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Emerging Pathways to Upgrade the US Housing Stock

A Review of the Home Energy Upgrade Literature

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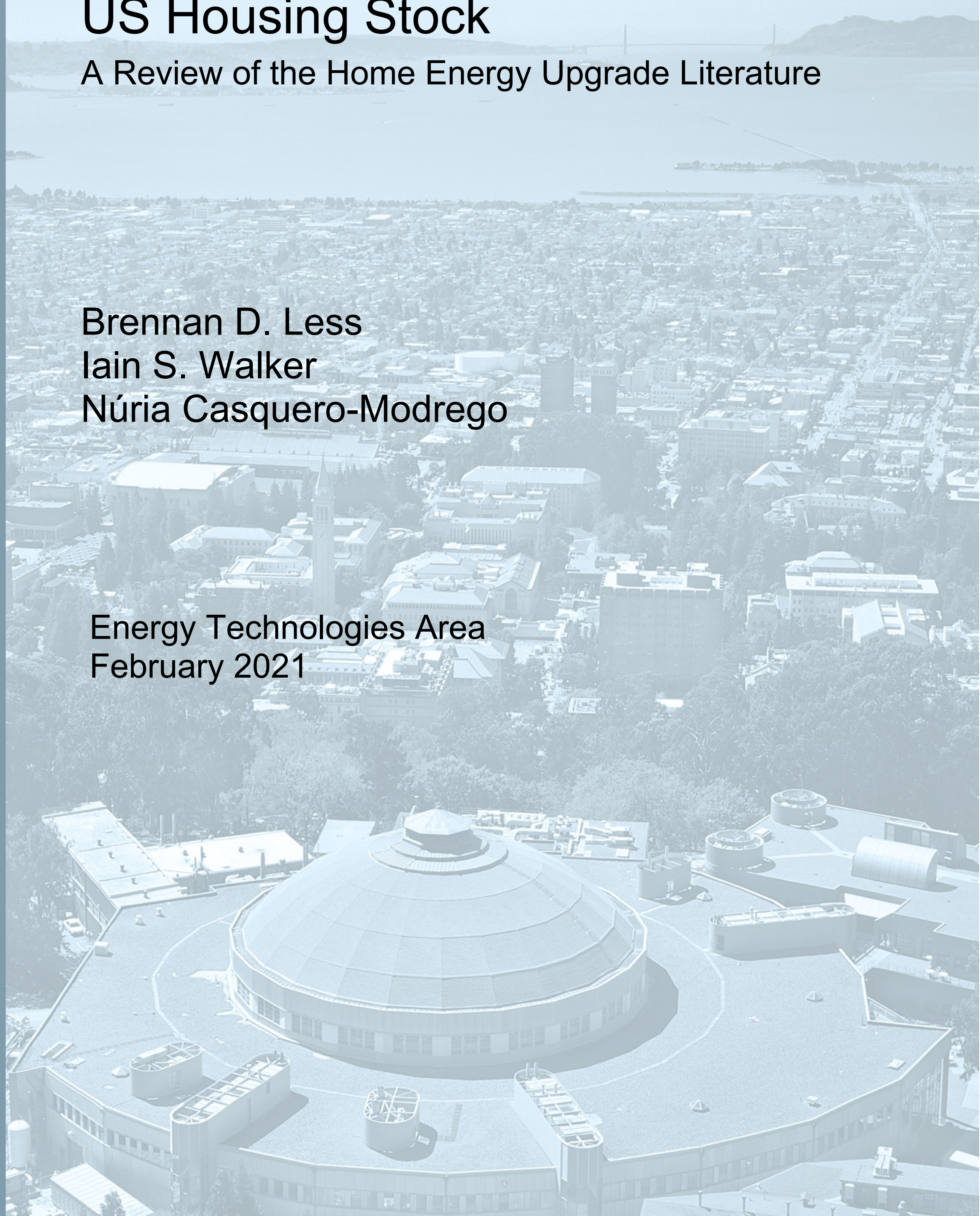

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Abstract

This review addresses whole home energy upgrades targeting deep energy reductions (i.e., Deep Energy Retrofits, or DERs), from 30 to >50% site energy savings. The intent of this work is to characterize how energy upgrade projects and programs have evolved and improved over the past decade, and to identify what changes are needed to drive expansion of the U.S. retrofit market in such a way that addresses carbon emission from buildings, improves resilience and upgrades the housing stock for the 21st century. The topics covered in this review are wide-ranging, including trends in U.S. and European retrofit programs, measure costs (e.g., ductless heat pumps, heat pump water heaters, exterior wall insulation), emerging technologies, advancements in simulation tools, surveys of energy upgrade homeowners and practitioners, business economics (e.g., soft costs, gross margins), and health effects. Key changes in project design noted in this review include the: (1) electrification of dwellings with rapidly improving heat pump systems and low-cost PV technology, (2) shift away from high-cost super-insulation strategies and towards more traditional home performance/weatherization envelope upgrades, (3) recognition of the importance of when energy is used and from what fuel sources in terms of both energy cost and carbon emissions, and (4) emerging smart home technologies, such as batteries or thermal storage, smart ventilation and HVAC controls, and energy feedback devices. Promising program design strategies covered in this review include: (1) end-use electrification programs, (2) novel financing approaches (e.g., Pay-As-You-Save and local lender networks), (3) Pay-for-Performance incentive structures, (4) securitization of portfolios of upgraded homes as investment products, and (5) One-Stop Shop programs that integrate financing, project management, design and support services. In addition to these project- and program-innovations, the industry should adopt new project performance metrics, namely those for carbon, peak demand and energy storage, along with metrics characterizing resilience and health. Market drivers are needed to spur widespread energy upgrades in the U.S. housing stock, which will require valuation of DERs by the real estate industry, reduced project costs (in part by cutting soft costs), and projects designed to appeal to homeowners while being enjoyable and profitable for contractors.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

The residential buildings sector is responsible for about 20% of total US energy use. In order to achieve climate goals, we need ways to reduce carbon emissions and energy use in this sector. In addition, resiliency, electric grid stability, emergency survivability and other energy and building-related issues are becoming increasingly important challenges. New homes in most of the US meet various energy codes and are reasonably energy efficient. However, the vast majority of energy use is from existing homes that were not required to conform to energy performance requirements. It is becoming imperative to reach as many of these existing homes as possible and find ways to improve their energy-related performance. This must be done in such a way that it meets the needs and desires of homeowners and building occupants, as well as those of the contractors and design professionals engaged in doing the upgrades themselves.

Energy retrofits of homes started in the 1970’s in response to the energy crisis, however, these retrofits were very limited in scope and relatively few homes were upgraded. Those homes that have been upgraded generally still have much scope for improvement. A huge effort is needed to get to scale to address the energy use in housing. The target population is effectively every home in the country, whether a large suburban single-family home, or a small downtown apartment. In order to provide a framework for analysis and the basis for plans to get to large-scale retrofits of homes, this literature review summarizes the state-of-the art in the US buildings industry. It identifies where more research, engineering, or technology is needed, as well as relevant industry trends, such as electrification, one-stop shop program design and others. It also examines other key topics, such as availability of financing, minimizing household disruption, and engaging home owners and occupants. This literature review builds on a similar review from several years ago (Less and Walker, 2014). The current review focuses on efforts in the intervening years. This literature review is part of a larger DOE study of deep energy upgrades that includes industry surveys and development of cost-stack analyses.

For this review, we gathered data not just from the published literature, but also from practitioners in conjunction with other aspects of the larger DOE study. In some cases, we refer to comments from specific individuals or companies, or refer to specific products by name. This is not intended as an endorsement, but rather to provide clarity on sources of information and examples of relevant technologies.

This review addresses the following topics related to whole home energy upgrades:

- Whole Home Retrofits in the US (Section 2)
- Whole Home Retrofits in Europe (Section 3)
- Deep Energy Retrofit Measure Costs (Section 4)
- Emerging Technologies for Deep Energy Retrofit Projects (Section 5)
- Advancements in Simulation Tools (Section 6)
- Surveys Assessing Deep Energy Retrofits and Home Performance (Section 7)
- Business Models, Gross Margins and Soft Costs in Home Performance (Section 8)
- Health Benefits of Energy Efficiency Retrofits (Section 9)

2 Whole Home Retrofits in the US

In recent years, whole home energy upgrades targeting deeper energy savings have moved beyond the phase of demonstration projects and have become more common in the industry. A number of programs have worked to extend these projects into the broader market of existing homes, largely driven by utility retrofit incentive programs, but also by other emerging program/business types. These programs have retrofitted thousands of US homes with widely varying incentive levels and performance targets, anywhere from relatively modest 25-30% savings, up to programs supporting much deeper reductions and more extensive projects saving >50%. Table 1 summarizes the results of the programs reviewed in sub-sections below. Many of this newer generation of home energy upgrade programs are addressing and engaging with emerging issues and design trends, at both the project-level and program-level. These issues and trends include electrification, carbon reductions, resilience, healthy homes, grid interactivity and others.

Table 1 Summary of performance for deep energy upgrade programs reviewed in this report.

Program Name	Number of Homes	Average Cost ($)	Average Site Energy Savings	Notes	Section
Energy Upgrade California - CA	20,000	$6,300	274 kWh, 16 Therms	Actual bill savings. Predicted savings were typically much higher.	Section 2.4.2
Zero Energy Now - VT	24	$54,500	39% delivered site energy savings; 64% fossil fuel and grid energy savings; 60% energy cost savings	Weather normalized savings from utility bills and fuel delivery invoices. Most projects electrified, including insulation, heat pumps and PV.	Section 2.4.3
Home MVP – MA: Deep	66	$49,126	48%	Predicted energy savings	Section 2.4.4
Home MVP – MA: All	341	$21,675	33%	Half were electrified	Section 2.4.4
Extreme Energy Makeovers - TN	3,420	$9,000	35% (4,900 kWh)	Deemed energy savings; affordable housing	Section 2.4.5
National Grid Deep Energy Retrofit Pilot Community - MA and RI	60	$34.59 /ft²	55%; 43% source energy savings	For 29 comprehensive projects	Section 2.4.6
FSEC DERs - FL	10	$14,323	38%	DER increment was $7,074; affordable housing	Section 2.4.7.1
FSEC DERs - FL	70	$16,424	30%	DER increment was $3,854; affordable housing	Section 2.4.7.2
EnergyFIT Philly - PA	67	$14,257	36% gas, 22% electric	Affordable housing	Section 2.4.8
EnergySmart Ohio - OH	11	$30,173		Cost data from Redwood Energy Guide	Section 2.4.9
Home Intel by Home Energy Analytics - CA	1,400	Effectively zero	10%	CA's first pay-for-performance utility program; Includes automated energy end-use feedback and customized coaching	Section 2.4.10
Home Intel by Home Energy Analytics - CA	16	Effectively zero	42% electric, 17% gas	Higher performing subset	Section 2.4.10
Sealed - NY	338	$10,000	20% heating, 5% electricity		Section 2.4.11

For decades, the canonical approach to energy retrofits has focused on load reduction, with the highest priority given to envelope improvements, followed by equipment (primarily Heating, Ventilation and Air Conditioning (HVAC) and hot water) and finally miscellaneous loads (lighting, appliances, plugs). Generally, the idiom and governing approaches of the home performance industry have not caught up to rapid changes in the related realms of the grid, carbon reduction imperatives, smart technologies, and emerging trends in equipment cost and performance. Solar photovoltaic (PV) systems, for example, have undergone dramatic changes in pricing, financing availability and customer experience over the past decade. These changes warrant a reconsideration of how energy use and carbon are addressed in existing homes. While much of the interest in Deep Energy Retrofits (DERs) at the turn of the last decade (2010's) was centered around super insulating existing homes, we could not find any recent deep retrofit programs using this approach. These high-cost approaches have been largely abandoned in favor of less invasive and lower cost means to reducing home energy use. It makes sense for homeowners, contractors and efficiency programs to consider how traditional efficiency measures can be best combined with smart technologies and renewable energy generation, both on-site and from the grid. Energy production and storage are now becoming cost competitive with traditional load reduction measures, and the efficiency industry must adapt its approaches accordingly. Furthermore, the market has been more willing to fund and install solar PV technologies, so energy upgrades should leverage this momentum. This new economic and technological landscape requires that we reassess what kinds of interventions are recommended in homes.

The following ideas/themes have emerged during this literature review and will be explored in more detail in this report:

- Shift away from super-insulation and ultra-airtightness to more standard weatherization and home performance, combined with heat pump technologies for water heating and space conditioning. This is moving projects away from the >$100,000 range reported in the early 2010s.
- Solar PV is becoming lower cost and more common in efficiency upgrade work, and PV can be seen as integral to energy upgrade work, rather than as a last resort strategy.
- Complex technological solutions lead to poor performance and energy savings, and their higher perceived risk is a barrier to wider adoption.
- Using models to predict energy savings is still very difficult for individual homes, but it may still be a useful tool for program evaluation averaged over many homes, as well as for securitization of portfolios of homes as investment products.
- Costs and performance are not well correlated. This is due to a combination of occupant behavior, the starting point of the home, and the high costs that can be incurred for measures that do not save a proportional amount of energy, or are done for non-energy reasons (e.g., window replacement).
- Many programs are still relatively small-scale pilots – typically targeting 100 homes or fewer and not (clearly) contributing to a larger market transformation.
- Behavioral changes are commonly overlooked but should not be – they can offer 10% savings for little or no cost – particularly if implemented with direct occupant feedback and energy coaching.

- Programs have had success with some innovative approaches, including:
    - Neighborhood-level recruitment.
    - Working with community organizations to engage homeowners, particularly for low income/disadvantaged communities.
    - Multi-fuel or fuel agnostic programs.
    - Electrification of heating and hot water end-uses.
    - Financing from the program using local networks of lenders.
    - Novel financing approaches, including Pay-As-You-Save (On-Bill) and Property Assessed Clean Energy (PACE) funding mechanisms.
    - Use of vetted contractor networks.
    - Incentive structures designed around achieving program goals.
    - Pay-for-performance program structures.
    - Emergence of one-stop-shop programs that integrate project management, design and support services into making the experience easy for homeowners.

2.1 Innovations in Retrofit Project Delivery

Efficiency programs in the US have been refined over the past decade to more directly appeal to consumers, to leverage multiple sources of funding and multiple drivers of home upgrade activity. Some of these trends are discussed elsewhere in this report, so the following list highlights some of the major program trends and only provides brief description of their key features.

- **Efficiency plus health.** The healthcare community has reached an important consensus that the social determinants of health, including housing, are critical to providing adequate healthcare in the U.S. Healthy housing interventions work best when they are coordinated as an effort involving both community health and energy efficiency organizations. These programs can provide referrals to one another's services, boosting program participation and benefits. In the near future, home energy and health upgrades may even be funded by government and/or private health insurance, allowing home performance and weatherization upgrades to be supported by medical expenditures.

- **Trigger points.** These are moments in time when an energy upgrade project can be made more cost-effective, for example, at the time of equipment replacement, the incremental cost of higher performance HVAC is often fairly low. Alternatively, these are moments when local jurisdictions can require minimum performance upgrades, such as insulation, health and safety measures, required at the time of home sale or during remodeling projects. Trigger point strategies can automate the upgrading of the housing stock as it is turned over between owners and otherwise remodeled.

- **One stop shop.** This is an approach designed to make the consumer experience of implementing an energy upgrade more convenient. A one stop shop program brings all of the difficult decision-making under the program's umbrella, including finding qualified contractors, specifying upgrade measures, securing financing, permitting, and ensuring quality work. Examples of these program types include Home Energy Squad in MN and Sealed in NY.

- **Guaranteed savings.** Given the long history of over-predicting energy savings from home upgrade work, guaranteed savings programs reduce risk to homeowners by guaranteeing utility bill savings in each project home. If a dwelling does not save the guaranteed amount, the difference is paid to the customer. In this scenario, the guarantor ensures their financial position by reducing prediction risk for savings. They do this by validating savings estimates using actual pre-retrofit energy use data, careful site inspections and quality upgrade work. Finally, they can spread the risk of an inaccurate savings prediction across a portfolio of dwellings.
- **Attractive financing**. Attractive project financing is critical to expanding home upgrades in the market place. For customers with good credit, traditional financing mechanisms are an option, including personal loans, home equity lines of credit, and mortgage refinancing. Newer financing mechanisms have emerged with a demonstrated ability to fund projects in dwellings lacking good credit, cash down payments, and the like. These include Pay-as-you-save financing, which leverages project costs on the monthly utility bill, and PACE financing, which leverages project costs on the property tax bill.
- **Pay for performance.** Rather than rely on energy models or deemed savings to determine project performance, some programs are using a pay-for-performance approach, where savings are only counted when they are measurable. This approach requires tracking of actual utility bill savings, which is best done using smart meter interval data. The publicly available CalTrack methods do exactly this, and this approach to counting program savings has been implemented in both NY and CA residential efficiency programs. Providers are only paid from program dollars for savings that are achieved in the real world, which drives careful savings predictions, project implementation, technology specification and quality control.
- **Securitization of home energy upgrades for investment and demand-side procurement.** Many argue that the variability in cost, performance and outcomes of energy upgrade work are too unpredictable to support the securitization of projects as investment products with reliable returns and performance. Some programs and companies are working to change this, in effect, to transform portfolios of home energy upgrade projects into investment-worthy securities that can be bought and sold. These can be investment products with reliable returns, or they can be bundled as demand-side energy procurement products.

2.2 Review Articles

2.2.1 Previous LBNL Deep Retrofit Meta-Analysis

About eight years ago Lawrence Berkeley National Laboratory (LBNL) undertook a study for the U.S. Department of Energy (DOE) on DER for homes. Part of this study was to summarize the extant deep retrofit literature. The resulting report (Less and Walker, 2014) assessed the current state of DER performance in the U.S. using performance data gathered from the available domestic literature on 116 homes across varying climate zones. The value of the analysis for some metrics was hindered by data gaps and inconsistent reporting. The authors suggested that future analyses are needed using a larger, more fully developed dataset. This could be facilitated by a centralized, standard database of high performance home projects, as envisioned in the U.S. DOE supported Building America Field Data Repository (Neymark and Roberts, 2013).

A limited number of projects had sufficient data to estimate the impact of the retrofits. These homes generally achieved good results, with average annual net-site, net-source and carbon reductions of 47%±20% (57 homes), 45%±24% (35 homes), and 47%±22% (23 homes), respectively (74.5±76.3 MMBtu, 103.8±103.0 MMBtu, and 9,152±5,309 pounds). The top 16% of DERs achieved 70% or greater savings. For most of the cases where 70% was not met, the targeted reduction was also below 70%, so this is indicative of varying project goals, not necessarily project "failure". While average performance was consistent across the reporting metrics, those homes (n=7) that increased electricity use achieved source energy and carbon reductions that were 57% and 42% lower than their net-site energy reductions. Reliance solely on-site energy performance was found to be insufficient for some policy goals, because of the potential impacts of fuel switching and of regional variation in the environmental (CO_2e) impacts of electrical generation. No substantial difference was observed between homes reporting actual energy savings and simulated energy savings, though no comparison was possible of simulated and actual results in the same home. Net-energy reductions did not vary reliably with house age, airtightness or reported project costs, but pre-retrofit usage was correlated with total reductions (MMBtu).

Substantial airtightness reductions averaging 63%±25% were reported (in 48 homes) with post-retrofit airtightness of 4.7±2.9 ACH_{50} (across 94 homes). Unfortunately, mechanical ventilation was not installed consistently in tightened post-retrofit homes, with approximately 30% of homes not installing mechanical venting (that were primarily outside of cold climate regions). It was recommended that all future DERs should comply with ASHRAE 62.2-2013 (now (ASHRAE 62.2, 2019)) requirements, given their potential to worsen Indoor Air Quality (IAQ).

Annual energy costs were reduced from a pre-retrofit average of $2,738±$1,065 to $1,588±$561 post-retrofit (for 25 and 39 homes respectively), with average annual energy cost savings of $1,283±$804 (from 31 homes). The average reported incremental project cost was $40,420 with a large range of ±$30,358 (from 59 homes). An analysis using a 30-year mortgage at 4.46% interest (this was the rate at time of the report), showed that the average net-homeownership costs increased by $15.67±$87.74 per month, with a median of $1 per month and that 48% of projects realized net-savings. The average cost per MMBtu net-site savings was $603, but this was approximately 45% lower in non-cold climate projects.

The report concluded that increasing retrofit energy and cost reductions will require broader scopes of work, which will only become common when the risks and benefits of DERs are better characterized for all actors involved—homeowners, contractors, lenders, buyers, etc.

Risk can be reduced through standardized retrofit packages and contract language, which can both reduce design costs and ensure that an effective, validated systems approach is employed. Risk can also be reduced through a better-trained workforce capable of delivering the quality of workmanship required in aggressive retrofits. The varied benefits of DERs also need better characterization, particularly since demand has proven to be a greater barrier to home energy retrofits than cost (Borgeson et al., 2012).

Nearly all the DER research at that time had focused on building improvements, energy, and economic performance, with only cursory efforts made to document thermal comfort improvements, changes in IAQ or health, convenience, and durability. Yet, these factors likely play a role that is at least as important in homeowner decision-making and market demand as those of energy and environmental performance. The lack of a transparent, consistent format and method for reporting project costs, limited the ability to better understanding of DER costs. Finally, the review concluded that, from a longer-term financial perspective, there is a need to establish the outcomes of DER investments at time of resale, as well as the loan performance of financed retrofit projects.

2.2.2 ACEEE Deep Energy Retrofit Review

A study conducted by the American Council for an Energy Efficient Economy (ACEEE) (Cluett and Amann, 2014), identified and reviewed a number of programs across the US, including pilots from National Grid, New York State Energy Research and Development Authority (NYSERDA), Building America and the 1000 Home Challenge. The results are summarized in

Table 2. Like the LBNL meta-analysis released the same year (Less and Walker, 2014), this review paper highlights the reported energy savings from the projects, confirming that greater than 50% savings are possible, though with substantial diversity in results. The report includes best practices and lessons learned from specific retrofit measures, including attics, above grade walls, foundations, windows, mechanical systems, etc. Reported DER costs are about the same as those for a kitchen renovation or room addition, though many of the pilot projects they highlight have costs exceeding $100,000. The greatest opportunities to reduce costs were to improve project management efficiency and to integrate DER measures with other renovation work.

The project time-lines of example home performance and DER projects were compared and the DER projects took much more time: 2 months for home performance vs. 6-7 months for DER. The programs, contractors/workers providing whole home upgrade services included home performance professionals, general contractors, affordable housing organizations and others. The diversity of market actors in the home upgrade space resulted in a lack of firmly established program-level best practices around workforce qualifications, technical program assistance and the potential for improvement in project delivery and costs with greater market/contractor experience. In this varied context, project delivery approaches are diverse, and the report highlights some examples that are gaining traction. First, there is the potential for workforce alliances between groups of contractors, assessors, and verifiers, with one party usually responsible for the project scope overall. An example of the workforce alliance approach is the RESNET EnergySmart Home Performance Team model. Another path to delivering whole home DERs is for existing trade companies (e.g., HVAC) to expand their offerings to include broader home upgrade work. Some programs rely solely on experienced builders with new home or renovation experience in green construction, which provides some level of quality control and assurance for participants and program managers.

Table 2 Overall project costs of DERs, (Cluett and Amann, 2014)

ORGANIZATION	COSTS
Research and Development Program on DERs. • Sacramento Municipal Utility District (SMUD) • National Renewable Energy Laboratory (NREL)	• Range $66,500 to $141,000 total project costs. ($112,489 average cost). • Range $16,957 to $40,800 total project energy efficiency upgrade costs. ($29,360, 26% average cost).
New York State Energy Research and Development Authority (NYSERDA)	• Range $67,000 to $144,000 total project costs. • $100,000 per home for the projects involved in the Pilot Phase I that were fully funded by NYSERDA.
• Vermont Energy Investment Corporation (VEIC) • Champlain Housing Trust (CHT)	• Range $58,000 to $218,000 total project costs. • Range $7,500 to $16,500 total project energy efficiency upgrade costs.
National Grid Deep Energy Retrofit Pilot Homes	Projects ranged from $50,000 to $180,000, with an average of about $40 per ft^2.
Lawrence Berkeley National Laboratory (LBNL)	Unknown

The major barriers to scaling up DERs were identified as:

- **Inadequately trained workforce with the necessary skills**: Typical remodeling contractors who are engaged in the home at the time when marginal DER costs are lowest simply do not have the skills or training to perform DER work. The trades are compartmentalized for the most part, yet DERs are most successful when they are comprehensive and integrated. Some home performance contractors have begun to take on the high-level managerial role required in this work.
- **Market interest and acceptance is low amongst homeowners**: To gain market acceptance, the authors recommend development of packages of solutions that are tested and proven to save energy in a variety of contexts. Homeowners need a clear picture of what improvements are required, the costs, and the benefits (energy and otherwise). Cost is a major constraint, particularly for households where the improvements are most valuable. Financing is most likely required. They note that cost-effectiveness is difficult to achieve using current utility program tests/metrics, as is also the case for standard whole home retrofit programs.

The authors acknowledge that even with improvements to project/program delivery, DERs may be appropriate only for a small subset of customers who are willing to undertake major home renovations and are dedicated to reducing their environmental footprint. Yet, there is some potential for the market to expand as the workforce improves, processes are streamlined, and funding sources are identified. In pursuit of these improvements, the authors suggest a need for streamlined project administration approaches, simplified contractor procedures, and an overall need to drive down project costs through increased competition and greater contractor experience with home upgrade work. They recommend achieving some of these improvements through the use of pilot programs, that should focus on developing workforce capacity, encouraging market valuation of DER works, increasing customer awareness, and targeting customers whose personal values align with DER work scopes and outcomes (e.g., environmental conscious consumers, high energy users, or those planning other renovation work). Some suggestions for pilot study features include educating contractors about energy upgrade opportunities in typical remodel work scopes, including non-energy benefits in cost-effectiveness tests, and relying on actual energy use to assess projects.

2.2.3 ACEEE Unlocking Ultra-Low Energy Performance

Another study conducted by ACEEE (Amann, 2017) demonstrated that deep energy savings are technically feasible in Ultra-Low Energy Building (ULEB) retrofit projects. To date, ULEB policies and programs have been mainly focused on new construction but moving ULEB concepts and practices from new construction to existing buildings could be an important step in transforming the buildings sector. Several authorities have policies to encourage and eventually require ULE performance in existing buildings. However, beyond targets and goals, policy activity specifying Zero Energy Buildings (ZEB) and/or ULEB is limited. The document estimates that more than half of the US building stock that will be in use in 2050 is already built an in use today, and that technical solutions exist even though the level of intervention and the cost required varies widely, the. Different programs and technical approaches offer the potential for Ultra-Low Energy (ULE) in existing residential buildings, as follows:

- Passive House: The passive house approach builds on concepts of passive building and building science principles to achieve high levels of energy efficiency with an emphasis on maintaining occupant comfort.
- 1000 Home Challenge: This is an integrated approach to reducing energy use in existing homes through technical, behavioral, and community approaches. The 1000 Home Challenge focusses on measured savings to demonstrate a range of creative solutions for reducing actual home energy use by 70–85%.
- Zero Energy Now (ZEN): The ZEN program is intended to support Vermont’s goal of supplying 90% of all state energy demands in 2050 using renewable sources.
- Energiesprong International: The Energiesprong (“Energy Leap”) program is a new market transformation approach to deep home retrofit which was launched in the Netherlands. It pursues a mass-customization strategy, incorporating prefabricated facades and insulated roofing systems along with advanced heating and cooling and PV to deliver ZEB retrofits.

2.2.4 ACEEE Scaling Up Home Performance Retrofits

This ACEEE study (Cluett and Amann, 2016) explored the opportunities for residential retrofit programs to grow participation and realize the anticipated energy savings. The report discusses the program challenges, followed by strategies to address those challenges and examples of current programs employing these strategies. Significant challenges identified were:

- Calculating accurate project-level savings estimates.
- Ensuring that upgrades are installed and perform as expected.
- Encouraging public buy-in and participation in programs.

The report explains how some strategies are being already implemented in some retrofit programs, as follows:

- Improving energy modeling outcomes through better access to energy use data, model calibration, and adoption of standardized home performance data protocols.
- Enabling real-time feedback on project and program performance during program operation, rather than after it is complete.
- Stimulating participation in retrofit programs.

The report concludes that programs should work to incorporate practices for delivering reliable savings, both to increase their own energy savings realization rates (i.e., the ratio of measured savings to predicted savings) and to contribute to transformation of the home performance market as a whole.

2.2.5 Energy Efficiency Retrofits for U.S. Housing: Removing the Bottlenecks

This study (Bardhan et al., 2014) investigated the decision process around energy retrofits to evaluate the alternative mechanisms that could expedite energy efficiency retrofits for U.S. housing, as summarized in Figure 1. They assess that significant energy reductions are, in fact, financially and physically achievable, comparing between techno-economic evaluations of US retrofit potential, and they conclude that significant savings are technically and financially feasible. They then explore the bottlenecks that are hampering current investment in deep energy savings in the US, and two key factors emerge: (1) imperfect information; and (2) loan market failures. They then evaluate the current state of the art in energy assessment scoring tools, and explore the On-Bill, PACE, and Solar programs to facilitate secured loans for energy retrofit work. The study focuses on the usability and accuracy of computer-based audit "tools" that allow residential property owners to evaluate the benefits from various energy-saving investments[1]. In addition, the research states that policy actions are constrained because of the limited understanding of how behavioral responses of individual homeowners affect their energy efficiency decisions. But based on the author's opinion, information obstacles and credit access barriers are clearly evident as observable market failures that inhibit energy-saving investments.

The report outlines the significant difference between the energy retrofit markets and the Solar PV market. The energy production (in kWh) for each PV module is standardized, therefore it

[1] Similar to the BETTER tool (https://better.lbl.gov) for commercial buildings currently in Beta format.

can be measured exactly, and the cost of installation can be much more uniformly measured and priced for consumers. The main components for the success of Solar PV are stated to be: (1) clear metrics for the costs and benefits of a solar investment; and (2) government tax benefits that have allowed the industry to reach an effective scale via third party funding.

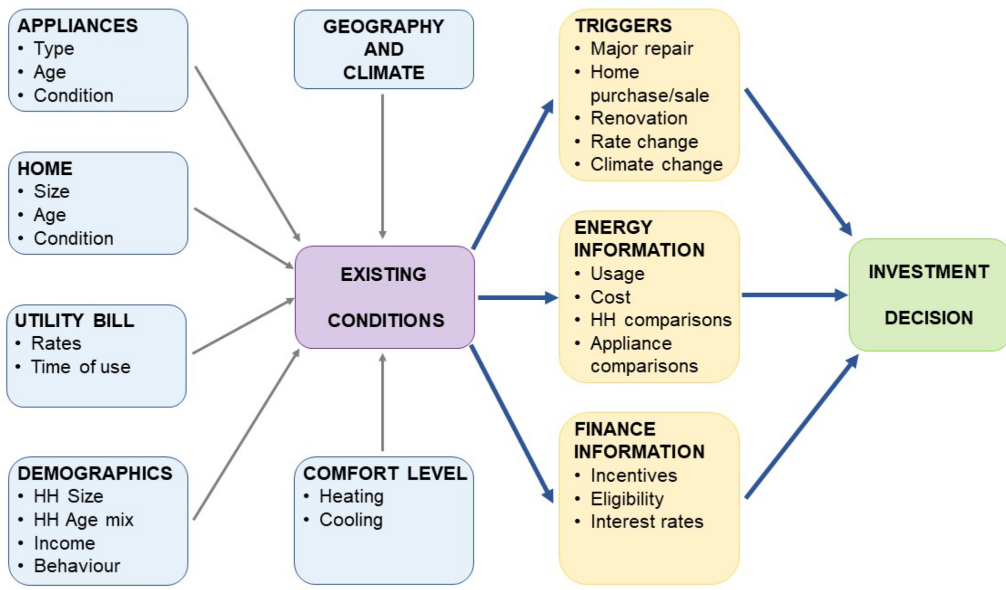

Figure 1 Residential energy efficiency investment decision process, (Bardhan et al., 2014)

The report outlined why financing terms might impede energy efficiency investments:

- Weak credit limits loan market access.
- Financing projects with relatively low investment returns.
- Owners are risk-averse and would seek borrowing costs that are below the Energy Efficiency rate of return. Uncertainty in the distribution of project returns necessitates even lower risk and loan costs.
- Large number of transaction costs, including time/expense to find and monitor contractors and to secure financing. Loan costs also must be low enough to offset these transactional, soft costs.

Despite the potential to be productive investments, most lenders do not see energy efficiency investments as collateral for secured loans. Nevertheless, the study concluded that borrowing costs in the single digits might be required to spur investment in many dwellings. Absent government subsidized loan programs, these low interest rates must be through secured loans, or special loans that require the property owner to make a *highly credible commitment to repay the loan*. Options include: (1) refinance an existing mortgage; and (2) Fannie Mae Energy Improvement Mortgage at time of purchase. The study concludes that first-lien mortgages are unlikely to be the source of Energy Efficiency funding that we need. In addition, second mortgages or Home Equity Lines of Credit are also unlikely to be primary funding sources, due to equity requirements, higher interest rates, and generally depressed house prices in the market. Federal Housing Administration (FHA) second mortgage program called PowerSaver is being piloted.

Potential funding sources that address mortgage-based limitations include: (1) Energy purchase contracts; (2) On-Bill financing; and (3) PACE loans.

- Bill neutrality is a goal for On-Bill financing, where the total bill remains either neutral or is reduced for the homeowner, while still financing upgrades.
- On-Bill might offer longer loan times better matched to energy efficiency payback periods, low interest rates (assuming default rates remain low), and customization for individual Multifamily units, avoiding split-incentive problem. On-Bill is limited because of: (1) harsh penalty of turning power off if defaulting on loan; (2) loan transfer to new property owners may be challenged; and (3) public utility funding for On-Bill is currently very low.
- All PACE plans are funded/created by a local government unit, and they include requirements to ensure that the expected present value of the savings exceeds the present value cost of the energy-saving investments. This condition ensures the property value should increase more than the investment. Can also be structured to provide bill neutrality. In summary, the incentives of the three participants in a PACE program are fully aligned to insure the projects are productive and the loans will be repaid, including homeowners, local government, and eventual owner of the loan. PACE has been seen as risky, for example, by the FHA. Additional requirements have been proposed to mitigate these risks.

In summary, there are information imperfections relating to energy-saving investments that deter the investments for both demand and supply reasons. For the demand, the information imperfections may limit the effective demand of property owners to carry out such investments. For the supply, the information imperfection may limit access to secured loans to finance the investments that property owners do desire to carry out. For this reason, likely policy solutions have to address these market failures. In addition, the study emphasizes the "Option to Take No Action" as a very strong persuasive element that limits homeowners from doing anything. For this reason, trigger points (such as equipment failure or home sale) are/may be critical, as owners are forced into action.

2.2.6 Scaling Up Participation and Savings in Residential Retrofit Programs

This ACEEE study (Cluett and Amann, 2016) reviewed current practice in residential retrofit programs in order to identify trends and opportunities for scaling up participation and increasing realized energy savings for whole home energy upgrades. They identify three key program challenges:

- Accurate project-level savings estimates.
- Measure installation is installed and performs as expected (i.e., quality assurance)
- Encourage public participation and buy-in.

The authors then highlight several best practices currently being leveraged by some programs in the US:

- Home performance data standardization using Home Performance eXtensible Markup Language (HPXML).
- Access to energy use data to allow for calibrating building models to pre-retrofit usage. They acknowledge the Green Button and other approaches used by individual states and utilities to facilitate this process.
- Real-time program evaluation using emerging technologies that allow program evaluation to occur in real-time, rather than post-facto.

Finally, they explore some opportunities for future programs to leverage to address the three key challenges identified:

- Home energy management systems as a source of performance data that includes data logging capabilities from internet-connected thermostats and other technology.
- HVAC system measurement and verification to avoid numerous potential performance faults
- Pay for performance pilots. These programs rely on aggregator providing verified energy savings to utilities using whatever means the aggregator deems appropriate/effective. This allows utilities to procure efficiency, and it avoids them needing to design and otherwise manage programs.

Retrofit programs targeting deep energy savings have had some limited success through targeting homes in specific geographic regions (Oregon, Washington and Vermont), alignment of energy upgrades with home improvements over-time, and targeting of high energy-use customers using interval meter data.

2.3 Electrification

In the past couple of years there has been increasing interest in home electrification for several reasons:

- More affordable solar generation and storage.
- As pointed out by (Griffith et al., 2020) we cannot “efficiency our way to zero carbon emissions”.
- Health and safety concerns (reducing risks from CO, NO_2, particles, etc. from fossil fueled appliances)
- There is existing consumer demand for PV and electrification (W. R. Chan et al., 2021).

The ZEN pilot program in Vermont (for more details, see Section 2.4.3) is a good example of a program that has developed electrification-based work scopes and priorities in energy upgrade projects because the explicit goals were reduction of fossil fuel energy and carbon emissions. This new design goal led them to limit envelope upgrades to those typical of non-deep home performance work, combined with cold climate heat pumps and roof top Solar PV. The envelope upgrades are those that the industry is already familiar with, there is an adequate work force and training, and the main materials and methods have not changed in decades. These tried-and-true interventions give homeowner's thermal comfort, resilience to heat waves/cold spells, improves occupant health and safety. This is done with a relatively modest $10,000 investment in the building envelope. This alternative approach delivered 64% energy savings at average costs that were well below those typical for previous cold climate DERs.

Most current analysis supports the argument that electrification of dwellings and end-uses is financially beneficial in many circumstances, depending on local rate structures, fuel sources and dwelling types. At least one study (Energy and Environmental Economics, 2019) has investigated the short- and long-term economics of building electrification in California, and concluded that electrification can lead to consumer capital cost savings, bill savings and lifecycle savings in many circumstances, namely in new home construction, and for high efficiency heat pumps in homes that replace air conditioners. The Rewiring America book (Griffith et al., 2020) takes a broad approach to the issues around electrification and highlights the importance of having a clean energy infrastructure. It also points out that if we make the commitments to electrify our infrastructure at the scale required, we will lower the energy costs making the future affordable for everyone. But the long-term success of electrification programs will depend on an appropriate set of financing mechanisms (e.g. loans, incentives, subsidies). Synapse Energy Economics reached broadly similar conclusions in their analysis of heating electrification in California buildings (Hopkins et al., 2018). In a similar vein, Rocky Mountain Institute (RMI) analyzed the economics of building electrification nationwide in both new and existing dwellings in (Billimoria et al., 2018), and reported that over the lifetime of the appliance, new home electrification is often a lower-cost solution. This holds true in some retrofit scenarios, including replacement of high-cost fuels (e.g., propane or fuel oil), when replacing a gas furnace and air conditioning at the same time, and when bundling electrification with rooftop Solar PV. Based on these promising technical analyses, resources have been developed to help guide local government and utility coordination on these strategies (Cadmus Group LLC, 2019). The Sierra Club has also offered a public policy action plan for building electrification (Golden, 2019).

