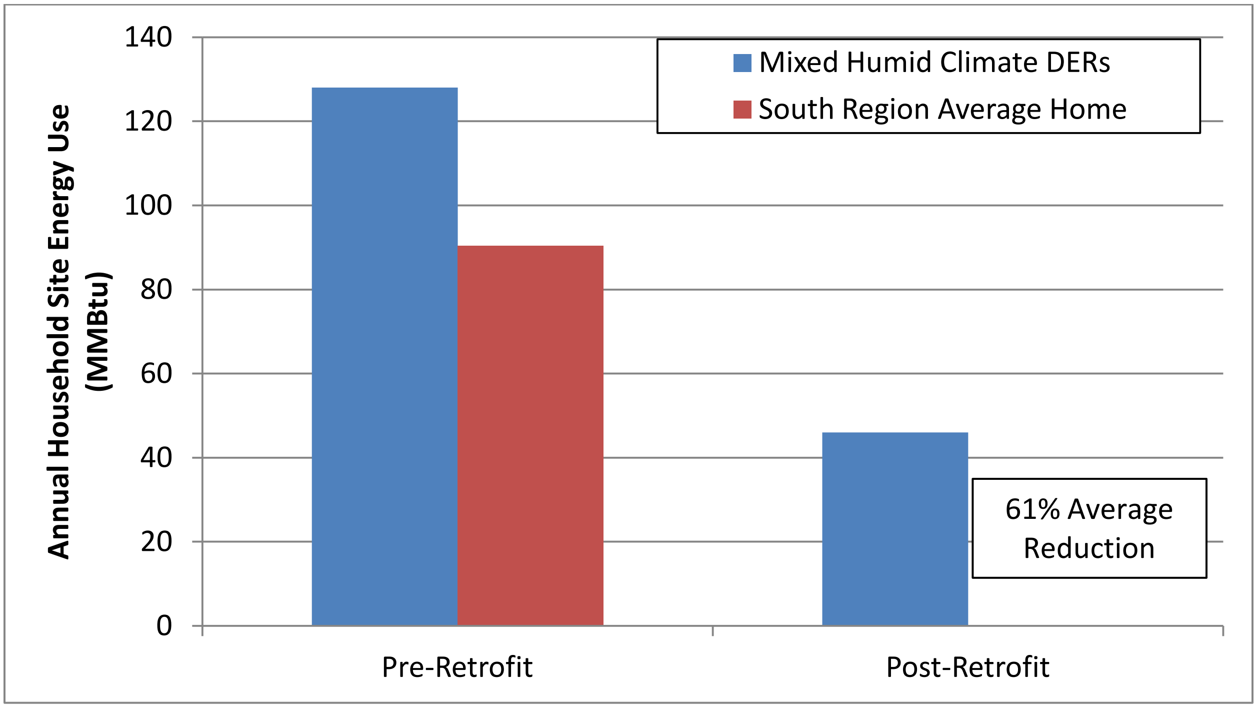


Figure 8 Average site energy use before and after deep retrofits in Mixed-Humid climate homes, compared with regional averages from the 2009 Residential Energy Consumption Survey (U.S. Energy Information Administration, 2009).

DER specifications

This Building America Optimized Solution describes a set of building practices necessary to achieve the next step in energy performance for existing homes. Any home that follows the specifications listed below can be considered a high performance existing home. There is a high likelihood that the energy use, utility bills and environmental footprint of the home will be substantially less than either the pre-retrofit home or other similar homes in the region. The home will also most likely have lower maintenance, as well as improved comfort, air quality, humidity control, durability and resale value. The specifications and case studies below reflect only a few examples of the hundreds of ways that existing homes can be transformed into high performance homes through deep energy retrofits.

Below we provide specific guidance for insulation levels, basic approaches and technical equipment in deep retrofits. This guidance was generated using a multifaceted and flexible approach. These recommendations are not guaranteed to provide any given level of energy savings or cost-effectiveness, because existing homes and their occupants are so varied. Rather, they represent strategies that are currently available on the market and have a demonstrated track record in deep retrofit projects. They are based on a mixture of engineering judgment, published guidance from DOE research in technologies and DERs, simulations of cost-optimal DERs, Energy Star and Consortium for Energy Efficiency (CEE) product criteria, and the International Energy Conservation Code (2012).

All deep retrofits will be unique projects that vary depending on the existing conditions of the home and the owners' goals and budget. Projects that deviate from this guidance can still be successful. Always comply with local codes and regulations, and use local design and engineering expertise (as well as common sense) wherever appropriate. And as always, do no harm.

<table>
<tr><th>Component</th><th>Deep Energy Retrofit Specification</th></tr>
<tr><td>Envelope</td><td></td></tr>
<tr><td>Foundation/Framed Floor</td><td>Address any bulk water issues through perimeter drains and site grading

Crawlspace:

Convert to unvented, conditioned crawlspace

Walls - continuous R10 or greater, after sealing walls and existing vents
Ground – continuous vapor barrier
Install HVAC supply vent to condition

Vented, unconditioned crawl

Framed floor – Air seal all subfloor penetrations. Fill framed floor cavity with insulation (~R19 to R30), ensuring no compression and full alignment with the air barrier (subfloor)
Ground – continuous vapor barrier
Note: May be most appropriate if crawlspace has no mechanical equipment located in it and framed floor is relatively clear of obstructions, such as plumbing, ducting and bracing

Basement:

Include basement in conditioned space

Interior walls - R10 continuous interior insulation (preferably closed cell spray polyurethane foam, with ignition barrier--either ½” gypsum board or intumescent paint)
Exterior walls - consider exterior insulation approaches if exposing foundation walls from exterior

Unconditioned space

See vented crawlspace specification

Uninsulated slab</td></tr>
<tr><td>Above Grade Wall</td><td>Address any bulk water leakage through weather resistive barrier;

Wall cavity:

Fill cavity to R13 (most likely drill and fill)
If removing sheetrock, ensure continuous air barrier at exterior sheathing, fill to R13
</td></tr>
</table>

	Exterior Insulation:
	• If replacing siding:
	  o Ensure continuous drainage plane using Weather Resistive Barrier on exterior of sheathing
	  o Add R5 continuous insulation
	• Or R20 continuous insulation (and no cavity insulation)

Windows	*Replacing existing windows:* • Replace existing windows if there is surrounding water damage, lead-based paint or other issues • Replace with U-value <0.35, SHGC <0.3 *Rehab existing windows;* • Air seal with caulk and weather-stripping • Add storm window units or additional panes • Apply solar control window film or exterior shading

Attic	Address any bulk water intrusion through roof leaks;
	
	Attic floor:
	• Ensure continuous air barrier at attic floor
	• Bring insulation level up to R49 or greater
	
	Cathedral attic:
	• Vented assembly
	  o Establish continuous air barrier at ceiling
	  o Add baffles providing ventilation airspace beneath roof sheathing
	  o Fill remaining space with insulation, according to available depth
	• Unvented assembly
	  o Use air impermeable insulation to fill cavity
	  o If using air permeable cavity insulation, must provide continuous air impermeable insulation (spf or foam board) above or below roof sheathing

Roof	If replacing roof finish, use light colored, low solar absorptance finish (solar reflectance >=0.25)
Airtightness	Interior/exterior gut-rehab, <= 3 ACH_{50}; Not gut-rehab, <= 5 ACH50
Mechanicals	
Heating	If replacing heating system:

	• Size according to ACCA Manuals J and S
	  o *Gas:* Sealed combustion, modulating, variable speed, gas furnace, >= 0.95 AFUE;
	  o *Electric:* traditional or ductless heat pump with HSPF >9;
	• Consider combined space and water heating (more info)
	
	If not replacing heating system:
	• *Gas:* system tune-up
	• *Electric:* heat pump tune-up (refrigerant charge using superheat/sub cooling methods, ensure correct air flow, etc.)

Cooling	If replacing air conditioner: • Air conditioner with SEER >16 • Size according to ACCA Manuals J and S If not replacing: • Perform tune-up (refrigerant charge using superheat/sub cooling methods, ensure correct air flow, etc.) Consider supplemental dehumidification and use passive cooling strategies (see suggestions below)
Ventilation	Conform to ASHRAE 62.2-2013: whole house, kitchen and bathroom fans exhausted to outside and sized per the standard (for further guidance);
Domestic Hot Water	Identify and fix any leaking distribution pipes; Replace all water fixtures with low-flow versions (<=1.5 gpm); Insulate all exposed hot water distribution pipes to >=R2; Consider lowering hot water set point; Consider demand pump for hot water delivery (due to increased wait times for hot water with low-flow fixtures); *If replacing domestic water heater:* • *Gas:* Condensing gas tankless water heater, EF >=0.95, Gas storage water heater, EF >0.7; • *Electric:* Heat pump water heater, EF >2.0 (Most effective when heating/cooling with electric heat pump) *If not replacing domestic water heater:* • Verify presence of or install heat trap on inlet/outlet ; • Insulate hot water tank to R5;
Air distribution	*Gut rehab:* • Move forced air ducts to conditioned space (unvented attic

	or crawlspace/basement) *Otherwise:* • Seal ducts so that duct leakage is <6% of nominal system airflow or 70% duct leakage is achieved • Bring duct insulation up to R8 with radiant barrier or bury & encapsulate ducts Consider eliminating the need for forced air ducting (e.g., ductless heat pump or point source gas heater); As necessary, address distribution, noise and comfort issues by adding support to sagging ducts, eliminating sharp bends and kinks, adding jump ducts, adding return area, addressing room air delivery issues, etc. Use ACCA Manual D for duct system re-design.
Other	
Lights	100% CFL or LED
Appliances	*Clothes washer and refrigerator:* • CEE Tier 2 or 3 (15-20% better than 2014 federal standards) *Dishwasher:* • CEE Tier 1 (10% better than 2014 federal standards)
Plugs/MELs	Specifically target for control or replacement the highest-consumption MELs or perform an MELs audit; Use smart receptacles or smart power strips, switched power outlets, whole house off switch, occupancy- or timer-based controls
Renewables	5 kW PV system (consider local weather and electricity rates, as well as PV financials (e.g., feed-in tariffs, net-generation issues))

Table 5 Mixed-humid climate DER specifications table.

Case Study Home—The Green Home

Figure 9 Front facade of the Green Home DER. ***Image courtesy of Oak Ridge National Lab.***

The Green home is located in Eastern Tennessee, and it was unoccupied for a substantial period of time prior to being purchased by an historic preservation society, who decided to do a gut-retrofit of the home to ready it for resale. Their goal was to achieve LEED certification. Measured energy reductions (relative to a pre-retrofit simulation model) were 80% (83% with PV), and utility bill savings were $1,460 annually. Originally built in 1909, this two-story, 2,300 ft2 single-family home had three bedrooms and two and a half bathrooms, with a vented attic and vented basement/crawlspace. The uninsulated basement and attic were connected by leaky, uninsulated balloon-framed walls. The home's entire envelope and systems were upgraded. The basement was insulated and conditioned (R10 interior, sealed foam board), new above grade wall weather resistive barrier (WRB) and R16 cavity fill were added, and the attic roof deck was sealed and insulated to R38 using closed cell spray foam (see Figure 10 below). The post-retrofit home was 5.5 ACH_{50} with 3% duct leakage to outside (cfm_{25} per unit floor area). In a transition to an all-electric home (see note below), a solar thermal hot water system (with electric resistance backup) and a new 20.5 SEER, 13 HSPF ducted heat pump was installed in the conditioned basement, with R6 ducts located in the conditioned basement and unvented attic. A solar PV system was also installed and most lights were upgraded to Energy Star CFLs. The project cost for these incremental DER measures was $45,000 ($35,000 without PV).

The lack of pre-retrofit data in this home is very common in deep retrofit projects, which more often than not occur when a home has been purchased and utility records for previous owners are unavailable. In these cases, pre-retrofit conditions are also generally not well characterized. For example, in this project no pre-retrofit blower door test was performed. In such cases, a pre-retrofit model can be developed for comparison (as was done to provide the savings estimates above), or more simply, a post-retrofit performance target can be selected, which is entirely unrelated to pre-retrofit performance. Examples of performance targets include HERS indices (such as 50 or less), site energy relative to the regional average (such as <50% the regional average in the RECS survey), or Energy Star V3. The Green Home's post-retrofit HERS index was 61, and its energy use was 14.4 $kBtu/ft^2$ which is 66% less than the regional average (~40 $kBtu/ft^2$). Targeting a post-retrofit performance threshold limits the value of pre-retrofit assessments and diagnostics. For example, a blower door test would only be useful for identifying leakage pathways, and even this might not be useful in a comprehensive project with massive changes envisioned.

Figure 10 ***Left***: **unvented attic sealed with closed cell spray foam.** ***Right:*** **insulated band-joist.** ***Images courtesy of Oak Ridge National Lab.***

What would we have done differently to improve performance and/or cost-effectiveness?

- As a gut-rehab project, we would recommend this home target an airtightness level of 3 ACH_{50}, rather than the 5.5 ACH_{50} that it achieved. Some efforts were made to connect the new wall WRB to the foundation and attic air control layers, but results were not exemplary. Possibly a hybrid flash and batt approach could have been used to more effectively establish a continuous air barrier.
- In this project, we would also consider eliminating the solar thermal system and investing those savings in a larger PV electric system. We would then substitute a heat pump water heater with Energy Factor >2.
- The Green Home switched from natural gas for space and water heating, and in these cases, we recommend source energy and carbon emission estimates be used in project planning, in order to avoid increasing emissions or source energy use. For example, in the Green Home, site energy savings were 80%, whereas source energy (and presumably carbon) savings were only 58% (a 28% reduction in savings). The switch to all electricity likely also reduced the energy costs savings achieved by the project, as electricity is generally more expensive than natural gas on a per Btu basis. Luckily, this home reduced its electricity consumption overall, but in cases where that does not occur, reductions in performance can be worse (even leading to increases in usage).

Special considerations based on climate

Place special emphasis on humidity control. With improvements in the thermal performance of the retrofitted home, the central cooling system will run less and provide less dehumidification. This can increase interior moisture levels, and additional mechanical ventilation may exacerbate this in certain cases or times of the year.

- Ensure proper venting of interior moisture sources through kitchen and bathroom ventilation designed to at least ASHRAE 62.2-2013.
- Provide supplemental dehumidification in low-load retrofits, or use other appropriate solutions:
    - Dehumidifiers, including stand-alone (closet or attic) and integrated with ventilation and central HVAC systems;
    - Enhanced cooling strategies, when indoor humidity is high:
        - Reduce airflow per ton to 200 cfm,
        - Sub-cooling of space by 2-3°F,
        - Cooling system reheat controls.

Prefer supply or balanced ventilation, due to condensation concerns in exhaust-vented, depressurized homes with mechanical cooling. In these homes, humid outside air can be sucked into building cavities by exhaust airflows, and if the interior surfaces are cooled below the dew point condensation can occur and possibly cause damage overtime. Vinyl wall paper is of particular concern.

Employ passive cooling strategies. Passive strategies take advantage of natural phenomenon to replace some of the energy-intensive mechanical cooling that is otherwise required in hot climates.

- Exterior shading wherever feasible, particularly on the Eastern and Western facades. Solutions include trees, shrubs, arbors, window shutters, window awnings, covered porches and deep roof overhangs.
- Select light-colored exterior finish materials that reflect, rather than absorb, the sun's energy. This includes "cool" roof and wall finish materials.

Beware fuel switching in states with high carbon electricity supply. Some states in the mixed-humid climate region have high carbon emissions in their delivered electricity, such as Kentucky, Indiana and Missouri. Special care should be taken in these states when switching from gas to electricity in retrofits and when adding electricity using features to a project, such as cooling, entertainment systems, etc. For a state-by-state estimate of electricity carbon intensity, see our guidance on Source Energy and Carbon Decisions

Climate-specific resources/case studies

Building America Guidance

Deep Residential Retrofits in East Tennessee (Phillip Boudreaux, Hendrick, Christian, & Jackson, 2012)

Advancing Residential Retrofits in the Mixed-Humid Climate to Achieve Deep Energy Savings: Final Report on Knoxville, TN Homes (Philip Boudreaux, Biswas, & Jackson, 2012)

References

Boudreaux, P., Biswas, K., & Jackson, R. (2012). *Advancing Residential Retrofits in the Mixed-Humid Climate to Achieve Deep Energy Savings: Final Report on Knoxville, TN Homes* (No. ORNL-27 (4-

00)). Oak Ridge, TN: Oak Ridge National Laboratory. Retrieved from http://inspire.ornl.gov/Document/View/be3b23ee-a47d-449d-ad62-5bb17299f99a?q=boudreaux

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://inspire.ornl.gov/Document/View/e89694bd-68c0-43fb-a6fa-3a17c6557a97?q=boudreaux

Less, B., & Walker, I. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* (No. LBNL-6601E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/sites/all/files/a_meta-analysis_0.pdf

U.S. Energy Information Administration. (2009). Residential Energy Consumption Survey (RECS) - Data - U.S. Energy Information Administration (EIA). Retrieved October 16, 2014, from http://www.eia.gov/consumption/residential/data/2009/

Hot-Humid Climate

There are nine states that are wholly or partially in the hot-humid Building America climate region of the United States, which stretches from Texas to Florida along the Gulf Coast, and from southern Florida to North Carolina along the Atlantic coastline. Building professionals in the hot-humid climate must be able to address large solar gains in the summer and significant levels of moisture in the ambient air most of the year, along with torrential downpours and high winds, including hurricanes.

Successful deep energy retrofits have been performed on existing homes in every climate zone in the U.S. A recent review of U.S. DERs reported on the performance of hot-humid climate deep energy retrofits (Less & Walker, 2014), and average energy use before and after the retrofits is pictured in Figure 11 in comparison with regional averages. Further reporting on 40 Florida projects was later provided from Florida (McIlvaine, Sutherland, & Martin, 2013). The average project cost was $9,500 ($\$7/ft^2$), with average annual energy cost savings of $831. The 46 DERs reported in Florida had average HERS index reductions of 41%, with project costs of $16,424 ($3,854 incrementally) and annual energy cost savings of $612. Site energy savings of 36% are lower than those targeted in an aggressive DER, but nearly all hot-humid projects were requiring that the installed measures be cost-effective and were low-income, developer projects rather than owner-occupied homes.