Accordingly, an increasing number of jurisdictions are already creating public policy or offering incentives to upgrade homes to be all-electric. Local new home electrification ordinances currently exist in Berkeley[2] and San Jose[3], CA (with support from Pacific, Gas and Electric (PG&E)), and many similar actions have been taken in other California cities[4]. The SMUD in California's Central Valley does not require electrification, but it does offer electrification rebates in new homes ($5k). At the state level, numerous states have enacted policy and planning documents aimed at the electrification of buildings as a key element to reducing carbon emissions, including California, Colorado, Maine, Massachusetts, Missouri, New

[2] https://www.nrdc.org/experts/pierre-delforge/berkeley-passes-nations-1st-all-electric-building-ordinance#:~:text=In%20a%20first%20for%20California,%2C%20apartments%2C%20and%20commercial%20buildings.
[3] https://www.nrdc.org/experts/olivia-walker/10th-largest-us-city-nixes-gas-nearly-all-new-buildings
[4] https://www.sierraclub.org/articles/2021/01/californias-cities-lead-way-gas-free-future

Jersey, New York, Washington, and others[5]. Maine, for example, is planning to reduce natural gas use in buildings, by encouraging the installation of 100,000 heat pumps[6]. New York State is embarking on a similar heat pump incentive program, targeting an increase from its current 2% market penetration to a target of 5% by 2025 (Napoleon et al., 2020).

There are very few whole-dwelling electrification programs for existing homes. One example is the current proposal from the City of Berkeley to require a minimum time-of-sale expenditure on electrification measures (including things like preparing for future electrification, e.g., upgrading electric services). The only electrification program we are aware of for existing dwellings is run by SMUD, where electrification rebates up to $13,750 are available for electrification work, including heat pumps for space and water heating, panel upgrades, wiring upgrades, etc.

Table 3 Budgets and participation by program, (Nadel, 2020)

Program Implementer	Prior Year	Current Year	Rebates	Customers
SMUD	$4,500,000	$12,500,000	2,500	
Palo Alto	$150,000	$300,000	43	
SCE CLEAR	$425,000	$1,600,000		
SCE plug-load and appliance		$17,000,000		
NYSERDA	$22,800,000		12,778	6,520
NYS Electric Utilities	Just started	$36,600,000	Just started	Just started
Efficiency Maine	$12,118,849		17,776	
Mass Save	$4,875,000	$9,705,000	2,530	
MassCEC		$500,000	27	
Massachusetts DOER	$1,333,333	$1,333,333	350	250
Vermont Department of Public Service		$5,942,339		8,993
Efficiency Vermont	$3,600,000	$4,100,000	5,291	
Burlington Electric Department	$627,905	$277,469	356	390
Building Performance Professionals Assoc. of VT	$10,000	$300,000		
Energize CT (Avangrid)	$6,853,734	$6,766,340	9,050	6,909
Energize CT (Eversource)	$5,846,348	$10,676,893	19,485	
Energize CT Optimization Pilot		$300,000		
National Grid Rhode Island	$190,000		490	378
Bonneville Power Administration			8,350	
City of Ashland, Oregon			225	
Eugene Water and Energy Board	$500,000	$500,000	288	268
City of Boulder, Colorado	$45,000	$45,000		40
DC Sustainable Energy Utility		$440,000		Just started
Total	**$63,875,169**	**$108,886,374**	**79,539**	**23,748**

Blank cells indicate no data provided.

Most electrification work in existing homes focuses on the installation of efficient heat pumps to operate alongside existing space heating appliances that use natural gas, propane or fuel oil. A recent review of these programs in the US was published by ACEEE (Nadel, 2020), and identified a number of programs that are in their early stages. A 70% increase was identified in funding from 2019 to 2020 in heating electrification program funding in the US, currently

[5] https://rmi.org/2020-watt-a-year-for-building-electrification/
[6] https://www.greentechmedia.com/articles/read/maine-wants-to-install-100000-heat-pumps-by-2025

totaling $110 million. A total of 80,000 rebates were provided in the most recent year. Programs are most extensive on the West coast and in the Northeast, but individual programs are identified in Colorado, Illinois, the District of Columbia and North Carolina. As seen in Table 3 , in all, 23 programs were identified, 22 of these included ductless heat pumps ($300-$1200 incentives), 21 include ducted heat pumps ($300 to >$10,000 incentives), and 20 included heat pump water heaters. 8 programs require weatherization work prior to heat pump installation, while another 15 programs encourage but do not require weatherization efforts. Weatherization incentives ranged from $1,000 to $10,000. Select programs are also encouraging installation of heat pump dryers and induction cooking. Nadel provides regional and state-by-state descriptions of the programs and their incentive structures.

Nadel identified the following important trends:

- Participation has been increased in some cases by offering upstream incentives to contractors or distributors, as well as by allowing credit for both electric and fossil fuel savings.
- Targeting dwellings that use delivered fuels (propane or fuel oil) increases program effectiveness, as the economics are strongest in these homes for heating fuel switching.
- As the majority of programs install heat pumps alongside existing heating equipment, several programs in the Northeast have noted the need to carefully control the integration of these systems. For example, by using integrated controls, or by carefully considering thermostat placement in the home and/or maintaining a backup heat set point that is a few degrees below the intended heat pump units set point. This ensures the existing inefficient (now “backup”) system only operates when the heat pump cannot meet the load.
- There is a limited availability of high capacity cold climate heat pumps to serve loads in larger, inefficient existing homes in cold climates. This supports the need to weatherize before electrifying space conditioning.
- Competition remains from natural gas programs and providers, who do not want to see a sharp reduction in gas system demand.

In addition to decarbonization of home energy use, there can be significant health and safety benefits associated with eliminating or reducing in-home combustion. These benefits include:

- Improved indoor environmental health from elimination of combustion pollution sources inside dwellings, including particles, NO_2, water vapor and CO. These contaminants have been measured in many studies. The following reports and papers provide recent summaries of measured kitchen contaminants from gas burning: (Singer et al.0, 2017), (Chan et al., 2020), (Zhao et al., 2020), and (Zhu et al., 2020).
- Reduced outdoor air pollution from the venting to outdoors of indoor combustion byproducts from gas appliances.
- Efficiency program benefits associated with elimination of costly and time-consuming combustion safety testing of retrofitted homes.

The fossil fuel appliances that need to be addressed for full dwelling electrification include:

- **Heating systems**: Fossil fuel appliances can be replaced with heat pumps. The introduction of cold climate and CO_2-based heat pumps has enabled this approach to be applied to almost all climates in the US. One downside from an energy use perspective is the opportunity for cooling in homes that previously had no centralized cooling equipment. However, there is a benefit from the perspective of resilience, e.g., homes are better able to deal with extreme heat events. In addition, the thermal comfort benefit of cooling may be a strong driver for homeowners to invest in energy upgrade work.

- **Domestic Hot Water (DHW):** Fossil fuel heated hot water systems can be replaced with heat pump water heaters. There are a few restrictions for these devices – primarily due to noise constraints in multifamily applications (e.g., water heaters located in bedroom closets), and in predominantly heating climates, they may benefit from improved installation practices that extract heat from outdoor air or ventilation exhaust air rather than from inside the dwelling.

- **Cooking appliances.** Gas and propane ovens and cooktops can be replaced by electric devices. For cooktops, induction units are preferred for their efficiency, better cooking experience, safety and lower air contaminant emissions. According to builders and contractors, this is the most difficult end-use to electrify, because many cooks are convinced that gas is by far the best cooking fuel.

- **Clothes dryers.** Replace natural gas and propane clothes dryers with electric resistance or heat pump alternatives. Another option is to use free solar clothes drying by hanging laundry outdoors, although this is often seen as socially unacceptable in the US and restricted in many circumstances, such as for homes with Home Owners Associations.

One key barrier for full electrification is that many older homes do not have enough capacity in their electric service. There is also the need to run appropriate wiring to the end-use locations. Most commonly this involves the need for 2-phase, dedicated appliance circuits. These electrical upgrades can be significant components of electrification retrofit cost. In order to avoid costly electric service upgrades, some home performance contractors have developed approaches that use lower power appliances and smart circuit-sharing devices to limit the total electric power needs for a home, including such high-power requirements as electric vehicles (EV) charging. These will be discussed in more detail under emerging technologies in Section 5.1 of this report.

Another rapidly changing aspect of electrification is the increased use of electric vehicles. In many single-family homes this additional load may be the largest load for much, if not all the year. There may an opportunity to use car batteries to store electricity for the home (and potentially for the grid), however, this has some regulatory barriers to overcome in terms of grid safety and warranty/engineering design issues for the automobiles themselves. Electric car charging capability should be an important element of DER projects in the future, and this should be considered along with the other end-uses in terms of project costs, planning and required electrical capacity.

2.4 Retrofit Program Summaries

2.4.1 Better Buildings Neighborhood Program (Nationwide)

The Better Buildings Neighborhood Program (BBNP) was a large DOE investment in whole home energy efficiency programs across the country that supported programs using unique and emerging program approaches to drive energy reductions in existing US homes. The program operated from roughly 2010 to 2014 and funded 41 organizations/programs nationwide with a total investment of $508 million. While most programs did not target "deep" energy retrofits, they often had substantial whole home energy savings targets on the order of 20-30%. The programs also attempted to leverage important market strategies that will be necessary to drive deeper energy upgrades in the future: one-stop shop programs, vetted contractor networks and mentoring, project financing, program designs that support both homeowners and participating contractors, etc.

While analysis of program data led to clear recommendations for home energy upgrade program design (see Section 2.4.1.1), a statistical analysis of the energy savings for single-family dwellings (see Section 2.4.1.2) showed low realization rates of 0.44 and 0.64 for natural gas and electricity savings, respectively. While project savings were generally positive and real, they were generally substantially over-predicted by either simulation tools or deemed savings approaches.

While these projects might not typically qualify as "deep" energy upgrades, they offer the best available example of large-scale programs and real-world implementation of comprehensive energy improvements in occupied homes in the US. The lessons learned are applicable to today's programs, even if the performance goals or strategies are different. In addition, our interpretation of the future of this industry is that projects targeting 20-30% are likely the sweet spot for home upgrades. Combining these upgrades with on-site solar PV and/or electrification strategies can drastically reduce site energy and carbon emissions.

2.4.1.1 Program Design Impacts

The efficacy[7] of these program design elements was explored in a statistical process evaluation for the BBNP as a whole, including 54 independent programs/grantees (Research Into Action, 2015). Programs were successfully clustered into three groups, from most to least successful, based on metrics including market penetration, present value of lifetime cost savings, savings-to-investment ratios, upgrade costs, etc. The most important drivers of program-level success included:

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[7] "Success" was defined using a set of 12 quantitative indicators of efficiency program outcomes. The indicators were based both on theory and on data-availability from the BBNP programs. They covered broad categories of: (1) Market Saturation, (2) Program Costs ($ per upgrade, $ per MMBtu saved, etc.), (3) Effectiveness (saving energy, having comprehensive projects), and (4) Wider Economic Impact. Programs were then clustered together using latent profile analysis to group programs with similar performance across the 12 indicators. Three clusters were constructed, where the average group values for the 12 indicators were consistent with an interpretation of group "success", from least, to average and most successful.

- **Contractor training.** Not providing training was the strongest predictor of membership in the least successful programs. More training and more types/topics of training led to better performance. Topics included sales skills, business operations, building science and program requirements/processes.
- **Multiple pathways to participation and achievement of energy savings.**
  - **Direct installation of low-cost measures** was the single strongest predictor of a program being high-performing. Allowing these less-deep energies saving projects to participate in the program led to more successful programs.
  - **Multiple audit types,** including online, phone, walk-through, comprehensive in-person, etc. Using a broader range of audit types led to greater program success, because different audit types may appeal to different retrofit decision-making approaches among households. They note some literature that documents similar project conversion rates (from audit to project) for various audit types.
  - **Large number of contractors eligible to perform program work,** leading to reduced waiting times and more contractor choice for homeowners. It makes it easier for homeowners to find a qualified contractor, and it maximizes the number of projects that can be completed at any given time. A secondary benefit is to amplify program messaging in the market through contractor-led advertising and outreach. Care must be taken to keep work quality high through QA/QC and training.

While not highlighted at a high-level in the report, the following were also significant predictors of programs in the top-performance tier when each program element was treated independently (i.e., not as a group of features):

- No required savings thresholds for each project.
- Ability of a program to ramp up to (and maintain) its peak performance.
- Staff experience (having one staff member with >15 years' experience).
- Target region population.
- Regional electricity cost.
- Combined index that includes weather variability and housing stock condition in treated areas.

2.4.1.2 Energy Savings and Realization Rates

The single-family retrofit work was analyzed for trends in energy savings and savings prediction accuracy (i.e., realization rates) (Heaney and Polly, 2015). In all, the analysis included data from 37 retrofit programs nationwide, including data from 50,102 energy retrofit projects (183,504 efficiency measures) supported by BBNP programs (excluding NYSERDA and Town of Bedford projects). In all, 41 unique measure types were installed in these efforts, making up 4,581 unique combinations of measures. By far, air sealing and attic insulation were the most commonly installed measures, appearing in roughly 60 and 55% of projects, respectively. Decidedly fewer projects installed lighting, hot water, furnace, duct sealing, wall and foundation insulation measures. The least common measures included air conditioning and heat pumps, duct insulation, thermostats, windows and mechanical ventilation. Variability in installed measures was identified for different regions of the country, as well as for the vintage of the home, with older homes showing higher predicted savings. The median invoiced costs for the projects was $4,910, with half the projects between $2,047 and $9,500. The most expensive projects were above $30,000.

Programs reported estimated energy savings associated with efficiency measures in roughly 47,500 projects. Nearly 60% of projects used a building simulation tool as part of the audit software package, and energy predictions were made using simulation tools in roughly 50% of projects and deemed savings were used in around 20% of cases. The remaining cases used unknown prediction methods. Savings predictions did not differ substantially between these prediction methods. When projects were split into quartiles based on source energy savings the mean savings within the groups were 11%, 26%, 43% and 94%. They were unable to determine which measures were associated consistently with source energy savings, due to diversity in the sample and the large mix of installed measures across projects. The 10 most frequent combinations of installed measures had median source energy savings ranging from 10 to 50%. To further identify savings associated with measures, the authors built several linear regression models, and they identified 22 measures as significant variables impacting energy savings, with 18 having positive coefficients (meaning they saved energy). The largest savings coefficients were associated with solar PV, heat pumps and solar thermal systems. Low flow faucet aerators and thermal expansion valve (TXV) valves on air conditioners had the lowest savings coefficients. In addition to efficiency measures, the models showed that greater reported loan amounts were associated with increased energy savings, likely because larger loans facilitated more comprehensive projects. Differences were also substantial between programs and regions. Customer motivations also revealed themselves, in that savings were lower in projects that listed “comfort” as a driving factor, whereas savings were greater in projects that listed “savings” as the driver. Program design and approaches were found to be more important than project location.

Finally, the estimated savings described/summarized above were compared with savings extracted from utility billing information for a subset of projects (5,349 for natural gas and 6,732 for electricity). R^2 correlations between predicted and weather normalized actual energy use were 0.447 for natural gas and 0.481 for electricity. Correlations were very poor when comparing estimated and actual savings (for 1,408 gas projects, R^2=0.244; and for 1,614 electric projects, R^2=0.122), and normalized savings were very often less than predicted for both fuel types, though this was much more pronounced for gas savings predictions. Realization rates were calculated using filtered data sets that removed extreme values. Variability in realization rates was high, and there was insufficient data to associate this variability with factors, such as savings prediction method or the individual programs themselves. Natural gas and electricity realization rates averaged 0.44 and 0.64, respectively. Overall, this means that savings were over-predicted by the programs by 36% and 56% for electricity and natural gas. For natural gas and electricity, 68% and 53% of projects over-predicted savings by 50% or more. Unfortunately, the realization rate data was very sparse, representing only roughly 2% of single-family projects supported by the BBNP program. Despite modestly low realization rates, the normalized savings were positive on average, with mean source energy savings per project of 17.1 MMBtu for electricity and 13.2 MMBtu for natural gas. The authors recommend that programs consider calibrating savings predictions estimates based on actual pre-retrofit usage in order to improve realization rates in the future.

2.4.2 Energy Upgrade California (CA)

Energy Upgrade California (EUC) is a ratepayer funded whole home energy efficiency improvement program launched in the state of California in 2010, and a version of this program is still operating in the state today. The EUC program has two primary paths to participation: (1) Home Upgrade (HUP), a menu-based prescriptive measure install of at least 3 measures with savings estimates >10% and incentives from $1,000 to $3,000 per household; or (2) Advanced Home Upgrade (AHUP), based on an on-site energy audit, a building simulation model (EnergyPro), and program incentives up to $5,500 that scaled based on predicted household savings. Additional energy saving measures are incentivized in the AHUP program. Both programs levered networks of participating insulation, HVAC and home performance contractors, who performed the work and handled program administration for participating households.

Overall, the program has proven very difficult to administer and track, due to its large scale, diversity of participants and climates, and multiple regional administrators (i.e., the state's investor-owned utilities and regional energy networks). Evaluations that used whole-home metered energy data found that energy savings were consistently over-estimated by the program. We will provide some illustrative details from the program year 2015 evaluation report (DNV GL, 2017). The authors note two prior program evaluations, one from 2011-2012 that covered both HUP and AHUP, and another from 2014 that included only HUP projects. Over the program years 2013-2015, the statewide expenditures on the EUC programs were $126 million. The number of homes upgraded for the HUP and AHUP programs were 7,002 and 12,818, respectively. A subset of these homes (roughly 1/3 of HUP homes, and 41 and 66% of AHUP homes for electric and gas) were evaluated using actual utility billing data combined with regional weather data to determine the energy savings.

The programs (combined HUP and AHUP) reported energy savings that were consistent with established targets, but the evaluated actual savings were much lower than either the estimated or reported levels. Electrical percent savings were consistently in the single digits across program years, which DNV GL claims are too low to accurately measure. Statewide (for both HUP and AHUP), the evaluated realization rates were 9% of the statewide kWh target, 14% of kW targets and 34% of target gas therm savings. These low savings are consistent with the prior reviews in 2011 and 2014. They note that the realization rates for kWh savings were not consistent (or improved) over-time and that they fluctuated dramatically from year to year and between implementers. Based on overall very poor realization rates, DNV GL concludes that the models used over-estimate savings and do not reflect the full set of influences on whole home energy use.

For the HUP programs (deemed savings), half of the implementers had evaluated net-increases in electricity use on average. The gas therm savings were more consistent, with between 40-50 therms saved and realization rates in the 60-90% range. For the more detailed AHUP program, actual evaluated savings across all implementers in program year 2015 were as follows:

- Electric kWh savings.
  - Predicted: 1,487 kWh
  - Evaluated: 274 kWh per home
  - 25% realization rate
- Peak kW demand per home.
  - Predicted 2300 W
  - Evaluated: 240 W
  - 14% realization rate
- Gas Therm savings.
  - Predicted: 182 therms
  - Evaluated: 16 therms per home
  - 11% realization rate

The evaluation determined that the two primary drivers of variable energy savings in the EUC programs were home vintage and climate zone variability. After these factors, a survey of EUC households suggested that energy saving behaviors of home occupants was then next most important factor influencing outcomes. Other factors with some correlation to savings included household demographics, contractor messaging, household income and customer values.

These outcomes are disappointing, particularly for AHUP projects with in-home audits and detailed performance models used to develop work scopes. This highlights the potential issues with relying on modeling or deemed energy savings in retrofit energy analyses. The California projects were likely affected by the state's mild climate, which leads to much energy use being discretionary and independent of traditional heating and cooling load end-uses targeted in energy savings programs.

A process evaluation of the 2014-2015 program years was performed for EUC that focused on survey and interview-based assessments of the program, from the perspectives of contractors, program managers and participants (EMI Consulting, 2016). This evaluation asked how the process could be streamlined, how did contractors get engaged with the program, what marketing messages successfully engaged participants, what training/mentoring approaches were effective, and have recent program changes improve outcomes?

The report highlighted that satisfaction with the program was high amongst both participating households and contractors, and that the main drivers of participation were energy cost savings and improved comfort. In general, contractors wanted a more streamlined program, including simplified promotional materials for homeowners, consistent program requirements across regions, simplified participation paths, and reduced documentation requirements and

Quality assurance/control. They identified the need to more clearly communicate program requirements to non-participating contractors to increase their participation rates, and to better-communicate program time requirements to contractors and homeowners. The program was contractor driven, with most homeowners learning about the program from contractors. Yet, contractors did not use the program promotional materials, because they were too complicated for most homeowners. Overall, contractors need better ways to distinguish themselves in the market, and they highlighted the value of mentoring contractors through side-by-side inspections with highly experienced partners. Participants are increasingly seeking financing options in order to address the primary barrier of high upfront costs. This was particularly relevant for near-participants in lower income households.

The report also highlights some recommendations:

- Foster peer-to-peer marketing on social media.
- Offer events and workshops.
- Build the future target market based on characteristics of past participants.
- Support contractor marketing.
- Reduce application processing times and QA/QC requirements.
- Focus training and mentoring on top-performing contractors to make them more successful.
- Adopt common statewide job reporting requirements.

2.4.3 Zero Energy Now (Vermont)

The ZEN pilot program in Vermont was developed in 2015 by the Building Performance Professionals Association of Vermont (BPPA-VT or BPPA), with funding from the Green Mountain Power's Community Energy and Efficiency Development Fund. The program implementer was the Energy Futures Group. Project performance from the ZEN pilot study is detailed in a pre-publication research report made available to LBNL by the ZEN project team, which includes post-retrofit assessments of energy savings, cost savings and homeowner satisfaction, along with an assessment of financing from a cash-flow perspective (Perry and Young, 2020). Overall, the 24 project homes in the pilot study with post-retrofit utility billing data achieved an average of 64% energy savings. The program, projects and performance outcomes are reviewed below.

The 2016 pilot program included 22 homes with detailed performance assessments, and an additional 13 projects were included in a less robust pilot in 2017. The ZEN pilot program combined weatherization, heat pumps for space and water heating (or high efficiency efficient biomass heating equipment), and renewable electricity generation. The goal was to maintain similar monthly net-costs of homeownership while reducing on-site fossil fuel use, carbon emissions and use of grid electricity in existing homes. Projects participating in the pilot program were modeled using building simulation software to predict savings and determine the best package of measures for each home. Savings guarantees were provided for participants using funding from the Green Mountain Power's Community Energy and Efficiency

Development Fund. The contractors were part of a network intended to provide turn-key design and constructions services. Due to time constraints, some projects were not designed to comply with the ZEN program from the outset but were instead made to fit post-facto into the pilot's framework. This led to some performance issues, largely around heat pump design/operation and PV system sizing.

The program offered incentives initially at $50 per MMBtu saved up to $5,000, without which the program posits it would have been very difficult to attract homeowners to such complex and costly construction works. These ZEN incentives were in addition to pre-existing incentives from Efficiency Vermont's Home Performance with Energy star program (up to $2,000), pellet boiler and furnace incentives (up to $6,000), solar hot water (up to $3,000) and the 30% federal tax credit.

Core requirements for each ZEN project included:

- 10% energy savings through weatherization.
- 50% reduction in fossil fuel and grid electricity.
- 50% of post-retrofit energy derived from renewable sources.

Across 24 projects with post-retrofit utility billing data, the average project cost was $54,500 (incentives and federal tax credit totaled $13,000), while fossil fuel and grid electricity savings were 64%, and utility bill cost savings were 60% ($1,878 saved per year). The average savings of delivered site energy were 39%, not including PV production or carbon neutral fuels. The average variance between predicted and actual energy savings was 22%. The project net costs were assessed using a hypothetical 5.25%, 20-year loan term product, and under these conditions, four projects were cash-flow positive on a monthly basis, while four additional projects would require small (less than $35/month) net-increases in homeownership cost. Some homes with poorer performance were characterized by substituting one renewable fuel for another (e.g., wood for PV electricity), insufficiently sized PV arrays, improper use of mild climate heat pumps, over-sized and poorly performing heat pump, and heat pump used as supplementary rather than primary heat.

The authors highlight the following project trends:

- Integrated project design was important to avoid performance issues, like those noted above.
- Comprehensive projects were most successful, combining weatherization, hot water, space heating and PV.
- Project cost and post-retrofit performance were not clearly correlated.
- Use of Solar PV was critical to project economics penciling out.
- ZEN approach was successful in a variety of house types.
- Heat pump design and installation was a challenge for an inexperienced industry.
- Biomass heaters were effective in parallel with heat pumps.

Effort breakdowns were estimated for different measures/aspects of the projects as shown in Table 4.

Table 4 Number of worker day to complete each project, (Perry and Young, 2020)

	Workers	Days	Worker Day
Weatherization	2-3	3-5	6-15
Heat Pump Installation	1-2	1-2	1-4
Solar Installation	2-5	3-5	6-25
Wood Heat Installation	2-3	2-3	4-9
Other Incidentals	1-2	1-4	1-8
Supervision/Administration		app. 1.5-3	11-26 hours

The pilot program also included occupant/homeowner and contractor surveys as part of the program assessment. Overall homeowners' and contractors' experiences were reported as positive. The general contractor model of delivering ZEN projects was reported to have worked well. Based on these surveys, the ZEN staff recommend that heat pump projects require homeowner education and performance follow-up post-occupancy. Most contractors did not routinely provide this sort of post-occupancy tuning/service, but it was important in many heat pump installations in the pilot. The authors also note that the program design and goals of ZEN are a challenge to market to the broader public, because the projects are, "complicated, intrusive and expensive".

2.4.4 HomeMVP (Home Energy Market Value Performance) (Massachusetts)

The Home Energy Market Value Performance (Home MVP) is a statewide pilot program run by the Massachusetts Department of Energy Resources (MA DOER) that provides performance-based incentives supporting whole home energy upgrade projects in 1-4-unit buildings, including weatherization and heat pumps. As outlined below, the program has performed 66 comprehensive energy upgrades (and many more HVAC or envelope-focused projects), with average predicted site savings of 48%, at an average cost of $49,126. The program features/design were based on a 12-month working group that was influenced by contractors in the state. Home MVP is unique and distinct from the ratepayer funded MassSave program of Massachusetts, in that it is contractor-driven, using a vetted network of regional companies who directly receive incentives that scale with the amount of energy savings achieved. In addition, the incentives are agnostic in terms of the materials and methods used.

Innovations in the Home MVP program include the following:

- Fuel-neutral, performance-based incentives based on whole dwelling site energy savings. Incentives are based on site energy saved ($/MMbtu) with the incentive rates based on a tiered incentive structure (i.e., 5-20%, 20-40%, etc.)[8].
- Site energy audit and prediction of energy savings using calibrated SnuggPro home energy models based on pre-retrofit customer billing data (when available). The purpose was to test if realization rates could be improved from the MassSave average of 80% using deemed savings.
- No reliance on lighting energy savings.
- 0% loans up to $25k with loan terms up to 7-years to fund non-fossil fuel efficiency measures. MA DOER provides a list of lenders in the region who participate.
- Incentives and loan availability are designed to encourage electrification of fossil fuel end-uses in the homes. More recently, incentives were adjusted to encourage envelope upgrades paired together with electrification measures.
- Provides integrated multi-fuel home energy scorecards to participants.
- Tracks metered savings for two years, with bonus incentives for contractors whose projects outperform project savings (must have completed >20 projects).

The following work can be supported by the program incentives:

- Envelope and duct sealing.
- Insulation.
- Electric HVAC equipment (regardless of pre-retrofit fuel types). New natural gas, oil or propane heating equipment is not eligible.
- Improved controls (e.g., smart thermostats, lighting controls, zoning, etc.)
- Installation of clean renewable heating system meeting DOER specifications
- High performance windows with U-value < 0.20.
- Mechanical ventilation with or without heat recovery.

Table 5 Mean reported project costs, incentives and energy savings for the MA DOER Home MVP program. (Source: Email from Lawrence Maslund, 2020-07-20 (Maslund, 2020))

Project Type	Project Count	Project Costs		Incentives		Savings			
		Cost ($)	Cost ($ / ft²)	Cost ($)	Fraction (%)	Energy (%)	Energy (MMbtu)	Cost ($)	Carbon (lbs. CO2e)
HVAC	173	23,967	10.11	6,762	28%	34%	49	322	3,894
Envelope	102	9,470	4.52	4,590	48%	21%	33	608	5,417
Both	66	49,126	20.24	10,864	22%	48%	82	1,152	9,918
All	**341**	**21,675**	**$9.63**	**6,769**	**31%**	**33%**	**50**	**562**	**5,697**

As the pilot period nears an end, the program managers reported that there are 341 projects that have been incentivized, and they anticipate roughly 400 projects by the end of the

[8] Based on high levels of consumer demand, in February 2020, incentives were made to better align with those offered for the MassSave program, which reduced the average incentives per home from $7,000 to $5,000.

program in November 2020. Roughly half of these projects have included electrification efforts. The average project costs, incentives and performance are summarized for the 341 projects in Table 5 below (complete as of July 2020).

2.4.5 Extreme Energy Makeovers in Tennessee (TN)

Stemming from a settlement with the U.S. Environmental Protection Agency (US EPA), the Tennessee Valley Authority (TVA) Extreme Energy Makeover (EEM) program emerged as part of TVA's broader Smart Communities effort. We were only able to identify very limited publicly available program design (TVA, 2014) and performance data for this program (TVA, 2017). The EEM program was designed to target low-income/income-qualified households and to create community partnerships, with a total investment of $43 million over 3-years. The targeted project cost was $10 per ft^2 with project savings of 25%. Seven project teams operated in the program throughout TN, and TVA paid for all upgrades. 3,420 projects were completed through the program's end in September of 2017, with average deemed electric savings of 35% (4,898 kWh per dwelling). The efficiency measures included air sealing, duct sealing, insulation, replacing windows and doors, replacing or repairing HVAC systems, and general repairs. Energy cost savings averaged approximately $500 per year, while project costs varied from roughly $8,000 to $10,000.

Some unique elements of the program included the following:

- Produced a collaborative group termed the Energy Efficiency Information Exchange (EEIX), which participated in the EEM program design. The EEIX included representatives from utilities, government, researchers, community organizations, non-profits, Habitat for Humanity staff, etc.
- Led to the development and pilot testing of a new cloud-based platform for managing and tracking weatherization upgrade work, termed WAPez. This platform integrates participant intake, field evaluations, cloud-based energy models, and project tracking into one platform, avoiding duplicate databases.
- Relied on community organizations to identify program participants.
- Provided homeowner education, which was considered very successful. So much so that TVA has continued homeowner-based do-it-yourself (DIY) weatherization training meetings.

2.4.6 National Grid Deep Energy Retrofit Pilot Community (Massachusetts and Rhode Island)

The National Grid DER pilot program from 2009 to 2012 included 42 existing homes in Massachusetts and Rhode Island, totaling 60 dwelling units (Gates and Neuhauser, 2014). The retrofit works included aggressive envelope upgrades, ventilation and combustion safety measures, and upgraded mechanical equipment. 37 of these projects were comprehensive, while an additional 5 were termed partial DERs. The projects were supported and assessed by the Building Science Corporation. This pilot program also led to creation of a detailed builder guide for executing the types of retrofit measures and work scopes evaluated in the pilot program (Pettit et al., 2013). Both pre- and post-retrofit utility billing data were provided for 29 of the 42 projects, and the average normalized site energy savings were 55%, while source energy savings were 43%. Average post-retrofit source energy use was 38% below the regional household average, while site energy use intensity averaged 50% below the regional means.

The incentives offered for these projects were very substantial. For Level 1 incentives, the homeowners were reimbursed 75% of the net-costs of the retrofit up to threshold values based on floor area and number of units per building. Level 2 incentives were available for especially groundbreaking projects, which were eligible for an additional 25% of the Level 1 incentive for that same household. Single unit dwellings were eligible for up to $35,000 to $42,000, depending on their floor area. Two-unit buildings were eligible for $50,000 to $60,000 in incentives, depending on unit floor areas. Multi-unit buildings of >3 units were eligible for $72,000 to $106,000 in incentives.

The pilot required that each home meet certain minimum thermal performance thresholds for each major envelope element (i.e., R-Value 10, 20, 40 and 60 for basement floors, foundation walls, above grade walls, and attic/roof, respectively), along with water managed envelope durability requirements. There was also an overall air leakage target (<0.1 cfm_{50} per ft^2 envelope surface area), and all projects were required to meet ASHRAE 62.2 ventilation requirements using heat recovery units. The pilot also specified minimum equipment efficiencies (>95% AFUE, >8.2 HSPF, >16 SEER) and no atmospherically vented combustion equipment was allowed. The projects were also to include Energy Star appliances and at least 90% efficient lighting. Energy-related measure costs ranged from a minimum of $31,500 up to a maximum of $194,350. These project costs average $34.59 per ft^2. Overall, the specific measures and equipment used were the results of homeowners/contractor preferences, without any evident impact on project energy performance (a ground source heat pump was an exception). A more detailed discussion of the measure costs for these pilot projects is provided in Section 4 of this report.

Pre-retrofit utility billing data was procured for 35 projects, and post-retrofit utility bills were available for 29 projects. The projects were evaluated for net-energy use, including on-site generation, if present. The mean site and source annual energy uses post-retrofit were 52.8 and 107.2 MMbtu, respectively. Average site energy savings for the comprehensive projects was 55% (n=29), while average source energy savings were 43%. The maximum site and source energy savings for any individual project were 84% and 75%, respectively. Envelope leakage was reduced by more than 50% in all comprehensive projects, and by more than 40% in all partial projects. More than half of projects achieved envelope leakage <1.5 ACH_{50}, which qualifies the dwellings as extremely airtight. Better envelope leakage results were associated with sealed and insulated attics (vs. vented attics) and conditioned basements (vs. basements insulated at framed floor).

Fractional energy savings were not clearly correlated with assessed project parameters, including no (or little) relationship between percent savings and pre-retrofit energy use, floor area, house vintage/age or pre-retrofit air leakage. Envelope leakage had a very weak correlation with post-retrofit source energy use. Electric heat pump retrofits were noted as having more variability in post-retrofit performance than for other heating system types; some performed as very low-energy homes while others had the highest post-retrofit usage in the sample.

Homeowner surveys were sent to all households 6-months after occupancy, and 12 households responded. Energy savings and improved comfort were reported as the initial reasons homeowners considered DERs. Fewer respondents noted a desired for more living space, and two reported wanting to be examples of DER for the broader market. Complaints were common about project costs, contractor or subcontractor performance, the construction process, and the environment impacts of foam insulation. One project reported numerous post-occupancy issues, including a pest infestation in the attic, cell phone reception issues due to foil-faced insulation, and added home maintenance. A few projects reported perceptibly improved IAQ in their homes.

2.4.7 Deep Energy Retrofits (Florida)

The buildings research team at the Florida Solar Energy Center (FSEC) has completed two DER research studies in the past 7-years. Unlike many of the programs discussed in this report, detailed pre and post-retrofit energy monitoring was performed allowed a more detailed analysis of energy performance. These two studies demonstrated substantial energy and peak demand reductions for DER packages in existing Florida homes, with 38% average savings for DER in all-electric Florida homes, and 34% reductions in HERS index for 70 FL homes retrofitted by affordable housing partners already engaged in remodeling activities. Total project costs were similar for each cohort of projects, averaging $14,323 in the 10 phased DER projects and $16,424 for the affordable housing partner projects. In both studies, the incremental costs of deep upgrade measures were economically justifiable, only if equipment was already being replaced, or upgrades were already planned at code performance levels. The FSEC researchers found that upgrades needed to be comprehensive, and that there were no silver bullet, one-size-fits-all solutions. They identified PV as the next logical step in making these dwellings low energy existing homes.

2.4.7.1 Phased Shallow and Deep Energy Retrofits

10 DERs were undertaken in Florida, as part of a larger study of phased energy retrofits in a cohort of 56 all-electric Florida homes from 2012 to 2016 (Parker et al., 2014) (Parker et al., 2016) (Fenaughty et al., 2017). This effort included detailed circuit level instrumentation of the project electric panels one year prior to energy upgrade work. Continued post-retrofit monitoring provides measured DER energy savings with end-use resolution, along with peak demand impacts of the energy upgrade works. The deep energy upgrade projects saved an average of 38% post-retrofit (7,068 kWh); savings were dominated by cooling energy reductions (4,336 kWh). The DER homes also produce substantial peak cooling and heating load reductions, averaging 39% and 60%, respectively (1.96 and 2.71 kW). These projects and results are explored in more detail below.

“Shallow” retrofit measures were installed in all 56 of the study homes, and additional “Deep” upgrade measures were also installed in 10 of these. Measures included:

- “*Shallow*” upgrades included lighting upgrades, hot water tank insulation, low flow showerheads, smart plug/power strips, cleaning refrigerator coils, and changing controls on pool pumps.
- “*Deep*” upgrades included installation of air source heat pumps for space conditioning and water heating, duct repairs, smart thermostats, variable speed pool pumps, and improved ceiling insulation. If warranted, refrigerators and dishwashers were also replaced with efficient new units.

A second phase of the phased retrofit study included the installation and assessment of less common measures that might augment the packages tested in the first phase. These single measures included: supplemental Mini-Split Heat Pump (MSHP), complete central system replacement with a mini-split or multi-split heat pump, ducted and space-coupled Heat Pump Water Heater (HPWH), Exterior Insulation Finish System (EIFS) for walls, high-efficiency window retrofit, learning thermostat, heat pump clothes dryer, and variable-speed pool pump.

The incremental project costs for the DERs was $7,074, with total project costs averaging $14,323. The HVAC systems dominated the total costs, while the incremental costs for deep measures were distributed fairly evenly across the measure types.

DER savings were evaluated in two ways. First, using 4-months (October-January) of pre- and post-energy data from 6 homes with detailed metering. Second, with utility metered data, disaggregated by heating, cooling and base load using weather normalization for all 10 DER projects.

- During the 4-month periods covering October through January, the 6 homes achieved whole house energy savings of 34.4% (16.5 kWh/day, ranging from 9-26 kWh/day). Notably, this did not include any cooling periods, which typically dominate space-conditioning loads in FL homes. For the monitored end-uses, percent savings were highest for the Air Handling Unit/strip heat (65%), the heat pump water heaters (71%), and the pool pump upgrades (90%). kWh savings were by far strongest for water heating (7.2 kWh/day).
- 12-months of utility billing data were weather normalized and disaggregated for all ten DER project homes, and average DER energy savings were 38%, varying from 22 to 52%. kWh savings were substantial across the three disaggregated end-uses, with 4,336 kWh cooling savings, 1,878 kWh baseload savings and 854 kWh heating energy. Annual whole house kWh savings averaged 7,068 across the 10 projects.
- Peak demand reductions were also observed across both the shallow and DER measures. The shallow retrofits led to observed reductions in peak cooling and heating demand periods of 20 and 7%, respectively (0.67 and 0.25 kW). The DER led to larger peak load reductions for cooling and heating peak demand periods, averaging 39% and

60%, respectively (1.96 and 2.71 kW). The individual advanced measures also had peak load reductions, particularly pool pumps and mini-split heat pumps.

The research team highlights the following general insights:

- Retrofits could be completed at time of HVAC or water heater upgrade in order to reduce costs and disruption to homeowners.
- Occupants did not always offer their feedback unless they were prompted specifically to give it. Explicit follow-up post-retrofit will be important to ensure project performance and owner satisfaction.
- Complicated equipment and controls made energy savings uncertain across many of the upgrade measures.
- Occupant preferences and experience are critical to DER success.

2.4.7.2 Affordable Housing Partner DERs

An additional set of 70 Central and North-Florida dwellings were energy retrofitted as part of a separate research effort (McIlvaine et al., 2013). These energy upgrades were add-ons to rehabilitation/remodeling projects otherwise being carried out by affordable housing partners in the state of Florida. The HERS index was the primary energy metric used in this research, as no energy measurements were made. The average HERS index improvement was from a pre-retrofit score of 129 to 83 post-retrofit, an average reduction of 34%. On average, HERS index reductions were greatest in older vintage dwellings; with average HERS index reductions of 54% in 1950s vintages, 35% in the 1980s and 20% in the 2000s. In projects with reported project costs, the projected utility bill savings averaged $612, while the energy efficiency measures cost an average of $16,424 with incremental costs over minimum improvement of $3,854. The vast majority of projects with >30% HERS index improvement included high efficiency HVAC equipment, ceiling insulation, envelope air sealing, windows, appliances and water heating. Fewer projects included other measures, such as smart thermostat, duct improvements, cooler wall or roof surfaces and ceiling fans.

From this work, the FSEC team concluded that deep energy upgrades in existing FL homes could only be economically justified at the time of natural equipment replacement or assembly renovation, when the incremental costs of higher performing equipment were compared relative to a minimum replacement scenario. The same logic applied to low performing existing building features, such as uninsulated assemblies, very leaky envelopes, etc. Outright replacement of otherwise functioning equipment could not be justified. While they did identify a 30% source energy savings package of measures based on the community of measure implemented across the 70 projects, they concluded that there was no one-size fits all package for all homes.

2.4.8 EnergyFIT Philly

EnergyFIT Philly is an innovative affordable housing energy upgrade program that aims to improve low-income properties in Philadelphia with substantial deferred maintenance needs, which typically render these structures ineligible for more traditional weatherization and efficiency program activities (Robinson, 2017). As of 2017, the program had upgraded 67 dwellings. Average air leakage reductions were 33% or 55% in these dwellings depending on the intervention types, and analysis of utility data suggests an average 36% natural gas savings (382 therms) and 22% electricity savings. Annual energy costs savings ranged from $500 to $3,500 per household, with average measure lifetime gas savings of $17,125. The greatest savings were identified in projects that switched from fuel oil to natural gas for space conditioning. The average energy measures cost $14,257 per household ($12,961 for envelope upgrades and $2,908 for HVAC upgrades), with an overall savings-to-investment ratio of 1.2. This program is unique in its block-level recruitment, use of alternative construction strategies, and integration of health and safety remediation alongside aggressive weatherization.

Home selection occurred uniquely through a street-level program called the *Coolest Block*, where deteriorated homes on the selected block are deeply retrofitted and received cool roof surfaces, helping to cool the surrounding micro-climate. This helped the program identify housing needs and motivated participants to organize and help themselves, which reduced program recruitment costs. The upgrades include a combination of hazard repairs (e.g., roof replacement, electrical upgrades, masonry repair), followed by air sealing, insulating and weatherization, high-efficiency HVAC equipment, duct sealing, programmable thermostats, advanced diagnostic techniques, and other innovative materials and approaches. Along with traditional energy upgrades and health/safety measures, the program also leverages education and bill pay assistance for its clients. In sum, this program reduces home ownership costs for low-income residences, allowing them to remain in their homes and to avoid gentrification forces.

The program experimented with different ways to address the low-sloped roofs of the renovated buildings, which often needed roof replacements, along with energy upgrades. They initially tested exterior closed cell spray foam insulation, to avoid addressing knob and tube wiring and placing cellulose insulation in the roof cavity. But in the end, this approach proved too costly, and EnergyFIT Philly selected open cell spray foam in the rafter cavity, with knob and tube repairs, and a cool roof top-side coating. The open cell foam approach cost only $7,000 per buildings, compared with $10,658 for the exterior closed cell approach. This is a great example of how experimenting with different approaches to address building assemblies can lead to a high performance, lower cost approach. The open cell foam approach achieved much better air sealing than either cellulose or exterior closed cell insulation (55% vs. 33%), more energy savings (220 vs. 128 therms), and reduced long-term maintenance and replacement costs for the cool roof surface, which can be indefinitely recoated.

2.4.9 Energy Smart Ohio and HVAC 2.0

Nate Adams' company Energy Smart Ohio provided 11 DER case studies (Energy Smart Ohio, 2020), based on the projects that his firm has completed in Ohio. (Armstrong et al., 2021) summarized the costs for nine of these homes and the average cost was $30,173. Each project document includes detailed background information on the home and its occupants, including their problems, motivations and goals for the work. Detailed photos are shared for all work, and work scope specifications are documented across the project. Actual and predicted energy performance is also shared, along with results for diagnostic tests, etc.

Nate and his colleague Ted Kidd's experience in home performance retrofits, HVAC contracting, and business management have led their focus away from performing deep energy upgrades of homes, and towards developing a repeatable business model for profitable and effective, HVAC-based home performance upgrades that are viable in today's market without support of external energy efficiency programs. They term this business process "HVAC 2.0".

HVAC 2.0 is an emerging trend that integrates home performance, HVAC contractors and comfort consultations. The HVAC 2.0 approach is a sales process and a set of design goals designed to improve the experience of HVAC and home performance contractors, as well as to improve the outcomes for their customers. The traditional HVAC sales approaches are often ineffective at addressing existing customer comfort and performance complaints, and they also do not encourage customers to select high performance systems. This leads to reduced contractor work scopes and profit. HVAC 2.0 posits the biggest opportunity in this industry to be addressing over-sized equipment that is standard practice in nearly all residential HVAC installations. This program has been billed as "a complete system to solve complex problems reliably and profitably with entry-level talent." (Duffy, 2020).

As of June 2020, HVAC 2.0 has gone to revenue, meaning that contractors are paying to join this network. Based on personal communication on December 10th 2020 from Nate Adams (Adams, 2020), he comments the following: The network contains over 1000 members in the Facebook discussion group, there are 33 paying subscribers presently, and the network is working on adding another 50 right now. In addition, over 200 clients have been entered in the system. At least 5 home electrifications have been performed and the network is seeing heat pumps become normalized in colder climates along with better air filtration for IAQ.

HVAC 2.0 avoids external programs and incentives, which are perceived to pervert the process of aligning work scopes and equipment with homeowner goals and needs. Participating contractors are reporting very high project conversion rates, around 70% of consulting jobs being converted to installed jobs (compared to 20-30% typical HVAC industry closing rates). This also leads to very low sales burdens. This program focuses on HVAC contractors, because they are already in homes at the critical juncture of equipment replacement. Nevertheless, many projects also require some envelope/home performance upgrades in order to achieve the intended comfort benefits. The leaders of HVAC 2.0 think that, in fact, many existing homes do not need envelope upgrades in order to meet the program's design goals. This could be particularly applicable in homes built since the 1990s that already have insulated envelopes but have poor equipment.

Based on our review of HVAC 2.0 materials, we characterize this program as having multiple elements, including:

- Consultative sales process targeted towards solving customer problems and being profitable for participating contractors, relying primarily on entry-level talent.
- Design goals focusing on energy, comfort and IAQ.
- Preferred equipment specs to meet those goals.
- Continuous improvement process, community, feedback.

The sales process includes no free consulting (i.e. unpaid hours spent on the job site advising the customer), and a job typically begins with a scripted interview (by an entry-level employee) to help homeowners identify and prioritize the issues and problems they would like to address at HVAC equipment replacement. Often, every homeowner is given a free chapter of *The Home Comfort Book* (Adams, 2017). Homeowners are then offered two optional paths to proceed with, which the HVAC 2.0 program characterizes as an "offer and decline" approach. This gets homeowners to own their decisions and shifts liability from the contractor to the homeowner. Path A is characterized as a free quote to replace equipment in-kind, with the same current comfort in the home; more or less a typical HVAC contractor model. Path B is a paid comfort consultation that offers improved comfort and design through a detailed on-site consultation, that typically includes use of a blower door and other auditing equipment (IR camera, smoke pencil, etc.). HVAC load calculations are a critical element of this Path B option. Path B attempts to provide equal focus on building a relationship, understanding the physical home, the occupant needs/goals and the budget. HVAC 2.0 recommends that this consultation be priced anywhere from $300 to $400 (2-3 hours on-site). A viable project for the program exists where there is meaningful overlap between the house, occupant goals and budget.

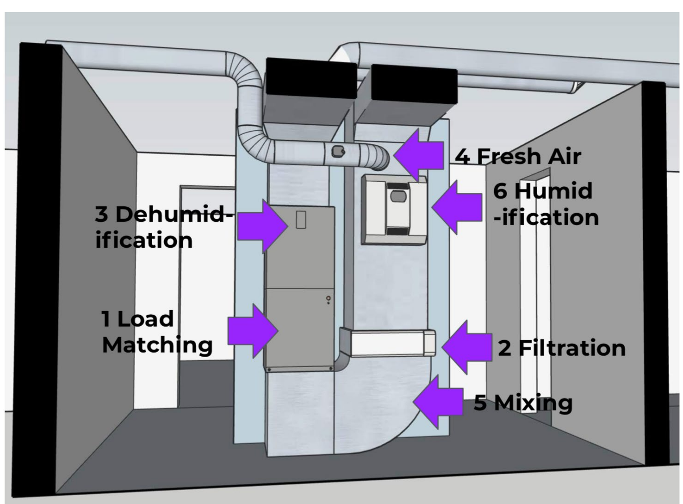


Figure 2 System diagram, (Adams, 2017)

Another unique element of the HVAC 2.0 approach is a very carefully constructed set of design goals and features that should be targeted in each home. These goals are outlined for homeowners in Nate Adams' Home Comfort book and in HVAC 101. In all, HVAC 2.0 identifies six design goals, as pictured in the diagram below. These features are billed as critical to reduce energy use, improve comfort and health/IAQ in homes. Overall, the goal is to address all of these goals using one system, or assemblage of systems, that are within the HVAC work scope.

In addition to identifying and exploring these design goals, much of the HVAC 2.0 materials and community offer actual equipment set up recommendations so that less experienced contactors can more quickly provide top-of-the-line performing systems: (1) Load Matching: Putting the right amount of heating or cooling into the house using multi-stage and multi-fan equipment, this is critical for comfort; (2) Filtration: Cleaning the air inside the house improves IAQ; (3) Dehumidification: Removing the moisture at any time is important for health and comfort reasons; (4) Fresh Air: Keeping the air of the house healthy by bringing in outside air; (5) Moving the right amount of heat or cool to different rooms for comfort and health reasons; and (6) Humidification: Add moisture to the house when needed. An example diagram is shown below, Figure 2, that matches pieces of equipment with the design goals they are designed to address. One unique example is the suggestion to use either hot-gas or electric re-heat to provide humidity control. They prefer electric, because heat strips often already exist, or can be added for $200 (compared with $3-5k for a whole house dehumidifier). This is not a commonly available feature set on residential HVAC. In line with this, the HVAC 2.0 group is working to change the manufacturing market by generating lists of desired equipment features (e.g., dew point controls, automated fault detection), and they are working to leverage these demands with equipment manufacturers. These approaches are being actively developed and revised through collaboration and sharing on the "HVAC 2.0 development" and the "HVAC 2.0: advanced discussion for comfort troubleshooters" Facebook groups. These social network tools are critical for contractors sharing their experiences, learning from others about the process and technologies/applications.

2.4.10 Home Intel by Home Energy Analytics (California)

While energy retrofits have traditionally focused on capital improvements to the building envelope or equipment, behavior and operational changes (i.e., retro-commissioning) can be equally important in achieving real-world energy reductions, sometimes with little or no traditional capital investment. The 1000 Home Challenge has long been a proponent of the potential for behavior-driven paths to deep energy savings, including partial-conditioning of buildings, occupant feedback devices, manual efficiency measures for passive solar, etc. These projects have traditionally been successful if the occupants were very engaged and dedicated to reducing their energy consumption. But a new breed of behavior-change programs has more recently entered the DER space, that are not directed at deeply-devoted building occupants. Instead, these behavior programs involve giving directed feedback to occupants, based on smart algorithms applied to interval smart meter data (i.e., Non-Intrusive Load Monitoring (NILM)). A number of NILM companies are offering such services to energy utilities, including Bidgley, Sense, EEme, Smapee, PlotWatt, and others. The benefit of these programs is that they can be deployed over thousands or millions of homes using automated web technologies.

The Home Intel program offered to PG&E customers by Home Energy Analytics (HEA) is an example of this program type. This program began in 2017 as the very first pay-for-performance efficiency program in the state. HEA is compensated by PG&E only for validated energy savings measured at the smart meter using CalTrack methods to estimate normalized energy savings from meter data. According to HEA's website[9], "We have a big incentive to help you save as much as possible, in the shortest time, at the lowest cost." The HEA algorithms split home energy use into heating, cooling, baseload, recurring and variable loads for each month of the year, and this information is reported to homeowners in an easy-to-use format. The energy use breakdown is supplemented by customized online education resources, an automated recommendation engine, and an expert home energy coach. After providing energy savings feedback, the program provides follow-up communications to track progress each month. The energy efficiency measures implemented in each home vary from no-cost behavior modifications, to the replacement of equipment or installation of other traditional retrofit measures. Ultimately, the program does not track exactly what happens in each home, it only validates/measures energy savings using smart meter data.

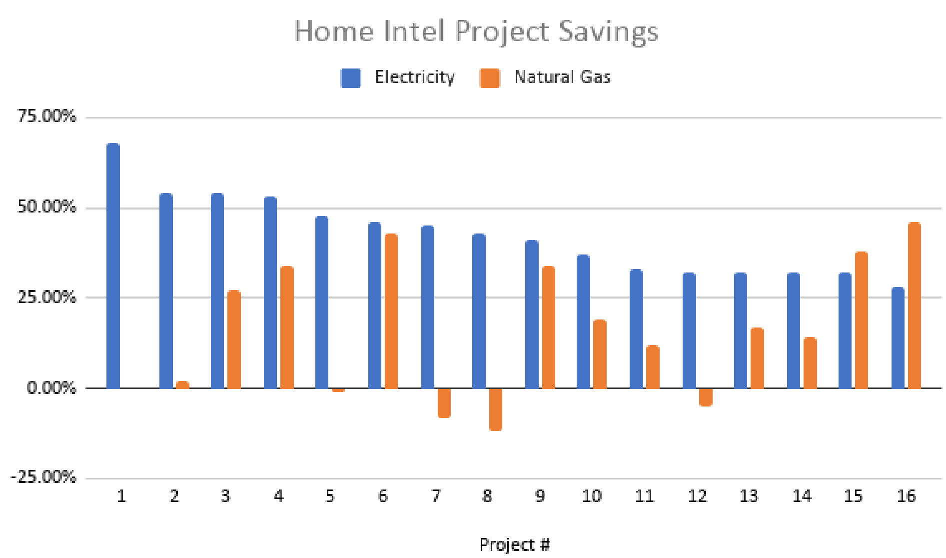


Figure 3 Home Intel top-performers project savings for electricity and natural gas.

In a personal communication with LBNL, HEA estimated that it has serviced more than 1,400 projects in California, with validated energy savings averaging 10%. In addition, HEA shared more detailed data from 16 of its most successful projects in the Central Valley and the Bay Area with the LBNL team during our data collection effort for the Deep Retrofit database. These 16 projects achieved median electricity savings of 42% (from 28 to 68%) and natural gas savings of 17% (from -12 to 46%), equating to 88 MMBtu's saved on average. Savings for each project are shown in Figure 3. Clearly, the savings are stronger and more consistent for electricity use, which likely reflects the program's focus on reducing baseload and variable

[9] https://corp.hea.com/hintel

plug loads in dwellings through low- or no-cost interventions. To reiterate, these savings are measured and confirmed using CalTrack methods applied to smart meter data, and most of these are achieved at little or no cost.

Deep retrofits have not traditionally included this type of energy analysis and feedback. Based on the typical results in thousands of homes from the Home Intel program, verified behavior-driven approaches could potentially improve energy savings in DERs by roughly 10%, at little to not cost. In addition to providing this feedback to building occupants, automated smart meter insights could also be shared with energy auditors/project managers as an aid to their project planning, implementation and performance tracking.

2.4.11 Sealed (New York)

Sealed[10] is a New York company that offers home performance upgrades to eligible households that include an energy savings guarantee combined with reduced upfront costs to the homeowners. Sealed directly pays for a portion of the energy upgrade measures based on the company's estimate of the energy savings potential for the proposed work scope. Any remaining measure costs that cannot be justified by Sealed through energy savings must be covered by either utility support or customer out-of-pocket expense. Customers receive a bill from Sealed each month that replaces their traditional utility bill, an approach Sealed has termed "synthetic on-bill repayment". The usage charges and fees are passed on from the utility, and Sealed adds its own charges, which are calculated each month based on the actual utility bill savings (i.e., baseline minus actual current energy use). The project energy savings are aggregated at a portfolio level and are securitized in a way that supports capital investment from financial institutions. By design, the consumer does not see monthly utility bill savings, because those savings are being used to compensate Sealed for its capital investment. As a result, projects are sold almost exclusively on their non-energy benefits, including comfort, health, improved home value, and the environment. Sealed operates primarily in single-family dwellings; see BlocPower[11] for a business providing a related offering for small to medium multi-family dwellings that leverages internet technologies, machine learning and one-stop-shop services to achieve electrification and energy upgrades.

[10] Most of the description of Sealed's programs and design are derived from the company website (https://sealed.com/), as well as from a presentation given by Andy Frank (CEO) at HabitatX (Frank, 2019).
[11] https://www.blocpower.io/

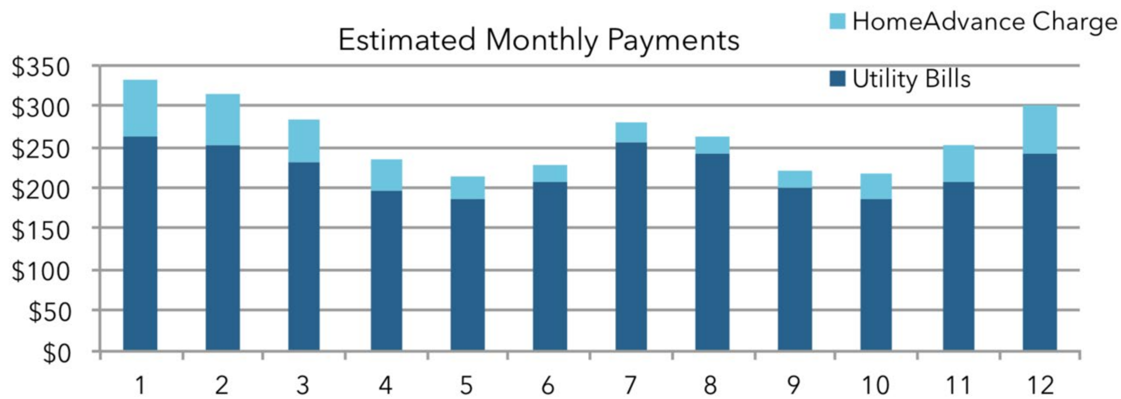


Figure 4 Illustration of the Synthetic on-bill replacement for Sealed. Source: (Frank, 2018)

This "Pay-as-you-save" program reports typical project costs of roughly $10,000. A common scenario is for 30% of that cost to come from utility incentives and customer out-of-pocket (e.g., 70% Sealed, 10% utility and 20% customer). Sealed suggests that they make a $10,000 decision feel like a $2,000 decision for their customers, which leads to higher conversion rates and reaching customer segments that traditionally have not performed energy upgrades of their homes. If the customer's out-of-pocket expense exceeds 50% of the total cost, Sealed has found much lower conversion rates. Two typical packages are offered to customers: the comfort plan and the climate control plan. The comfort plan typically includes air sealing, insulation, smart thermostats and LED lighting, while the climate control package includes heat pump space conditioning and heat pump water heating, and a smart thermostat. Sealed reports that typical savings for these packages are 20% of heating fuel use and 5% of electricity.

Sealed uses predictive analytics and high-quality data sets to produce accurate savings predictions that are sufficiently reliable to support investment by insurance and other lenders. They are able to aggregate the energy cost savings of projects at a portfolio level, which eliminates the risk of inaccurate energy saving predictions for any individual home. At this portfolio level, Sealed has shown an overall 99% prediction accuracy for electricity savings in a population of 338 homes (Frank, 2018). This is critical to Sealed's business model, as their past work in selling efficiency to customers has shown that consumers typically discount predicted energy savings down to $0.25 for each $1.00 of predicted savings. This perception severely dampens consumer willingness to invest in energy upgrades to their property. Instead, Sealed makes the up-front capital investment in the energy upgrades and savings, and the consumer is offered qualitative upgrades to their home (e.g., improved comfort and home value, reduced noise, etc.) at little out-of-pocket expense.

3 Whole Home Retrofits in Europe

Significant home retrofit programs and legislation are underway in Europe driven by a combination of higher energy prices and a need to decarbonize the buildings sector. While there are some EU-wide initiatives, several of the activities outlined below are a national level. Nevertheless, there is a strong push to have standardized coordinated activities and tracking or project performance for upgrading European homes.

3.1 European Legislation

The European's Directive 2018/844 (European Commission, 2018) on Energy Performance of Buildings Directive addresses both new and existing buildings. In addition to addressing CO_2 reductions it directs members states to also consider energy poverty, healthy indoor environments, removal of existing harmful substances (such as asbestos), and mobilization of the financial industry.

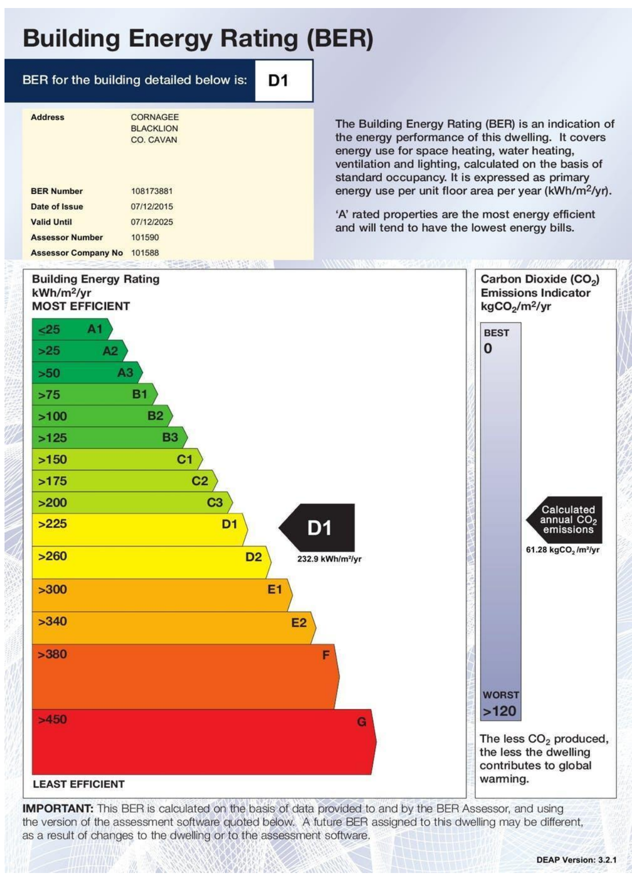


Figure 5 Graphic from Dwelling Energy Assessment Procedure. Building Energy Rating (BER), (Sustainable Energy Authority of Ireland, 2006)

According to the European Commission Recommendation (EU) 2019/786 on building renovation (European Commission, 2019), each state member has the "Obligation to establish a long-term comprehensive strategy to achieve a highly decarbonized building stock by 2050".

In addition, each state member has to set cost-optimal minimum energy performance requirements for new buildings, for existing buildings undergoing major renovation, and for the replacement or retrofit of building elements like heating and cooling systems, roofs and walls. Also, health and well-being of building users is addressed, for instance through the consideration of air quality and ventilation. Each country must draw up lists of national financial measures to improve the energy efficiency of buildings. And finally, a stronger reference to energy poverty.

The (EU) 2019/786 includes the determination of cost-effective approaches to renovations appropriate to the building type and climate zone, taking into account, where appropriate, corresponding potential trigger points in the building's life cycle. Where a trigger point for building renovation could be:

- Transaction (e.g. the sale, rental or lease of a building, its refinancing, or a change in its use)
- Renovation (e.g. an already planned wider non-energy-related renovation)
- Disaster/incident (e.g. fire, earthquake, flood)

The legislation recognized market failures that are barriers to innovation or achieving program goals, energy poverty issues, split-incentive dilemmas, the need to reduce the perceived risk of energy upgrades, and the smart building technologies and workforce skills need to be developed, that there needs to be mobilization of investment and public funding to leverage private-sector investment and to address market failures.

The EU has developed an Energy Efficiency Certificate (EEC) or Energy Performance Certificate (EPC), Figure 5, that covers most building loads (the most significant emission being plug loads). The building is given a rating between A (Very efficient) to G (Inefficient). It is similar to the energy label for household appliances.

3.2 Passive House Retrofit

3.2.1 General Guidelines

EnerPHit is the standard issued by the Passivhaus Institute that focuses on retrofit projects. The passive house retrofit guidelines in EU (Passive House Institute, 2016), have energy targets, building details to help reach the targets and a guided planning process – the Passive House Planning Package that includes energy simulations of proposed upgrades. The planning guidance includes ideas such as planners for staging upgrades over time, Figure 6.

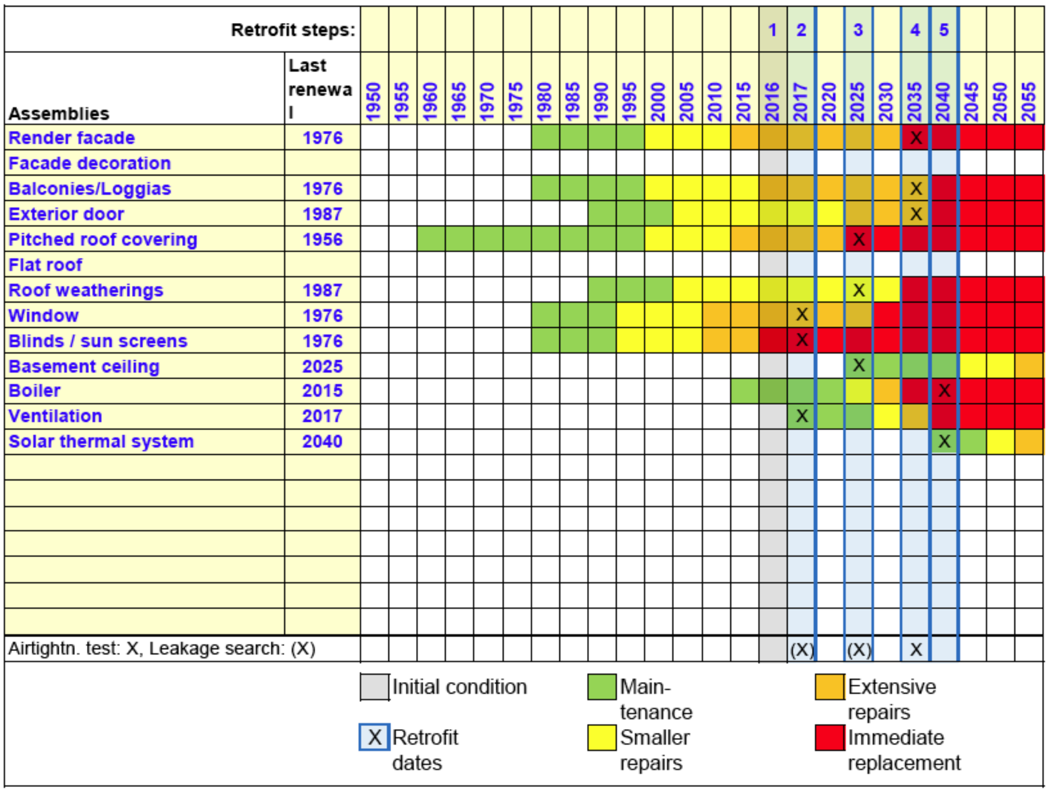


Figure 6 Scheduler in an EnerPHit retrofit plan, (Passive House Institute, 2016)

The guidelines have considerable discussion of retrofit costs. The discussion covers topics such as: the cost for an installers first use of the passive house approach – where high costs are expected for the first projects but these costs will go down in time, separating the costs of the energy upgrades from other home upgrades that may be part of a total project cost, spreading costs over time with staged retrofits, and the extra planning associated with passive retrofit (estimated at 10% of the project cost). Example costs are given for Germany in 2015 as a guide for individual measures, Table 6.

Table 6 Examples for costs of individual components up to the year 2015 (for Germany), with only the costs associated with the measures, (Passive House Institute, 2016)

Thermal insulation	1 €/cm/m² cost for 1 cm of additional insulation thickness
Mitigation of thermal bridges	100 €/m
Windows	250 €/m² (legal minimum standard) 350 €/m² (Passive House standard)
Airtightness	5 €/m² floor area
Ventilation system with HR	50-80 €/m² floor area

Other cost metrics such as life-cycle costs are presented together with standard calculations for these metrics, Figure 7.

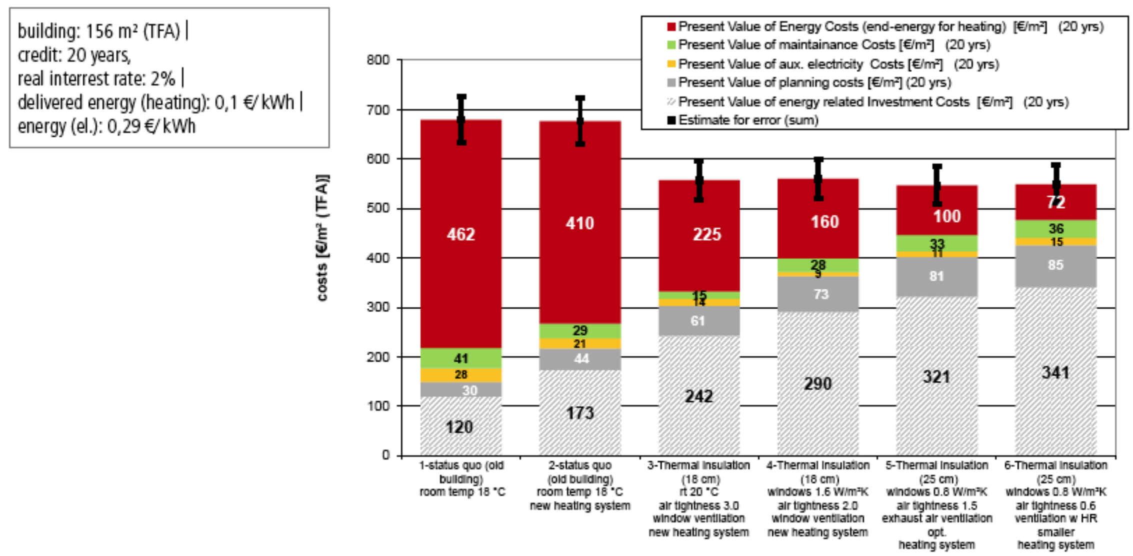


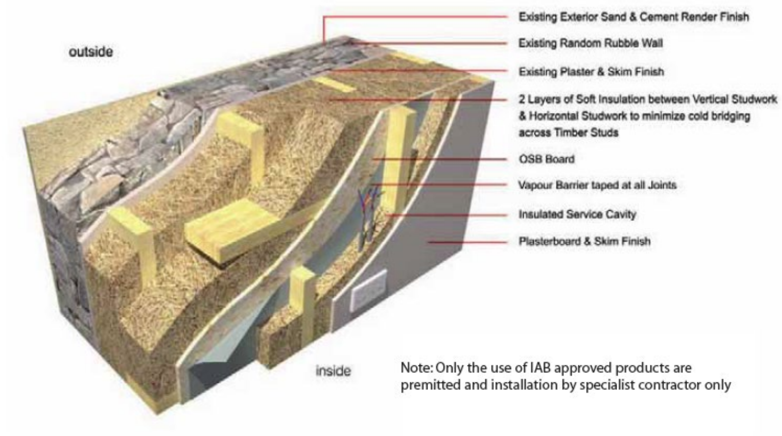
Figure 7 Example showing the total life-cycle costs for different typical modernization variants, (Passive House Institute, 2016)

3.2.2 Irish Guidelines

Irish Guidelines (Sustainable Energy Ireland, 2009) have been developed for turning existing homes into passive homes. The basic performance requirements are:

- Annual space heating requirement of 15 kWh/m^2 treated floor area;
- The upper limit for total primary energy demand for space and water heating, ventilation, electricity for fans and pumps, household appliances, and lighting not exceeding 120 kWh/m^2, regardless of energy source; and
- Air-leakage test results must not exceed 0.6 ACH_{50}.

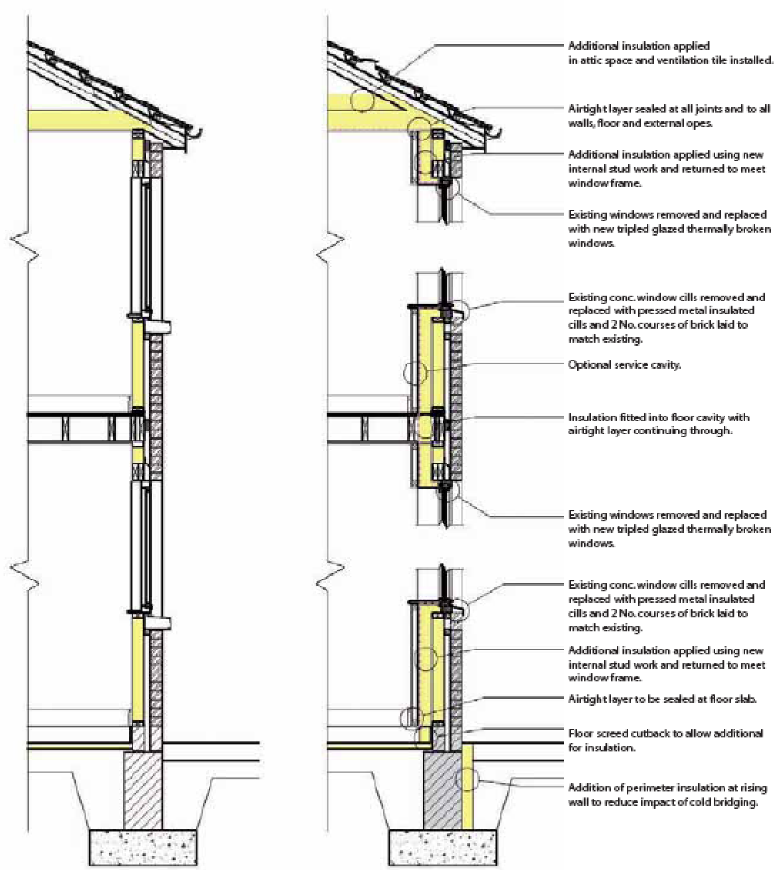
Guidelines for Upgrading Existing Dwellings in Ireland to the Passive House Standard, specify insulation levels, the use of an efficient heat recovery ventilation (HRV) passive solar specifications for windows and other household appliance performance characteristics. The guidelines give construction and technical examples based on typical Irish construction practice, Figure 8 for how to insulate existing walls and air seal to passive house standards. An example is given in the figure below.



Random Rubble Exterior Wall Upgraded to Passivhaus Standard - Internal "Loose" Insulation

Figure 8 Typical Irish construction detail for how to insulate existing walls and air seal to passive house standards, (Sustainable Energy Ireland, 2009)

The guidelines also include architectural detailing such as for window replacement and case studies for some typical Irish homes, Figure 9.



Standard Timber Frame Construction | Retrofit for Timber Frame Construction

Figure 9 Architectural details for typical Irish homes, (Sustainable Energy Ireland, 2009)

These guidelines do provide some cost estimates. For example, one case study stated that the extra cost to achieve passive house levels was 14% of total project cost. It also included the disclaimer that this could not be taken as general guidance for retrofit projects. Nevertheless, these guides represent examples of the level of detail needed to change industry practice, e.g., so that a contractor can clearly understand the engineering and architectural detailing for a wall retrofit.

3.3 Sustainable Energy Authority of Ireland

Sustainable Energy Authority Of Ireland (SEAI) have a 2 year 5 million Euros pilot program for deep home energy retrofits. The guiding principles are:

- Minimum A3[12] Building Energy Rating and uplift of 150 kWh/m^2/yr
- Whole house solution with an efficiency-first philosophy
- Renewable technologies only; fossil fuels are not funded
- Air permeability ≤ 5 m^3/hr/m^2 (bonus for achievement of ≤ 3 m^3/hr/m^2)
- Mechanical ventilation required

SEAI has set up a database of projects[13] that include deep home retrofits. These projects include air quality and other aspects of renovation as well as energy (e.g., IAQ, ventilation and occupant comfort in Irish domestic dwelling's pre and post deep energy renovations. This is the case of the ARDEN Project[14], which aims to investigate the impact that retrofitting homes to a higher energy efficient standard has on IAQ and thermal comfort.

3.4 Deep Energy Renovations in the United Kingdom

The Building regulation in the UK is less strict than other European countries, like Passivhaus standard in Germany. In the UK the construction industry only meets the standard in force at the time of construction. With the Climate Change Act in 2009, the UK has committed itself to an 80% reduction in all greenhouse gases by 2050 over 1990 levels. However, different political government introduced many programs such as: Carbon Emission Reduction Target (CERT), Community Energy Saving Programs (CESP), Housing Health and Safety Regulation, EPC and Standard Assessment Procedure (SAP) rating to bring the households to a certain standards and alleviate fuel poverty (Bhuiyan et al., 2015). Currently the UK operates independently the Dutch Energisprong model. It has the potential for policymakers looking to promote energy business model innovation in other sectors (Brown et al., 2019).

3.4.1 Retrofit for the Future (RfF)

One approach to address to support a retrofit market in the UK was the Retrofit for the Future (RfF) program sponsored by the UK Government’s Technology Strategy Board (TSB), now Innovate UK, from 2009 to 2013 (Gupta and Gregg, 2016). With the support of the Homes

[12] This is from the European building energy labeling scheme, Figure 6.
[13] https://www.seai.ie/data-and-insights/seai-research/research-projects/index.xml
[14] https://www.nuigalway.ie/arden/#

and Communities Agency and the Department for Communities and Local Government, the TSB was able to provide grants of up to £150,000 to demonstrate innovative whole-house retrofit. RfT enabled over 500 organizations to take part in a whole-house retrofit project (Sweett Group, 2014). Gupta et al., presented a case study based on the RfF programme, of an older Victorian home and a more modern home with targets of 80% CO_2 reductions[15]. The homes achieved 40-50% measured reductions in CO_2 emissions. This study showed that pre-retrofit energy use tends to be underestimated for newer homes and overestimated for older homes and that this pattern was claimed to be commonly found in other studies. Data on CO_2 reductions from 52 RfF program homes were shown with most homes showing large reductions but only four meeting the RfF target (based on passive house of 17 or 20 kg CO_2/m^2/yr). Cost data were not provided.

3.4.1.1 Analysis of Cost Data

Based on RfF program, below are the factors that caused cost variations that were observed across the projects. Cost breakdown by building component and intervention measure/type are shown in Table 7.

- The average and range of costs of the retrofit interventions made by the project teams.
- The factors that caused cost variations and opportunities to reduce these variations.
    - Caused variation:
        - Using non-standard and bespoke products.
        - Procuring products not available locally.
        - Specification of the final product/finish.
        - Poor system design/installation, requiring further cost to fix.
    - Opportunities to reduce costs:
        - Use standard products that the workforce is familiar with.
        - Source comparable products locally.
        - Do not over-specify, spec only what is needed.
        - Take time to design and install systems carefully to avoid re-work.
- Actions that should be encouraged in retrofit projects (and what should be avoided), and
- Advice as to how to approach cost planning/ data management in retrofit projects.