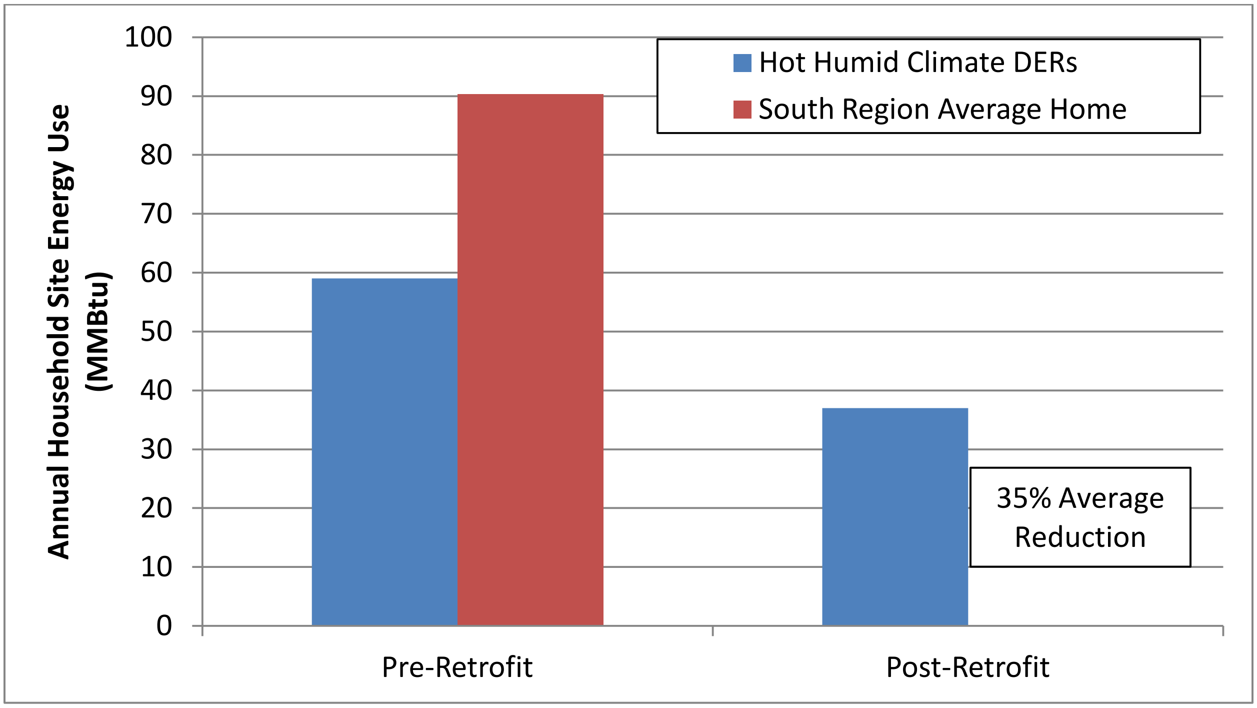


Figure 11 Average site energy use before and after deep retrofits in Hot-Humid climate homes, compared with regional averages from the 2009 Residential Energy Consumption Survey (U.S. Energy Information Administration, 2009).

DER specifications

This Building America Optimized Solution describes a set of building practices necessary to achieve the next step in energy performance for existing homes. Any home that follows the specifications listed below can be considered a high performance existing home. There is a high likelihood that the energy use, utility bills and environmental footprint of the home will be substantially less than either the pre-retrofit home or other similar homes in the region. The home will also most likely have lower maintenance, as well as improved comfort, air quality, humidity control, durability and resale value. The specifications and case studies below reflect only a few examples of the hundreds of ways that existing homes can be transformed into high performance homes through deep energy retrofits.

Below we provide specific guidance for insulation levels, basic approaches and technical equipment in deep retrofits. This guidance was generated using a multifaceted and flexible approach. These recommendations are not guaranteed to provide any given level of energy savings or cost-effectiveness, because existing homes and their occupants are so varied. Rather, they represent strategies that are currently available on the market and have a demonstrated track record in deep retrofit projects. They are based on a mixture of engineering judgment, published guidance from DOE research in technologies and DERs, simulations of cost-optimal DERs, Energy Star and Consortium for Energy Efficiency (CEE) product criteria, and the International Energy Conservation Code (2012).

All deep retrofits will be unique projects that vary depending on the existing conditions of the home and the owners' goals and budget. Projects that deviate from this guidance can still be successful. Always comply with local codes and regulations, and use local design and engineering expertise (as well as common sense) wherever appropriate. And as always, do no harm.

Component	**Deep Energy Retrofit Specification**
Envelope	

Foundation/Framed Floor	Address any bulk water issues through perimeter drains and site grading
	
	Crawlspace:
	• Convert to unvented, conditioned crawlspace
	    o Walls - continuous R5 or greater, after sealing walls and existing vents
	    o Ground – continuous vapor barrier
	    o Install HVAC supply vent to condition
	• Vented, unconditioned crawl
	    o Framed floor – Air seal all subfloor penetrations. Fill framed floor cavity with insulation (~R13 to R30), ensuring no compression and full alignment with the air barrier (subfloor)
	    o Ground – continuous vapor barrier
	    o *Note:* May be most appropriate if crawlspace has no mechanical equipment located in it and framed floor is relatively clear of obstructions, such as plumbing, ducting and bracing
	
	Basement:
	• Include basement in conditioned space
	    o See conditioned crawlspace specification
	• Unconditioned space
	    o See vented crawlspace specification
	
	Uninsulated slab

Above Grade Wall	Address any bulk water leakage through weather resistive barrier; *Wall cavity:* • If cavity is not insulated, fill to R13 • If removing sheetrock, ensure continuous air barrier at exterior sheathing, fill to R13 *Concrete block construction:* • Consider exterior continuous insulation, R5
Windows	*Replacing existing windows:* • Replace existing windows if there is surrounding water

	damage, lead-based paint or other issues • Replace with U-value <0. 5, SHGC <0.27 *Rehab existing windows:* • Air seal with caulk and weather-stripping • Add storm window units or additional panes • Apply solar control window film or exterior shading (prioritize South and West facades)

Attic	Address any bulk water intrusion through roof leaks;
	
	Attic floor:
	• Ensure continuous air barrier at attic floor
	• Bring insulation level up to R38 or greater
	
	Cathedral attic:
	• Vented assembly
	  o Establish continuous air barrier at ceiling
	  o Add baffles providing ventilation airspace beneath roof sheathing
	  o Fill remaining space with insulation, according to available depth
	• Unvented assembly
	  o Use air impermeable insulation to fill cavity
	  o If using air permeable cavity insulation, must provide continuous air impermeable insulation (spf or foam board) above or below roof sheathing

Roof	If replacing roof finish, use light colored, low solar absorptance finish (solar reflectance >=0.25)
Airtightness	Interior/exterior gut-rehab: <= 5ACH$_{50}$; Not gut-rehab: <= 7 ACH$_{50}$
Mechanicals	

Heating	If replacing heating system:
	• Size according to ACCA Manuals J and S
	  o *Gas:* Sealed combustion, modulating, variable speed, gas furnace, >= 0.9 AFUE;
	  o *Electric:* traditional or ductless heat pump with HSPF >9;
	• Consider combined space and water heating (more info)
	
	If not replacing heating system:
	• *Gas:* system tune-up
	• *Electric:* heat pump tune-up (refrigerant charge using

	superheat/sub cooling methods, ensure correct air flow, etc.)
Cooling	If replacing air conditioner: • Air conditioner with SEER >18 • Size according to ACCA Manuals J and S If not replacing: • Perform tune-up (refrigerant charge using superheat/sub cooling methods, ensure correct air flow, etc.) Consider supplemental dehumidification (see suggestions below)
Ventilation	Conform to ASHRAE 62.2-2013: whole house, kitchen and bathroom fans exhausted to outside and sized per the standard (for further guidance);
Domestic Hot Water	Identify and fix any leaking distribution pipes; Replace all water fixtures with low-flow versions (<=1.5 gpm); Insulate all exposed hot water distribution pipes to >=R2; Consider lowering hot water set point; Consider demand pump for hot water delivery (due to increased wait times for hot water with low-flow fixtures); *If replacing domestic water heater:* • *Gas:* Condensing gas tankless water heater, EF >=0.95, Gas storage water heater, EF >0.7; • *Electric:* Heat pump water heater, EF >2.0 (savings much greater when in conditioned space, also greater when replacing existing electric resistance tank heater and smaller when replacing gas dhw) • Consider heat pump combined with a 40-gallon solar thermal system with collector integrated storage *If not replacing domestic water heater:* • Verify presence of or install heat trap on inlet/outlet • Insulate hot water tank to R5
Air distribution	*Gut rehab:* • Move forced air ducts to conditioned space *Otherwise:* • Seal ducts so that duct leakage is <6% of nominal system airflow or 70% duct leakage is achieved • Bring duct insulation up to R8 with radiant barrier or bury & encapsulate ducts

	Consider eliminating the need for forced air ducting (e.g., ductless heat pump or point source gas heater); As necessary, address distribution, noise and comfort issues by adding support to sagging ducts, eliminating sharp bends and kinks, adding jump ducts, adding return area, addressing room air delivery issues, etc. Use ACCA Manual D for duct system re-design.
Other	
Lights	100% CFL or LED
Appliances	*Clothes washer and refrigerator:* • CEE Tier 2 or 3 (15-20% better than 2014 federal standards) *Dishwasher:* • CEE Tier 1 (10% better than 2014 federal standards)
Plugs/MELs	Specifically target for control or replacement the highest-consumption MELs or perform an MELs audit; Use smart receptacles or smart power strips, switched power outlets, whole house off switch, occupancy- or timer-based controls; Pool pumps should be controlled by timer to operate a maximum of 5 hours per day, consider solar powered pump.
Renewables	5 kW PV system (consider local weather and electricity rates, as well as PV financials (e.g., feed-in tariffs, net-generation issues))

Table 6 Hot-humid climate DER specifications table.