[15] Note that this UK study and may other European studies have shifted to carbon reduction from energy savings.

Table 7 Average costs incurred for the various retrofit interventions, (Sweett Group, 2014).

Component	Specification	Average cost (£/m²)
Windows	Double	£261
	Triple	£567
Internal wall insulation	Rigid	£123
	Natural	£368
	Hi-tech	£359
External wall insulation	Rigid	£161
	Natural	£150
Floor insulation	Rigid	£65
	Natural	£94
	Hi-tech	£130
Roof insulation	Rigid	£82
	Natural	£30
	Loose-fill	£14
Mechanical Ventilation with Heat Recovery (MVHR)	System + ancillary works	£6,117 per system
Low/ Zero Carbon (LZC) technologies	Air Source Heat Pump (ASHP)	£1,310 per kW
	Biomass	£1,742 per kW
	Ground Source Heat Pump (GSHP)	£2,893 per kW
	PV	£5,627 per kW_p
	Solar thermal	£1,739 per m^2

3.4.2 Lower Energy Building

The Lower Energy Building website[16], is an online database that DOE could use as a template for archiving project cost data and case studies for demonstrating to contractors how deep retrofits are accomplished for different house types in in different climates. Figure 10 shows a screenshot of one of the summary pages. Clicking on the bar for any home takes you to the home project page that has detailed project information and a downloadable pdf summary. Figure 11 shows a screen show of the Post-development primary energy and CO_2 emissions of all the projects of the database.

[16] https://www.lowenergybuildings.org.uk

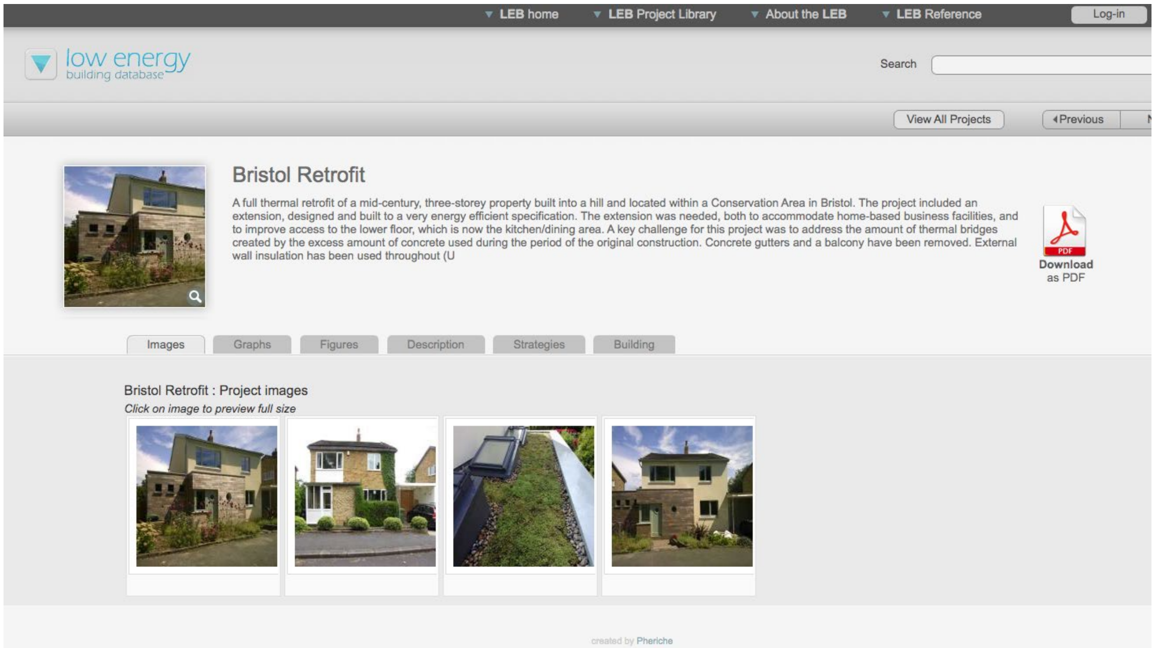


Figure 10 Low Energy Building Database: Case study example (Source: www.lowenergybuildings.org.uk)

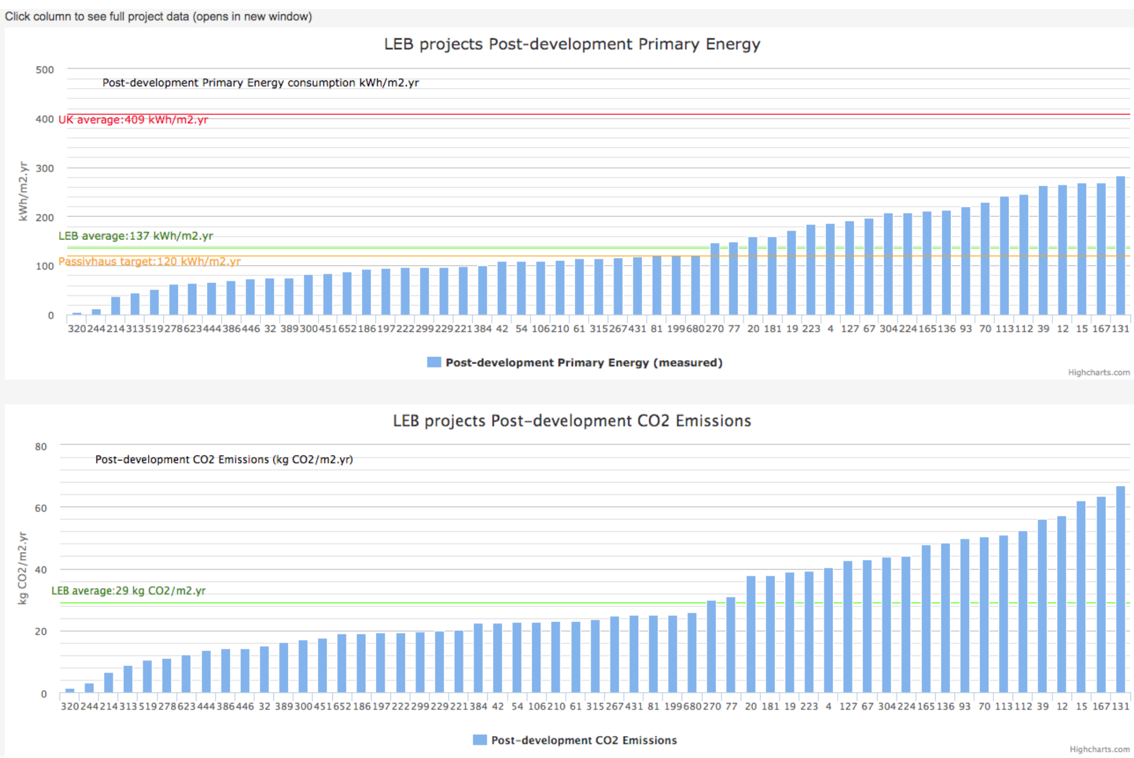


Figure 11 Low Energy Building Database: Post-development primary energy and CO_2 emissions (Source: www.lowenergybuildings.org.uk)

3.5 Belgium

The Meer met Minder program is aiming to reduce energy consumption 2.4 million homes by 2020 using subsidies and low-interest loans. It planned(s) to use comprehensive packages of retrofits with much of the coordination effort taken up by the program rather than individual building owners.

According to McKinsey report (McKinsey & Company, 2009) discusses how high energy consumption represents an important cost to society in an export-dependent economy such as Belgium. Energy inefficiency makes the country more vulnerable to fluctuating commodity prices and geopolitical risks. In addition, the issues with costs in terms of how energy savings payback the cost of retrofits over much shorter timelines than most people think. Some of this may be due to higher energy costs in Belgium compared to the US.

3.6 The Netherlands

The gas valve in Groningen will be closed by 2030, and the government has determined that the price of natural gas will increase significantly and strives for a 100% sustainable Netherlands in 2050. The Climate Mission The Netherlands[17] is developing strategies for homes without natural gas, with optimal living comfort and a healthy indoor climate.
Climate mission The Netherlands, have put together a method for getting to scale with retrofits. Their approach is to completely streamline the process for the owner/occupant. Their system takes care of financing, planning, packaged designs, installation, sourcing materials/equipment (to get good prices), etc.

The guidance includes packages pre-developed for vintages of home and different level of commitment together with cost estimates, Figure 12:

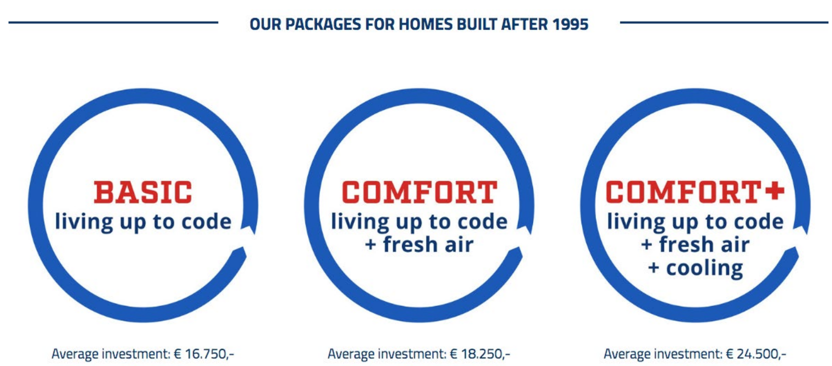


Figure 12 Offered packages at the Climate mission The Netherlands. (Source: www.climatemission.eu)

It also includes pre-arranged partnerships with implementers and manufacturers, development of personalized climate action plans, the use of a phone app to access your homes energy performance. A recent development has been to emphasize the need to stop using natural gas and decarbonize home energy use.

[17] www.climatemission.eu

3.7 Energiesprong

The Energiesprong approach began in The Netherlands and has expanded to other European countries. The key to this program's success is to transform the market such that no subsidies are required – it is changing the business model for residential retrofitting (Brown et al., 2019). Energiesprong is a coordinated approach that combines the following:

- Guaranteed zero net energy retrofits combining envelope, appliance and other end-uses upgrades with on-site generation that have long-term (40 year) performance warranties. Net zero is much more attractive to people than energy savings and is key to engaging occupants and owners.
- Use energy cost savings and on-site renewables to make the retrofits affordable[18]. This addresses issues of fuel poverty and social impact of mass implementation and allows access to financing.
- Reduce the disruption to occupants by having retrofits complete in as little as a day (more realistically under a week).
- Start with a focus on a single market that demonstrates how this approach can be successful. Many initial projects focused on buildings with homogeneous topology, limited issues with planning rules, required maintenance and that present a secure investment (typically for local/social housing associations).

From a technology point of view the Energiesprong approach uses laser scanning of the building that is then used to factory-assemble retrofit packages for the building envelope that combine insulated opaque surfaces, with windows and heating/cooling systems.

5000 homes in the Netherlands and a couple of dozen in other EU countries have undergone an Energiesprong retrofit, and more than 20,000 homes in Europe are currently planned to undergo an Energiesprong retrofit. The energy use of at least 700 homes has been monitored and the results show that these homes meet the net zero specification, as summarized in Figure 13. The financial approach has been analyzed by (Brown et al., 2019).

[18] This is a vitally important point. We need to change the narrative form "cost" to "affordability" when discussing retrofits.

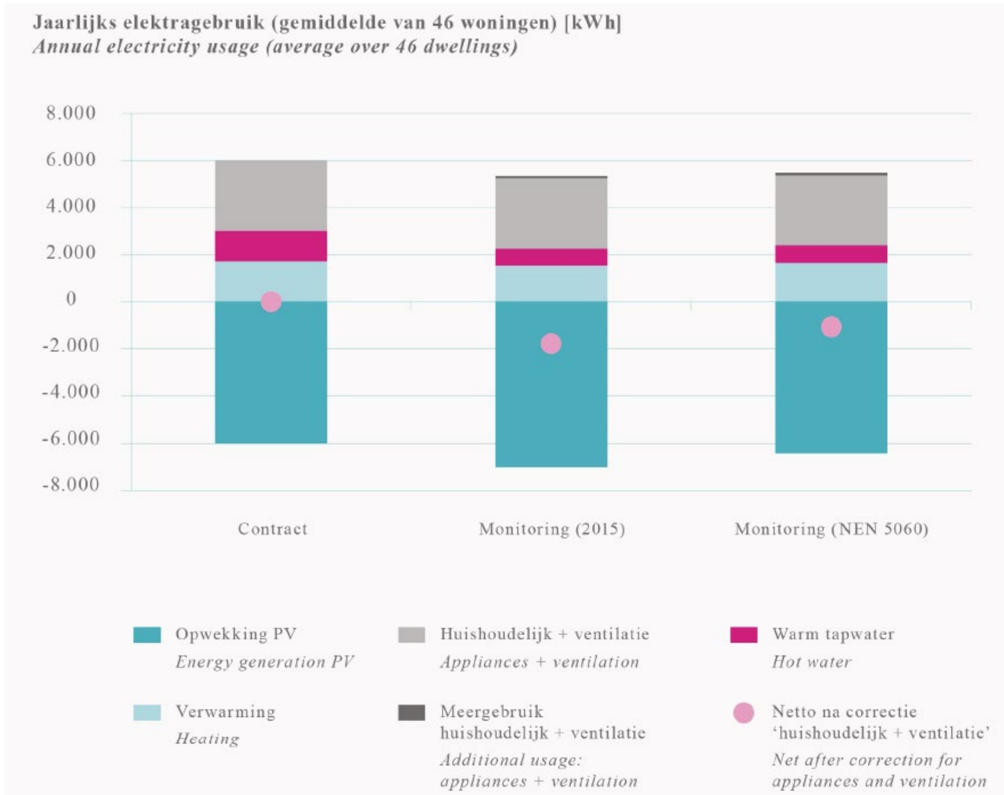


Figure 13 Figure from EnergieSprong Works 2019[19].

3.8 Efficient Retrofit of Built Cultural Heritage

As a requirement of the Energy Performance of Buildings Directive (EPBD), the EU state members must set energy performance requirements for existing buildings when they undergo major renovation, and at the same time, as a requirement of the Energy Efficiency Directive (EED), they must formulate a national strategy for renovation of existing buildings. Heritage buildings, in their original condition, usually have very poor energy performance. It may be unreasonably expensive, or otherwise impracticable, to comply with the energy performance regulations applicable to renovation. As architectural characteristics have to be preserved, standard solutions that are feasible for other buildings will be unacceptable for heritage buildings if they bring a change in appearance and character.

Historic buildings are the trademark of European cities. For this reason, the protection of built cultural heritage has been subject of legal regulations in all European countries since the 19th century. With climate change posing a real and urgent threat to humanity, it is necessary to guide an improved approach to all refurbishment actions in historic buildings. The European 3ENCULT[20] Project bridges the gap between conservation of historic buildings and climate protection. It has also studied the needs of historic buildings and the conflict presented regarding energy targets. Historic buildings will only survive if maintained as living space.

[19] https://energiesprong.org/wp-content/uploads/2019/04/Energiesprong-works_DEF.pdf
[20] http://www.3encult.eu/en/project/welcome/default.html

Energy efficient retrofit is useful for structural protection as well as for comfort reasons - comfort for users and “comfort” for heritage collections. 3ENCULT Project aims to demonstrate the feasibility of “Factor 4” to “Factor 10” reduction in energy demand, depending on the case and the heritage value. Currently there are some documents suggesting possible integrations and/or implementations of the present European regulation framework for improving the energy efficiency of historic buildings in urban areas have been issued. Many countries have published detailed guidance on how to approach the restoration of historic buildings and monuments with the help of various national organizations, based on previous experience. The 3ENCULT Project edited a handbook on energy efficient solutions for historic buildings, (Troi and Bastian, 2015), which develops passive and active energy retrofit solutions, starting with materials and products already available on the market and from solutions already applied to new buildings. The project ensures the widest possible dissemination of the results achieved all around Europe. In addition, diagnosis and monitoring tools have been defined in order to study the buildings and find the best retrofit solution. Moreover, the project defines a methodological approach on the integration of monitoring and control systems in a dedicated BMS system for historic buildings, with the aim to ensure the best Indoor Environmental Quality (IEQ) for the comfort of inhabitants, for avoiding deterioration of the building fabric, and for optimal conservation of valuable interiors with the lowest possible energy demand.

3.9 International Energy Agency (IEA) Energy in Buildings and Communities (EBC) Programme

The International Energy Agency (IEA) Energy in Buildings and Communities (EBC) Programme is a European energy research and innovation programme in the buildings and communities’ field. carries out research and development activities toward near-zero energy and carbon emissions in the built environment. These joint research projects are directed at energy saving technologies and activities that support technology application in practice. Results are also used in the formulation of international and national energy conservation policies and standards in Europe. IEA EBC produces high quality scientific reports and summary information for policy makers.

3.9.1 EBC Annex 50 – Prefab Systems for Low-Energy Renovation

Many building renovations address isolated building components, such as roofs, façades or heating systems. This often results in inefficient and in the end expensive solutions, without an appropriate long-term energy reduction. The EBC Annex 50[21] project objectives were focused on the development and demonstration of an innovative whole building renovation concept for typical apartment buildings based on: Prototype, prefabricated roof systems with integrated HVAC, hot water and solar systems, highly insulated envelopes with integrated new distribution systems for heating, cooling and ventilation.

[21] https://www.iea-ebc.org/projects/project?AnnexID=50

3.9.2 EBC Annex 55 - Reliability of Energy Retrofitting of Buildings

Building owners use to be interested in the initial capital cost of the retrofit measures. For this reason, the EBC Annex 55[22] project looked at the risks associated with the actual performance of such measures and the costs incurred. The project: (1) developed and validated probabilistic methods and tools for prediction of energy use, lifecycle cost and functional performance based on assessment of energy retrofitting measures; (2) applied and demonstrated probabilistic methodologies on real life case studies to enhance energy savings, secure performance and apply cost analyses; and (3) created guidelines for practitioners, including assessment of common retrofitting techniques.

3.9.3 EBC Annex 56 – Cost-Effective CO_2 and Energy Optimization in Building Renovation

The current standards and regulations for energy consumption in buildings have improved the levels of energy efficiency compared with earlier versions. The problem is that they are mainly focused on new construction and they do not give answers to the technical and economic constraints of existing buildings. Therefore, energy efficient measures for existing buildings result in expensive processes and complex procedures, seldom accepted by occupants, owners or developers. For this reason, the EBC Annex 56[23] project aimed to: (1) Define a methodology for establishing cost optimized targets for energy consumption and CO_2 emissions in building renovation; (2) Clarify the relationship between CO_2 emissions and energy targets and their eventual hierarchy; (3) Determine cost effective combinations of energy efficiency and renewable energy supply measures; (4) Highlight additional benefits achieved in the renovation process; (5) Develop tools to support decision makers in accordance with the developed methodology; (6) Select exemplary case studies to encourage decision makers to promote efficient and cost effective renovations.

[22] https://www.iea-ebc.org/projects/project?AnnexID=55
[23] https://www.iea-ebc.org/projects/project?AnnexID=56

4 Deep Energy Retrofit Measure Costs

Many cost-breakdowns are available for whole energy upgrade projects in the research literature. In Table 8, we show the sources identified in the literature that provided project costs and indicate if these are incorporated into the LBNL database for this project.

Table 8 DER project cost breakdowns identified in the research literature.

Description	Number of Projects	Included in Database	Notes
National Grid DER pilot in MA and RI (Gates and Neuhauser, 2014)	42	No	Provide some cost resolution, in terms of above grade walls and attic/roof insulation. All data is in figures, no tabular data provided.
1000 Home Challenge – Lutz (1000 Homes Challenge, 2012a)	1	Yes	
1000 Home Challenge – Turner (1000 Homes Challenge, 2015)	1	Yes	
1000 Home Challenge - Gold Acorn Ferret Cabilow (1000 Homes Challenge, 2016)	1	Yes	
1000 Home Challenge – Monahan (1000 Homes Challenge, 2012b)	1	Yes	
1000 Home Challenge –Brownsberger (1000 Homes Challenge, 2012c)	1	Yes	
1000 Home Challenge – Livermore (1000 Homes Challenge, 2013)	1	Yes	
ORNL Deep Retrofits – TN (P. R. Boudreaux et al., 2012)	10	Yes	Measure costs extracted from tables for each project
ORNL Deep Retrofits – GA (Jackson et al., 2012)	9	Yes	Measure costs extracted from tables for each project
NYSERDA DER – Pilots (Pedrick, 2012)	4	Yes	Summary costs extracted from presentation, no formal reporting available.
NYSERDA DER – Taitem (Mielbrecht and Harrod, 2015)	4	Yes	
Davis Energy Group (German et al., 2014)	2	Yes	
PNNL Pilot Homes (Chandra et al., 2012)		No	Costs are estimated using NREL efficiency measure database, with contractor review
Byggmeister projects (Eldrenkamp, 2010)		Yes	
Affordable DERs in Cleveland OH (Berges and Metcalf, 2013)	6	No	Average measure costs are presented for 6 projects
FSEC - Affordable Housing Partners (McIlvaine et al., 2013)	55	Yes	Cost data for each project provided to LBNL by FSEC
FSEC – Phased Deep Retrofits (Parker et al., 2016)	10	Yes	Cost data for each project provided to LBNL by FSEC

In addition to these whole project break-downs, there are also useful cost summaries available for individual measures that would be part of a comprehensive upgrade. The following sections chronicle and summarize some of the DER measure costs from the literature for the following categories:

- **Attic/Roof Insulation and Air Sealing** (Table 9, Section 4.1)
  - Attic floor: \$2.37 - \$16.00 per ft^2
  - Below roof deck: \$6.24 - \$18.39 per ft^2
  - Above roof deck: \$10.05 - \$22.22 per ft^2

- **Crawlspace / Basement foundation / Slab and Slab-on-grade foundation** (Table 10, Section 4.2)
    - Sealed and insulated crawl: \$3.61 - \$5.80 per ft^2; total: \$5,500
    - Basement wall exterior: \$3,792 - \$7,593 (up to \$20,300)
    - Basement wall and slab interior: \$21,500 - \$28,406 (wall-only: \$7,000)
    - Slab-on-grade perimeter: \$16.51 per linear foot
- **Exterior Wall Insulation** (Table 11, Section 4.3):
    - Exterior insulation without finish: \$4.94 - \$15.00 per ft^2
    - Exterior insulation with finish: \$13.10 - \$23.05 per ft^2
    - Exterior finish: \$6.10 - \$8.50 per ft^2
- **Buried or encapsulated ducts** (Table 12, Section 4.4):
    - Fully buried: \$360 - \$895
    - Encapsulated with SPF: \$1,678
    - Fully buried and encapsulated with SPF: \$1,472 to \$2,791
- **Ductless heat pumps** (Table 13, Section 4.5):
    - For 1-ton, 1-zone ductless heat pump:
        - Standard: \$3,957 - \$5,464
        - Cold climate: \$4,058 - \$6,705
    - Cost Premiums:
        - Cold climate: \$100-\$400
        - Efficiency: \$239 - \$689
        - Variable speed compressor: \$266 - \$759
        - Additional interior zones: \$1,173 - \$2,800 per zone
        - Gas-to-electric conversion: \$267
- **Heat pump water heater** (Table 14, Section 4.6):
    - Cost curve: \$2,263 - \$2,714
    - Contractor estimates: \$2,602 - \$4,705
    - SMUD +/- 1 Standard Deviation, 50-gallon: \$3,000 - \$5,000, typically \$3,800

The remaining subsections below (4.1 through 4.6) address deep retrofit technologies/measures in further detail. These sections largely identify where cost data was acquired from, and they highlight any insights or important outcomes from the work that are relevant for future projects or for understanding cost variability.

Table 9 DER Measure Costs: Attic/Roof Insulation and Air Sealing.

DER Measure	Location	Description	Costs	Reference
Attic/Roof Insulation and Air Sealing	US	New Single-Family Homes	● Range $700 to $3,000 (average ~$1,000 per new home). Does not address retrofit costs. ● $0.60 to $1.40 per attic ft^2	(Less et al., 2016)
	Chicago (IL)	Attic framed floor Insulation Upgrade	● R-40 attic framed floor (11" of cellulose): $2.37 per ft^2 ● Cost Project range $2,944- $5,574	(Neuhauser, 2012) Table 15 Table 16 Table 19
		Attic/Roof Insulation Upgrade	● R-41 roof rafters (3" polyiso and R-21 fiberglass batt): $6.97 per ft^2 ● Cost Project range $10,130 - $14,035	
		Attic/Roof Insulation Upgrade	● Upgrade R-40 continuous: $2.82 per ft^2	(Neuhauser, 2013)
	US	Attic/Roof Insulation Upgrade	Unvented attic with ccSFP ● $17.75 per ft^2 (Standard retrofit) ● $5.19 per ft^2 (Incremental performance improvement cost) Exterior insulation and framing cavity insulation ● $22.22 per ft^2 (Standard retrofit) ● $7.44 per ft^2 (Incremental performance improvement cost)	(Cluett and Amann, 2014) Table 20
	Massachusetts (MA) & Rhode Island (RI)	Attic/Roof Insulation Upgrades in DER Community	● Attic floor insulation: $8.40 per ft^2 (from $4.21 to $16.00; n=5) ● Roof rafter cavity insulation: $11.59 per ft^2 (from $6.24 to $18.39; n=10) ● Roof exterior and cavity insulation: $14.21 per ft^2 (from $10.05 to $21.84; n=23). These do not include the cost to re-roof. ● Other (mix of attic floor and rafter): $8.50 per ft^2 (from $6.66 to $10.25; n=3)	(Gates and Neuhauser, 2014)
	Massachusetts (MA)	Ice Dam Retrofits, Cost Estimates from Experienced Retrofit Contractors	$16.00 per ft^2 (for materials and labor)	(Ojczyk et al., 2013) Table 17
	Vermont (VT)		$21.74 per ft^2 (for materials and labor)	
	Minnesota (MN)		$12.00 per ft^2 (for materials and labor)	
SUMMARY			**Attic floor: $2.37 - $16.00 per ft^2** **Below roof deck: $6.24 - $18.39 per ft^2** **Above roof deck: $10.05 - $22.22 per ft^2**	

Table 10 DER Measure Costs: Foundation Insulation Upgrades.

DER Measure	Location	Description	Costs	Reference
Sealed and Insulated Crawlspace	Chicago (IL)	Insulation Crawlspace Walls	• $3.61 per ft^2 (2" ccSFP and 2" mineral wool on crawlspace walls)	(Neuhauser, 2012) Table 19
	US	Insulation Crawlspace Walls ccSPF insulation	• Range from $3.77 to $5.80 per ft^2 (Standard retrofit) • Range from $2.15 to $4.00 per ft^2 (Incremental performance improvement cost)	(Cluett and Amann, 2014) Table 20
	US	Crawlspace encapsulation	• Typical $5,500 (from $1,500 to $15,000)	(HomeAdvisor, n.d.) Table 18
Basement Foundation Retrofit	Duluth (MN), 2009	Exterior Foundation Insulation Upgrade (Single-Family)	• $7,142 (3" XPS for below-grade insulation. Rim joist – 3" polyurethane on the inside, 2" polyisocyanurate on the outside. Waterproofing to the soil side of the XPS. Including labor. Does not include slab.)	ORNL Foundation Design Handbook[24]
	Lanesboro (MN), 2011		• $20,300 (6" XPS to the exterior of the foundation wall. Fiber cement panels as a protective surface above grade. Including labor. Does not include slab.)	
	Minneapolis (MN), 2006	Interior Foundation Insulation Upgrade (Single-Family)	• Slab and Basement Walls: $28,406 (Slab – Demo existing, excavate, new granular fill, perimeter draintile, sump, insulation, new slab; Walls – dimple matt and ccSPF)	
	Madison (WI), 2011		• Slab: $14,500 (Demo existing, new granular fill, perimeter draintile, sump, SPF, new slab) • Basement walls: $7,000 (dimple matt and ccSPF) • Total: $21,500	
	Minneapolis (MN)	Excavationless Exterior Foundation Retrofit	• Tradition excavation: $7,593 ($6.00 per ft^2) (3" XPS, R-15)	(Schirber et al., 2014) Table 22
			• Excavationless: $6,572 ($6.40 per ft^2) (Liquid foam 4", BG, hybrid XPS/liquid AG, R-20. Including labor)	
			• Excavationless with changes: $3,792 ($2.75 per ft^2) (1.5" XPS, 1" liquid foam from top of rim to bottom of trench, R-12.5. Including labor) Solution with proposed changes.	
Slab-On-Grade Foundation Insulation Retrofits	Minneapolis (MN)	Slab-on-Grade Foundation Insulation Retrofits	• $16.51 per linear foot (Hydro-Vac, 4" XPS + Tapered Pourable B.G ½ depth. Excluding above-grade flashing and trim. Including labor.)	(Goldberg and Mosiman, 2015) Table 23
SUMMARY			**Sealed and insulated crawl: $3.61 - $5.80 per ft^2; total: $5,500** **Basement wall exterior: $3,792 - $7,593 (up to $20,300)** **Basement wall and slab interior: $21,500 - $28,406 (wall-only: $7,000)** **Slab-on-grade perimeter: $16.51 per linear foot**	

[24] https://foundationhandbook.ornl.gov/handbook/

Table 11 DER Measure Costs: Exterior wall insulation.

DER Measure	Location	Description	Costs	Reference
Exterior Wall Insulation	West Hill (NY)	Optimized Polyiso Foam Board Wall Retrofits	• \$12.46 per ft^2 (Demolition; Dense pack walls; Foam board, tape and flashing; Window and door trim; No windows, doors or siding)	(Mielbrecht and Harrod, 2015) Table 24
	Hawthorne (NY)		• \$4.94 per ft^2 (Demolition; Targeted dense-pack; Foam board, tape, and flashing; No windows, doors or siding)	
	Ellis Hollow (NY)		• \$10.81 per ft^2 (Demolition; Extend overhangs; Sheathing replacement; Cavity insulation; Foam board, tape, and flashing; No windows, doors or siding)	
	Cayuga Heights (NY)		• \$13.13 per ft^2 (Demolition; Cavity insulation; Foam board, tape, and flashing; No windows, doors or siding)	
	Central Islip (NY)	Exterior Insulated Finish System Retrofits	• On-site: \$15.42 per ft^2 of net wall area (4" EIFS, water resistive barrier and a standard finish coat. Including labor costs. Excluding exterior fenestration)	(Dentz, 2017) Table 26 Table 27
	Saugerties (NY)		• Off-site, panelized: \$20.03 per ft^2 of net wall area (4" EIFS, water resistive barrier, adhesive, caulking, and foam backer rods. Including labor costs. Excluding exterior fenestration)	
	Portland (OR)	Thermal Break Shear (TBS) Wall Retrofits	• Complete project: \$23.05 per ft^2 • Re-siding: \$14.46 per ft^2 (\$6.73 material / \$7.73 labor) (\$13,469 for house) • Shear wall retrofit: \$4.24 (\$0.75 material / \$3.49 labor) (\$17,420 for house) • Exterior insulation: \$4.35 (\$0.86 material / \$3.49 labor) (\$21,448 for house)	(Earth Advantage Institute, 2018) Table 28
	Syracuse (NY)	Spray Foam Exterior Insulation with Stand-Off Furring (Single-Family)	• Including siding \$19.26 per ft^2 (\$42,093 for the house) • Without siding \$10.76 per ft^2 (\$23,518 for the house). \$8.50 ft^2 for siding. (Install 2x4 framing directly to existing siding, fill with SPF, 3/8" sheathing, vinyl siding, insect guard and new windows)	(Herk et al., 2014) Table 32
	Albany (NY)	Nail Base Panels Over Existing framing. (Multi-Family)	• NYSERDA offers range for traditional exterior insulation of \$8.94–\$10.75 per ft^2. (7,172 ft^2 of nail base panels, mix of 4" and 6" panels, mostly 6". Approx. R25 walls. Excluding fenestration) • \$13.10 per ft^2 (\$7 for nailbase material and installation; \$6.10 for siding). \$93,962 for the building.	(Bianco and Wiehagen, 2016) Table 29 Table 30 Table 31
		DER Single-Family One Floor	• \$20.47 per ft^2 (3.5" ccSPF); Insulation: \$8.94; Siding: \$11.53 • \$22.70 per ft^2 (2" Rigid foam); Insulation: \$9.99; Siding: \$12.71	
		DER Single-Family Two Floors	• \$19.62 per ft^2 (XPS and R-15 blown); Insulation: \$10.75; Siding: \$8.87	
	Chicago (IL)	Exterior Foam Board and Strapping on Uninsulated 3 Wythe Brick Masonry (Single-Family)	• \$11.12 per ft^2 (R-4.6 continuous insulation exterior (selected to represent 1.5" XPS between wood 2×4 on flat at 24". o.c. and cladding) • \$14.82 per ft^2 (for an additional 2" foam board and extra strapping) • \$16.82/ ft^2 (for another 2" layer (4" total) • Contractor suggested \$12.60 per ft^2 for future projects 2-stories or less	(Neuhauser, 2013)
		Exterior Foam Board and Strapping on Uninsulated 3 Wythe Brick Masonry (Multy-Family)	• \$15.96 per ft^2 (R-4.6 continuous insulation exterior (selected to represent 1.5" XPS between wood 2×4 on flat at 24". o.c. and cladding) • \$21.28 per ft^2 (for an additional 2" foam board and extra strapping) • \$23.28/ ft^2 (for another 2" layer (4" total)	
	Massachusetts (MA) & Rhode Island (RI)	Above Grade Measure Exterior Wall DER Measure	• \$10.51 per ft^2 (from \$4.67 per ft^2 to \$19.15 per ft^2; n=37) (Includes wall insulation materials and labor. They exclude costs for re-siding and any re-framing required for the measure)	(Gates and Neuhauser, 2014)

			● Prices updated by contractor after completing the work: from initial $4 per ft^2 to $7-$15 per ft^2	
	US	Above Grade Wall	Option 1 - Rigid foam insulating sheathing with air permeable framing cavity insulation. ● $10.41 per ft^2 (Standard retrofit) ● $4.46 per ft^2 (Incremental performance improvement cost) Option 2 - Rigid foam insulating sheathing with ccSPF cavity insulation. ● $17.73 per ft^2 (Standard retrofit) ● $11.59 per ft^2 (Incremental performance improvement cost)	(Cluett and Amann, 2014) Table 20
SUMMARY			**Exterior insulation without finish: $4.94 - $15 per ft^2** **Exterior insulation with finish: $13.10 - $23.05 per ft^2** **Exterior finish: $6.10 - $8.50 per ft^2 (up to $14.46 per ft^2)**	

Table 12 DER Measure Costs: Buried or Encapsulated Ducts. Costs do not include attic floor insulation.

DER Measure	Location	Description	Costs	Reference
Buried or Encapsulated Ducts	Baltimore (MD), Jacksonville (FL)	Compact Buried and Deeply Buried Ducts	• Fully buried: $697 to $895 • Fully buried and encapsulated with SPF: $1,472 to $2,791	Buried Ducts: The Newest Way to Uncover Savings[25]
	Climate Zones 1, 2, or 3	Fully Buried (Single-Family)	• Fully buried R-42 fiberglass: $360 • Encapsulation with SPF: $1,678 • Fully buried R-46 fiberglass: $507 • Fully buried and encapsulated: $2,185	(Shapiro et al., 2013) Table 33
SUMMARY			**Fully buried: $360 - $895** **Encapsulated with SPF: $1,678** **Fully buried and encapsulated with SPF: $1,472 to $2,791**	

[25] https://insulationinstitute.org/wp-content/uploads/2019/03/N087-Buried-Ducts-The-newest-way-to-uncover-savings.pdf
http://insulationinstitute.org/wp-content/uploads/2017/01/TechSpec-Buried-Ducts_FINAL.pdf

Table 13 DER Measure Costs: Ductless Heat Pumps.

DER Measure	Location	Description	Costs	Reference
Ductless Heat Pumps	New York (NY)	NYSERDA cost estimates based on rebate program data and past reviews	• $5,682 - $6,107 (SEER 18, 2 tons)	(NYSERDA, 2019)
	New York (NY)	NYSERDA Multi-Family Cold Climate Ductless Heat Pump Pilot	• Cold climate ductless heat pumps. Mitsubishi or Fujitsu equipment. n = 21 • $4,442 per ton (from $2,500 to $5,766) • $3,476 per indoor zone • $23,552 total per site (6.5 zones, 54 kBtu/hr heat load) • 46% equipment / 54% labor, but the equipment fraction varied from 35-72%.	(Dentz and Liu, 2019) Table 35
	Oregon (OR)	Discussion with Mike Moscatello from the Heat Pump Store in Portland, OR	Costs across five manufacturers: • $4,450 - $5,400 (12 kBtu, 1 zone) • $5,200 - $6,400 (24 kBtu, 1 zone) Each additional indoor zone can add between $1,300 and $2,800 to the cost.	(Redwood Energy, 2020)
	Illinois (IL)	ComEd Multi-Family Cold Climate Ductless Heat Pump Pilot	• $8,148, n = 80 cold climate heat pumps (from $7,373 to $8,928)	(CMC Energy Services, 2020) Table 36
	Massachusetts (MA)	Data from contractor surveys and web-scraping	SEER 18/ HSPF 10: • 12 kBtu: $3,957 ($4,058 Cold), 1 zone • 18 kBtu: $4,475 ($4,646 Cold), 1 zone • 24 kBtu: $4,811 ($5,016 Cold), 1 zone • 24 kBtu: $6,679 ($7,060 Cold), 2 zone • 24 kBtu: $7,852 ($8,202 Cold), 3 zone • 30 kBtu: $8,024 ($9,049 Cold), 3 zones • 36 kBtu: $8,857 ($10,438 Cold), 4 zones Cold climate premium: • $100-200 for 1-zone systems • $400 for 2-zone • $400-$1,000 for 3-zones • >$1,500 for 4-zones Extra zones premium for 24 kBtu ($4,811): • +1 zone ($1,868) • +2 zones ($3,041) Efficiency premium for 12 kBtu (15 SEER / HSPF 8.2): • $239 (to SEER 18 / HSPF 10) • $689 (to SEER 20 / HSPF 12) Location and dwelling details: • Brick exterior walls: +$260 • Outdoor unit mounted on roof: +$400 • Outdoor unit on exterior wall above ground floor: +$1,000 • Recessed ceiling cassette: +$1,050 than typical wall-mounted head unit	(Navigant Consulting, Inc., 2018a)
	Massachusetts (MA)	Data from program invoices	104 program invoices for ductless heat pumps. New Installation: • $5,121 per ton ($3,676 - $6,705) (SEER 16, n=16) • $5,259 per ton ($4,566 - $6,400) (SEER 18, n=16) Replacement: • $4,685 per ton ($3,948 - $5,253) (SEER 16, n=39); • $5,033 ($3,999 - $5,766) (SEER 18, n=22)	(Navigant Consulting, Inc., 2018b)

	California (CA)	SMUD electrification program	Costs may include both ductless and traditional split heat pumps. Packaged (n=276): • 8-10 HSPF, 2-speed: $5,194 per ton • 8-10 HSPF, Variable: $5,953 per ton • >10 HSPF, Variable $5,691 per ton Split (n=304): • 8-10 HSPF, 2-speed: $4,652 per ton • >10 HSPF, 2-speed: $5,198 per ton • 8-10 HSPF, Variable: $5,395 per ton • >10 HSPF, Variable $5,464 per ton Gas-to-electric conversion: $267 Variable speed compressor: $266 - $759 (depends on unit efficiency)	(Scott Blunk, 2021)
SUMMARY			**• For 1-ton, 1-zone ductless heat pump:** **▪ Standard: $3,957 - $5,464** **▪ Cold climate: $4,058 - $6,705** **• Cost Premiums:** **▪ Cold climate: $100-$400** **▪ Efficiency: $239 - $689** **▪ Variable speed compressor: $266 - $759** **▪ Additional interior zones: $1,173 - $2,800 per zone** **▪ Gas-to-electric conversion: $267**	

Table 14 DER Measure Costs: Heat Pump Water Heaters

DER Measure	Location	Description	Costs	Reference
Heat Pump Water Heater	Massachusetts (MA)	HPWH Cost-Efficiency Study	50-gallon, UEF >2.0: • Cost curve: $2,110 • Contractor survey: $2,972 80-gallon, UEF 2.2: • Cost curve: $2,263 • Contractor survey: $2,602 80-gallon, UEF >2.7: • Cost curve: $2,714 • Contractor survey: $4,705	Navigant Consulting, Inc. (2018) Table 38
	California (CA) Central Valley	SMUD electrification program	Based on roughly 1,400 rebated 50-gallon heat pump water heater installations from June 2018 to May 2020: $4,200 Most recent 2020 installations averaged: $3,800	(Scott Blunk, 2021)
SUMMARY			**Cost curve: $2,263 - $2,714** **Contractor estimates: $2,602 - $4,705** **SMUD +/- 1 Standard Deviation, 50-gallon: $3,000 - $5,000, typically $3,800**	

4.1 Sealed and Insulated Attics

Sealed and insulated attics locate the air and thermal boundaries of a dwelling at the sloped roof surface, as opposed to the traditional location of the attic framed floor. This approach includes the attic volume inside the conditioned volume of the dwelling. If HVAC equipment or ducts are located in the attic space, the substantial energy savings are possible due to the recovery of heat losses/gains that would otherwise occur in the vented attic. This strategy has been used in high performance new homes for several decades, but it is less common as a retrofit measure. A variety of insulation materials can be used, and the insulation layers can be located below the roof deck or above the roof deck (or a combination of both). Moisture control is typically achieved by using air and/or vapor impermeable insulation layers above or in direct contact with the underside of the roof sheathing. Further details on executing this assembly can be found at the Building America Solution Center[26].