Case Study Home—Net-Zero Phased Florida Retrofit

Figure 12 Phased DER home in Florida. ***Image courtesy of Danny Parker at the Florida Solar Energy Center.***

While many DERs may be completed all at once, most homes are more likely to be upgraded over-time, as funds and occupant patience allow, and as failing equipment and maintenance require. This Florida home is a great example of a successful, real-life, over-time retrofit. It was retrofitted over a 23-year period, with several retrofit phases, and extensive energy and performance measurement (see 23 years of energy use data in Figure 13). 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 are combined. During the 23-year retrofit period, the household experienced additions to the family (2 children), a 660 ft^2 floor area 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.

Upon moving into the home, the owners added attic insulation, cut pool pump run-time by >50% and exposed terrazzo tile flooring throughout the home, providing valuable thermal mass and added moisture resistance. Subsequent energy auditing revealed 9 ACH_{50} envelope and approximately 18% duct leakage. A blower door test 20 years later revealed much greater leakage—24 ACH_{50}—which reflects common changes in homes over-time, such as windows failing to close, added recessed can lights, and undampered bathroom fans. Experiments in compressor less cooling failed, leading to the central A/C and heating being upgraded in 1995 along with the ducts being sealed to 5% leakage (a 72% reduction!). Finally, in 2010 an aggressive upgrade was implemented, with a ¾ ton mini-split heat pump (SEER 26), exterior R5 wall insulation, new windows and other varied upgrades. All retrofits and phases are documented in painstaking detail in (Parker & Sherwin, 2012). These retrofit phases and developments provide a great example of the experimentation and learning that can occur as a home is lived in. Efforts to reduce energy use and to increase comfort can be assessed, and future efforts can be adjusted based on lessons learned. This feedback loop is key to a successful over-time DER.

This project is also exemplary for its comprehensive approach to reducing energy consumption. Not only were the obvious areas targeted for improvement (e.g., HVAC, wall insulation, windows), but so were energy efficient appliances, eliminating unnecessary appliances (e.g., garage freezer), appliance maintenance (e.g., cleaning refrigerator evaporator coil), operational performance (e.g., pool pump controls) and lighting. A whole house energy meter was also used to provide feedback to the occupants and to help them discover sources of wasted energy. This comprehensive approach helps to ensure that no savings opportunities are left off the table.

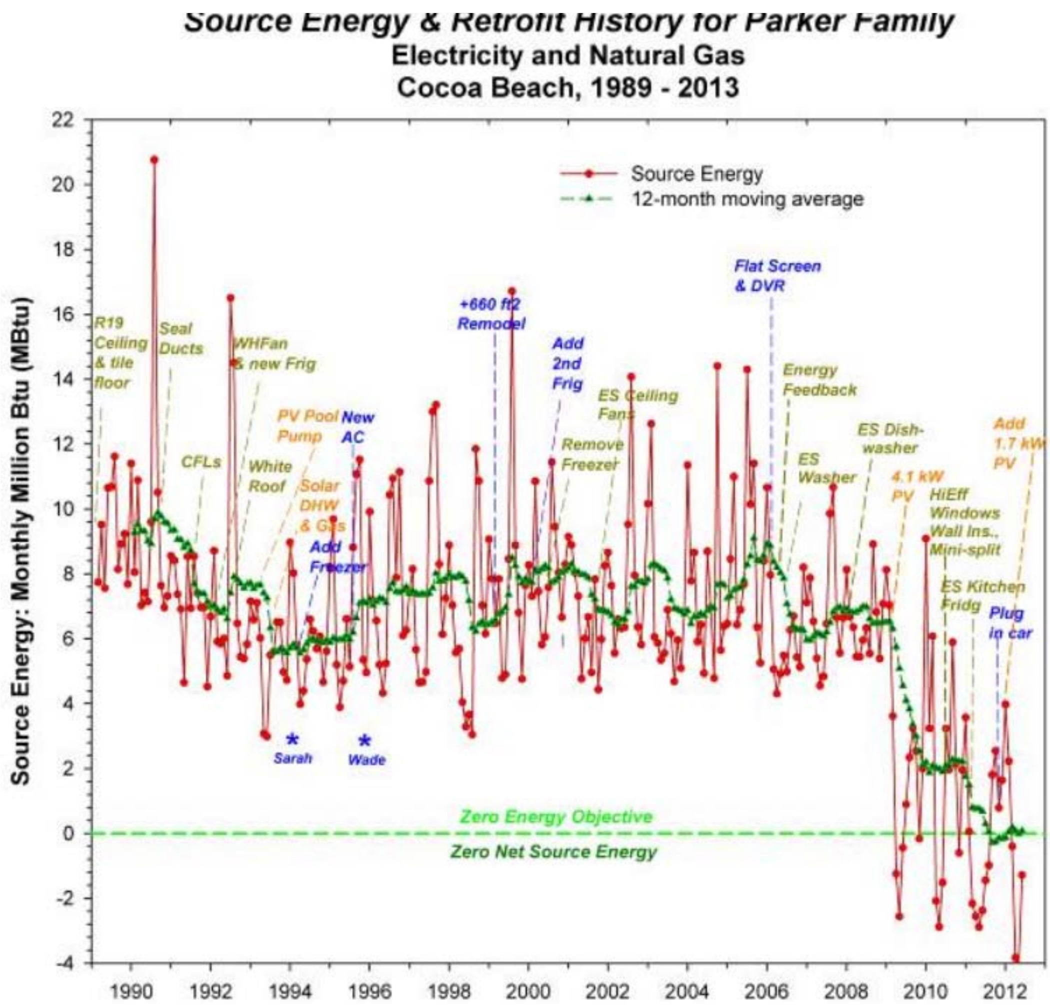


Figure 13 Plot showing annual household source energy use over a 23-year period (1983-2013). Green triangles are the 12-month running averages. Source energy use dropped ~90% over 23-years. *Figure courtesy of Danny Parker at the Florida Solar Energy Center.*

What would we have done differently to improve performance and/or cost-effectiveness?

- All phased retrofit projects benefit by developing detailed retrofit plans from the outset. For example, in this home, the HVAC system was converted from heat pump to gas furnace and back to heat pump again. With carefully planning, the heating and cooling system could have only been replaced once, rather than twice, and the added cost of bringing in gas service could have been avoided.
- Similarly, the hot water system was upgraded in three separate phases. First a solar thermal system (40 gal) was added to the existing tanked gas system (40 gal), then a tankless gas heater was added as backup, and then finally the solar storage tank was increased from 40 to 80 gallons. Again, careful planning could have avoided the added costs and disruption of this somewhat disjointed upgrade process.
- While not readily available at the time of the upgrade, we would recommend use of an electric heat pump water heater with solar thermal in this project.

Special considerations based on climate

Place special emphasis on humidity control. With improvements in the thermal performance of the retrofitted home, the central cooling system will run less and provide less dehumidification. This can increase interior moisture levels, and additional mechanical ventilation may exacerbate this in certain cases.

- Ensure proper venting of interior moisture sources through kitchen and bathroom ventilation designed to at least ASHRAE 62.2-2013.
- Provide supplemental dehumidification in low-load retrofits, or use other appropriate solutions:
    - Dehumidifiers, including stand-alone (closet or attic) and integrated with ventilation and central HVAC systems;
    - Enhanced cooling strategies, when indoor humidity is high:
        - Reduce airflow per ton to 200 cfm,
        - Sub-cooling of space by 2-3°F,
        - Cooling system reheat controls.

Prefer supply or balanced ventilation, due to condensation concerns in exhaust-vented, depressurized homes with mechanical cooling. In these homes, humid outside air can be sucked into building cavities by exhaust airflows, and if the interior surfaces are cooled below the dew point condensation can occur and possibly cause damage overtime. Vinyl wall paper is of particular concern.

Employ passive cooling strategies. Passive strategies take advantage of natural phenomenon to replace some of the energy-intensive mechanical cooling that is otherwise required in hot climates.

- Exterior shading wherever feasible, particularly on the Eastern and Western facades. Solutions include trees, shrubs, arbors, window shutters, window awnings, covered porches and deep roof overhangs.
- Select light-colored exterior finish materials that reflect, rather than absorb, the sun's energy. This includes "cool" roof and wall finish materials.

Watch out small HVAC blower closets and difficult to access low-sloped roofs. These problems are common in hot-humid climate homes, causing issues with air leakage, as well as difficulty in fitting higher SEER cooling equipment and failure to provide mechanical ventilation using central fan integrated supply systems.

- Build a platform return lined with duct board and sealed at the edges and seams.
- Consider expanding the HVAC closet and/or pursuing other ventilation strategies, such as balanced or supply ventilation.

Be careful when fuel switching. States in the hot-humid climate region have carbon emissions in their delivered electricity similar to the U.S. average, with no states having either high or low emissions. Special care should be taken in these states when fuel switching in retrofits and when adding energy using features to a project, such as cooling, entertainment systems, etc.

- For a state-by-state estimate of electricity carbon intensity, see our guidance on Source Energy and Carbon Decisions.

Climate-specific resources/case studies

Energy Retrofit Field Study and Best Practices in a Hot-Humid Climate (McIlvaine, Sutherland, & Martin, 2013)

Exploring Cost-Effective, High Performance Residential Retrofits for Affordable Housing in the Hot Humid Climate (McIlvaine, Sutherland, Schleith, & Chandra, 2010)

Current Best Practices for High Performance, Deep Energy Retrofits in Florida Affordable Housing (McIlvaine, Sutherland, & Beal, 2013)

Measured Results of Phased Shallow and Deep Retrofits in Existing Homes (Parker, Sutherland, Chasar, Montemurno, & Kono, 2014)

Building America Guides and Case Studies for Hot-Humid Climates

References

Less, B., & Walker, I. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* (No. LBNL-6601E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/sites/all/files/a_meta-analysis_0.pdf

McIlvaine, J., Sutherland, K., & Beal, D. (2013). *Current Best Practices for High Performance, Deep Energy Retrofits in Florida Affordable Housing* (No. FSEC-RR-444-13). Cocoa, FL: Florida Solar Energy Center. Retrieved from C:\\Users\\BLess\\GoogleDrive2\\VentilationTemperatureControl\\Optimization\\

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

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

Parker, D., Sutherland, K., Chasar, D., Montemurno, J., & Kono, J. (2014). *Measured Results of Phased Shallow and Deep Retrofits in Existing Homes* (No. FSEC-PF-463-14). Cocoa, FL: Florida Solar

Energy Center. Retrieved from http://www.fsec.ucf.edu/en/publications/pdf/FSEC-RR-510-14.pdf

U.S. Energy Information Administration. (2009). Residential Energy Consumption Survey (RECS) - Data - U.S. Energy Information Administration (EIA). Retrieved October 16, 2014, from http://www.eia.gov/consumption/residential/data/2009/

Hot-Dry Climate

The hot-dry and mixed-dry climates of the desert southwest run from west Texas and the Oklahoma panhandle west though the bottom portions of New Mexico and Arizona, and include most of California. Small portions of the southern parts of Nevada, Utah, and Colorado are included in the hot-dry and mixed-dry regions. These climates experience the sunniest, warmest, and driest weather in the United States.

Successful deep energy retrofits have been performed on existing homes in every climate zone in the U.S. A recent review of U.S. DERs reported on the performance of hot-dry climate deep energy retrofits, and average energy use before and after the retrofits is pictured in Figure 14 in comparison with regional averages (Less & Walker, 2014). The average project cost was $28,350 ($20/ft^2), with average annual energy cost savings of $1,596. Average airtightness was reduced from 12 to 5 ACH_{50}.

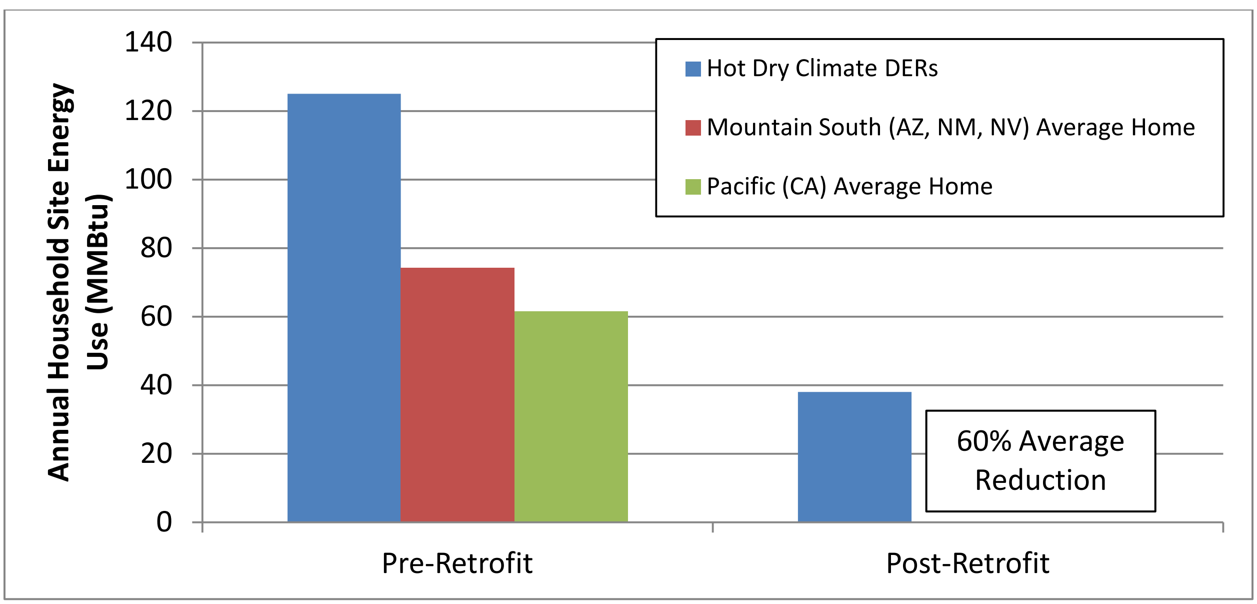


Figure 14 Average site energy use before and after deep retrofits in Hot Dry climate homes, compared with regional averages from the 2009 Residential Energy Consumption Survey (U.S. Energy Information Administration, 2009).

DER specifications

This Building America Optimized Solution describes a set of building practices necessary to achieve the next step in energy performance for existing homes. Any home that follows the specifications listed below can be considered a high performance existing home. There is a high likelihood that the energy use, utility bills and environmental footprint of the home will be substantially less than either the pre-retrofit home or other similar homes in the region. The home will also most likely have lower maintenance, as well as improved comfort, air quality, humidity control, durability and resale value. The specifications and case studies below reflect only a few examples of the hundreds of ways that existing homes can be transformed into high performance homes through deep energy retrofits.

Below we provide specific guidance for insulation levels, basic approaches and technical equipment in deep retrofits. This guidance was generated using a multifaceted and flexible approach. These recommendations are not guaranteed to provide any given level of energy savings or cost-effectiveness, because existing homes and their occupants are so varied. Rather, they represent strategies that are currently available on the market and have a demonstrated track record in deep retrofit projects. They are based on a mixture of engineering judgment, published guidance from DOE research in technologies and DERs, simulations of cost-optimal DERs, Energy Star and Consortium for Energy Efficiency (CEE) product criteria, and the International Energy Conservation Code (2012).

All deep retrofits will be unique projects that vary depending on the existing conditions of the home and the owners' goals and budget. Projects that deviate from this guidance can still be successful. Always comply with local codes and regulations, and use local design and engineering expertise (as well as common sense) wherever appropriate. And as always, do no harm.

Component	**Deep Energy Retrofit Specification**
Envelope	

Foundation/Framed Floor	Address any bulk water issues through perimeter drains and site grading
	
	Crawlspace:
	• Convert to unvented, conditioned crawlspace
	    o Walls - continuous R10 or greater, after sealing walls and existing vents
	    o Ground – continuous vapor barrier
	    o Install HVAC supply vent to condition
	• Vented, unconditioned crawl
	    o Framed floor – Air seal all subfloor penetrations. Fill framed floor cavity with insulation (~R19 to R30), ensuring no compression and full alignment with the air barrier (subfloor)
	    o Ground – continuous vapor barrier
	    o *Note:* May be most appropriate if crawlspace has no mechanical equipment located in it and framed floor is

<table>
<tr><td></td><td>
relatively clear of obstructions, such as plumbing, ducting and bracing
Basement:

Include basement in conditioned space

Interior walls - R10 continuous interior insulation (preferably closed cell spray polyurethane foam, with ignition barrier--either ½” gypsum board or intumescent paint)
Exterior walls - consider exterior insulation approaches if exposing foundation walls from exterior

Unconditioned space
See vented crawlspace specification

Uninsulated Slab
</td></tr>
<tr><td>Above Grade Wall</td><td>
Address any bulk water leakage through weather resistive barrier;
Wall cavity:

Fill cavity to R13 (most likely drill and fill)
If removing sheetrock, ensure continuous air barrier at exterior sheathing, fill to R13

Exterior Insulation:

If replacing siding:

Ensure continuous drainage plane using Weather Resistive Barrier on exterior of sheathing
Add R5 continuous insulation
Or R20 continuous insulation (and no cavity insulation)

</td></tr>
<tr><td>Windows</td><td>
Replacing existing windows:

Replace existing windows if there is surrounding water damage, lead-based paint or other issues
Replace with U-value <0.35, SHGC <0.3

Rehab existing windows:

Air seal with caulk and weather-stripping
Add storm window units or additional panes
Apply solar control window film or exterior shading

</td></tr>
<tr><td>Attic</td><td>
Address any bulk water intrusion through roof leaks;
Attic floor:

Ensure continuous air barrier at attic floor
Bring insulation level up to R38 or greater

</td></tr>
</table>

	Cathedral attic:
	• Vented assembly
	  o Establish continuous air barrier at ceiling
	  o Add baffles providing ventilation airspace beneath roof sheathing
	  o Fill remaining space with insulation, according to available rafter depth
	• Unvented assembly
	  o Use air impermeable insulation to fill cavity
	  o If using air permeable cavity insulation, must provide continuous air impermeable insulation (spf or foam board) above or below roof sheathing

Roof	Light colored, low solar absorptance (solar reflectance >=0.25)
Airtightness	Interior/exterior gut-rehab: <= 3 ACH_{50} Not gut-rehab: <= 5 ACH_{50}
Mechanicals	

Heating	If replacing heating system:
	• Size according to ACCA Manuals J and S
	  o *Gas:* Sealed combustion, modulating, variable speed, gas furnace, >= 0.95 AFUE;
	  o *Electric:* traditional or ductless heat pump with HSPF >9
	• Ensure that 2nd compressor stage is used for back-up heat, not electric resistance. Lock-out back-up heat to <25°F.
	• Consider combined space and water heating (more info)
	
	If not replacing heating system:
	• *Gas:* system tune-up
	• *Electric:* heat pump tune-up (refrigerant charge using superheat/sub cooling methods, ensure correct air flow, etc.)