Estimates in new homes for sealed and insulated attics are typically much less costly than in retrofit. New home costs can range typically between \$700 and \$3,000 per a single-family home (\$0.60 to \$1.40 per ft^2 attic floor area) (Less et al., 2016). Retrofit costs are substantially higher.

Below we highlight some cost estimates identified in the research literature for retrofit implementations of sealed and insulated attics. The costs vary substantially based on the types of insulation material used and the location of the insulation layers (i.e., above or below the roof sheathing). All reported costs we identified were for projects located in cold climate regions. The following ranges summarize the costs found throughout the literature:

- Attic floor: \$2.37 - \$16.00 per ft^2
- Below roof deck: \$6.24 - \$18.39 per ft^2
- Above roof deck: \$10.05 - \$22.22 per ft^2 (do not include re-roofing costs)

4.1.1 Chicago Retrofits

An exploratory retrofit design in Chicago area homes reports on comparative costs of insulating the attic floor vs. the sloped roof rafters (Neuhauser, 2012). These work out to \$2.37 and \$6.97 per ft^2 of attic floor area for the insulated attic floor and insulated attic rafter packages, respectively. See the detailed cost breakdowns reproduced in Table 15 and Table 16 for the attic floor and roof rafter insulation measures, respectively. For the framed floor attic insulation package (Table 15), we see that the insulation itself is only roughly half the cost of the attic insulation retrofit, with demolition, air sealing and addressing existing attic ventilation making up the other half. In contrast, the rigid foam insulation used in the attic rafter package (Table 16) makes up a substantial majority (68%) of the unit costs.

[26] https://basc.pnnl.gov/resource-guides/unvented-attic-insulation

Table 15 Attic floor insulating retrofit and air sealing strategy cost breakdown, (Neuhauser, 2012)

Component / Measure	Unit Cost ($) per ft² or Unit	Cost ($) / Project Average	Cost ($) / Project Range
Remove all attic flooring	$0.35 per ft²	$240	$0 - $514
Air Sealing package and contractor kit		$630	$630
Box in exhaust fan housing	$26.00 ea	$13	$26.00
Box in recessed light	$26.00 ea	$30	$0 - $270
Attic hatch cover		$162	$162
Attic stair cover		$287	$228 - $412
Storage platform		$384	$44 - $1,055
Soffit chutes	$3.62 ea	$238	$167 - $344
Cellulose R-40 11" settled density	$1.29 - $1.32 per ft²	$1,620	$1,250 - $2,312
Other		$117	$0 - $464
Subtotal for Attic Floor Approach		**$3,493**	**$2,944 - $5,574**

Table 16 Roof rafter insulating retrofit and air sealing strategy cost breakdown, (Neuhauser, 2012)

Component / Measure	Unit Cost ($) per ft² or Unit	Cost ($) / Project Average	Cost ($) / Project Range
Remove pull floor boards around perimeter of attic	$0.35 per ft²	$185	$64 – 386
Thermax rigid board insulation	$4.75 per ft²	$7,633	$6,945 - $8,954
Air Sealing package and contractor kit		$630	$630
XPS and 1x2 wood strapping for extending rafters	$0.42 / linear foot of rafter	$342	$314 - $386
Fasteners and adhesive	$12/box $2.81/tube	$78	$14 - $94
High density fiberglass batt (R21)	$1.09 per ft²	$1,787	$1,594 - $2,055
Weathermate™ insulation cover	$0.21 per ft²	$530	$189 - $1,896
Other		$1,670	$1,285 - $1,912
Subtotal for Attic Floor Approach		**$11,087**	**$10,130 - $14,035**

4.1.2 National Grid Deep Retrofits

The National Grid pilot project documented the construction costs of roughly 40 DER homes in the Massachusetts and Rhode Island (see Section 2.4.6), and nearly all homes included attic/roof insulation upgrades. (Gates and Neuhauser, 2014) reported on these costs per unit floor area of the attic. The average area-normalized costs are reproduced below, and the costs for each individual project are shown in Figure 14. Notably, these average roof insulations retrofit costs are substantially higher than those estimated in (Neuhauser, 2012). The National Grid roof/attic insulation measures were divided by intervention type:

- Attic floor insulation: $8.40 per ft² (from $4.21 to $16.00; n=5)
- Roof rafter cavity insulation: $11.59 per ft² (from $6.24 to $18.39; n=10)
- Roof exterior and cavity insulation: $14.21 per ft² (from $10.05 to $21.84; n=23)
- These do not include the cost to re-roof.
- Other (mix of attic floor and rafter): $8.50 per ft² (from $6.66 to $10.25; n=3)

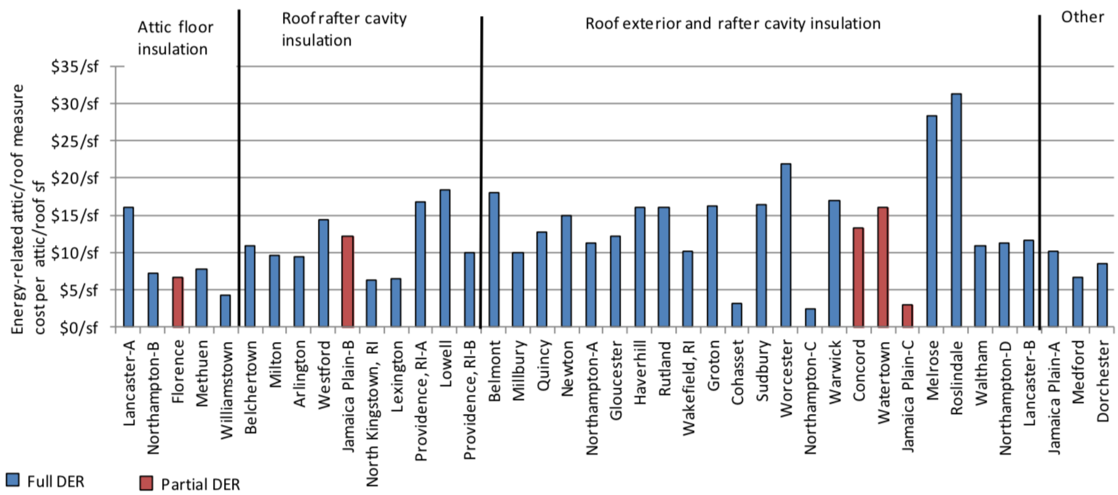


Figure 14 Roof/attic insulation retrofit costs for each DER project reported by (Gates and Neuhauser, 2014)

4.1.3 Project Overcoat

A project examining ice dam retrofits in existing homes (Ojczyk et al., 2013) determined that an exterior roof insulation approach was most appropriate. However, this technique has been mainly documented for whole-house DERs, leaving a void in data for roof-only applications and durability, constructability, and cost. As seen in Table 17, the six contractors interviewed for the report documented a cost per square foot that ranged between $12 and $21.74 per ft^2. The roof SIP panels were a notable outlier, with estimated roof insulation costs of only $5.60 per ft^2. These ranges are consistent with those reported by (Neuhauser, 2012) for whole dwelling energy upgrade projects.

Table 17 Contractor overview, (Ojczyk et al., 2013)

Contractor	Garland Mill Timberframes	Synergy Construction	Byggmeister	Mindel and Morse Builders	Cocoon	Panelworks Plus
Location	New Hampshire	Massachusetts	Massachusetts	Vermont	Minnesota	Minnesota
Years in Energy Retrofit	25	3	20	30	4	10
# Ice Dam Retrofits in Past 5 Years	4–5 as part of whole house overcoat	2, roof only	20–25	2–3	112	5
Type of Case Study Provided	NA	NA	Interior Retrofit	Interior Retrofit	ETMMS	SIP Roof Retrofit Panel
Cost per Square Foot for Case Study Provided	NA	NA	$16.00 for materials and labor	$21.74 for materials and labor	$12.00 for materials and labor	$5.60 for 4" panel and labor

4.2 Foundation Measures

Foundation upgrades are common in aggressive energy upgrade projects, but foundations take a wide variety of forms (slab, crawlspace, basement, mixed) and can be addressed in many ways. The thermal and moisture performance of foundations are likely the least well understood of any building element. As a result, the standard practices to retrofit these building elements are less widely known and understood. Based on our review of the literature, the following cost ranges can be expected for different foundation types and strategies:

- Sealed and insulated crawl: \$3.61 - \$5.80 per ft²; total: \$5,500.
- Basement wall exterior: \$3,792 - \$7,593 (up to \$20,300).
- Basement wall and slab interior: \$21,500 - \$28,406.
- Slab-on-grade perimeter: \$16.51 per linear foot.

The costs of each of these are explored in more detail in the sections below.

4.2.1 Sealed and Insulated Crawlspace

Sealed and insulated crawlspaces eliminate existing vent openings in the foundation stem wall and move the air and thermal boundary from the foundation framed floor to the crawlspace walls. This approach commonly involves removing existing framed floor insulation, installation of a vapor barrier at the ground level, addressing drainage, placement of either board or spray foam insulation along the stem wall, and sealing and insulation of the rim joist. Some projects include dehumidification in the crawlspace. This approach was originally developed to address mold and moisture issues in vented crawlspaces, but it is also an appropriate solution for bringing HVAC equipment and ducts located in the crawlspace into the home's conditioned volume. More details on this construction approach are provided at the Building America Solution Center[27].

Very few estimates or reports of the cost of sealed and insulated crawlspaces were found in the literature. The consumer website HomeAdvisor suggests that crawlspace encapsulation costs anywhere from \$1,500 to \$15,000, with a typical value of \$5,500 for a US home (HomeAdvisor, n.d.). A summary of the component costs of this project from HomeAdvisor are tabulated in Table 18.

Table 18 Estimated costs for each component of crawlspace encapsulation from HomeAdvisor.

Sealed Crawlspace Component	Estimated Costs
Stem wall insulation	Spray foam: \$0.50 - \$2.00 per board foot
Ground vapor barrier	\$0.50-\$0.70 per ft² \$50 for tape
Sump pump	Sump pump: \$1,100
Dehumidifier	\$780-\$1,000
Sealing existing vents	\$15-\$22 each

(Neuhauser, 2012) provided the only cost estimate we could find in the literature based on CEDA Chicago area retrofit designs. A project description that includes insulating crawlspace walls to encapsulate is shown in Table 19, with a per ft² cost of \$3.61. This estimate likely only includes insulation costs, and not the other costs identified above.

[27] https://basc.pnnl.gov/resource-guides/unvented-insulated-crawlspaces

(Cluett and Amann, 2014) also provide estimates for closed cell spray foam used as crawlspace wall insulation. They suggest the standard retrofit costs range from $3.77 to $5.80 per ft², while the incremental performance improvement costs were $2.15 to $4.00 per ft².

Table 19 BEopt modeling inputs, (Neuhauser, 2012)

Building Component	Pre-retrofit Parameter	Post-retrofit Parameter and Alternatives	Cost of Upgrade	Cost source
Infiltration	10.3 ACH_{50}	4.6 ACH_{50} (55% reduction)	Included in other costs	N/A
Attic/Roof Insulation and Air Sealing	R-5 attic floor	R-40 attic deck (11" of cellulose)	$2.37/sf	CEDA work orders
		R-41 roof rafters (3" polyiso and R-21 fiberglass batt)	$6.97/sf	CEDA work orders
Crawlspace Insulation	Uninsulated	R-20 (2" ccSPF and 2" mineral wool) on crawlspace walls	$3.61/sf	CEDA work orders
Basement	Uninsulated	Uninsulated (no improvement)	N/A	N/A
Above-grade walls	Brick, uninsulated	Brick, uninsulated (no improvement)	N/A	N/A
Ventilation	No ventilation provided	Exhaust-only ventilation, 50% of ASHRAE 62.2	$438	CEDA work orders
Thermostat	Non-programmable 71 F heating, 78 F cooling	Programmable thermostat installed with 65F heating set back	$86.50	CEDA work orders
Boiler	Approximately 80% AFUE, gas fired	Condensing, 94% AFUE, gas-fired	$6,389	CEDA work orders
Domestic hot water heater	Assume gas standard, EF 0.59	High efficiency, indirect fired heater, modeled as BEopt "gas premium, EF 0.67"	$1,553	CEDA work orders

Table 20 Incremental improvement costs for measures in the National Grid Pilot program, (Cluett and Amann, 2014)

Component	Total Measure Cost (ft²)	Incremental Performance Improvement Cost (ft²)
Roof/attic: unvented attic with closed-cell spray foam	$17.75	$5.19
Roof/attic: exterior insulation and framing cavity insulation	$22.22	$7.44
Above-grade wall: rigid foam insulating sheathing with air permeable framing cavity insulation	$10.41	$4.46
Above-grade wall: rigid foam insulating sheathing with ccSPF cavity insulation	$17.73	$11.59
Foundation wall: ccSPF insulation	Project A: $3.77 Project B: $5.80	Project A: $2.15 Project B: $4.00
Measure costs reflect builder proposals and estimates prior to construction		

4.2.2 Basement Foundation Retrofits

Basement foundations can represent large fractions of dwelling heat loss, particularly in cold climates, and they are uniquely challenging to retrofit in an existing home, due to accessibility issues below grade, variability of foundation wall construction/material, exposure to moisture and freezing temperatures. Typically, the majority of the heat loss occurs in the upper portion of the basement wall, most notably in the portion of the stem wall that is exposed above grade. A number of basement wall retrofit strategies have been tested and assessed in existing cold climate US homes. Basement insulation retrofits can place insulation on the interior of the foundation walls, which has the benefit of easy access, but leaves the foundation itself subject to freezing/thawing conditions. Exterior insulation is generally agreed upon as the best approach, but the perimeter excavation can be very disruptive and costly. Recent research and development have shown some potential for excavation-less approaches using "hyrdovac" technology to reduce the costs (by 23-50%) and disturbance of exterior insulation for foundation walls.

Table 21 Basement foundation retrofit costs, interior and exterior approaches. Source: ORNL Foundation Handbook.

	Location and Date	Measure Description	Reported Cost
Interior basement foundation retrofit	Minneapolis (MN), 2006, CZ 6A	Walls: Dimple mat and ccSPF; Slab: demo existing, excavate, new granular fill, perimeter draintile, sump, insulation, new slab	$28,406
	Madison (WI), 2011, CZ 6A	Walls: Dimple mat and ccSPF; Slab: demo existing, new granular fill, perimeter draintile, sump, SPF, new slab	Total: $21,500 Walls: $7,000 Slab: $14,500
Exterior basement foundation retrofit	Lanesboro (MN), 2011, CZ 6A	Exterior of foundation walls excavated, 6" of XPS placed on walls, finished with fiber cement panels above grade	$20,300
	Duluth (MN), 2009, CZ 7A	Exterior of foundation walls excavated, 3" of XPS was placed on walls, rim joist treated with mix of XPS and ccSPF, no new drainage.	$7,142

The ORNL Foundation Design Handbook[28] provides several Building America case studies for both interior and exterior basement foundation retrofits. Cost breakdowns are not detailed, but the project descriptions explore the technical, design and homeowner details in a useful manner (see summary of each project in Table 21). Several of these case studies noted the difficulty in connecting the above-grade and below-grade wall insulation measures at the same plane, while maintaining appropriate flashing and drainage details. In general, home owners were reported to solely be interested in a beautiful and dry finished basement, and they required significant encouragement to invest in the robust details used in these demonstration projects.

[28] https://foundationhandbook.ornl.gov/handbook/caseStudies.shtml

Excavation-less basement foundation retrofits were examined in a Minneapolis demonstration project, and this demonstration showed that the excavation-less approach reduced project costs by 23% compared with traditional excavation approach (Schirber et al., 2014). The authors suggested refinements to the insulation strategy that led to further costs reductions of 50% compared with traditional excavation. Notably, this 50% reduction comes with a reduction in R-value from 15 to 12.5. The detailed costs from this demonstration project are reproduced below in Table 22. Row one is based on interviews with local excavation and home performance contractors. Row 2 represents the costs from the demonstration project itself. Row 3 are estimates of further reductions in insulation costs from proposed design changes.

Table 22 Comparison of costs: Excavationless versus traditional foundation retrofit with backhoe, (Schirber et al., 2014)

Retrofit Approach	Insulation Type	Nominal Wall R-Value	Material Cost	Labor Cost	Cost per ft^2/ R-Value	Excavation Cost	Total Cost*
1 Traditional Excavation	3-in. XPS @ \$1.25 per ft^2	R-15	\$960 XPS, \$833 for water barrier	\$2,880	\$0.40 (\$6.00 per ft^2)	\$2,920 (traditional power shovel	\$7,593
2 Excavationless as Applied in the Field Study	Liquid foam (4") BG, hybrid XPS/liquid AG	R-20 (ave)	\$4,224 BG, \$698 AG	Included	\$0.32 (\$6.40 per ft^2)	\$1,650 (hydrovac)	\$6,572
3 Excavationless With Proposed Changes	1.5" XPS plus 1" liquid foam from top of rim to bottom of trench	R-12.5	\$2,142	Included	\$0.22 (\$2.75 per ft^2)	\$1,650 (hydrovac)	\$3,792

*Does not include repairs to landscape, building structures such as porches and stoops, exterior features such as driveways, sidewalks, patios, or utilities.

4.2.3 Slab-On-Grade Foundation Retrofits

Homes with slab on grade foundations are also candidates for foundation retrofits using exterior insulation along the slab edge (Goldberg and Mosiman, 2015). This subject has not received substantial attention, largely due to the perceived difficulty of addressing below grade envelope elements. Goldberg and Mosiman developed optimized slab-on-grade retrofits for existing an existing home in Minneapolis, MN using cost estimates and Building Foundation Energy Transport Simulation in EnergyPlus. They paired this simulation effort with experimental measurements of energy savings from a slab-on-grade foundation insulation retrofit. The optimal strategy consisted of R-20 foam board insulation applied to the stem wall above grade, with a taper (from R-20 to R-10) below grade, extending half the way to the footing. The tapered triangular volume was filled against the concrete with pourable polyurethane foam. The optimized strategy cost was \$16.51 per linear foot of slab perimeter, which excludes above grade trim and flashing. This is comprised of \$3.22 per linear foot for excavation using hydrovac[29], \$2.48 for XPS foam, \$3.37 for pourable foam, and \$7.44 in labor costs (Detailed in Table 23).

[29] The hydrovac excavation process uses either pressurized air or water to remove earth adjacent to a foundation wall, concurrent with a strong suction vacuum that removes the material (Mosimann et al., 2013). This process allows a minimally invasive approach to excavating 4-5" around an existing foundation.

The authors then extended this optimized slab design to reference homes in DOE climate zones 4-7. They found that slab heat loss could be reduced from 15-31%, with total site energy savings of 3-5% (from zone 4 through 7), which were not cost-effective (simple paybacks of 18-45 years). They note important non-energy benefits for slab insulation upgrades, including improve slab edge temperatures and thermal comfort, as well as reduced risk for elevated surface Relative Humidity (RH) or condensation near the slab perimeter.

Table 23 Insulation upgrade system costs per linear foot, (Goldberg and Mosiman, 2015)

Module	Excavation	XPS	PPU Foam	Labor	Floor Foam (option if only, 5 ft^2 per linear foot)	Total Cost per Linear Foot
a.	$4.83	$2.27	$0.00	$6.81	$0.00	$13.91
b.	$7.21	$3.92	$0.00	$6.81	$0.00	$17.94
c.	$7.21	$2.27	$5.51	$6.81	$0.00	$21.80
d.	$9.66	$4.33	$5.51	$6.81	$0.00	$26.31
e.	$4.83	$2.93	$4.50	$9.09	$0.00	$21.35
f.	$3.62	$2.79	$4.21	$8.37	$0.00	$18.99
g.	$3.22	$2.48	$3.37	$7.44	$0.00	$16.51
h.	$4.83	$2.56	$3.26	$4.03	$0.00	$14.68
i.	$9.66	$4.33	$5.51	$6.81	$12.40	$38.71
j.	$38.76	$7.00	$0.00	$14.76	$0.00	$60.52

4.3 Exterior Wall Insulation Retrofits

In an effort to drive down thermal loads and to protect against moisture damage, substantial effort has been expended to identify appropriate and lower-cost methods to add exterior insulation to above grade walls of energy upgrade projects. Exterior wall insulation can be added to a dwelling using a variety of material types and methods. The placement of insulation layers to the outside of the wall framing is generally considered to reduce the risk of moisture accumulation, rot or mold growth in the insulated assembly. It is generally agreed upon that this approach is only appropriate during the replacement of the existing exterior cladding. Similarly, recent work in the Pacific Northwest has also explored the addition of exterior insulation during shear wall retrofits for seismic safety (Earth Advantage Institute, 2018). If insulation is added as part of a general re-cladding project, the incremental costs are reduced. Yet, even during cladding replacement, the additional costs of exterior insulation are substantial, in part due to expensive insulation materials (e.g., foam board or spray), labor-intensive installation practices (e.g., rain screen furring strips, multiple layers of foam board), and required changes to the home's structure/exterior (e.g., extending window frames, extending roof overhangs, etc.).

Recognizing this, recent studies have performed time and motion studies and developed new construction tools to reduce the cost of adding exterior insulation while re-cladding homes. These approaches have included the use of external insulation and finishing system (EIFS), nail-base sheathing/insulation, spray foam and others. PNNL recently performed a literature review exploring the cost and performance of all of these technologies (C.A. Antonopoulos et al., 2019). While effective at reducing air leakage and reducing wall conduction losses, these studies show that the high cost of this work (about $20 per square foot) leads to long payback times greater than 50 years (Mielbrecht and Harrod, 2015). Other studies (Dentz, 2017) have reported much higher costs when looking at Exterior Insulated Finish Systems of up to $35 per square foot when including preparation costs such as removing existing siding, adding roof overhangs, and demolishing chimneys. In addition to (or possibly because of) persistent high-costs and technical difficulty, our review of deep energy upgrade programs in the past decade have shown a strong move away from these types of aggressive envelope upgrades.

In the sub-sections below (from 4.3.1 to 4.3.4), we review a variety of exterior wall insulation pilot projects that provided cost data, often involving detailed cost breakdowns by component or material. These cover a number of NYSERDA pilot projects (4.3.1), National Grid Deep Retrofit Projects (4.3.3), exterior SPF techniques by IBACOS (4.3.4), and we summarize the PNNL review mentioned above (4.3.2). Overall, we can summarize the exterior wall insulation costs as follows:

- Exterior insulation without cladding/finish: \$4.94 - \$15 per ft^2
- Exterior insulation with cladding/finish: \$13.10 - \$23.05 per ft^2
- Exterior finish: \$6.10 - \$8.50 per ft^2 (and up to \$14.46 per ft^2)

Important drivers of cost variability are based on installation issues such as jobsite access due to the height of the building (e.g., is scaffolding needed?), and clearances to neighboring buildings/property.

4.3.1 NYERDA Exterior Wall Insulation Pilots

After initial pilot projects showed deep retrofit project costs consistently exceeding $100,000, NYSERDA redirected much of its pilot funding to the topic of reducing the cost of exterior wall insulation upgrades. Some of these efforts are described below for optimized foam board (Taitem) and EIFS (Dentz).

4.3.1.1 Taitem Engineering Optimized Polylso Foam Board

(Mielbrecht and Harrod, 2015) worked to develop an optimized approach to insulating existing dwellings with polyiso foam board from the exterior. They used time-and-motion studies to develop and hone the installation methods, and they then applied the approach on four pilot projects in NY. The cost breakdowns for these four pilot projects are tabulated in Table 24 The proposed wall system was slightly greater than R-25, and it was implemented on average for \$10.34 per ft^2, from \$4.94 to \$13.13 per ft^2 (not including siding/cladding replacement, windows or doors). The wall insulation demos were part of larger comprehensive energy upgrades in these dwellings, and taken as a complete package, envelope leakage was reduced 56-77%, heating energy by 47-60% (in 3 of 4 homes), and whole project costs ranged from \$46k to \$138k. All projects were modeled to save more energy than was actually achieved. Despite improvements made to the process of applying exterior foam board insulation (see time and motion study in Section 4.3.1.2), framing, bucks and flashing around windows and doors remained challenging.

Table 24 Combined material and labor cost involved in the implementing the above-grade wall insulation strategy at four projects, (Mielbrecht and Harrod, 2015)

	Contract Amount (ft²)			
Wall Work	**West Hill Wall**	**Hawthorne Wall**	**Ellis Hollow Wall**	**Cayuga Heights Wall**
Demolition	$1.99	$0.53	$0.94	$1.36
Dense pack walls	$3.51			
Targeted dense-pack		$2.29		
Extend overhangs			$1.11	
Sheathing replacement			$0.89	
Cavity insulation			$4.06	$4.50
Foam board, tape and flashing	$4.23	$2.12	$3.26	$5.92
Window and door bucks			$0.55	$1.35
Window and door trim	$2.73			
TOTAL (no windows, doors or siding)	$12.46	$4.94	$10.81	$13.13
Install siding	$4.40	$6.44	$6.07	$16.01
TOTAL (nor windows or doors	$16.86	$11.38	$16.88	$29.14
Windows and doors	$2.51	$5.90	$9.18	$6.32
TOTAL (with windows and doors)	**$19.37**	**$17.28**	**$26.06**	**$35.46**

Costs were distributed between a variety of tasks for adding exterior foam insulation, including demolition, cavity insulation and foam insulation. All projects included demolition, which accounted for an average of 11% ($1.21 per ft2). The cavity insulation and exterior foam insulation costs were roughly equal (on average), with cavity insulation accounting for 37% of total costs ($3.59 per ft2), and exterior foam board for 38% ($3.88 per ft2). The other costs were variable and dependent on the individual project.

Mielbrecht and Harrod reported the following approaches to reducing costs:

- Single layer of foam reduces the costs, compared with double layers.
- Utilizing incentives and rebates (including low-income).
- Sourcing foam board insulation from reclaimed construction supply yards.
- Keep existing good-quality 2x pane windows.
- Leverage homeowner cooperation to improve site access and work efficiency.
- Sweat equity.
- Use energy upgrade measures to improve home aesthetics, health and safety.
- Use creative strategies and be flexible rather than perfect.
- Accu-cutter foam sheathing cutter tool was the fastest and most reliable.

4.3.1.2 Taitem Time and Motion Examples

Taitem and Snug Planet performed a series of time-and-motion studies aimed at honing the optimal installation practices for exterior foam insulation retrofits in support of the demo projects outlined above. The construction stages addressed by these studies and the resulting recommendations are summarized below:

- Foam cutting types and techniques
  - AccuCutter[30] with two passes produced the best Full-Length cuts, with the least noise and dust. Slightly more expensive per cut than using table saw ($0.91 vs. $1.25 per 8' cut).
  - PVC saw for cross-cuts and L-cuts
  - Keyhole saw for circular penetrations
- Fasteners
  - Ci-lock screws spaced at 32"
- Foam seam taping
  - Weathermate construction tape using dispenser/applicator
- Window bucks
  - Plywood buck
- Flashing
  - Weathermate straight flashing

These recommendations were arrived at through analyses of time, cost and user-experience for 3-5 competing methods of applying each upgrade element. Some examples of this are illustrated in Table 25 for fastening foam board to wood framed walls and for full length foam board cuts.

Table 25 Thermax: Fastening to wood-frame wall and Marking and cutting full lengths, (Mielbrecht and Harrod, 2015)

Activity	Timing	Cost
Thermax Attachment to Wood Frame Wall (Thermax in place; Lines chalked; 1st Sheet fastened; 2nd Sheet fastened; 3rd Sheet fastened; Assembly of fasteners)	• Nails - 23:55 minutes. • Ci-Lock Screws - 24:29 minutes.	• Nails - $7.36 (Materials) / $30.03 (Labor) / $37.39 (Total) • Ci-Lock Screws - $16.38 (Materials) / $24.45 (Labor) / $40.83 (Total)
Marking and Cutting Full Lengths of Thermax	• Accucutter (2 passes) – 75 sec. • Accucutter – 79 sec. • Handsaw – 123 sec. • Table saw – 55 sec.	(Labor only) • Accucutter (2 passes) - $1.25 • Accucutter - $30.03 • Handsaw - $2.05 • Table saw - $0.91

4.3.1.3 Levy EIFS Retrofit

The Levy Partnership engaged in R&D for the use of EIFS technology for exterior insulation of two existing dwellings (Dentz and Podorson, 2014; Dentz, 2017). The Central Islip project used site-applied EIFS, while the Saugerties project experimented with an off-site panelized approach. The total subcontract costs per net-ft^2 (excluding window/door area) were $15.42

[30] This foam cutting tool appears to still exist but is not widely available in the market. (http://cutitritevt.com/Magnum_RFC/Home.html)

for the site-applied system at Central Islip and $20.03 for the off-site panelized system at Saugerties. At Saugerties, the labor and materials were roughly equal at $10 per ft2 each. The authors noted that EIFS costs were dependent on the dwelling's geometric complexity, the EIFS installation crew level of experience, and whether existing siding requires replacement, thereby offsetting EIFS costs. Each project used a 4" thick EIFS with an R-value of 16, with site-specific details required on both projects. The site work and costs for each of these projects are documented in greater detail in Table 26 (Central Islip) and Table 27 (Saugerties).

Table 26 Central Islip site costs, (Dentz, 2017)

	Based on Gross Wall Area	Based on Net Wall Area (Deducting Fenestration)
EIFS Cost	$32,000	$32,000
Wall Area	2,374 ft^2	2,075 ft^2
Labor costs, assuming 278 hours x $25 per hour	$2.93	$3.35
Total Subcontract Cost per Square Foot (including labor, materials, overhead and profit)	$13.47	$15.42

Overall, the panelized approach used at Saugerties was more expensive, but the authors suggest this may be justifiable for certain projects under certain conditions, such as in poor weather and/or where site labor costs are high or working conditions are difficult. The reported benefits of the panelized approach included:

- Greater speed and schedule reliability
- Less dust and dirt on site that are a result of rasping backs of panels to fit on walls for a site-fabricated system
- Greater safety because of less time on scaffolds and fewer trips around the building.

Table 27 Saugerties site costs, (Dentz, 2017)

	Based on Net Wall Area
Wall Area	3,825 ft^2
EIFS Materials Cost	$37,010
Material Cost per ft^2	$9.68
Site Labor Cost (not including prep)	$39,600
Site Labor Cost per ft^2	$10.35
Total Cost	$76,610
Total Cost per ft^2	$20.03

4.3.2 PNNL Literature Review

In 2019, researchers at PNNL produced a detailed literature of DER wall insulation solutions and market structures, with a focus on advanced envelope insulation strategies (Chrissi A. Antonopoulos et al., 2019). They note that the standard practice of drill-and-fill is insufficient for DER, due to its limited thermal performance. The authors provide a detailed list of all

Building America research on wall insulation retrofits, highlighting 16 research projects dating from 2009 through 2016. They also highlight promising emerging technologies, including aerogel insulation, vacuum insulated panels, phase change materials, and highly insulated vinyl siding. Insulation materials are compared in terms of their cost, advantages, disadvantages and formats (i.e., blown, batt, spray).

A large part of the review explores details on the following wall insulation strategies:

- Ventilated facades / rain screens
- Exterior wall insulation retrofits
  - Exterior insulate sheathing / super insulation
  - Thermal break shear wall assembly
  - Spray foam outer shell retrofits
- Modular/Panelized systems
  - Retrofit insulated panels
  - Solid panel perfect wall
- Insulated siding/cladding systems
  - Insulated vinyl siding
  - Exterior insulation and finish system (EIFS)
- Masonry walls
- EnergieSprong

Cost estimates were reproduced in the review of wall insulation strategies for a subset of wall insulation types. Based on the summary in (Chrissi A. Antonopoulos et al., 2019) and upon our further review of the referenced source material, we compiled the surface area normalized costs shown in Table 28 through Table 31. Thermal break shear wall retrofit costs are highlighted in Table 28, a method pioneered in the Pacific Northwest. Board and spray foam example cost breakdowns are highlighted in Table 29. Nail base insulation and sheathing options are described in Table 30. Finally, the costs of just re-siding are expanded up on Table 31.

Costs for exterior wall insulation, including the cost of replacing siding/cladding, ranged from \$14.46 to \$23.05 per ft^2. The split in costs between siding and insulation-related measures were widely varying, with insulation measures sometimes exceeding the exterior cladding costs, and other times vice versa. Based on board and spray foam projects highlighted in Table 29, the insulation costs were 44% of the total for 1-story homes and 56% for the 2-story example. For the nail base example, the insulation measures were somewhat more expensive than the siding alone (e.g., \$6.10 vs. \$7 for siding and insulation respectively in Table 30 and Table 31) (Bianco and Wiehagen, 2016). In all of these examples, the insulation and siding are roughly equivalent in cost (+/- 10%). This suggests that exterior insulation will somewhat more than double the total wall upgrade costs over a siding-only replacement. A counter point to this is the thermal break shear wall estimates from Oregon, where the siding cost was estimated as \$14.46 per ft^2, while the addition of sheathing, WRB and insulation increased the total to \$23.05 per ft^2, for an insulation increment of \$8.59. The lowest reported incremental insulation upgrade cost was $7 per ft^2 for nail base insulation (integrated foam board and sheathing in one product). This supports the notion that material design improvements could drive down labor costs and complexity during construction phase, leading to substantially lower project costs.

Table 28 Thermal Break Shear (TBS) installation cost, (Earth Advantage Institute, 2018)

Activity	Job Type	Line Item	Cost ($)	Cost ($) / ft^2	Total Cost
Baseline 1	Basic siding (cedar lap siding) replacement project with no added insulation or sheathing.	New siding & rainscreen - materials.	$6,269.04	$6.73	$13, 469.04 ($14.46 ft^2)
		Labor to install siding & rainscreen	$7,200.00	$7.73	
Baseline 2	Typical siding replacement project (above) with addition of standard sheathing and weather resistant barrier.	OSB and WRB materials	$702.00	$0.75	$17,420.00 ($18.70 ft^2)
		Labor to install OSB or plywood	$3,249.00	$3.49	
TBS Wall	Complete TBS wall assembly – additional wall studs, rigid insulation, sheathing, rainscreen, exterior jamb extension, and new siding.	Materials	$779.20	$0.86	$21,448.20 ($23.05 ft^2)
		Labor to install rigid foam insulation etc.	$3249.00	$3.49	
Incremental Cost -					**$4,028 - $7,979 ($4.35 - $8.59 ft^2)**

Table 29 Wall retrofit project costs (2012-2013), (Bianco and Wiehagen, 2016)

Wall Insulation Method	DER #1-One-Story 2 × 4 Studs	DER #2-One-Story	DER #3-Two-Story
	With 3.5" Closed-Cell Spray Polyurethane Foam	**Two-Ply 2" Rigid Foam**	**3" Extruded Polystyrene and R-15 Blown**
Approximate Added R-Value	18.6	20	30
Floor Area (Conditioned), ft^2	2,276	1,804	2,688
Wall area (Above Grade), ft^2	2,056	1,600	2,032
Wall Retrofit Cost (Above Grade)	$18,378	$15,978	$21,855
Wall Retrofit Cost, $ per ft^2	$8.94	$9.99	$10.75
Siding Cost	$23,714	$20,334	$18,026
Siding Cost, $ per ft^2	$11.53	$12.71	$8.87
Total Wall Cost, $ per ft^2	**$20.47**	**$22.70**	**$19.62**
Wall Retrofit Cost Fraction of Total	**43.7%**	**44.0%**	**55.8%**
Siding Retrofit Cost Fraction of Total	**56.3%**	**56.0%**	**44.2%**
Floor-Wall Ratio	**1.11:1.00**	**1.13:1.00**	**1.32:1.00**

Table 30 Cost of 4" and 6" retrofit panel installation per ft^2, (Bianco and Wiehagen, 2016)

Task	Cost per ft^2 ($)
Aerogel Insulation	$0.04
2" Nail Base Panels	---
4" Nail Base Panels	---
6" Nail Base Panels[a]	$3.12
Panel Labor	$2.19
Equipment	$0.33
Design - Panels	$0.27
Accessories	$0.58
Windows	$0.14
Extensions[b]	$0.33
Total Cost - Retrofit Panels	**$7.00**

a Average cost per square foot for all nail base panels.
b Polyvinyl chloride, boiler exhaust pipe, and sprinkler pipe through-wall extensions to accommodate panel thickness.

Table 31 Cost of re-siding per ft^2 of installed surface, (Bianco and Wiehagen, 2016)

Task	Cost per ft^2 ($)
Siding and Accessories, Vinyl	$2.40
Siding Labor	$2.51
Equipment	$0.17
Demo Existing Siding	$0.75
Design	$0.27
Total Cost—Retrofit Panels	**$6.10**

4.3.3 National Grid

The final report summarizing the costs and performance of the National Grid DER pilot program summarized the exterior wall insulation costs for 37 dwellings, Figure 15. According to (Gates and Neuhauser, 2014), almost all projects added exterior insulation and also upgraded the cavity insulation, if warranted. The surface area normalized exterior wall insulation costs are reproduced for each project below. These costs include only the wall insulation materials and labor. They exclude costs for re-siding and any re-framing required for the measure. The average exterior wall insulation retrofit in the National Grid pilot cost $10.51 per ft^2 (from $4.67 to $19.15). Notably, relative to initial lower estimates for this work reported elsewhere, the implementing contractor actually revised their estimates up during and after completion of the work (from $4 per ft^2 initially up to $7-$15 per ft^2 depending on access, detailing and secondary factors of each project). This suggests that rather than contractor experience driving down costs, the full burden of the work emerged and actually increased their cost estimates over-time.

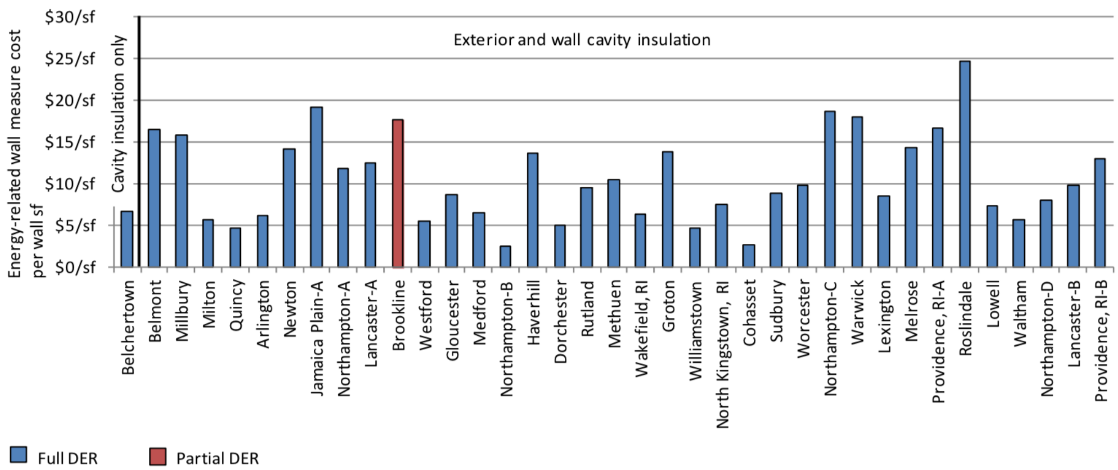


Figure 15 Total energy related exterior wall costa per wall ft² (Gates and Neuhauser, 2014)

4.3.4 IBACOS Exterior Spray Foam Insulation

IBACOS implemented exterior spray foam insulation supported with 2x4 furring from the exterior of several New York DER homes (Herk et al., 2014). They describe the difficulty in getting code/inspector approval for this novel approach, which eventually required a structural engineer's stamp to demonstrate the integrity of the exterior wall system. This approach only very marginally reduced envelope leakage, by approximately 5%. The work occurred over roughly a 3-week period, which included removing existing siding, exterior framing and foam, and replacement siding. The components costs for tasks making up the exterior wall insulation retrofit strategy are reproduced in the Table 32 below, with an insulation component cost of $10.76 per ft², $8.50 for siding, and $19.26 total cost per ft². Framing and SPF costs dominated the total insulation cost, with substantial contributions from window trim and sheathing tasks.

Table 32 Wall cost estimates versus actual cost, (Herk et al., 2014)

Wall Work	Total Actual	Cost per ft² ($)
New Framing	$5,625	$2.57
Removal of Windows	$671	$0.31
Window Trim	$3,606	$1.65
Spray Foam	$7,198	$3.29
Thin Profile Sheathing	$3,717	$1.70
Insect Screen	$1,167	$0.53
Total Without Siding	**$23,518**	**$10.76**
Install Siding	$18,574	$8.50
Total With Siding	**$42,093**	**$19.26**

4.4 Buried / Encapsulated Ducts

Available cost estimates for buried and encapsulated ducts are all based on estimates for new construction. We are not aware of any estimates for existing dwellings. In addition, the costs are widely varying for this measure, due to the variety of materials used. Material specification can be largely driven by moisture concerns around condensation forming on the outside of ducts buried in insulation. For example, in extremely hot-dry climates with little moisture risk, ducts can be entirely buried in loose-fill insulation with very marginal added cost. But in more humid locations, the condensing surface temperature of the ducts must be controlled, typically using closed cell spray foam insulation ("encapsulation"), which substantially increases costs. These differences are reflected in the tables provided below, but again, they do not apply to existing dwellings.

Table 33 Example cost for 2,400 ft² single-story house with 6:12 gable roof in climate zones 1, 2, or 3. Duct surface areas based on BA benchmark with two returns, (Shapiro et al., 2013)

	Partially Buried	Fully Buried	Deeply Buried	Unvented ccSPF	Encap-sulated	Partially Buried and Encap-sulated	Fully Buried and Encap-sulated	Deeply Buried and Encap-sulated	Interior Ducts
R-30 ccSPF Roof Deck				$8,363					
Encapsulated ducts					$1,678	$1,678	$1,678	$1,678	
Partially Buried (R-33 Fiberglass)	$95								
Fully Buried (R-42 Fiberglass)		$380							
Deeply Buried (R-51 Fiberglass)			$665						
Partially Buried and Encapsulated (R-37 Fiberglass)						$222			
Fully Buried and Encapsulated (R-46 Fiberglass)							$507		
Deeply Buried and Encapsulated (R-54 Fiberglass)								$760	
Interior Ducts									$1,680
Total Cost	**$95**	**$380**	**$665**	**$8,363**	**$1,678**	**$1,900**	**$2,185**	**$2,439**	**$1,680**

Building America has produced a measure guideline for buried and encapsulated ducts, which allow for very efficient duct systems in vented attics. Part of that effort includes producing cost estimates for a prototype home (see

Table 33) (Shapiro et al., 2013). Note: these estimates do not appear to include the cost to insulate the framed floor of the attic, so the comparison with the "unvented ccSPF" approach is not an equal comparison. These results suggest that costs can be particularly attractive in dwellings with compact duct systems, and in locations where encapsulation with spray foam insulation is unnecessary for moisture control.

The Insulation Institute worked with the Home Innovation Research Labs (HIRL) to create a technical specification that lays out how to bury/encapsulate ducts using simple practices. The technical specification also provides a table summarizing the costs and savings of buried insulated ducts[31,32]. According to their analysis, fully buried ducts range from $697 to $895, while fully buried and encapsulated ducts with spray polyurethane foam (for moisture protection) adds cost, with total expense varying from $1,472 to $2,791. This analysis also supports the cost savings available for compactly-designed duct systems, with less overall surface area.

4.5 Ductless Heat Pumps

Numerous states are running substantial heat pump installation initiatives, particularly in the Northeastern U.S. and on the West coast. Notable examples include the states of Maine, New York, Massachusetts and Vermont. Maine has the goal of installing 100,000 heat pumps by 2025 (Opalka, 2019) (Office of Governor Janet T Mills, 2019). This program is focused on incentives for low-income households and includes support of installer training through community college. New York is in the midst of creating a $500 million program aimed at heat pump deployment. Heat pumps are an area where our research suggests that costs may be changing rapidly, potentially driven by expanding economies of scale, installer experience and regional supply chains. In addition, to these emerging initiatives to drive increased adoption in colder climates, most heat pumps are installed in existing markets in the Pacific Northwest and South-East regions of the US.

Many factors affect the cost of ductless heat pumps, including the number of zones, the number of indoor and outdoor units (e.g., one outdoor unit to multiple indoor; multiple outdoor to multiple indoor; etc.), the rated efficiency, system capacity, cold climate status, location of the outdoor unit, housing construction types, and others. The subsections below describe a number of pilot programs and evaluations that provided useful ductless heat pump installation cost data.

Based on our review, ductless heat pump costs can be summarized as follows:

- For 1-ton, 1-zone ductless heat pump:
    - Standard: $3,957 - $5,464
    - Cold climate: $4,058 - $6,705

- Cost Premiums:
    - Cold climate: $100-$400
    - Efficiency: $239 - $689
    - Variable speed compressor: $266 - $759
    - Additional interior zones: $1,173 - $2,800 per zone
    - Gas-to-electric conversion: $267

[31] https://insulationinstitute.org/wp-content/uploads/2019/03/N087-Buried-Ducts-The-newest-way-to-uncover-savings.pdf
[32] http://insulationinstitute.org/wp-content/uploads/2017/01/TechSpec-Buried-Ducts_FINAL.pdf

4.5.1 Massachusetts Residential Heating and Cooling Program

Navigant Consulting, Inc. reported on the most comprehensive assessment that we are aware of documenting the cost efficiency curves of ductless heat pumps in cold climates. This effort was on behalf of the Massachusetts Residential Heating and Cooling Program, in support of revisions to the program's heat pump incentives/rebates for single-family dwellings. They based their cost estimates on three data sources: web scraping of equipment retail costs, contractor interviews, and program invoice data. The results of the web scraping and interviews are documented in (Navigant Consulting, Inc., 2018a) and the invoice data are assessed separately in (Navigant Consulting, Inc., 2018b).

Disaggregating ductless heat pump costs between equipment, labor, and other costs was an important aspect of this work. Based on contractor surveys, Navigant made labor/materials estimates for a baseline install (i.e., 1-ton unit at 15 SEER / 8.2 HSPF with total installed cost of $3,717) of 30% labor, 55% equipment, 10% supplies, and 5% other costs. Contractors reported charging equipment costs to customers that were on average $875 greater than the lowest retail values available online. This mark-up was consistent irrespective of system size/type. The non-equipment costs were $1,751 for the baseline 1-ton unit described above, which breaks out to $1,123 labor, $396 supplies and $232 for other costs. Navigant concluded that only equipment costs changed with efficiency, whereas labor, supplies and other costs were constant across installations with different efficiency ratings. They also found that longer line sets for systems >18kBtu led to a installation labor price premium of $250. Install labor costs also increased with each indoor head unit installed, such that a 2-zone system cost $974 more on average than a 1-zone system, and additional zones each add an average of $887 beyond that.

Below is a condensed summary of the cost-efficiency curves and cost insights produced in this work:

SEER 18/ HSPF 10:

- 12 kBtu: $3,957 ($4,058 Cold climate), 1 zone
- 18 kBtu: $4,475 ($4,646 Cold), 1 zone
- 24 kBtu: $4,811 ($5,016 Cold), 1 zone
- 24 kBtu: $6,679 ($7,060 Cold), 2 zone
- 24 kBtu: $7,852 ($8,202 Cold), 3 zone
- 30 kBtu: $8,024 ($9,049 Cold), 3 zones
- 36 kBtu: $8,857 ($10,438 Cold), 4 zones

Cold climate premium:

- $100-200 for 1-zone systems
- $400 for 2-zone
- $400-$1,000 for 3-zones
- >$1,500 for 4-zones

Extra zones premium for 24 kBtu:

- +1 zone ($1,868)
- +2 zones ($3,041)

Efficiency premium relative to the 12 kBtu (15 SEER / HSPF 8.2):

- $239 (to SEER 18 / HSPF 10)
- $689 (to SEER 20 / HSPF 12)

Location and dwelling details:

- Brick exterior walls: +$260
- Outdoor unit mounted on roof: +$400
- Outdoor unit mounted on exterior wall above ground floor: +$1,000
- Indoor recessed ceiling cassette: +$1,050 than typical wall-mounted head unit

The invoice data that Navigant collected was also analyzed and compared with the cost-efficiency curves developed from the web-scraping and contractor surveys. In all, 104 ductless heat pump invoices were identified to contain useful and valid information for analysis. The typical invoiced costs for new and replacement systems were:

New:

- $5,121 ($3,676 - $6,705) (SEER 16, n=16)
- $5,259 ($4,566 - $6,400) (SEER 18, n=16)

Replacement:

- $4,685 ($3,948 - $5,253) (SEER 16, n=39)
- $5,033 ($3,999 - $5,766) (SEER 18, n=22)

4.5.2 Redwood Energy All-Electric Construction Guide

Redwood Energy is a builder and designer of net-zero energy, all-electric, affordable multi-family housing in Northern California. They recently published a single-family all-electric zero-energy construction guide (Redwood Energy, 2020), which includes a detailed section exploring the installation costs and pricing practices of the ductless heat pump industry. Much of the cost discussion is based on input and interviews with Jonathan Moscatello of the Heat Pump Store in Portland, Oregon.

Moscatello provided costs across five manufacturers for 1- and 2-ton, single-zone ductless heat pumps:

- $4,450 - $5,400 (12 kBtu, 1 zone)
- $5,200 - $6,400 (24 kBtu, 1 zone)

The basic supply chain is Manufacturer -> Distributor -> Contractor -> Customer, and mark-ups are 25-50% at each step. The equipment cost to the contractor is $800 to $1,400, but typically $1,200 per ton. This is marked up to $1,110 to $2,100 to the customer. Labor, materials and other costs are added on top of this. An example cost breakdown is provided for a 1-ton, 1-zone system to illustrate how costs are typically distributed in a project:

- Labor: $300 (5 hours at $60/hr)
- Equipment: 40% of sales price, or $1,200 - $2,400
- Materials: 5% of sale (~$300)
- Electrical: $600-1000
- Permits: $100-150
- Subtotal: $2,500 plus 40% margin
- Total retail: $4,166

Finally, Moscatello discusses factors that can affect the cost of ductless heat pump installations:

- **Level of contractor experience.** Install of a 1-ton heat pump required 2-4 hours for an experienced contractor, but an inexperienced installer could easily require 4-8 hours.

- **Jobsite efficiency.** Multi-family installations, where installation crews are on-site for several days executing upwards of 4-6 systems per day, can achieve significant improvements in efficiency, leading to roughly 30% reduced costs, with 1-ton systems commonly installed for $3,000.

- **Home layout.** 25' or longer refrigerant line sets lead to an increase of $500 per indoor unit, due to additional and labor to add refrigerant to the system. Similarly, indoor units located on interior walls necessitating that the line set and electrical run through the crawlspace or attic increases costs by $1,000.

- **Number of indoor zones.** Fewer indoor zones are always cheaper. For some example Fujitsu units, each additional indoor zone adds $1,300 - $2,200. For a Mitsubishi example, $2,000 - $2,800 is added for each additional indoor zone.

- **Installation company.** The company size, revenue and experience can all affect the overhead charges from the installer. They suggest that small companies have typical overhead charges of 25-35%, medium companies 35-45%, and the largest companies can have >45% overhead.

- **Indoor unit type.** They note that ducted mini-split pricing operates on very different terms, with much less predictability than the ductless versions. All duct work tends to be bespoke, and installers often find that the material costs of the duct work exceed the whole sale cost of the heat pumps themselves. Costs for these systems are much more difficult to predict.

4.5.3 NYSERDA Multi-Family Pilot

(Dentz and Liu, 2019) conducted a study where they tried to understand and demonstrate the viability costs and savings about the installation of cold climate ductless heat pumps in 21 existing residential buildings in New York. Most of the units were either Mitsubishi or Fujitsu.

The goal of the study was to increase awareness and confidence, market exposure and provide resources for NYSERDA to promote benefits. The case study buildings were owner occupied with rental units located in tight urban lots. Most were old masonry attached buildings with minimal insulation, and some were wood frame SFD. They used gas and oil for space heating. The projects conducted boiler replacement and some weatherization.

Table 34 Installation summary, (Dentz and Liu, 2019)

Site	Zones	Living Units	Heat pump equip. cost	Heat pump labor cost	Heat pump total cost	Weath er-ization cost	Total cost	Heat pump total/zone	Heat pump total/ton	Zones per apt.	Htg load	Cap @ 47	Cap/ Load
1	6	1	$ 8,290	$ 15,610	$ 23,900	---	$ 23,900	$ 3,983	$ 4,686	6	42,998	61,400	143%
3	7	1	$ 11,156	$ 20,992	$ 32,148	$ 5,500	$ 37,648	$ 4,593	$ 5,358	7	99,462	78,600	79%
5	10	1	$ 18,024	$ 34,166	$ 52,190	$ 5,500	$ 57,690	$ 5,219	$ 8,698	10	80,226	78,600	98%
10	10	2	$ 15,000	$ 20,783	$ 35,783	$ 10,736	$ 46,519	$ 3,578	$ 4,647	5	110,633	102,200	92%
12	8	2	$ 12,687	$ 24,443	$ 37,130	$ 10,000	$ 47,130	$ 3,523	$ 4,271	4	74,167	82,200	111%
14	7	1	$ 13,530	$ 9,500	$ 23,030	$ 28,431	$ 51,461	$ 3,290	$ 3,715	7	76,224	75,000	98%
19	5	2	$ 12,083	$ 7,917	$ 20,000	---	$ 20,000	$ 4,000	$ 4,762	2.5	53,612	53,600	100%
21	4	2	$ 6,555	$ 11,319	$ 17,874	$ 5,500	$ 23,374	$ 4,469	$ 5,766	2	43,095	45,000	104%
23	7	1	$ 15,576	$ 6,000	$ 21,576	$ 13,596	$ 35,172	$ 3,082	$ 3,657	7	54,411	64,900	119%
25	8	1	$ 10,696	$ 11,304	$ 22,000	$ 7,350	$ 29,350	$ 2,750	$ 3,729	8	31,719	77,400	244%
31	7	1	$ 7,429	$ 15,571	$ 23,000	---	$ 23,000	$ 1,714	$ 2,500	7	41,397	64,200	155%
32	4	1	$ 5,682	$ 6,318	$ 12,000	$ 3,500	$ 15,500	$ 3,000	$ 4,138	4	20,009	39,341	197%
35	6	1	$ 10,200	$ 14,800	$ 25,000	$ 1,000	$ 26,000	$ 4,167	$ 5,208	6	45,252	54,000	119%
39	4	1	$ 4,903	$ 7,097	$ 12,000	---	$ 12,000	$ 2,000	$ 2,759	4	31,967	39,341	123%
40	3	1	$ 4,488	$ 7,512	$ 12,000	$ 9,750	$ 21,750	$ 4,000	$ 6,667	3	23,694	26,000	110%
41	4	1	$ 7,444	$ 6,000	$ 13,444	$ 14,327	$ 27,771	$ 3,361	$ 3,361	4	47,871	42,500	89%
42	4	1	$ 10,431	$ 8,000	$ 18,431	---	$ 18,431	$ 4,608	$ 4,608	4	45,320	48,000	106%
44	5	1	$ 7,000	$ 9,000	$ 16,000	---	$ 16,000	$ 3,200	$ 4,324	5	37,926	52,000	137%
45	11	3	$ 14,000	$ 10,000	$ 24,000	$ 10,000	$ 24,000	$ 2,182	$ 3,000	3.7	69,456	115,000	166%
46	8	1	$ 19,100	$ 8,900	$ 28,000	---	$ 28,000	$ 3,500	$ 4,000	8	53,864	96,000	178%
18	9	2	$ 15,243	$ 9,840	$ 25,083	$ 26,500	$ 51,583	$ 2,787	$ 3,420	4.5	51,660	95,000	184%
Avg	**6.5**	**1.3**	**$ 10,929**	**$ 12,622**	**$ 23,552**	**$ 7,223**	**$ 30,299**	**$ 3,476**	**$ 4,442**	**5.3**	**54,046**	**66,204**	**131%**

In Table 34 and Table 35, we have reproduced the costs and other relevant information for each site, including the number of zones, equipment and labor costs, costs per zone and per ton, etc. It is notable that while the average equipment vs. labor breakdown was 46% (equipment cost / total cost), the ratio was not consistent between projects, with projects varying between roughly 35% up to 72% for equipment. The typical costs were $4,442 per ton (12 kBtu/hr) of installed capacity (from $2,500 to $5,766 per ton) and $3,476 per indoor zone. The total heat pump costs per site averaged $23,552 for an average of 6.5 zones to satisfy a 54 kBtu/hr heating load. They noted that in some units, the existing equipment was not removed, and in those units, the fossil fuel fired units still provided a substantial fraction of the total heat load (typically 10-30%, but up to 80% in a couple units). They also noted numerous installation faults, most frequently with the outside units and the condensate plumbing. Finally, they noted the measured COPs were lower than expected, with all units performing at <2.5 and substantial fractions of units <1.5.

Table 35 Installation summary, (Dentz and Liu, 2019)

	Average
Zones per site	6.5
Living units per site	1.3
Zones per apt.	5.3
Heat pump equip. cost per site	$10,929
Heat pump labor cost per site	$12,622
Heat pump total cost per site	$23,552
Weatherization cost per site	$7,223
Total cost per site	$30,299
Heat pump cost per zone	$3,476
Heat pump cost per ton	$4,442
Heating load (Btu/hr) per site	54,046
Rated heating capacity (Btu/hr) per site	66,204
Capacity/Load avg. of all sites	1.3

4.5.4 ComEd Multi-Family Pilot

(CMC Energy Services, 2020) explores the pilot experience of installing 80 cold climate ductless heat pumps in 7 multi-family buildings located in Illinois with existing electric resistance baseboard heat. The goal of the project was to test displacement of resistance heat in income-eligible, multifamily apartments with the use of high-performance ccDHPs. The average cost per installed heat pump for this pilot was $8,148. This cost includes the ccDHP equipment, associated materials, the ecobee smart thermostat and all labor associated with installation. The average cost per installed heat pump varied by location with a high average of $8,928 at the Centennial site and a low average of $7,373 at the Grand site (in Illinois) (see Table 36). The evaluation noted that multi-head units (multiple indoor units) generally performed more poorly than single-head units (one indoor unit). The authors also explored some pathways to reduce the installed cost of cold climate ductless heat pumps. They plotted a path from an installed cost of $7,500 for 80 units to a bulk price for a 1,000 units of $4,725 each. These included seeking a volume discount (-12%), simplified and standardized installation and controls (-6%), competitive bidding process (-15%), and improved site evaluation and selection process (-4%). The installed capacity of the units was not reported.

The evaluation recommends the following programmatic changes to increase cold climate ductless heat pump adoption and cost-effectiveness in ComEd territory:

- Pre-heat usage guidelines specifying a minimum pre-retrofit heating usage.
- Weatherization measures to address building shell.
- Lock-out technology based on outside temperature to limit resistance heat.

- Single-head units are preferred over multi-heads due to improved efficiency.
- Program to take advantage of off-peak shoulder months.
- Target heat pump-ready buildings.
- Contractor bidding process to secure best installation prices
- Select 2-3 highly qualified installation contractors
- Educate homeowners/participants

Table 36 Equipment costs summary, (CMC Energy Services, 2020)

Location / Metric	Grand Ave	North Lewis Ave	Centennial Court	147th St	S Bennett Ave	70th St	Zion
Total equipment cost including installation	$88,474	$66,419	$107,133	$69,453	$142,310	$142,997	$124,673
Average cost per heat pump	$7,373	$8,302	$8,928	$8,682	$7,906	$8,412	$7,792

4.5.5 SMUD Residential Electrification Program

The SMUD electrification program has provided incentives for the installation of hundreds of heat pumps for space conditioning in California's Central Valley, including both gas-to-electric and electric-to-electric conversions. While we cannot distinguish mini-split from traditional split heat pump installations, this data provides a unique understanding of the costs of packaged unitary vs. split systems, as well as any cost differences of converting previously gas equipment vs. previously electric equipment. It also provides information on the cost increments for variable speed equipment and for high HSPF ratings. The data in Table 37 is extracted from a presentation by Scott Blunk of SMUD and represents 764 heat pump installations, 580 gas-to-electric and 184 electric-to-electric conversions (Scott Blunk, 2021).

We expect the replacement of gas equipment with a heat pump to have costs in addition to those incurred when replacing existing electric equipment. This is due mostly to new electrical requirements and possibly the demolition and removal of gas piping infrastructure. Yet, the data in Table 37 shows quite a mix, with only a small additional cost for converting gas vs. electric equipment. Overall, the median additional cost for a gas conversion project was $267. The increments were sometimes positive and other times negative, depending on the specific equipment, ranging anywhere from $394 cheaper to convert gas equipment (for packaged variable speed equipment with HSPF > 10) to $915 more expensive to convert gas equipment (for 2-stage packaged units with HSPF 8-10). On its face, this suggests that the data set is not sufficiently large to estimate the cost differences based on pre-retrofit fuel type, and in addition, it suggests that the differences based on pre-fuel type are likely less important than other factors affecting cost (e.g., contractor choice, labor rates, site access, etc.).

Interestingly, the cost increments for either improved HSPF ratings or for variable speed compressors were dependent on one another, such that for variable speed equipment, it cost less to increase the HSPF, and for higher HSPF equipment, it cost less to get variable speed.

The opposite was true for 2-stage or lower efficiency equipment, where the cost increments were greater to get those features. For 2-stage, split equipment, the typical cost increment for higher vs. lower efficiency equipment (>10 vs. 8-10 HSPF) was $546, whereas the same increment for variable speed equipment was only $69. Similarly, the cost increment for variable speed vs. 2-stage equipment was $759 (for packaged, 8-10 HSPF), $743 (for split, 8-10 HSPF), and only $266 (for split, >10 HSPF).

Table 37 SMUD heat pump space conditioning system costs

Heat Pump Efficiency	Type	Gas-To-Electric		Electric-to-Electric	
		$ per ton	Count	$ per ton	Count
HSPF 8 - 10, 2-stage	Packaged	$5,194	119	$4,279	49
	Split	$4,652	206	$4,706	88
HSPF > 10, 2-stage	Packaged				
	Split	$5,198	32	$4,713	11
HSPF 8 - 10, Variable	Packaged	$5,953	79		18
	Split	$5,395	12	$5,007	3
HSPF > 10, Variable	Packaged	$5,691	78	$6,085	12
	Split	$5,464	54	$5,319	3
Rebates		$2,500		$750	

4.6 Heat Pump Water Heaters

Heat pump water heaters are an emerging alternative to both existing tank and tankless water heating technologies, both electric resistance and gas-fired. Replacement of resistance electric heaters for heat pump units is fairly straightforward, as the electric service is already in-place. In contrast, replacing existing gas-fired heaters with heat pump units can require expensive electrical service upgrades. Irrespective of the type of unit being replaced, all unitary heat pump water heaters require some additional space for heat extraction, which can be difficult in tight space (e.g., utility closets). In addition, the noise produced by heat pump units can be problematic for dwellings where the water heater is in the laundry room or other connected areas.

Overall, heat pump water heaters are installed at a wide variety of prices (details in the following sub-sections):

- Cost curve: $2,263 - $2,714
- Contractor estimates: $2,602 - $4,705
- SMUD +/- 1 Standard Deviation, 50-gallon: $3,000 - $5,000, typically $3,800

4.6.1 Navigant Cost Efficiency Study

(Navigant Consulting, Inc., 2018c) provides cost efficiency curves for heating and hot water equipment, including heat pump water heaters. Their method is similar to the ductless heat pump cost efficiency study executed by Navigant described in Section 4.5.1, The data are based on web-scraping retail prices for equipment, contractor surveys for installation costs, and program rebate/invoice data. Heat pump water heaters are broken down by tank size—

50-gallon and 80-gallon units—and total installation cost estimates are provided based on the Uniform Energy Factor (UEF). Based upon contractor surveys, they also break down the installation costs by labor, equipment, materials and other. These breakdowns are compared against the same estimates for resistance electric water heaters. The predicted total installed costs for three configurations of heat pump water heater are detailed in Table 38.

The efficiency curve installed costs are notably lower than those estimated by the contractors surveyed by Navigant, because the efficiency curve uses the minimum retail price extracted during web-scraping and applies to it contractor mark-up add-on values, plus labor and materials. This approach yielded lower overall costs and better alignment with actual program invoice data for water heater installations. One reason for this was that electric storage water heaters are typically purchased directly by the customers, and contractors are paid for installation only. Contractor estimates were based on them procuring and delivering the units to the jobsite, but this is not typical. In addition, Navigant identified that the contractors were over-estimating the equipment costs relative to the retail cost data identified during web-scraping.

Table 38 Heat pump water heater installation costs, Source: (Navigant Consulting, Inc., 2018c)

	Efficiency Curve Total Installed Cost ($)	Minimum Retail Price ($)	Contractor Cost Breakdown ($)				
			Total	Labor	Equipment	Supplies	Other
50-gallon HPWH (UEF >2.0)	2,110	899	2,972	813 (27%)	1,625 (55%)	371 (12%)	163 (5%)
80-gallon HPWH (UEF 2.2)	2,263	1,703	2,602	730 (28%)	1,461 (56%)	251 (10%)	160 (6%)
80-gallon HPWH (UEF >2.7)	2,714	1,781	4,705	1,090 (23%)	3,090 (66%)	345 (7%)	180 (4%)

Heat pump water heater total installed costs varied by efficiency (i.e., UEF). For the <55-gallon units, the cost increases at each level of UEF were small (<$150), such that going from a 2.1 to the 3.55 unit, the estimated total installed cost increased by only $291. The average incremental cost from an electric resistance unit to a UEF of 2.0 was $1,500. Retail equipment costs were higher for the heat pump units compared with electric resistance, but the labor and supply cost components also increased by $365 and $225, respectively. Navigant suggests that these increases may be due to the addition of vent openings and other adjustments to the water heater location. The larger tank sizes showed only slightly more variability in price by efficiency, with an estimated price increase of $560 going from 2.2 to 3.7 UEF when using the cost-efficiency curves. Notably, the contractor estimates for total installed cost were quite different, suggesting a $2,100 increase for the same increase in efficiency (from 2.2 to 3.7 UEF). The labor and supplies costs were again higher for the heat pump units, at a $360 and $94, respectively.

4.6.2 SMUD Hot Water Electrification Program

SMUD has been operating an electrification program in California's Central Valley for the past several years that have included the incentivization of heat pumps for water heating and space conditioning. In a February 11th, 2021 presentation to the Building Decarbonization Coalition, Scott Blunk of SMUD reported the following cost data for replacing gas hot water with electric heat pump water heating equipment (Scott Blunk, 2021). Mr. Blunk quoted a typical cost for gas-to-electric conversion of $4,200 per installation over the life of SMUD's program (from June 2018 to May 2020), with the most recent 2020 costs averaging $3,800 per replacement. The typical installation cost and range of costs are plotted over-time in Figure 16. The majority of the installations over time have fallen in the range of $3,000 to $5,000. Based on a rough estimate from visually reviewing the plot, we expect this data represents roughly 1,400 heat pump water heater installations. The impact of appliance incentives can be seen with the reduction from $3,000 to $2,500 in April of 2020. Notably, these are still very high incentives, covering more than 50% of costs.

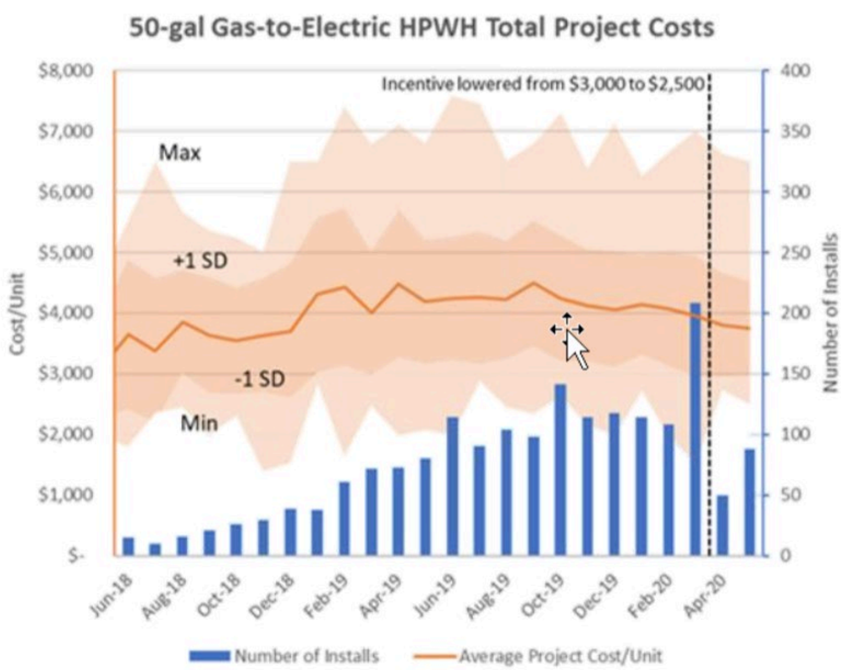


Figure 16 SMUD electrification program heat pump water heater installation costs over time.

4.6.3 Northwest Water Heater Initiative

A study conducted by (Webb, 2018), addresses the high variation in total installed price of HPWH, and they note that the market practice is to use something referred to as "value-pricing". Value-pricing is where HPWH are sold and installed based on the price the market will bear, rather than based on competitive pricing between companies. This can occur when either the installers and/or the customers are not familiar with the typical costs. The physical installation constraints unique to HPWH can cause longer, and therefore more expensive, installations than standard electric resistance tanks of the same capacity. The team analyzed customer data on HPWH installation labor cost in the Northwest and found a standard deviation of $1,479.79 for the cost of labor. The equipment costs for HPWH were also both higher and more varied than for resistance electric tanks, with mean costs of $825 vs. $542 (standard deviations of $307 and $92). The study did not have pricing data for ER tank labor costs, however, the installers are much more consistent in their labor costs for ER tanks, likely because they are a commodity.

4.6.4 Beneficial Electrification of Water Heating

(Farnsworth et al., 2019) studied two technology options for electrification of water heating: (1) Electrical Resistance (ER) water heaters; and (2) air source heat pump (HP) water heaters. The main difference between both technologies is that ER heaters are tanks containing one or more submerged electric heating elements. HP water heaters are tanks with heat pumps attached directly to them. Both have different cost and operating characteristics. ER water heaters are not dominant in the US. The study highlights that for multi-family units with central water heating, an HP system can be efficient. New construction offers the opportunity to outfit homes for all-electric service, including HP water heaters, avoiding the cost of extending natural gas service.

The study conducted by (Farnsworth et al., 2019), recommend the following:

- Existing Single-Family Buildings: Homeowners desiring electric water heating will need to consider the following factors: Available space and the suitability of existing plumbing and electric service installation. Owners may need to enlist specialists to ensure proper installation, because HP water heaters expel cool air and can be as loud as a dehumidifier. HP water heaters require air circulation and space around the unit. In addition, it is important to ensure proper sizing of the appliance itself.

  Houses with existing natural gas service will be the least cost-effective to convert to electric water heating. Conversion will be more attractive where a dwelling can also switch to heat pumps for space heating and thereby potentially eliminate monthly fixed charges for natural gas service. Converting space heating and cooling and water heating simultaneously could also reduce the incremental cost of electric water heat installation. Because converting from natural gas represents a major investment, it is less likely without support or incentive programs.
  Houses that heat with oil or propane may be good candidates for conversion to electric water heating. Homes that heat with these fuels tend to be in colder climates, so the performance of cold climate heat pumps may be a factor in the economic calculation.

- Existing Multi-Family Buildings: Most low-rise apartments in the US that heat water electrically, have individual electric resistance water heaters. These dwellings are typically built with only cold-water service to each unit, meaning that retrofit to solar or central hot water systems could be difficult and expensive. For these buildings, controlled ER water heaters may be suitable. Several utilities are implementing this strategy, including Portland General Electric and Hawaiian Electric Co. In existing apartments, the economical choice may be to install controlled ER water heaters when existing appliances fail or to retrofit existing water heaters with control devices. Although space and other constraints in some multi-family buildings will pose a challenge to installing heat pump water heaters, that is not universally the case. Where these are not concerns, HP models are also well-suited for this housing type.

The study states that HP water heaters offer substantial life cycle savings relative to oil and modest savings by comparison to propane water heaters Table 39. HP water heaters cost less to purchase and install than oil water heaters and that the simple payback relative to oil water heaters is immediate. Regarding the replacement of propane water heaters, heat pump alternatives typically pay back in about 3-4 years at reference case prices, 2-3 years at high prices, and 5-8 years at low prices.

Table 39 Life cycle cost of water heaters, (Farnsworth et al., 2019)

		COST ($)
Oil	Base	$7,068
	Standard	$6,570
	Top-tier	$5,716
Propane	Base	$4,586
	Standard	$4,526
	Better	$4,287
	Top-tier	$4,623
Electric Heat Pump	Better	$3,796
	Top-tier	$3,303

4.6.5 California Retrofit Ready Program

The California Retrofit-Ready HPWH Program (New Buildings Institute, 2019), can help catalyze market transformation in California and make HPWHs the favored application in existing building water heater retrofits. The successful transformation of the water heater industry to a mature, coordinated, statewide effort is one of the key objectives of the program. This will help achieve the goal of 10% market replacement of the 2014 existing water heater stock by 2025, and 50% market replacement of the 2014 existing water heater stock by year 2030. Finally, 95% market replacement of the 2014 existing water heater stock by 2045.

5 Emerging Technologies for Deep Energy Retrofit Projects

As part of LBNL's deep retrofit cost stack work we have performed a survey of key practitioners and stakeholders (W. R. Chan et al., 2021). This survey included questions on new technologies that are perceived by the industry to be most promising. The results are summarized in Figure 17. Heat pumps and ventilation-related technologies were the clear favorites.

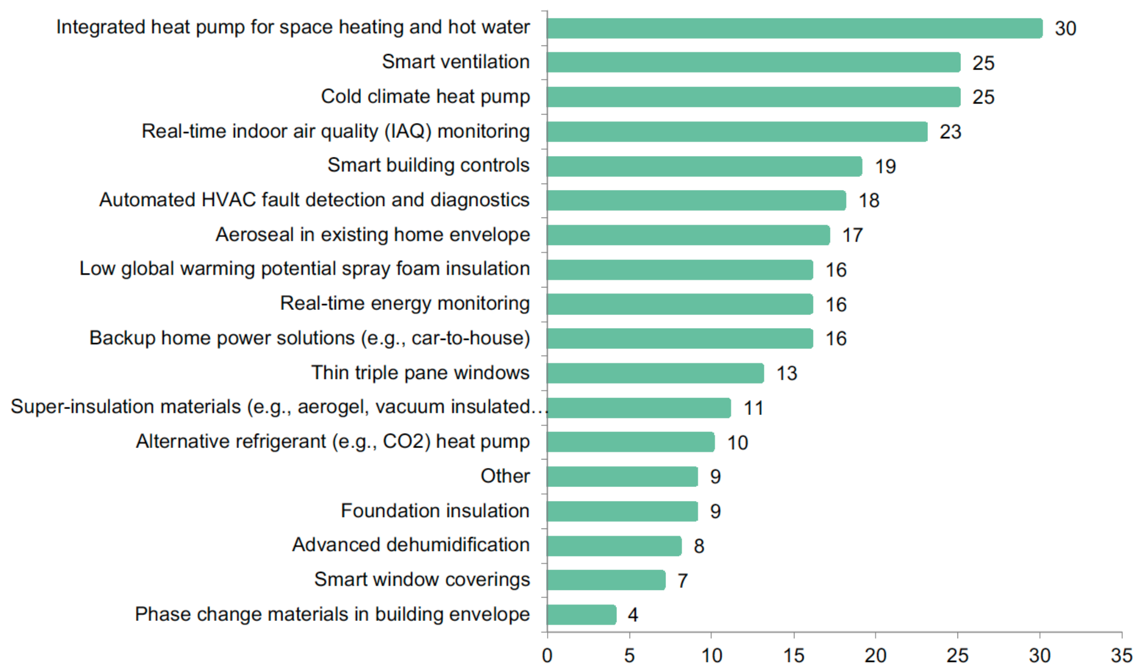


Figure 17 Retrofit Industry Survey Responses for most promising emerging technologies – number of respondents for each technology, (W. R. Chan et al., 2021)

5.1 Innovation for Easier Home Electrification

A key area of innovation is home electrification because we need to electrify homes in order to eliminate or significantly their CO_2 emissions. A recent review (Armstrong, 2020) was focused on technologies that have either become recently available or are in pilot testing phase where we expect them to be available within the next year or two. Many of these technologies are intended to eliminate the need to install a new electric service in a home because this can be a significant cost ($1,954[33]). Figure 18 and Figure 19 illustrate devices for circuit sharing that limit the total power requirements for a home. This includes applications where several high-use appliances share a single circuit in a smart and programmable way. Other applications are to allow home with limited power to charge EV's by sharing the EV circuit with other circuits in the home.