Cooling	If replacing air conditioner: • Air conditioner with SEER >16 o See dry climate heat pump design guidance below • Size according to ACCA Manuals J and S If not replacing: • Perform tune-up (refrigerant charge using superheat/sub cooling methods, ensure correct air flow, etc.) Consider eliminating need for compressor cooling (see suggestions below)

Ventilation	Conform to ASHRAE 62.2-2013: whole house, kitchen and bathroom fans exhausted to outside and sized per the standard (for further guidance);

Domestic Hot Water	Identify and fix any leaking distribution pipes;
	Replace all water fixtures with low-flow versions (<=1.5 gpm);
	Insulate all exposed hot water distribution pipes to >=R2;
	Consider lowering hot water set point;
	Consider demand pump for hot water delivery (due to increased wait times for hot water with low-flow fixtures);
	
	If replacing domestic water heater:
	• *Gas:* Condensing gas tankless water heater, EF >=0.95, Gas storage water heater, EF >0.7;
	• *Electric:* Heat pump water heater, EF >2.0 (savings much greater when in conditioned space, also greater when replacing existing electric resistance tank heater and smaller when replacing gas dhw; do not use if space heating is gas)
	• Consider *solar thermal system*:
	    o Integrated collector storage system with heat pump water heater backup
	    o Or 40 ft^2 solar collector system with 80 gallon storage and PV pumping
	
	If not replacing domestic water heater:
	• Verify presence of or install heat trap on inlet/outlet
	• Insulate hot water tank to R5

Air distribution	*Gut rehab:* • Move forced air ducts to conditioned space *Otherwise:* • Seal ducts so that duct leakage is <6% of nominal system airflow or 70% duct leakage is achieved • Bring duct insulation up to R8 with radiant barrier or bury & encapsulate ducts Consider eliminating the need for forced air ducting (e.g., ductless heat pump or point source gas heater); As necessary, address distribution, noise and comfort issues by adding support to sagging ducts, eliminating sharp bends and kinks, adding jump ducts, adding return area, addressing room air delivery issues, etc. Use ACCA Manual D for duct system re-design.
Other	

Lights	100% CFL or LED
Appliances	*Clothes washer and refrigerator:* • CEE Tier 2 or 3 (15-20% better than 2014 federal standards) *Dishwasher:* • CEE Tier 1 (10% better than 2014 federal standards)
Plugs/MELs	Specifically target for control or replacement the highest-consumption MELs or perform an MELs audit; Use smart receptacles or smart power strips, switched power outlets, whole house off switch, occupancy- or timer-based controls
Renewables	5 kW PV system (consider local weather and electricity rates, as well as PV financials (e.g., feed-in tariffs, net-generation issues))

Table 7 Hot-dry climate DER specifications table.

Case Study Home—P6 North

This exemplary DER project is located in Davis, CA in the hot-dry central valley (Less, Fisher, & Walker, 2012). It combined an aggressive envelope retrofit with passive cooling strategies, a simple approach to heating, and renewable technologies. These features, along with occupant conservation and low energy use in lighting, plugs and appliances, led to monitored energy use of only 4,300 kWh/yr--79% less than the California single-family average (no pre-retrofit usage was available). This energy performance does not include the estimated production of the PV system (~3,500 kWh/yr) which would make the home nearly zero net-energy.

The 1,462 ft2 home was part of a co-housing project, with four adult occupants. The structure and finishes were in poor shape throughout and in-need of replacement and repair, which made the home a great candidate for incremental deep green upgrades. For example, due to damaged exterior stucco, the entire home was reskinned and provisioned with proper moisture management (see Figure 15 below). The home's envelope is super-insulated with 12" of blown attic cellulose, double-stud walls filled with blown cellulose, and a sealed crawl space. Yet, it remained relatively loose post-retrofit (5 ACH_{50}). Having completely eliminated compressor cooling, the home is a showcase for passive cooling and adaptive comfort strategies in a hot-dry climate retrofit. The images below show the strategies employed in this home, including a whole house ventilation cooling fan (see Figure 15), as well as ample overhangs for exposed windows (Figure 16). Clay plaster was used as an interior wall finish over top of sheetrock, which provides some amount of moisture buffering and thermal storage. This project combines these cooling strategies with high-efficiency point-source gas heating, as well as solar thermal hot water (with tankless condensing gas backup) and solar PV electricity. The occupants brought a strong conservation ethic to their lifestyles, which was reflected in the home's very low metered electric base load (42 watts), as well as in its very low usages of lighting energy (282 kWh/yr) and plug load energy (1,085 kWh/yr). Similarly, the occupants maintained low winter temperatures in the lower 60s, due to a combination of comfort preference and ardent conservation ethic. Kitchen and bathroom fans were installed and vented to outside, and a whole house ventilation cooling fan was installed with ~1,200 cfm airflow. No whole house, continuous mechanical ventilation system was installed.

Figure 15 ***Left*****: existing, cracked stucco was removed and house was re-clad with a continuous weather resistive barrier beneath the new stucco.** ***Right:*** **Whole-house fan used for nighttime ventilation cooling, insulated and self-sealing when not operating.**

Figure 16 ***Left:*** **example of passive cooling strategy in this retrofit that eliminated compressor cooling through use of creative shading solutions and ventilation cooling.** ***Right:*** **Deep overhang providing protection from intense sun of California's central valley, as well as protecting doors from water intrusion.**

What would we have done differently to improve performance and/or cost-effectiveness?

- This home should be equipped with a continuous, whole house mechanical ventilation system compliant with ASHRAE 62.2-2013. A quiet, efficient bathroom fan was provided, but it was not set-up to operate continuously.
- Airtightness levels post-retrofit (5 ACH_{50}) were higher than anticipated for a double stud wall, super-insulated home. We would recommend more attention be paid to air sealing throughout, with a target of 3 ACH_{50} for gut-rehabbed homes.
- While temperatures were fairly even between the central and bedroom areas, we would consider adding some small ventilation fans to enhance heat distribution from the point-source gas heater.
- We also recommend that winter temperatures be increased somewhat, both for comfort and humidity control reasons.
- The double stud wall (2nd wall built to interior of existing framing) required that some of the interior floor area be eliminated, and in a project where the exterior cladding is removed, we would recommend continuous exterior insulation as a lower-cost and more effective measure.

Special considerations based on climate

Use passive cooling strategies. Many passive cooling strategies are available and can save energy in very sunny, hot-dry climates.

- Use exterior shading wherever feasible, particularly on the Eastern and Western facades. Solutions include trees, shrubs, arbors, window shutters, window awnings and deep overhangs.
- Select light-colored exterior finish materials that reflect, rather than absorb, the sun's energy. This includes "cool" roof and wall finish materials.
- If appropriate, use strategies that still admit solar gain during heating months, such as deciduous plantings and overhangs designed according to winter and summer solar angles.
- Use thermal mass inside the building envelope to buffer daily swings in temperature and solar gain. For example, multiple layers of sheetrock, concrete slab or ceramic tile floors can be effective.

Use pre-cooling strategies. Pre-cooling can shift a home's peak load, avoiding high-cost electricity rates and reducing the burden on the electrical grid. Or it can eliminate loads altogether by using colder nighttime air to cool a home.

- Pre-cool before daily peak (4-6pm) using mechanical system thermostat setback schedule. This mostly reduces peak period energy use, rather than total energy use.
- Pre-cool using ventilation cooling, with either an independent whole house fan or a central fan system (typically at night). This can reduce both peak and total energy usage. Consider nighttime outdoor pollutant levels before using unfiltered nighttime ventilation cooling. For example, high nighttime ozone is common along much of the western slope of the Sierra Nevada Mountains in California, due to transport from westward population centers.

Use hot-dry climate mechanical cooling strategies. Due to a lack of concern about moisture in hot-dry climates, many compressor-less and/or smart cooling strategies are available and can save energy.