[33] Demolish and install 200A Main Service panel (Gordian, 2019).

- For expanding capacity for EV charging and avoiding expensive charger installs
- These are best used for non-EV appliances when one load is a short interruption of the other
- For extremely small electrical panels, these will be crucial, especially 120V devices

	BSA Electronics[xli] Dryer Buddy	Neo Charge[xlii] Smart Splitter	EV-PowerShare[xliii] EV-PS Smart	SimpleSwitch[xliv] 240V / EV Circuit Switch
				
Cost	\$200 - 365	\$450 (smart splitter) \$500 (dual car splitter)	\$375	\$575 / \$675
Description	• Plugs into a 30A circuit (common dryer plug) and allows for vehicle charging while dryer is not in use. • It has a digital display that shows the draw of each load.	• Level 2 charging without rewiring or panel upgrade • Pauses EV charging for other large loads then resumes charging • Also have a "dual car" option – charge two EVS at half power, or fully charge one then the other	• Plug into a NEMA 10-30 or NEMA 14-30 high voltage wall socket. • Set EV service equipment to 24 Amps. (24 amps max recommended continuous load for 30-amp circuit) • Plug high voltage appliance into left socket, plug your EVSE into the right.	• One load is the "primary" load and the other is the "auxiliary" – if the primary load comes on, the auxiliary load will shut off. • EV version is EVSE • Useful for short-load/long-load sharing such as electric baseboard heating with overnight EV charging

Figure 18 Smart circuit splitters and sharing, (Armstrong, 2020)

Eaton[xxxix] Energy Management Circuit Breaker (EMCB) 	• Programmable breakers to prioritize loads in power outage scenarios, control shedding of lighting and plug loads • Remote cycling of HVAC, WH, to offset energy demands and save money • Can connect with solar monitoring, home networks and demand response • In the future could simplify EV charging	Lumin[xl] Smart Panel 	• Real time balancing of battery use and charging • Manages renewable generation, energy use and storage • Dynamic switching of loads based on time of use rates • Off-grid mode sheds non-critical loads and islands • Can pair with batteries to create an integrated energy management system, removes requirement of a subpanel or protected loads panel • Programmable schedules to automatically control loads • Max size: (x6) 60A, (x6) 30A

Figure 19 Programmable subpanels, (Armstrong, 2020)

Another way to control total power requirements of a home and avoid costly home rewiring for 240V circuits is to use appliances that can operate off existing 15A, 120V circuits. Figure 20 summarizes new products that provide, heating, cooling DHW and clothes washing/drying using low power. In addition, there are new 3-burner induction cooktops coming to market that utilize power sharing between the burners to operate of a single 120V circuit. For many homes, particularly smaller existing homes and apartments, the capacity of these devices is sufficient, thus negating the need for panel upgrades and home rewiring as shown in the recent guide from Redwood Energy ((Armstrong et al., 2021)).

Product Type	4.5 cu ft Condensing Washer/Dryer Combo	Heat Pump Water Heater	Through-Wall Heat Pump	Mini-Split Heat Pump
Maximum Rating (Amps, Watts)	10A, **1200W**	8.3A, **1000W**	6.3-15A, ~**1400W**	10.4A, **1090W**
Make and Model	LG WM3998HBA	GE GeoSpring	Innova HPAC 2.0	LG LS-120HXV
Image				

Figure 20 Power efficient appliances (120V), (Armstrong, 2020)

5.2 Smart Ventilation

Smart ventilation allows for time-shifting of ventilation for energy saving purposes without sacrificing indoor air quality (Less et al., 2019). It is also a technology that allows time shifting to off-peak as part of grid-integration strategies (Young et al., 2020). Recently, control algorithms have been developed that reliably save about half of ventilation-related energy. Figure 21 illustrates the annual ventilation energy savings for a controller that varied the flow depending on outdoor air temperature. A key aspect of smart ventilation is that it can be applied in both new and retrofit situations. For retrofits, its best application is for homes that have been made sufficiently tight that mechanical ventilation is required and where mechanical ventilation provides a substantial amount of total ventilation. To enable smart controls also requires that the ventilation fans have excess capacity above the minimum needed for compliance. The added cost of the smart control is estimated to be $100-300 (see Table 40 for current products on market), making this a very cost-effective strategy. For a home with an existing ventilation system the upgrade to smart ventilation is also quick and easy – with a simple replacement of the on-off switch with a smart control device. Some manufacturers are already implementing smart ventilation strategies into their ventilation controllers and work is underway (via a study funded by the DOE Building America program) to perform detailed pilot demonstrations and evaluations homes throughout the country.

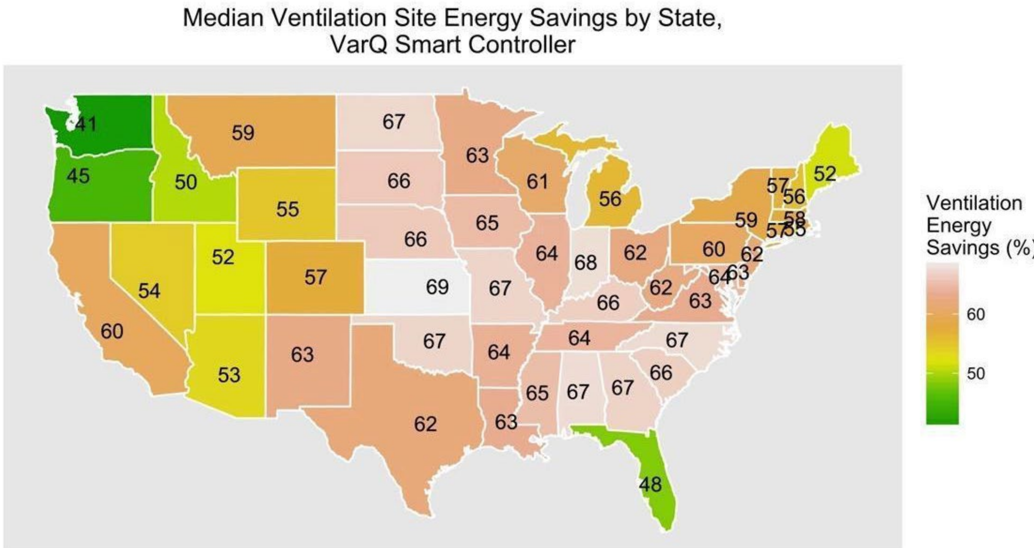


Figure 21 Annual ventilation energy savings for a smart ventilation controller.

Table 40 below represents a market search for ventilation control technologies that are currently available and include some amount of controls based on sensing of temperature, humidity or other inputs. It does not include simple timer-based controls or controls that meet ventilation standards, but do not offer sensor integration with the controls. This list is not necessarily exhaustive, nor can we fully confirm the details of the control functions, or current pricing.

Table 40 Descriptions of currently available ventilation technologies that enable control based on temperature, humidity or other inputs. Note: none of these that we are aware of are designed to maintain equivalent exposure, as required by the ASHRAE 62.2-2016 ventilation standard.

Manufacturer	Model	Cost ($)	RH Sensor		Temperature Sensor		"Smart" Control Functions and Description
			In	Out	In	Out	
Field Controls[34]	Fresh Air Ventilation Control	$100	x			x	Control up to 4 appliances, including dampers, ERV/HRV, HVAC central blower and various exhaust fans. Climate modes: Normal, Hot, Cold or Disabled. They have relations of indoor RH and outside temperature at which they either eliminate all venting, restrict to 25% of target, or vent fully. Optionally monitoring bath and laundry exhaust, etc. using pressure or current sensors, which credits against airflow requirement! 30-minute venting decision. Hot Climate: off <25F, during heating but limited to 25% of target 25-32F, during heating only 32-40F, normal venting from 40-90F (with indoor RH limits), 25% 90-100F, off >100F. Cold Climate: off <0F, during heating but limited to 25% of target 0-25F, during heating only 25-50F, normal venting from 50-90F (with indoor RH limits), 25% 90-100F, off >100F. "Normal" Climate: off <17F, during heating but limited to 25% of target 17-25F, during heating only 25-40F, normal venting from 40-90F (with indoor RH limits), 25% 90-100F, off >100F.
Honeywell[35]	TrueIAQ	$55	x	x	x	x	Controls humidifier, dehumidifier, whole house and local exhaust fans. ASHRAE 62.2 fan controls. Day/night timer-based ventilation. Manually enter # of bedrooms and floor area (or cfm for 62.2). Vent Shut Offs: 0=Auto vent regardless of outdoor conditions 1=Off at 75°F dew point or 99°F air temp 2=Low speed at 65°F dew point or 85°F air temp. Off at 75°F dew point or 99°F air temp Note: If option 1 or 2 is selected, then ASHRAE 62.2 Standard will not be met.
Honeywell[36]	Vision Pro IAQ	$280	x		x	x	Controls humidifier, dehumidifier, whole house and local exhaust fans. ASHRAE 62.2 fan controls. Day/night timer-based ventilation. Manually enter # of bedrooms and floor area (or cfm for 62.2). There is an indicator on the thermostat saying it "P" or "F" 62.2. Ventilation control 0 No ventilation 1 Ventilation always allowed 2 Ventilation not allowed during sleep period 3 Vent all with lockouts 4 Vent off sleep with lockouts. Select high, low or both ventilation lockouts for temperature. 90 to 110 by 5F. -20 to 0F by 5F. Also, high indoor humidity control can increase ventilation in heating mode.
Aprilaire[37]	8126A Ventilation System	$165	x		x	x	CFIS only. 62.2-2010 target airflows. High and low temperature cutoffs. Humidity control with high indoor RH limit and corresponding behavior based on outdoor temp. Default is to turn venting off <0F, allow with heating operation between 0 and 20F, otherwise on but with humidity limits. Turns off >100F. Between 50 and 100F, humidity dependent with 55% indoor RH cutoff (so no ventilation "drying" is allowed). 90F high limit for "warm" climate setting. They've got good outdoor temp vs. indoor RH figures showing control operation.

34 https://www.fieldcontrols.com/fresh-air-ventilation-control?page_id=92
35 https://customer.honeywell.com/en-US/pages/product.aspx?cat=HonECC+Catalog&pid=DG115EZIAQ/U
36 https://forwardthinking.honeywell.com/products/thermostats/visionpro/visionpro_iaq.html
37 https://www.aprilaire.com/whole-house-products/ventilation/model-8126a

Broan/Venmar[38]	Altitude/Platinum Controller	$180			x	x	CFIS only. Low temp cutoff -40 to 32F. High temp cutoff 33 to 104F.
Broan/Venmar[39]	X-Touch/Gold-Touch	$120	x			x	CFIS. Indoor RH controller increases AER when exceeding limits, manual tells user to turn this dehumidistat feature off during cooling season. One of five CFIS speeds is selected by the controller depending on combination of indoor RH and outdoor temperature.
AirKing[40]	QuFresh	$260 (includes fan)		x		x	Supply Fan, 40-120 cfm. Energy Saving Mode, allows user to configure upper and lower limits for temp and rh
Build Equinox[41]	CERV2	Unknown	x	x	x	x	Integrated CO2 and VOC measurement and ventilation control. Integrates on-board heat pump rather than traditional ERV heat exchanger, to provide boost heating/cooling in recirc mode. MERV13 standard filtration. Can recirc and condition, ventilate and condition, just ventilate, or turn off. Seems like there are CO2 and VOC thresholds set by user, which the system then controls to. This limit-based approach can be combined with scheduled or continuous ventilation, as well.
Broan/Venmar[42]	FIN-180P	Unknown		x		x	Supply fan, 25-180 cfm. Continuous option, otherwise 5 comfort settings based on climate zone. A sophisticated algorithm selects the best time of the day for ventilation and takes advantage of air handler usage. MERV8 or MERV 13 filter. High and low cutoffs for outside temperature and dew point, vary by climate zone (covering CZ1-4). Low end 40F cutoff with 23F Dewpoint upper limit between 85 and 90F, dewpoints of 73-75F. There are separate temperature settings if a heating/cooling call exists, it looks like they preferentially ventilate during heating/cooling calls.
Ultra-Aire[43]	DEH 3000/3000R	Unknown	x	x		x	Designed to integrate with the Ultra-Aire line of whole house ventilating dehumidifiers and allows homeowners to precisely monitor and control moisture levels, manage fresh air ventilation (with optional damper), and activate air filtration. Can lock dehumidifier in with or out when cooling calls occur. There is only a high temperature cutoff, no low temp option.
AirCycler[44]	TempGaurd	Unknown				x	Cold off temperature, 35F +/- 5F. Hot off temperature, 95F +/- 5F.

5.3 Smart Appliances

An overview by (Ford et al., 2017) stated that smart appliances could save 12-20% of appliance energy in homes. However, most of the studies were for custom displays/interfaces developed for a particular study, rather than a commercially available device. Therefore, little is known about the contribution of commercially available load monitors and feedback functionalities of smart appliances to energy savings. Another study (Sastry et al., 2010) estimated much smaller savings of 3-6% for commercially available devices (smart refrigerator/freezers, clothes washers, clothes dryers, room air-conditioners, and dishwashers).

As residential billing for electricity moves away from flat rates to include time of use, peak demand charges and other time-varying electricity costs there is interest in developing controls for appliances to allow them to avoid times of high electricity cost. While some studies have investigated the effectiveness of these advanced controls (e.g., (Southern California Edison, 2012)).

A new "appliance" that is becoming more common is an energy monitoring display. These displays provide feedback to occupants that appliances in general do not. These devices are much more widespread in places like the UK that has an open market for electricity. Users can choose their providers, unlike the primarily monopoly system in the US, and use the ability of these devices to estimate costs using the various tariffs from different electricity suppliers to inform choices when choosing between different suppliers. In the US, this facility could be used by consumers to choose among different tariffs from their electricity suppliers. A study by (Hargreaves et al., 2010) showed that users were fascinated to learn about where energy goes

38 https://www.venmar.ca/224-accessories-air-exchangers-accessories-altitude-wall-control.html
39 https://www.venmar.ca/508-accessories-x-touch-wall-control-40455.html
40 http://www.airkinglimited.com/page/qfam-fresh-air-machine.html
41 http://www.buildequinox.com/cerv2/
42 http://www.broan.com/Fresh-Air-Systems/Supply-Fan/Fresh-In%E2%84%A2-Supply-Fan/FIN-180P#resources
43 https://www.ultra-aire.com/deh-30003000r/#health5c24-870a
44 https://www.aircycler.com/pages/tempguard

in their homes (i.e., a useful educational tool) but when asked to consider various curtailments (such as changing TV or cooking times), then there was significant resistance to change. The price range is large, from about $50 for the simplest whole house displays to several hundred dollars for systems that can monitor several sub-circuits and communicate with cellular devices using applications.

Overall, it does not appear that smart appliances will have a significant impact on energy savings however, they may be useful as part of grid integration to limit peak loads or respond to distress signals from the grid and as an educational tool for consumers. Smart grid integration needs to be limited to services that are invisible to occupants, or do not have direct immediate impacts (such as smart ventilation or water heater operation).

5.4 Combi-System Heat Pump

Heat pumps that combine the provision of domestic hot water with home heating offer an opportunity to potentially reduce the materials costs for DERs, particularly in homes that are already all-electric or are switching to have electric heat and DHW. To date almost all combi-system heat pumps have been installed as part of experimental programs to evaluate the technology and have been low global worming potential CO_2-based. These studies have found that controls design and operation are critical to good performance. Maintaining tank stratification is essential and strategies have been developed to ensure this. One way to achieve this is with a larger tank of 120 gallons, for example. However, this implies that a highly qualified and knowledgeable installer is required for these systems and that knowledge base does not exist in the current contractor market. More recent studies (Eklund and Banks, 2017) (Larson and Logsdon, 2017) have found that it is very important to correctly match the system capacity to the load. While in its infancy, combi-system heat pumps offer the potential for high thermal performance but current availability of both the equipment and knowledgeable contractors to install it limit its potential.

5.5 Low Global Warming Potential Heat Pumps

Compared to most other refrigerants, CO_2 has very low global warming potential (GWP). CO_2-based heat pumps are commonly available that have been proven to work well in all US climate zones (with the exception of Alaska) (Lubliner et al., 2016, 2015). This ability to work well at low ambient temperatures makes them a key resource for DERs in climates where previously a fossil fuel furnace or boiler were required. CO_2-based systems do have some potential drawbacks, e.g., they operate at much higher pressures than traditional systems, although this has not been shown to be problematic in practice. Other low GWP refrigerants are available, with a range of performance and safety characteristics. The cost to utilize these low GWP systems is currently unclear because they are rare and new to the residential market. Adoption of low GWP refrigerants varies greatly from state to state due to the EPA (currently) being disallowed from introducing federal regulation. The disallowed regulations are called SNAP 20 and 21, Table 41. The new proposal is the American Innovation and Manufacturing Act 2019.

However new federal legislation is being proposed that may smooth this transition to low GWP refrigerants.

Table 41 Adoption of low GWP refrigerants[45].

STATE	SNAP 20/21
California	SNAP 20/21 Plus GWP Limits
Colorado	SNAP 20/21 In process
Connecticut	SNAP 20/21 In process
Delaware	SNAP 20/21 In process
Hawaii	SNAP 20/21 In process
Illinois	No action on SNAP
Maine	SNAP 20/21 In process
Maryland	SNAP 20/21 In process
Massachusetts	SNAP 20/21 In process
Michigan	No action on SNAP
Minnesota	No action on SNAP
Montana	No action on SNAP
Nevada	No action on SNAP
New Jersey	SNAP 20/21 Legislation
New Mexico	No action on SNAP
New York	SNAP 20/21 In process
North Carolina	No action on SNAP
Oregon	SNAP 20/21 In process
Pennsylvania	No action on SNAP
Puerto Rico	No action on SNAP
Rhode Island	SNAP 20/21 In process
Vermont	SNAP 20/21 Legislation
Virginia	No action on SNAP
Washington	SNAP 20/21 Legislation
Wisconsin	No action on SNAP

5.6 Panelized Retrofit Assemblies

The ideas behind panelized retrofits are twofold: (1) To minimize disruption to building occupants by minimizing on-site time and applying the physical changes to the exterior of the home; and (2) Control costs and ensure good quality construction through factory assembly of major components.

The first mass-produced panelized efforts began several years ago in Europe. The Energiesprong approach (begun by the Netherlands government) has been applied to social housing and a number of buildings have been retrofitted. EnergieSprong includes financing, planning and contracting in addition to the panelized retrofit technologies. Recent partnerships are launching similar Energiesprong platforms in the U.K., France, and Germany. In the U.S., NYSERDA is partnered with Energiesprong in a program called RetrofitNY and has issued six pilot design projects for large multifamily buildings in New York using a panelized approach to retrofits. Rocky Mountain Institute's REALIZE[46] initiative has performed techno-economic feasibility studies in New York City and San Francisco, both of which proved the cost-effectiveness of the Energiesprong approach in a U.S. context. Also notable was the super-

45 https://www.ac-heatingconnect.com/contractors/move-low-gwp-alternatives-air-conditioning-underway/
46 https://rmi.org/our-work/buildings/realize/

insulation retrofit of the 192-unit, 1960s-era Castle Square apartments in Boston using pre-fabricated metal, super-insulated panels from Kingspan (Bertram, 2014).

Applications to date have focused on simple building geometries – such as low-rise multifamily row housing that is common in Europe. Emerging technologies include laser scanning of building exteriors to generate detailed three-dimensional maps of the building to be renovated that can be used directly in the manufacture of the new exterior envelope. A major technological challenge is to expand the applicability to single-family homes with their much more complex exterior envelopes.

Timber framed pre-fabricated envelope elements have been developed in Europe (Ochs et al., 2016) that integrate the new envelope with packages for: (1) ventilation and heating; (2) Water sewage and electricity, and 3. a thermal collector. These packages are currently undergoing pilot testing in several homes. The EnergieSprong approach is similar using pre-fabricated exteriors – sometimes with integrated heating equipment (see Section 3.7) that has successfully renovated thousands of dwellings.

In California a pilot program is under way in disadvantaged communities with a focus on multifamily buildings. This project called "REALIZE[47]" is led by the Rocky Mountain Institute and is being funded by California Energy Commission EPIC program and DOE's Building America program. REALIZE is inspired by Energysprong model, and combines demand aggregation, using a "zero over time" approach, and supply chain coordination to deploy high-quality, prefabricated mass-scale retrofit packages that are easy to install and are financed through utility cost savings.

The NYSERDA RetrofitNY program is funding six pilot studies for retrofitting multifamily buildings in New York. The initial design phase was complete in May 2019. Related to this, New York has developed Deep Energy Retrofit Planning Analysis (DERPA) reports that summarize current building energy use together with estimated savings from different packages (primarily for multi-family buildings), as shown in Figure 22. There is also a training/awareness element of these developments in New York through the "building energy exchange" that is providing educational resources[48].

[47] https://rmi.org/our-work/buildings/realize/
[48] https://be-exchange.org/

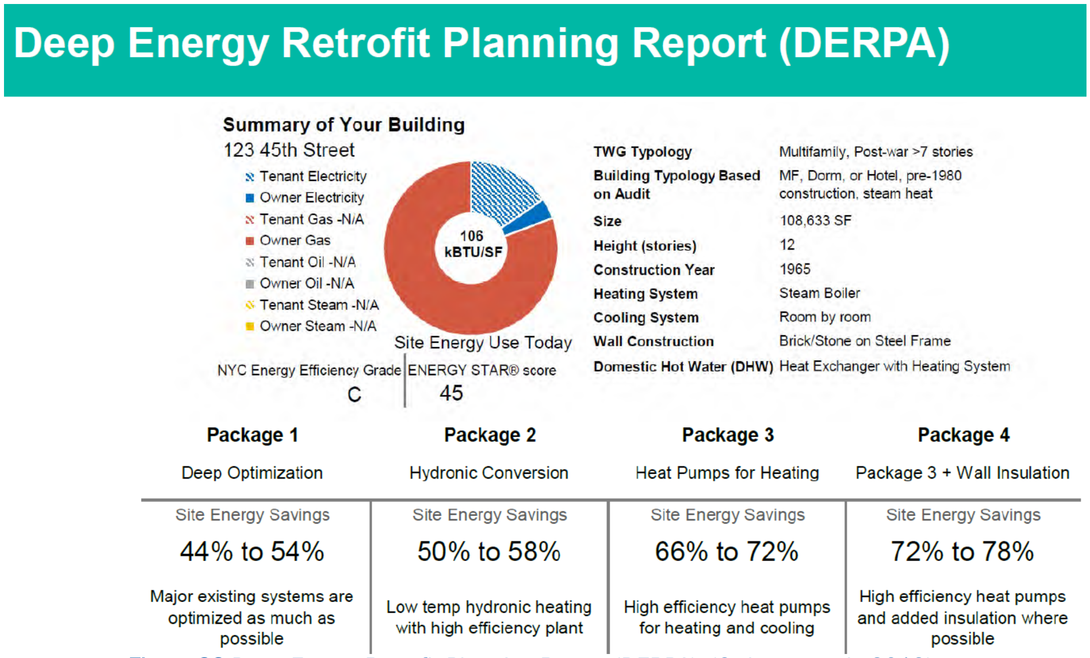


Figure 22 Deep Energy Retrofit Planning Report (DERPA), (Ordower et al., 2019)

5.7 Aerosol sealing

While the aerosol sealing technique has been used for 20 years for air sealing ducts, new applications are expanding this to envelope sealing. In new construction this has been shown to be effective, however, work needs to be done for retrofit applications. The biggest problem is that the interior of the home to be sealed needs to be filled with sticky aerosol particles. Some work has been done in apartments where all interior furnishing and household possessions were removed and remaining items such as kitchen/bathroom cabinets, carpets, electrical and plumbing services, lighting, etc. carefully covered to prevent contamination. While successful, this severe disruption and dwelling preparation requirements probably limit the application to unoccupied dwellings that are undergoing major renovation.

Practitioners are developing strategies regarding how best to use aerosol-based sealing to ensure the best results, e.g., at what stage in the construction process should the sealing take place and how to deal with the large leaks that the aerosol sealing system does not address (about 10mm (½ in.)) and perform cost-comparisons with traditional manual sealing efforts. The time required to seal leaks increases exponentially with the size of the leaks. Sealing larger leaks can be done but takes some considerable time (on the order of hours) (Harrington and Modera, 2012). While still a very new technology, Aerobarrier has the potential to be a key technique for builders when other methods are too costly or very tight envelope leakage (< 1 ACH50) is a target as demonstrated in (Bohac et al., 2007) (Bohac et al., 2018). There is also the potential to better seal unoccupied spaces such as crawlspaces where any residue is of less consequence.

5.8 Thin Triple Pane Windows

Thin triple-pane windows represent a path to much higher performance (R5 rather than R3, RSI 0.9 and 0.5, respectively) windows that can be installed in the same space as a traditional double-pane window. Thin triple pane windows use a middle pane that is much thinner than typical glass resulting in an assembly that offers the performance of triple pane window in a much thinner, lighter and lower-cost package (the same size as a traditional double-pane window). This makes for much easier installation – particularly in retrofits where a traditional triple pane window often requires the extra cost and effort of reframing the window opening to account of the larger dimensions and greater weight for the window. This could significantly reduce the installation costs in retrofit applications, but we have not been able to find any studies or information estimating these cost reductions. Work by LBNL[49] reports about a two-year longer payback for thin-triple windows compared to traditional double glazing.

(Hart et al., 2019) have used building simulations to show the energy savings potential of the thin-triple glazing in place of typical low-e windows in residential buildings is 16% in heating dominated climates such as Minneapolis, MN, 12% in mixed climates such as Washington DC, and 7% in cooling dominated climates such as Houston, TX.

5.9 Small Capacity Heat Pumps

Small capacity packaged unitary heat pumps are becoming available that are well-matched to the low loads in DERs and are easy to install due to their compact dimensions. These systems are usually designed for through-the-wall applications and appear to be very well suited for retrofits of dwellings with wall furnaces or in dwellings currently using window-mounted air conditioners that are common in multifamily buildings, shows some example installations from Innova[50].

The US DOE Building America program has investigated installing high efficiency split system heat pumps without removing existing systems (Building America Case Study: Supplemental Ductless Mini-Split Heat Pump in the Hot Humid Climate[51]). This saves on the cost of system removal and allows for a less expensive new system installation. Controls are used such that the new high-performance system provides the majority of heating and cooling needs and the retained existing system only operates at times of highest load for a small fraction of the time. Another US DOE effort led by NREL[52] has developed lower-cost installation techniques for mini-split heat pumps that may lower the cost of installation – although primarily aimed at the packaged terminal air conditioning systems used in the multifamily and motels/hotel market.

[49] https://windows.lbl.gov/triple-glazing-thin-non-structural-center-glass
[50] https://www.innovaenergie.com/en/
[51] https://www.energy.gov/sites/prod/files/2016/02/f29/ba_case_study_65367.pdf
[52] https://www.ashrae.org/news/ashraejournal/new-technology

5.10 Solar Power and Energy Storage

The rapidly lowering costs of Solar PV and storage (both in electric batteries (e.g., Tesla Powerwall) and thermal storage (e.g., SunAmp)) are allowing greater flexibility and lower cost approaches to reducing the carbon footprint of home energy and being more responsive to grid needs. The ability to use stored energy at peak times to reduce grid loads is becoming increasingly valuable from a utility perspective, and this is likely to become even more critical for grid stability and reliability with trends towards more home electrification. Storage enables more direct use of on-site renewables, a key example being to use daytime solar energy to meet heating, cooling, DHW and lighting/plug loads at night, or in early morning hours. For utilities with time-of-use pricing, the use of battery or thermal storage can also be optimized to reduce consumer energy costs by preferentially storing energy during low-cost periods. This typically has associated benefits for carbon emissions from electricity generation and with grid performance. On-site generation and storage have the potential to make homes more resilient, for example if gas or electric supplies are curtailed due to grid failure or natural disasters. However, the systems to allow this to be done practically in homes are still under development and we did not find any studies examining performance of these systems for this application.

Thermal storage using phase-change materials is well-suited to retrofits for providing heating, cooling and DHW. The systems that have been developed in other countries (e.g., Sunamp in the UK) fit the thermal storage units, heat pump and heat exchangers in the same space as the original storage water tank. Large scale demonstration projects in about a thousand homes have shown the effectiveness of this technology even in the weak solar climate of the northern UK. One limiting factor is that the demonstrations have been in hydronically heated homes, rather than with the forced-air systems typical in the US and research is needed on how best to integrate into US housing using fan coils to replace furnaces. Sunamp[53] claim cost-parity with storage water heaters for their thermal storage system. Some research studies are currently under way or are proposed in the US to investigate the adaption of this technology to US homes.

Electric batteries are needed for non-thermal end uses such as lighting, cooking and plug loads. the estimated costs[54] for electric batteries range from $5,000 to $7,000+ and from $400 dollars per kilowatt hour (kWh) to $750/kWh. Note that these prices are only for the battery itself, not for the cost of installation or additional necessary equipment. The installed cost of a battery is closer to $11,000 to $18,000+, and $800/kWh to $1,300/kWh. As with many aspects of home energy retrofit ancillary and installation costs are a significant fraction of the total cost. Simply getting to very cheap battery components will not be sufficient for large scale adoption of this technology. Figure 23 from the Solar Energy Industries Research Association (SEIA) market analysis shows that storage is increasingly being paired with PV installations and this will continue to increase in the future.

[53] Sunamp. 2018. Optimising Electrical Systems via Smart Heat Batteries. https://www.sunamp.com/wp-content/uploads/2018/02/Sunamp-Optimising-Electrical-Systems-via-Smart-Heat-Batteries-PUBLIC.pdf
[54] https://www.energysage.com/solar/solar-energy-storage/what-do-solar-batteries-cost/

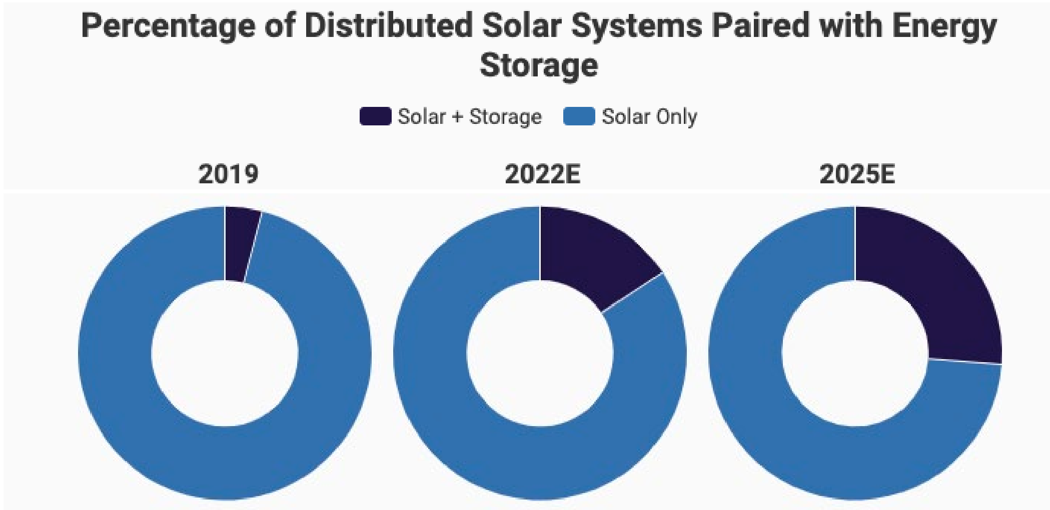


Figure 23 Fraction of home solar PV installations that include storage[55].

The cost to install residential PV continues to decline. With the decline in panel costs the soft costs are now dominant (see Figure 34). The US lags other countries in addressing these soft costs that include labor, permitting/inspection/interconnection, supply chain, customer acquisition and other overhead costs (Griffith et al., 2020). Despite these high soft costs, the overall lowering of PV costs has got to the point where PV is a very cost-effective way to reduce net energy use for a home, particularly when net of incentives. A lot of work has gone into analyzing the costs of PV installations – with detailed cost breakdowns that we will not go into in detail here. For further information see (Fu et al., 2018).

5.11 Ductless Heat Recovery

Lower cost and easier to install ductless heat recovery systems are coming to market that have been developed in Europe to provide HRV/ERV ventilation performance at lower costs[56,57]. Common brands are Twin-Fresh, Lunos, Blauberg, and Cyclone. These devices cost between $350 to $1000. The smaller single duct devices are usually designed to ventilate smaller spaces and two or three would be required for a typical single-family home. The lower cost simpler devices need only a single hole in an exterior wall and act as a supply ventilator half the time then reverse flow to act as an exhaust. During the exhaust phase, a ceramic heat exchanger is either heated or cooled (depending on the season) by the exhausted air. This heat exchanger then warms (or cools) the supply air when the direction of air flow is changed. Some of these devices some with sensors for moisture and CO_2 together with wireless applications and remote controls that allow the heat recovery function to be bypassed and used in exhaust-only mode to allow the user to remove odors from cooking, for example. A major advantage of these devices is that they are much simpler to install than normal HRV/ERVs – requiring only a single opening to outside and no complex ducting – making them much easier to use in retrofit applications. There are also larger 2-duct wall mounted ductless

[55] https://www.seia.org/solar-industry-research-data
[56] https://www.arttec.net/Mini_HRV/RA1-50-2_install.html
[57] https://vents-us.com/cat/704/

HRVs that are designed for whole house applications (and are recommended by the Passive Haus Institute) but are difficult to find in the US market. The low cost and ease of installation make these new devices an appealing new technology for home retrofits. Some technical information and videos are included in these links.

6 Advancements in Simulation Tools

While technical improvements to building energy simulation algorithms and calculation methods are still a topic of active research, most of the building physics is well understood and implemented in end-user tools for many years. As such, most simulation tools used in home energy analysis rely on existing/trusted simulation engines (e.g., use of SUNREL simulation engine in TREAT audit software), and the simulation algorithms and building physics are not the primary subject of innovation in industry. However, many energy calculation tools do not address fuel shifting, and there is a need to address this shortcoming if CO_2 emission goals are to be met.

Innovation is focused on making the tools more useful, fast and accurate to the end-users, including both auditors and program managers. This is occurring in a number of ways:

- **Design optimization in retrofits and new construction.** Older generations of home energy tools relied on user-specified efficiency measures and were executed in an uncoordinated and labor-intensive fashion. The most advanced current tools perform hundreds of simulations, designed to optimize energy use and cost of ownership. The BEopt simulation tool based on EnergyPlus and DOE-2 first implemented automated assessment of cost-optimal measure packages for new homes. The tool was later adapted for use in analysis of cost-optimal energy retrofits, including long-term cost of ownership analysis. This approach has also been included in the Ekotrope RESNET-approved HERS rating software for new home energy ratings. Package optimization is currently rare in most simulation tools used in home energy analysis.

- **Automatic model calibration methods.** A key method for improving predictions of energy savings from retrofits is to start by having a good model prediction of pre-retrofit performance. This is done by using pre-retrofit energy use data to calibrate the model. Model calibration adjusts building inputs (e.g., envelope thermal resistance, window surface area, etc.) until the predicted energy consumption is within acceptable range of measured usage. Manual adjustment is very time-consuming and requires costly expert input. Some tools on the market include automated calibration procedures. Despite industry criteria for considering a model "calibrated" (ANSI/BPI-2400), model calibration is an over-defined problem (meeting calibration criteria does not ensure the model is physically "correct", as there are many valid solutions), and there are a lack of standard methods, procedures and ways of assessing the calibration. Current research is developing and assessing methods of automated model calibration, such as AutoTune from ORNL, as well as comparing the performance of differing automated calibration methods.

- **Smart user wizards with flexible input levels and automatic error checks.** Engineering references for research grade simulation engines are generally far too detailed for a home energy auditor or rater. Lower-level user guides for simulation tools have otherwise been static documents, as have been the inputs required to build and run a model. The latest generation of auditor/rater tools are beginning to offer smart input wizards that not only interactively guide the user through the appropriate model specification path, but also allow for varying levels of user input. These tools claim to create the most accurate model from the information that is entered, while not being constrained to any but the most minimal of input requirements. The LBNL Home Energy Saver web-based tool has offered three levels of flexible inputs, and many newer generation auditing software platforms offer similar flexible input methods. These input wizards can also be used to perform automated model input checks (impossible or unlikely geometry, etc.) that improve the quality control/quality assurance of audits. However, there is little evidence that these features reduce time to model of home or improve accuracy.

- **Machine learning based approaches to simplify modeling.** Machine intelligence approaches are being investigated in the commercial buildings sector to determine the potential to improve accuracy of energy models and to reduce model generation time by identifying the parameters that are most important to accurate results.

- **User-flexibility in technology platforms (PC, laptop, smartphone, tablet, cloud-based).** The vast majority of home energy modeling tools have historically been implemented on an isolated personal computer by a single auditor or rater. Paper note taking, sketches and photos were later translated to simulation inputs after leaving the site. Web-based tools have generally been limited to less-comprehensive assessments. Many new assessment tools maintain PC options, while offering increased flexibility to use smart phones, tablets or cloud-based tools. These web-enabled tools allow the auditor/rater to populate some model entries in advance, some during an onsite inspection and others back in the office. While the convenience is obvious, it is not yet clear if these tools offer improved accuracy, reduced audit/model time/costs, or improved program outcomes. While not currently used in any tools we are aware of, cloud-based tools could allow leveraging of cloud-computing resources to increase the speed of parallel simulations required for advanced calibration or optimization approaches. This web-connection also could allow the population of model parameters from web-scraped data (e.g., MLS listing data, tax records, physical location for weather, etc.).

- **Enterprise integration with customer management platforms for job tracking, coordination, assessment and planning (e.g., SalesForce).** As noted above, many tools are now offering enterprise-level integration for customer and job tracking at scale. This can allow new levels of active program monitoring and management, as well as error checking, contractor monitoring, etc.

There are some remaining fundamental questions that impact real world accuracy and validity of energy simulations. Examples include:

- Infiltration heat recovery and infiltration/ventilation modeling in general.
- Modeling of uninsulated envelope elements, which can be strongly driven by model assumptions such as the impact of boundary layers on overall heat transfer (e.g., single-pane windows and empty wall cavities).
- Modeling of super-insulated building envelopes and their comfort systems.
- Accurate solar modeling of exterior building surfaces, such as roofing materials.
- Advanced building technologies, such as phase change materials, zoned HVAC systems, lighting controls, smart ventilation controls, etc.
- Treatment of occupant behavior patterns, which vary dramatically and can have outsized impacts on predicted energy use. A key question for utility programs is the difference between getting an individual house right (e.g., if making bill guarantees) and getting it right over the whole utility portfolio. In the first case occupant behavior can be significant, while in the latter much less so.
- Time of use pricing and carbon intensity of electricity
- Battery and thermal storage and integrating on-site generation/storage and grid dynamics.
- Modeling of buffer spaces, such as attics, crawlspaces and attached garages.