- Central cooling systems should use Time Delay Relays set to a 15 minute over-run period. These run the air handler once the refrigerant flow has ceased, which provides free cooling by re-evaporating the moisture condensed on the heat exchange coil.
- Consider use of direct and indirect evaporative cooling technologies, including swamp coolers, two-stage evaporative coolers, and evaporatively cooled outside condensing units.
- Optimize mechanical compressor-based cooling for hot-dry climates:
  - Target HVAC system airflow at 500-700 cfm/ton of rated capacity and size ducts and registers accordingly
  - Maintain total external static pressure (with filter) at less than 0.5” water column
  - Subcool to the manufacturer’s lower target
  - Superheat to between 5 and 10, possibly using adjustable thermal expansion valve
  - Consider sizing the system based only on sensible loads

Climate-specific resources/case studies

Building America Guides and Case Studies for Hot-Dry and Mixed-Dry Climates

Deep Energy Retrofits: Six Real World Examples and Lessons Learned (Keesee, 2012)

Deep Energy Retrofits—Eleven California Case Studies (Less et al., 2012)

Measured Home Performance: Best Practices for Home Energy Retrofits (Chitwood & Harriman, 2012)

References

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

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

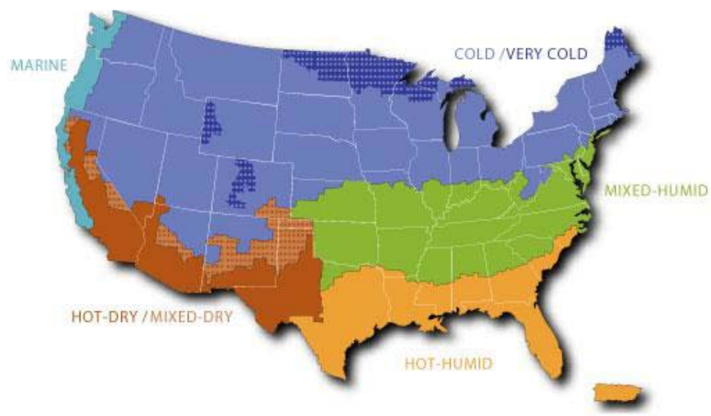
Less, B., Fisher, J., & Walker, I. (2012). *Deep Energy Retrofits-11 California Case Studies* (No. LBNL-6166E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/publications/deep-energy-retrofits-eleven-california-case-studies

Less, B., & Walker, I. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* (No. LBNL-6601E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/sites/all/files/a_meta-analysis_0.pdf

U.S. Energy Information Administration. (2009). Residential Energy Consumption Survey (RECS) - Data - U.S. Energy Information Administration (EIA). Retrieved October 16, 2014, from http://www.eia.gov/consumption/residential/data/2009/

Marine Climate

The marine climate covers a narrow band paralleling the West Coast from the Canadian border south to the county boundary separating Ventura and Los Angeles counties in California. In some stretches, this band is only one county deep inland from the Pacific Ocean. The marine climate was designated in recognition of the mild temperatures and moist conditions found along the coast. However, the marine climate borders on the cold climate in the north and the hot-dry climate in the south and the more extreme conditions of these neighbors are found in some inland areas. Homes in the marine climate are faced with high levels of moisture, often in the form of rain, fog, or snow.



Successful deep energy retrofits have been performed on existing homes in every climate zone in the U.S. A recent review of U.S. deep retrofits reported on the performance of marine climate DERs (Less & Walker, 2014), and average energy use before and after the retrofits is pictured in Figure 17, in comparison with the regional average. The average project cost was \$27,000 (\$14/ft^2), and average airtightness was reduced from 12 to 5 ACH_{50}. HERS (2006) indices averaged 63 post-retrofit.

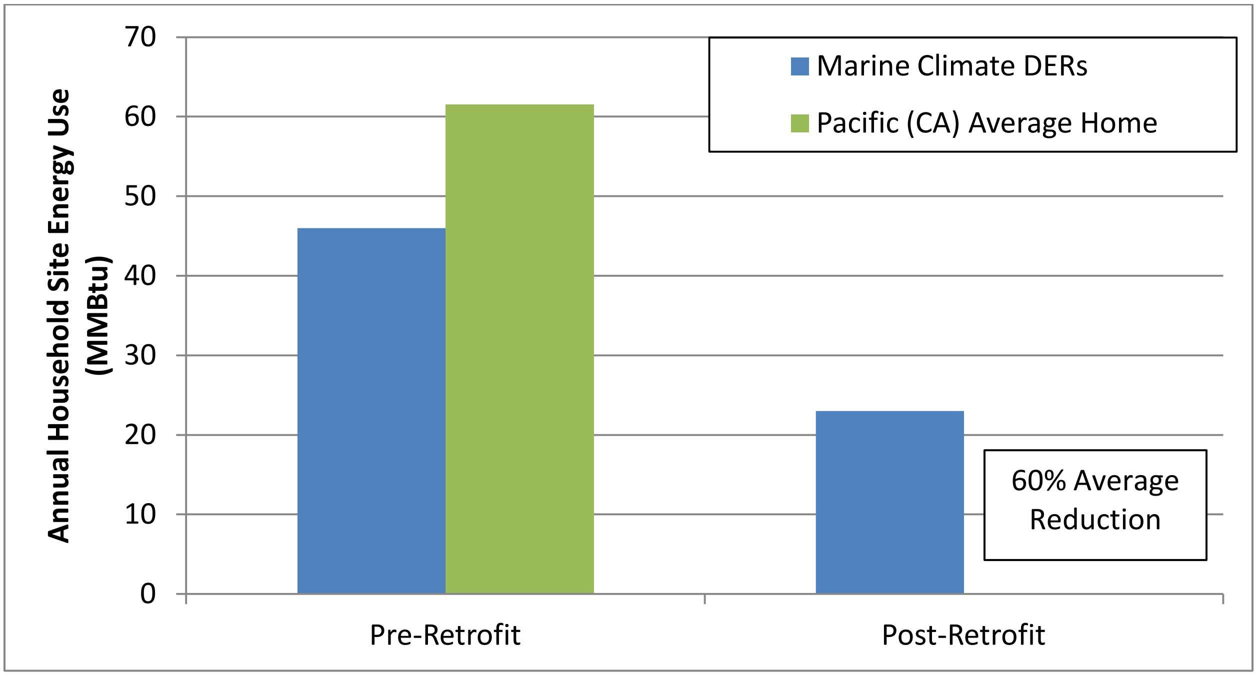


Figure 17 Average site energy use before and after deep retrofits in Marine climate homes, compared with regional averages from the 2009 Residential Energy Consumption Survey (U.S. Energy Information Administration, 2009).

DER specifications

This Building America Optimized Solution describes a set of building practices necessary to achieve the next step in energy performance for existing homes. Any home that follows the specifications listed below can be considered a high performance existing home. There is a high likelihood that the energy use, utility bills and environmental footprint of the home will be substantially less than either the pre-retrofit home or other similar homes in the region. The home will also most likely have lower maintenance, as well as improved comfort, air quality, humidity control, durability and resale value. The specifications and case studies below reflect only a few examples of the hundreds of ways that existing homes can be transformed into high performance homes through deep energy retrofits.

Below we provide specific guidance for insulation levels, basic approaches and technical equipment in deep retrofits. This guidance was generated using a multifaceted and flexible approach. These recommendations are not guaranteed to provide any given level of energy savings or cost-effectiveness, because existing homes and their occupants are so varied. Rather, they represent strategies that are currently available on the market and have a demonstrated track record in deep retrofit projects. They are based on a mixture of engineering judgment, published guidance from DOE research in technologies and DERs, simulations of cost-optimal DERs, Energy Star and Consortium for Energy Efficiency (CEE) product criteria, and the International Energy Conservation Code (2012).

All deep retrofits will be unique projects that vary depending on the existing conditions of the home and the owners' goals and budget. Projects that deviate from this guidance can still be successful. Always comply with local codes and regulations, and use local design and engineering expertise (as well as common sense) wherever appropriate. And as always, do no harm.

<table>
<tr><th>Component</th><th>Deep Energy Retrofit Specification</th></tr>
<tr><td>Envelope</td><td></td></tr>
<tr><td>Foundation/Framed Floor</td><td>Address any bulk water issues through perimeter drains and site grading

Crawlspace:

Convert to unvented, conditioned crawlspace

Walls - continuous R10 or greater, after sealing walls and existing vents
Ground – continuous vapor barrier
Install HVAC supply vent to condition

Vented, unconditioned crawl

Framed floor – Air seal all subfloor penetrations. Fill framed floor cavity with insulation (~R19 to R30), ensuring no compression and full alignment with the air barrier (subfloor)
Ground – continuous vapor barrier
Note: May be most appropriate if crawlspace has no mechanical equipment located in it and framed floor is relatively clear of obstructions, such as plumbing, ducting and bracing

Basement:

Unconditioned basement

See vented crawlspace specification

Unvented, conditioned basement

Interior walls - R10 continuous interior insulation (preferably close cell spray polyurethane foam, with ignition barrier--either ½” gypsum board or intumescent paint)

Uninsulated Slab</td></tr>
<tr><td>Above Grade Wall</td><td>Address any bulk water leakage through weather resistive barrier;

Wall cavity:

Fill cavity to R13 (most likely drill and fill)
If removing sheetrock, ensure continuous air barrier at exterior sheathing, fill to R13

Exterior Insulation:

If replacing siding:

Ensure continuous drainage plane using Weather Resistive Barrier on exterior of sheathing

</td></tr>
</table>

<table>
<tr><td></td><td>Add R5 continuous insulation
Or R20 continuous insulation (and no cavity insulation)</td></tr>
<tr><td>Windows</td><td>Replacing existing windows:
Replace existing windows if there is surrounding water damage, lead-based paint or other issues
Replace with U-value <0.32, SHGC <0.4
Rehab existing windows:
Air seal with caulk and weather-stripping
Add storm window units or additional panes
Apply solar control window film or exterior shading</td></tr>
<tr><td>Attic</td><td>Address any bulk water intrusion through roof leaks;

Attic floor:
Ensure continuous air barrier at attic floor
Bring insulation level up to R38 or greater
Cathedral attic:
Vented assembly
Establish continuous air barrier at ceiling
Add baffles providing ventilation airspace beneath roof sheathing
Fill remaining space with insulation, according to available rafter depth
Unvented assembly
Use air impermeable insulation to fill cavity
If using air permeable cavity insulation, must provide continuous air impermeable insulation (spf or foam board) above or below roof sheathing</td></tr>
<tr><td>Roof</td><td>None</td></tr>
<tr><td>Airtightness</td><td>Interior/exterior gut-rehab: <= 3 ACH_{50}

Not gut-rehab: <= 5 ACH_{50}</td></tr>
<tr><td>Mechanicals</td><td></td></tr>
<tr><td>Heating</td><td>If replacing heating system:
Size according to ACCA Manuals J and S
Gas: Sealed combustion, modulating, variable speed, gas furnace, >= 0.95 AFUE;
Electric: traditional or ductless heat pump with HSPF >9</td></tr>
</table>

	• Recommend ductless heat pumps in the Pacific Northwest due to low electricity rates • Ensure that 2nd compressor stage is used for back-up heat, not electric resistance. Lock-out back-up heat to <25°F. • Consider combined space and water heating (more info) If not replacing heating system: • *Gas:* system tune-up • *Electric:* heat pump tune-up (refrigerant charge using superheat/sub cooling methods, ensure correct air flow, etc.)
Cooling	Consider eliminating need for compressor cooling If replacing air conditioner: • Air conditioner with SEER >16 • Size according to ACCA Manuals J and S If not replacing: • Perform tune-up (refrigerant charge using superheat/sub cooling methods, ensure correct air flow, etc.)
Ventilation	Conform to ASHRAE 62.2-2013: whole house, kitchen and bathroom fans exhausted to outside and sized per the standard (for further guidance)
Domestic Hot Water	Identify and fix any leaking distribution pipes; Replace all water fixtures with low-flow versions (<=1.5 gpm); Insulate all exposed hot water distribution pipes to >=R2; Consider lowering hot water set point; Consider demand pump for hot water delivery (due to increased wait times for hot water with low-flow fixtures); *If replacing domestic water heater:* • *Gas:* Condensing gas tankless water heater, EF >=0.95, Gas storage water heater, EF >0.7; • *Electric:* Heat pump water heater, EF >2.0 (Most effective when heating/cooling with electric heat pump, recommend gas tankless dhw in gas heated homes) *If not replacing domestic water heater:* • Verify presence of or install heat trap on inlet/outlet • Insulate hot water tank to R5
Air distribution	*Gut rehab:* • Move forced air ducts to conditioned space

	Otherwise: • Seal ducts so that duct leakage is <6% of nominal system airflow or 70% duct leakage is achieved • Bring duct insulation up to R8 with radiant barrier or bury & encapsulate ducts Consider eliminating the need for forced air ducting (e.g., ductless heat pump or point source gas heater); As necessary, address distribution, noise and comfort issues by adding support to sagging ducts, eliminating sharp bends and kinks, adding jump ducts, adding return area, addressing room air delivery issues, etc. Use ACCA Manual D for duct system re-design.
Other	
Lights	100% CFL or LED
Appliances	*Clothes washer and refrigerator:* • CEE Tier 2 or 3 (15-20% better than 2014 federal standards) *Dishwasher:* • CEE Tier 1 (10% better than 2014 federal standards)
Plugs/MELs	Specifically target for control or replacement the highest-consumption MELs or perform an MELs audit; Use smart receptacles or smart power strips, switched power outlets, whole house off switch, occupancy- or timer-based controls
Renewables	5 kW PV system (consider local weather and electricity rates, as well as PV financials (e.g., feed-in tariffs, net-generation issues))

Table 8 Marine climate DER specifications table.

Case Study Home—P5 in Marin County California

Figure 18 Front view of the compact deep retrofit home in Marin county California.

This Marin County home is a small, single-story, 900 ft^2 affordable housing project located in Point Reyes Station, CA. The original 1920's structure was remodeled using Passive House design principles, with the hope that it would provide the lowest operating costs for the future tenants. The very small, compact ranch-style home had a simple layout, which made it a good candidate for super insulation and airtightness. A dedicated local contractor and local Passive House consultants developed the plan for the retrofit, which focused on the building envelope and other basic upgrades, rather than complex heating, ventilation or water heating systems. Beyond-code insulation was installed throughout (unvented crawlspace with framed floor ~R40 (see Figure 20), walls ~R20, Roof ~R60), and very airtight construction was achieved (2.4 ACH_{50}). The Passive House standard was not met, but remained a guide for design and construction. A wood-burning fireplace was replaced with electric resistance wall radiators, and a point-source ERV (see Figure 20 below) was installed for whole house, continuous ventilation. A new front porch was also added as part of the retrofit, along with a laundry room containing a new electric resistance tank water heater. The monthly post-retrofit usage (Figure 19) showed very little seasonal variability, with almost no heating signal. This was due both to the super-insulated envelope and to low heating set points (winter average temperatures low to mid 60s) and as-needed usage. While pre-retrofit data were not available for this home, the project used 67% less net-site energy than the average CA single family home.

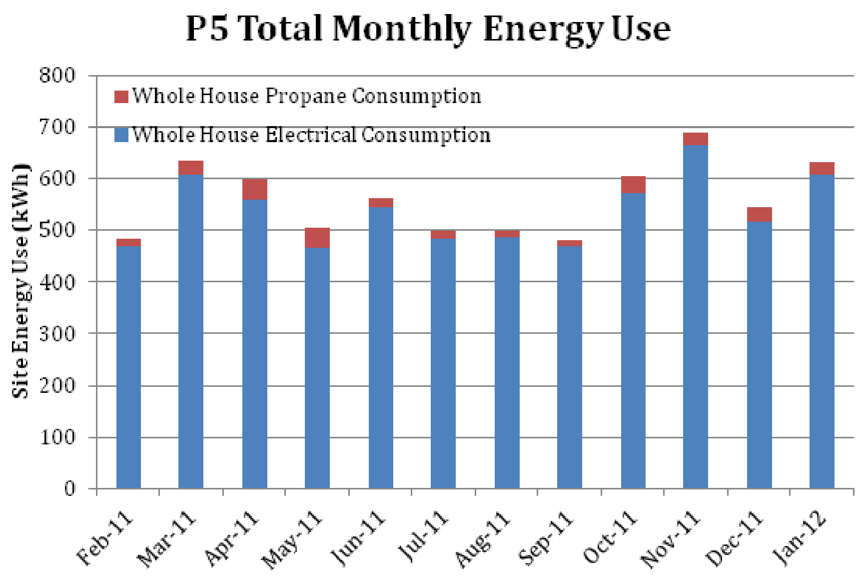


Figure 19 Summary of monthly post-retrofit energy use in P5 DER. Very little response to varying weather was observed in this super insulated, airtight retrofit.

Figure 20 *Left*: whole house mechanical ventilation was provided by a point-source energy recovery ventilator located in the living room. No distribution was provided to other areas of the home. *Right:* the unvented crawlspace of the home was air sealed, insulated and water managed.

What would we have done differently to improve performance and/or cost-effectiveness?

- In a sample of 11 CA DERs, this project was amongst the highest source energy consumers, while being amongst the lowest site energy consumers. Use of electric resistance space and water heating drove this effect. Over a third of total energy use was due to water heating. If costs were less constrained, we would recommend that this project use a heat pump water heater, and possibly use a ductless mini-split heat pump.
- Site visits to this home revealed that the ERV system had been turned off, either by accident or on purpose. The on-off switch was a bland, unlabeled wall switch that could easily have been mistaken for any other switch in the house. Particularly in airtight homes, it is essential that

ventilation both be provided and that its operation be obvious and clearly explained to occupants.

- High efficiency appliances, rather than existing appliances, should have been installed in this home.
- Overall, given the largely benign climate, we would recommend that priorities and money be spread across other energy uses, rather than strictly focusing on space heating. In other words, lower cost envelope strategies could have been used, in order to free up money for a heat pump water heater, better appliances and possibly a mini-split heat pump.

Special considerations based on climate

Many homes are not strictly driven by heating and cooling energy. Energy use in many existing homes in the marine climate is not strongly dominated by heating and cooling, and as a result, other end-uses play a larger role in overall performance. An aggressive envelope and HVAC retrofit might provide enhanced comfort and improved IEQ, but it will be much more successful if hot water, appliances, lighting, etc. are also targeted. As noted in the example home above, some trade-offs between reduced envelope measures and other efficiency measures may be beneficial.

- Comprehensively target all end-uses, leaving nothing off the table.
- Use the assessment of pre-retrofit energy use to ensure that retrofit measures are addressing the largest energy uses in the home.

Be aware of high and low electricity prices in marine climates. Marine climates include regions with high energy costs and low energy costs, namely expensive electricity in most of California, and very low electric rates in the Pacific Northwest, largely due to hydropower generation. These energy costs may have strong effects of the cost-effectiveness of projects, and retrofits should be carefully designed to take advantage of these effects. For example, tiered and peak electricity rates in California may provide strong incentives to reduce peak demand. Similarly, low electricity costs limit the financial value of PV electricity generation, but make electric heat pumps a great option.

Low carbon emissions for electricity in marine climates. All states in the marine climate region have below average carbon emissions in their delivered electricity. This makes the use of electric heat pumps particularly environmentally advantageous relative to natural gas heating technologies, if heat pump COPs are greater than ~1.5. As noted above, electricity prices may still lead some projects to use gas. For a state-by-state estimate of electricity carbon intensity, see our guidance on Source Energy and Carbon Decisions.

Climate-specific resources/case studies

40% Whole-House Energy Savings in the Marine Climate

Deep Energy Retrofits: 11 California Case Studies (Less, Fisher, & Walker, 2012)

References

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

Less, B., & Walker, I. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* (No. LBNL-6601E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/sites/all/files/a_meta-analysis_0.pdf

U.S. Energy Information Administration. (2009). Residential Energy Consumption Survey (RECS) - Data - U.S. Energy Information Administration (EIA). Retrieved October 16, 2014, from http://www.eia.gov/consumption/residential/data/2009/