One recent advance in modeling practice is BeOpt-CA (a California-specific version of NREL's BeOpt tool) that includes energy efficiency demand response and on-site generation for retrofits. However, this is specific to California and requires development for other climates and utilities.

7 Surveys Assessing Deep Energy Retrofits and Home Performance

A survey performed as part of the same study as this literature review (W. R. Chan et al., 2021), showed that the people currently undertaking deep energy retrofits want tangible assets (e.g., green/sustainable attributes) that go beyond saving money and energy. The primary instance of this is solar PV, where older studies (e.g. (Hoen et al., 2013)) have shown significant increases in home value (on the order of $15,000 – or at least as much as the cost of the solar install). Similarly, a recent analysis from Zillow[58] on current (2020) trends shows a $10,000 average increase for solar PV in home values across the country – with big geographical variation. The added home value associated with different aspects of improved home energy performance needs to be revisited in the light of reduced solar costs and increased public interest in PV.

Numerous other surveys of contractors and participants have been carried out on the topics of home performance and home energy upgrades. We explore some of these in the sections below. We begin by highlighting the outcomes of a previous LBNL meta-analysis of the energy upgrade survey literature pre-dating 2010 (Section 7.1). Following that, we examine some more recent individual surveys/interviews in greater detail, starting with those addressing deep energy retrofits directly (Section 7.2 and 7.3), followed by those addressing home performance more generally (Section 7.4 through 7.6).

Overall, based on the surveys and interviews reviewed below, we offer the following general insights:

- Motivations to undertake an energy upgrade project are diverse, even amongst deep upgrade participants.
    - Energy cost savings are rarely the primary motivating factor.
    - Key motivators are comfort, health, aesthetics.
- High upfront costs are a key barrier. "Sticker shock" is very real.
- Most customers do not use financing even when it is offered.
- Rebates and incentives are considered important to spurring more investment.
- The majority of homeowners execute at least some of the recommendations from an energy audit.
- Information needs (e.g., what is an audit, what is a heat pump?) are still a major challenge in supporting the industry in executing projects.
- Diagnostic tests and audit procedures can contribute to increased perception of energy auditors as providing reliable information.

[58] https://www.zillow.com/research/solar-panels-house-sell-more-23798/

7.1 LBNL Meta-Review of Past Home Performance Surveys

A previous summary of surveys addressing home performance and energy upgrades was made by (Fuller et al., 2010). The following Sections 7.1.1 and 7.1.2 quote (in italics) directly from the Fuller report, because it provides a good summary of the issues, with a focus on what is needed for successful program design. We have broken the quotations down by topic area: (1) Marketing and outreach, and (2) Program design and implementation.

7.1.1 Marketing and Outreach

- ***It is not enough to provide information:*** *Programs must sell something people want. High home energy use is not currently a pressing issue for many people; find a more appealing draw such as health, comfort, energy security, competition, or community engagement to attract interest.*
- ***Time spent studying the target population is important:*** *A blanket marketing campaign to reach everyone will likely be ineffective and expensive, especially at the start of a program. Find and target early adopters. Tailor messages to this audience. Demographics can help segment the market and select optimal strategies, but you can also segment the market by personal values, interest in hot issues such as health concerns, or likelihood of getting savings.*
- ***Partner with trusted messengers:*** *Larger subsidies and more voluminous mailings don't necessarily win over more customers. Programs can and should have a local face, with buy-in from community leaders. Tapping trusted parties, such as local leaders and local organizations, builds upon existing relationships and networks.*
- ***Language is powerful:*** *Avoid meaningless or negatively-associated words like "retrofit" and "audit". Use words and ways of communicating that tap into customers' existing mental frames. Encourage program staff and contractors to use specific vivid examples, personalize the material wherever possible, frame statements in terms of loss rather than gain, and induce a public commitment from the homeowners.*
- ***Contractors are program ambassadors:*** *Contractors, more than any other party, are the people sitting across the kitchen counter making the final sales pitch to a homeowner—contractors are often the public face and primary sales force for the program. Most programs that succeed in performing a significant number of energy upgrades have worked closely with contractors. Conversely, poor first impressions or shoddy work by contractors can reflect poorly on the program.*
- ***One touch is not enough****: The advertising industry's "three-times convincer" concept means that the majority of people need to be exposed to a product message at least three times before they buy into it. Energy efficiency is an especially tough product. It can be expensive and can't be readily touched, tasted, or seen, and that calls for a layered marketing and outreach approach that achieves multiple touches on potential participants.*

7.1.2 Program Design and Implementation

- ***Make it easy, make it fast***: *Offer seamless, streamlined services—package incentives, minimize paperwork, and pre-approve contractors—give people fewer reasons to decide against home improvements by making it simple.*
- ***Contractors should be full partners***: *Contractors are the key point of sale for home energy improvements. They already understand the traditional renovation and home improvement market and have access to customers who may initially want to replace a furnace but may be open to other improvements. It's imperative to design a program that contractors want to sell—and convince them that the opportunity is worth the time and money to get the appropriate training and equipment.*
- ***Rebates, financing and other incentives do matter***: *Program experience shows that incentives do motivate the choice to do home upgrades and can be extremely important to get a program off the ground.*
- ***A well-qualified workforce and trustworthy work are vital***: *Promoting a program aggressively before contractors can handle the workload can lead to disgruntled customers. Solid performance builds trust with customers by reliably producing energy savings, as well as the health, safety, and comfort benefits of home energy improvements.*
- ***Persistence and consistency are valuable***: *It takes time for partnerships to take root, for word to reach consumers, and for contractors to respond to the opportunity. Consistent programs that last for more than a year or two can create a more robust market for home energy improvements; ephemeral programs can undermine trust.*
- ***Know success and failure by measuring it, and experiment to figure out what works***: *Designing for data collection and evaluation at the start allows for mid-stream adjustments, better selection among strategies, and knowing success when it arrives. It is important to pilot strategies before launching full-scale programs and to test a variety of strategies to learn what works.*

7.2 East Tennessee DER Homeowner Interviews

ORNL conducted a study on residential energy retrofits in the mixed-humid climate of East Tennessee (P. Boudreaux et al., 2012; P. R. Boudreaux et al., 2012) by selecting 10 homes and guiding the homeowners in the energy retrofit process. Homeowners were entirely responsible for funding the energy upgrade work. The predicted and actual energy performance was tracked in detail, along with the specifications and costs for each project. The study aimed to understand through a series of homeowner interviews why they decided to partake in energy retrofits, how much energy these whole house retrofits saved, and if the retrofits were cost-effective. The interpretation of the interviews is explored in a paper dedicated to that topic (Wolfe and Hendrick, 2012).

Overall, the upfront costs were a significant barrier to implementing DER projects, and the willingness to invest in energy efficiency was highly variable. Many participants experienced a strong sense of "sticker shock" when working with contractors to quote out their project work scopes. While project costs were a primary concern, the energy bill savings were not the main driver to carry out an upgrade project. Motivating factors were variable, and often included improved comfort, IAQ, sustainability, and even doing one's patriotic duty. The quality of the work executed by contractors was also highly variable, which impacted the potential energy savings of some projects.

Wolfe and Hendrick (2012) summarize the participant interviews. They acknowledge important points, namely that homeowner actions do not follow directly from either the existence of energy efficiency technologies, nor from the ability to achieve large savings. Other motivating factors are required, and they interview process worked to not pre-assume that users were driven by energy savings, costs or payback periods. The intent was to leave open the likelihood that comfort, aesthetics, environmental ethos, and other factors might be just as (or even more) important than energy savings. It left open why homeowners performed DERs, and why they chose certain project elements/technologies over others. The authors also highlight that the interview cohort is a small, atypical group that paid $10,000-20,000 for their DER projects, which were otherwise supported and monitored by ORNL. Homes were typical, though very inefficient before upgrades. The interviews were targeted at addressing three critical questions:

- What affects homeowner's decisions?
- What do homeowners experience during the retrofit life-cycle?
- What do homeowners recommend for other homeowners, contractors and utilities/government agencies?

Wolfe and Hendrick conducted a series of three interviews with retrofit homeowners, each using semi-structured interview protocols:

- Shortly after receiving recommendations for energy efficient measures (why did they participate at all, and what did they consider when assessing the list of recommended measures).
- Shortly after installation of the energy efficient measures (tap homeowner thoughts about the retrofit process—effects on daily life, expectations met/not met, etc.).
- Approximately 1-year after retrofit completion. Assess how the retrofit was performing, any behavioral changes that had emerged, etc.

They noted remarkable variation even within the small group of motivated and financially capable participants. They grouped participants into three categories, based on their decision to install:

- **All recommended measures:**
    - 5 / 11 participants implemented comprehensive multi-system DERs. Two were already planning to renovate, and decided to add on DER. Two said project goals were consistent with their personal goals (e.g., living a greener lifestyle, patriotic duty, have a model home for energy efficiency).

- Unbiased expertise was a major motivating factor, particularly involvement of ORNL. This expertise also raised homeowner expectations for the retrofits.
- Expected increased savings and energy efficiency.
- Experiences with auditors were positive, particularly for the ORNL recommendations.
- Interactions with contractors were mixed. 3 reported negative contractor experiences, ranging from bad cost estimates, bad equipment settings, and poor clean up. One case reported mixed results even from different crews from the same contractor.
- All owners expressed satisfaction with the results, with noticeable energy savings and improved comfort.
- No reported behavior changes resulting from retrofit.
  - Four homeowners recommended careful researching of a reliable contractor for the work. Two owners suggested working in small steps and tackling issues as they arise. One suggested adding 20% to the budget for incidentals.

- Some recommended measures:
  - 3 / 11 homeowners.
  - Two said finances led to installation of only some measures. One owner spent nearly $20,000, but just ran out of money to finish. Another was worried about payback and how long they would be in the dwelling. Third homeowner simply installed measures until they felt they had met their personal and project needs/goals.
  - Some owners used an informal cost-benefit approach in their heads. This varied from a spreadsheet to a more casual assessment of whether something was "worth it". Sometimes past experience with the home mediated these judgments (e.g., owner thought basement was not drafty, so declined to insulate basement walls).
  - Many owners engaged in their own research about the recommended measures, sometimes adjusting recommendations to their liking (e.g., from GSHP to an ASHP, or from HPDHW to tankless gas DHW).
  - One owner thought the DER aligned with their existing renovation plans, another wanted improved IAQ, and a 3rd was driven by the availability of expert advice.
  - 2/3 were pleased with the projects.
  - All three recommended that homeowners should carefully research any energy efficiency recommendations they receive. They cautioned about the source of information, and wariness about recommendations without diagnostic tests. Also, be prepared for "sticker shock".

- No recommended measures:
  - One owner got 8 contractor bids and felt they were all unfair and unreasonable, so decided to do nothing, particularly when they were unconvinced about efficiency measure efficacy.
  - One planned to implement DER measures as part of larger historical preservation project, which would be implemented in the future.

- One was part of a national park complex and did not have adequate funds for the work.
- All three owners expressed positive interactions with auditors and felt that the list of recommended measures were good.
- Recommend carefully researching contractors, with one owner saying the mark-ups are huge, and warned to be prepared “for your jaw to drop”.

Multiple motivations were always present, including energy savings (most commonly), sometimes energy cost savings, but also comfort, health, green, patriotic duty, etc. May need to distinguish between motivations vs. catalysts to action. Some owners perceived relatively large energy efficiency investments as “small elements” in otherwise massive costly renovations of their homes. When framed as marginal costs, these have less “sticker shock”. Access to expert guidance was also a catalyst to action mentioned by all participants. Expert involvement boosted confidence in the project and positive perception of the results. All owners were motivated to save energy, yet some did all and some did none of the work. Two owners were motivated by historic preservation, which again led one owner to implement many measures and another to do nothing. Other important factors were pre-existing remodeling plans, desired comfort levels, and IAQ concerns.

Information did not solve all problems. Three owners got as much information as anyone could ever expect, yet they installed no measures. They needed something more. One needed help with contractors, and another needed more time to plan. Sometimes they needed more guidance on measure implementation and contractor management/interaction. Contractor performance and experience varied, though was mostly positive, but all groups of homeowners consider contractor costs to be high. Overall, owners were satisfied with the process.

Homeowner advice. All types of homeowners suggested careful researching of contractors in their area. Also recommended researching the energy efficiency measures, to have better understanding of what is happening, what contractors should be doing, etc. For contractors, the owners recommended getting educated on energy efficiency, and getting certifications to provide distinction from other contractors with no expertise. They had difficulty distinguishing knowledge contractors from ignorant ones. The homeowners said utility involvement would give credibility to retrofit programs that would be meaningful to them.

Recommendations. Authors recommend framing DERs are marginal investment during otherwise larger remodeling projects. Non-energy benefits were commonly discussed, including comfort, IAQ, patriotism and being ‘green’. None of the homeowners reported changes in behavior, so behavior change does not happen automatically, potentially behavior-oriented programs could be leveraged alongside DERs. The authors recommend study with a large number of participating contractors, to learn about their attitudes, beliefs and knowledge about energy efficiency.

7.3 RESNET Deep Energy Retrofit Industry Stakeholder Survey Results

The RESNET Deep Retrofit Industry Stakeholder Survey (McIlvaine et al., 2013) was conducted shortly after launching of the EnergySmart Home Performance Team program. The survey asked EnergySmart Team members and outside stakeholders questions about market and technical barriers in performing home energy retrofits. The survey was focused on DER, including barriers to working in existing homes and was answered by 702 participants.

The survey asked about the greatest financial/marketing barriers the participants have discovered with home energy retrofits of existing homes. 81% responded that lack of consumer awareness what the greatest barrier, followed by lack of affordable financing for consumers (53.2%), lack of government policy (29.5%), and finding other trained contractors/raters (22.6%). In their written comments, many survey respondents also noted that the high costs of retrofit paired with low energy prices is a substantial market barrier. On the other hand, the greatest technical barrier for the participants was certain housing characteristics that prevent effective retrofit (57.3%), followed by energy analysis software inaccuracy or limitations (44.5%), and access to utility bills and combining them with energy analysis (30.3%). Their choices for technical barriers were reflective of the energy rater/auditor role played by the majority (78%) of the survey respondents.

The majority of participants (77%) were auditors/raters, with 12% trade contractors, and about 9% general contractors. Over 25% of the participants had project costs <$1,000, and only 10% had projects >$10,000. It is noted that 59.7% confirmed that their clients contact them through the website, 30.4% through the utility list and 5.6% used the newspaper. However, 26% of the respondents were not involved with home energy retrofit work, mainly because of low profits, hard work. Nevertheless, about 55% of them were interested in becoming involved.

About 66% of the survey participants were involved in private home energy retrofit work, followed by Home Performance with ENERGY STAR (55.6%), utility (53%) and local government program (43.8%). However, 69.9% of the respondents were involved as consultant or independent assessor, 28.2% as a general contractor, 25.9% as a trade contractor, and 33.5% as whole house energy upgrade contractor. Most of the respondents followed various standardized procedures for performing the retrofits, with 69.5% followed BPI as a standard for retrofits, followed by RESNET (Energy Smart Contractor) (48.4%), and industry quality installation (22.4%). About half of the respondents always do the initial home assessment as well as quality assurance post-retrofit. In addition, the participants considered that quality assurance is very important to consumers and program sponsors.

7.4 Efficiency Vermont Home Performance

7.4.1 Efficiency Vermont Home Performance with Energy Star[59]

Nationally, all Home Performance with ENERGY STAR (HPwES) programs are designed to ensure a comprehensive, whole-house approach to energy efficiency and maximize long-term savings for homeowners. The market-based program structure is designed to increase the number of contractors with advanced building science skills, while simultaneously connecting them with customers who want to complete projects in their homes.

The state of Vermont had a goal is to weatherize 80,000 dwellings by 2020. In support of this goal, a survey was conducted to assess the factors that motivated participation in Efficiency Vermont's HPwES program, from 2011 to 2013 (Gamble, 2014). The primary research questions explored by Gamble were:

- What factors motivated customers to initiate and carry out a home retrofit?
- How did these factors influence the programs development/growth?
- What are the best options to cost-effectively increase project completion rates, while keeping the market-based program structure?
- What other program opportunities exist?

Outcomes:

- Incentives are the single most important factor in converting energy audits into project completions. Other factors affecting project conversion from audit to energy upgrade are shown in Figure 24.
- The dual roles that contractors play in both performing and selling the work are key to building long-term customer demand for retrofits — and maintaining a program that is cost effective to operate.
- Identified a strong correlation between statewide marketing and customer interest in thermal efficiency. The 2012 decision to stop all marketing had a reverberating negative impact, which lasted well into 2013.
- Annual project completion increased 377% from 2008 to 2013. Efficiency Vermont estimates that the building performance industry now supports more than 170 jobs and annual revenues of $40 million in the state. In 2008, when the Legislature set its retrofit goal, roughly 300 projects were completed under Efficiency Vermont's HPwES program, by 2013, annual completions had nearly quadrupled, to 1,165.
- High project costs are the most important deterrent. In recent market research, 65% of respondents who had not completed a comprehensive energy efficiency project in their homes identified 'project costs' as the reason they had not yet taken action.
- Incentives have been capped at a maximum of $2,000 since June 2012, when program uptake was increasing, and there were strong concerns that Efficiency Vermont would not have the resources to fairly and predictably meet customer demand.

[59] https://www.efficiencyvermont.com/news-blog/whitepapers/efficiency-vermont-s-home-performance-with-energy-star-sup-reg-sup-program-report-and-analysis

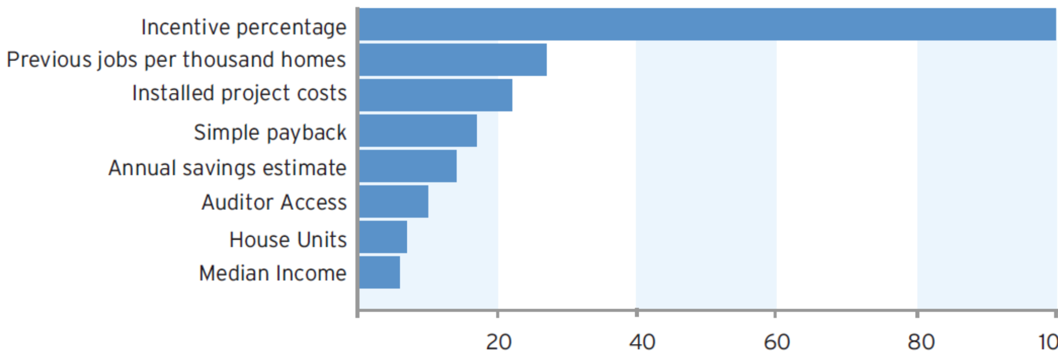


Figure 24 Relative importance of factors in converting audits to completed projects, (Gamble, 2014). The strongest factor is set at 100 and all other factors are weighed against it to show their relative influence.

7.4.2 Efficiency Vermont, the Benefits of Home Performance with Energy Star[60]

According to (Malmgren and Capps, 2018), the Home Performance with ENERGY STAR energy upgrade process has been supported by Efficiency Vermont in more than 7,000 VT homes. Energy Vermont surveyed a sample of 318 qualifying HPwES customers. The results shed light on the non-energy benefits the customers experienced as a result of their energy efficiency investments, and how they valued those benefits.

The results from the Efficiency Vermont survey highlighted that cost savings and energy reduction were leading factors in the customers' decision to participate in HPwES program. Aside from these motivators, respondents cited improved comfort as the most significant benefit from efficiency improvements. Collectively, survey respondents valued non-energy benefits from their efficiency projects as being even more valuable than their energy savings. Moreover, the survey revealed that participants valued combined non-energy benefits at 150% of the value of energy cost savings; that is, energy cost savings accounted for only 40% of the total perceived value of participants' home improvements, while the combined non-energy benefits accounted for the other 60%. The authors had initially hypothesized that the value of non-energy benefits would nearly equal the value of energy savings, but they underestimated the full value of thermal comfort to energy efficiency program participants in Vermont. As HPwES is a nationally recognized market rate efficiency and weatherization program, the results of this research in Vermont could be applied in other locations offering the HPwES program.

7.5 Energy Upgrade California Surveys

The Energy Upgrade California – Home Upgrade Program (HUP) and Advanced Home Upgrade Program (AHUP) are single-family residential energy efficiency programs operated by PG&E, SCE, SCG, and SDG&E. These programs are discussed in greater detail in Section 2.4.2. HUP

[60] https://www.efficiencyvermont.com/news-blog/whitepapers/non-energy-benefits-of-efficiency-vermont-s-home-performance-with-energy-star-program

promotes long-term energy savings in single-family dwellings through comprehensive energy efficiency retrofit measures. The program seeks to transform the single-family retrofit market from one of discrete appliances and shell upgrades to a comprehensive building system approach. This includes bundling building shell upgrades such as attic, wall, and floor insulation, windows, high-efficiency HVAC units, hot water heating, and other deep energy savings opportunities. The HUP is considered one statewide program. The program operates in all 52 counties and spans 16 climate zones throughout California. The structure and offerings of the HUP have evolved since the program's introduction in 2010. The program was implemented by investor-owned utilities (IOUs) and regional area networks (RENs).

(DNV GL, 2017) conducted a study which assessed the energy impact of the 2015 HUP for the California Public Utilities Commission (CPUC). The purpose of this study was to: (1) Verify the gross and net savings reported for both programs; and (2) Gain insight about program activity and participants.

The study conducted a survey whose data provide information to identify and understand any trends observed in the results from factors outside the program. The survey divided participating households into three segments based on their level of energy savings: Savers, Inerts and Gainers. The study conducted an on-line survey from November 2016 through February 2017, with participants in the 2013-15 cycle of HUP and AHUP.

The survey concluded the following:

- Savers (top-performing households) used financing for their projects in significantly higher proportions than the Gainers (49% vs 30%).
- Gainers (92%) reported experiencing home comfort at a higher rate than Inerts (81%) and Savers (81%).
- A higher proportion of Savers (71%) live in homes built before the 1980s compared to Gainers (57%).
- Inerts and Savers (27%) acknowledged that their contractor mentioned improved safety of HVAC.

Overall, these findings suggest that financing can help support projects with greater energy savings (an insight supported by analysis of the BBNP programs, see Section 2.4.1.1). They also support the relatively intuitive idea that most households report improved thermal comfort following energy upgrade work, but this effect is particularly strong in households that increased energy consumption, possibly due to inadequate heating/cooling pre-upgrade.

(EMI Consulting, 2016) conducted another study focused on the programs run by PG&E, SCG, SCE, and SDG&E. The IOUs coordinate to ensure key processes were consistent across the state. The EMI Consulting and Tetra Tech process evaluation of the HUP began in January 2015 and concluded mid-year 2016. This evaluation focuses on the 2014-2015 program years.

The study conducted 400 Computer-Assisted Telephone Interviewing (CATI) telephone surveys of program participants and near-participants between February 15 and March 11, 2016. The aims of the survey were:

- Identify how program participants and near-participants became aware of the program.
- Identify program participants' motivations for participating.
- Assess participants' satisfaction with the program.
- Examine participants' perceptions of the program's energy and non-energy benefits.
- Identify near-participants' barriers to participating in the program.
- Solicit suggestions for improving the program.

In addition, the study conducted 27 qualitative in-depth telephone interviews with participating and non-participating California contractors between November 10, 2015 and February 29, 2016. The aim of the survey was the following:

- Identify key drivers for contractor participation.
- Identify key barriers to increased contractor participation.
- Assess the program's administrative burden on contractors.
- Assess the effectiveness of contractor training and mentorship offerings on installation quality.

Some of the key findings from the survey are:

Participants:

- Across IOUs, participants were very satisfied with the HUP and AHUP.
- Saving money and improving comfort continue to be the primary customer motivations for completing Home Upgrade projects.
- High project costs were the primary barriers among near-participants, particularly among lower-income brackets. Participants with incomes under $50,000 reported that the cost of equipment was a barrier to their participation in the program, while only 28% of the participants with incomes above $250,000 reported the cost of equipment as barrier. The high first cost barrier may continue to present attribution-related cost-effectiveness concerns as participants with higher incomes that can afford expensive whole-home retrofits continue to participate in the program without the need for financial incentives.
- Most participants are relying on financing options to complete Home Upgrade projects.

Contractors:

- Contractors need improved program support, particularly in terms of marketing and mentorship.
- Contractors are increasingly proactive in engaging customers. 46% of participants reported that they became aware of the program through contractors.
- Non-participating contractors do not see energy efficiency as cost-effective and misunderstand program participation requirements.

- The program has improved on many of the issues identified in previous evaluations. Contractors, in particular, were generally pleased with changes to the program, namely the increased incentive limits and simplified Home Upgrade pathway point system.

7.6 Resources for the Future Surveys of Contractors and Homeowners

Earlier in the 2010's, Resources for the Future (RFF) implemented a number of surveys aimed at addressing current offerings and opportunities in the home performance energy upgrade industry. They executed and reported on surveys of both contractors/energy professionals (Section 7.6.1) and homeowners (Section 7.6.2 and 7.6.3). Overall, they concluded that many homeowners still are not aware of energy audits, but when audits are provided, the majority of homeowners implement at least some of the recommendations. High upfront costs, low energy cost and associated low predicted savings are still major limitations from the contractors' perspective.

The Resources for the Future (RFF) Home Energy Audit and Retrofit Survey was conducted in 2011 (Palmer et al., 2013) by recruiting energy auditors and retrofit installers through members of Efficiency First and Building Performance Institute (BPI) accredited contractors. The survey asked about the business and services that respondents provide, how often homeowners follow their recommendations to retrofit their homes, and the respondents' opinion on barriers faced by the industry. The survey found that not enough homeowners know about energy audits, but more importantly, it is the high cost of retrofits compared to low energy prices that is responsible for few energy audits and retrofits being completed.

7.6.1 Assessing the Energy- Efficiency Information Gap: Results from a Survey of Home Energy Auditors

A study conducted by (Palmer et al., 2013), reported the results of a survey of 459 home energy auditors and contractors that Resources for the Future conducted in summer 2011. The survey asked about the characteristics of these businesses and the services they provided, the degree to which homeowners follow up on their recommendations, and the respondents' opinions on barriers to home energy retrofits and the role for government. The study concluded that the industry believes it faces a litany of challenges going forward. The auditors who responded feel the public knows too little about them or does not trust their advice, while government incentives have not done enough to lower the costs of efficiency investments relative to the price of energy. At the same time, many auditors comment about threats to their industry from within, citing a lack of professionalism from their competitors or endless amounts of red tape resulting from interaction with government programs or certification requirements slowing their growth. Some additional detail is provided on the survey questions and responses below.

The characteristics of survey respondents show that nearly 50% of the respondents were energy-efficiency consultants/building analysts (49.4%), followed by general contractors (15.9%) and HVAC professionals (10.3%). The study also asked to the auditor about how often they performed standard audit practices. 91% of the respondents reported conducting blower door test fairly often or always (i.e., almost standard practice in the auditing industry). Other frequent activities included obtaining bills, computer modeling and infrared imagining. HERS rating was a less common audit practice.

In order to understand the types of information revealed in a typical audit, the study asked how often the auditors recommended homeowners make improvements or retrofits related to 15 commonly cited sources of potential inefficiency in building energy use (see Figure 25). Attic insulation, attic or other air sealing, and caulking and sealing of windows/doors were the most common cited sources. On the other hand, windows, doors and computers, TVs or other electronics were the least cited. The report also asked respondents to estimate approximately what share of customers pay for their improvements. As seen in Table 42, most homeowners pay for these investments with cash or check (57.6%). However, a study conducted by (Guerrero, 2003), estimated that almost 72% of general remodeling expenditures are covered by homeowner savings (including tax returns and gifts) or credit cards. These findings are notable, because even when financing is offered to support energy upgrade work, it is not frequently used by homeowners. This could be a substantial barrier to supporting widespread energy upgrades using emerging financing approaches (e.g., PACE or on-bill).

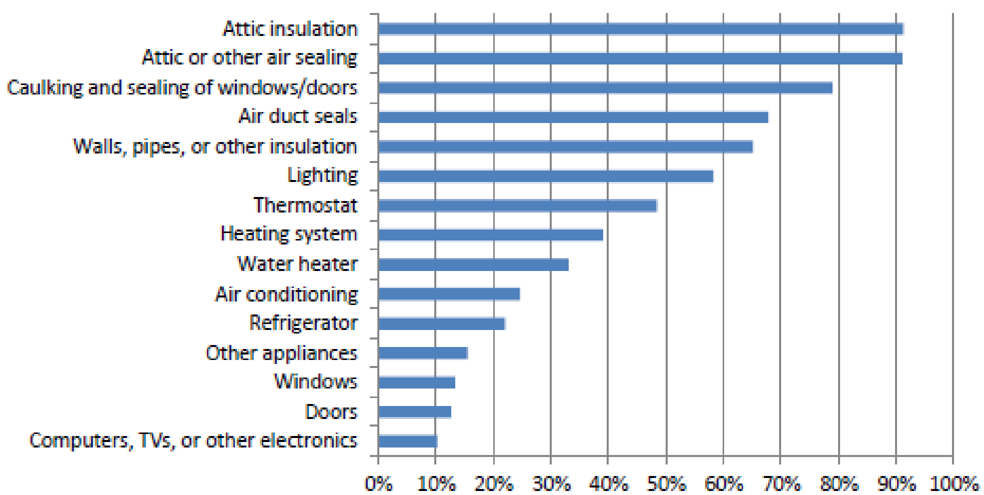


Figure 25 Percent of respondents who recommend selected improvements fairly often or always, (Palmer et al., 2011)

Table 42 How homeowners pay for retrofits (unweighted average across respondents).

Method of Payment	All Respondents (N=261)	Respondents who do not provide financing or act as gateway (%) (N=102)	Respondents who provide financing or act as a gateway to financing (%) (N=159)
Cash or check	57.6%	68.3%	50.7%
Credit card	14.1%	13.6%	14.2%
Energy-efficiency finance	17.3%	6.1%	24.4%
Home equity loan	6.5%	5.9%	6.8%
Other	4.5%	6.1%	3.6%
Total	**100%**	**100%**	**100%**

In addition, the study conducted by (Palmer et al., 2013) assessed the reasons homeowners make improvements (as reported by contractors). As seen in Figure 26, auditors see the most important motivator to be saving money on utility bills (72%), followed by low costs of improvements (66%), which suggests that the financial aspects of energy efficiency are of chief concern to homeowners in this cohort. The third most cited reason improvements are undertaken were other benefits provided by improvements (58%), which could include comfort, health, safety, etc. "Green" preferences and improvement of property values do not appear to be important factors in retrofit decisions as reported by these contractors.

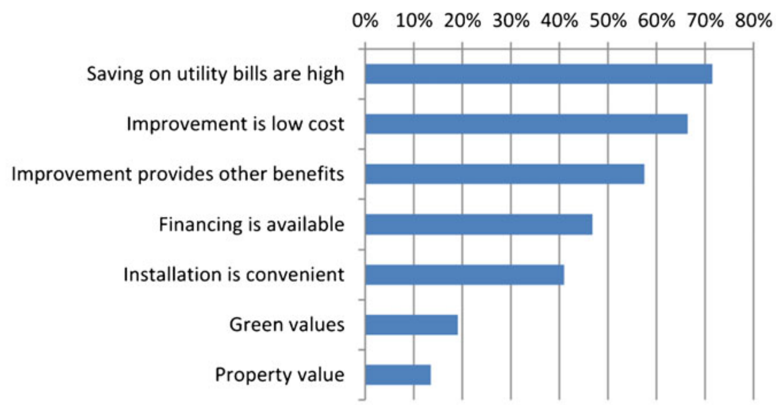


Figure 26 Reasons homeowners make improvements: percent responding "of major importance" or "critical issue", (Palmer et al., 2013)

The study also asked about the best way to improve increase the number of energy upgrades from the contractor's perspective. As seen in Figure 27, 54% of the respondents listed a higher price for energy as the most or second most important way to increase energy-efficiency retrofits, making it the highest-ranked option. Followed by "more government rebates and subsidies," with 49% of the respondents listing this as the second most important option. Few respondents reported that better access to financing was the most important way to increase retrofits. This confirms how few customers use financing when paying for retrofits, even in the case where specific programs are available.

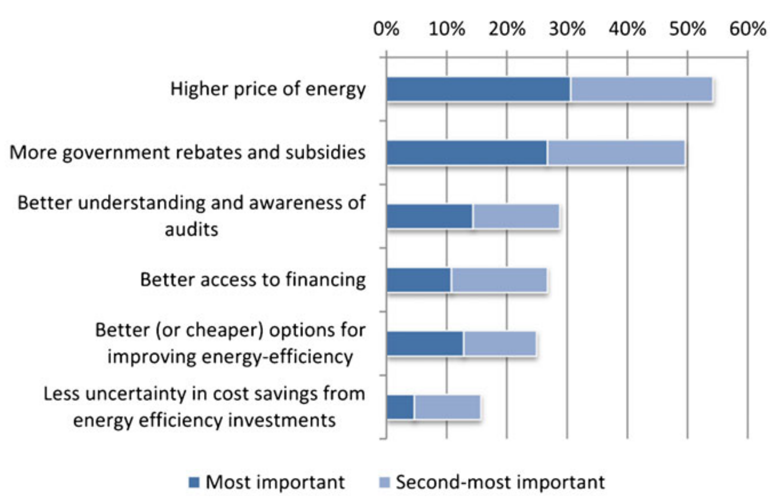


Figure 27 Best ways to increase adoption of home energy-efficiency improvements, (Palmer et al., 2013)

7.6.2 The Costs and Quality of Home Energy Audits: What Homeowners Say[61]

RFF in 2014 posted on their website the results of a series of homeowner surveys as part of their Energy Efficiency Information Initiative. The study surveyed 1,784 homeowners across 24 states to help address why consumers are not investing in energy upgrade measures that can pay for themselves and provide other benefits. A total of 566 respondents said they had an audit in the past four years, and roughly two-thirds of those were free to the homeowners. Of those who had not had an audit, 29% said they had "never heard of them" and 16% said that they "had heard of them but didn't know anything about them". Clearly, this lack of information on the part of homeowners is limiting the potential for energy upgrades to scale in the market.

The study asked the respondents who had audits about what the auditor's assessment included and how much the audit cost. The results are reproduced in Figure 28. Only about one-third of audits were reported to have included cost estimates for the recommended upgrades, and just under half provided estimates of potential energy savings. Other audit features were more common, including blower door testing, infrared imaging and energy bill analysis in about two-thirds of audits. Almost 80% of respondents reported that their auditor "personally showed them trouble spots", but only 26% were provided photos of the trouble spots. The study seems to suggest that many homeowners may be using auditors who are not BPI certified.

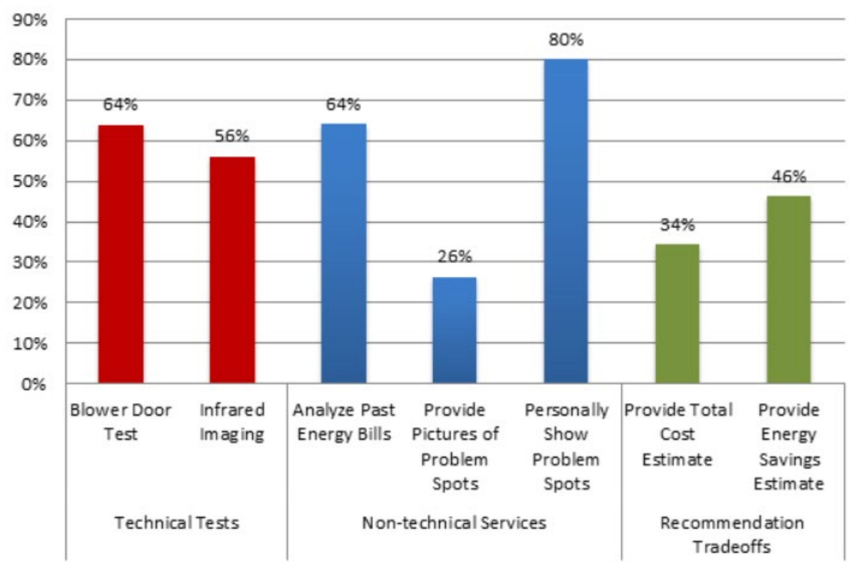


Figure 28 Percentage of people whose audits included these characteristics.

[61] https://www.resourcesmag.org/common-resources/the-costs-and-quality-of-home-energy-audits-what-homeowners-say/

7.6.3 Taking Advice: Do Homeowners Follow Up on Home Energy Audits?[62]

As a follow up to the homeowner survey addressing energy audits described in Section 7.6.2, RFF in 2014 posted results of a survey addressing if people followed their auditors' recommendations. At least some follow through on upgrade recommendations was reported in approximately 70-80% of homes, and the implementation rates were improved with higher-quality audit practices (e.g., blower door testing). Homeowner's generally trusted the information provided in energy audits, but their main barriers to implementing work were procrastination, low predicted savings and high upfront costs. The details of the survey are discussed further below.

The most common recommendations from home energy audits were to air seal (67%) and insulate (56%), followed by equipment upgrades (HVAC or hot water, 30%). While equipment upgrades were less frequently recommended, they were more commonly implemented when a recommendation was made (62%). Implementation of air sealing and insulation was more mixed. 41% of homeowners implemented all sealing and insulation work recommended, while smaller fractions did some of the recommended work (38% and 23% for sealing and insulation, respectively).

The frequency with which homeowners actually executed upgrade measures varied with the quality and features of the audit. Based on the obtained results, follow-up is higher when the audit includes special tests and services that are indicators of higher quality. For example, when the audit included a blower door test, 83% of households followed up on at least some air sealing recommendations and 75% followed up on insulation; without a blower door test, the percentages were 72% and just less than 50%, respectively. The auditor personally showing spots that needed improvement and providing an estimate of energy savings also aligned with similarly significant increases in both types of follow-up.

The survey asked about the main reasons people do not take their auditor's advice, and the key reasons were procrastination, insufficient savings, and high upfront costs. Procrastination seems to be the most important reason: nearly 50% of homeowners said the main reason for their failure to seal air gaps was that they "had not gotten around to it", with a slightly smaller percentage saying the same for insulation. Insufficient energy savings is the second most cited reason for failure to do air sealing, and both insufficient savings and high cost of improvements were equally cited as reasons for not adding insulation. Lack of trust in or disagreement with the auditor's recommendations was rarely selected as a reason for lack of follow-up. In addition, the results concluded that homeowners rated the quality of the information in their home energy audit with greater satisfaction.

[62] https://www.resourcesmag.org/common-resources/taking-advice-do-homeowners-follow-up-on-home-energy-audits/

8 Business Models, Gross Margins and Soft Costs in Home Performance

Topical reviews and industry surveys have highlighted the critical need for a well-trained home performance workforce and trusted local contractor networks, both to perform the work and to act as the key customer-facing agents selling the upgrades. The ability of companies offering home energy upgrades to thrive financially and with personal fulfillment for the owners/employees is critical to expanding the market for home upgrades. If this work is not profitable and enjoyable, the industry will not scale.

In this section, we review some of the potential business models for deploying home performance upgrade projects, including remodeling, HVAC, and home performance contractors, as well as big-box retail networks (Section 8.1). We then explore some of the business economics that impact energy upgrade contractors (e.g., gross margins, overhead and profit), and we compare energy upgrade companies against those in residential remodeling and other construction industries (Section 8.2). Finally, we outline the numerous soft costs associated with energy upgrade projects, some of which are unique to home performance work, and others that are shared with standard remodeling (Section 8.3). We explore some options for reducing those soft costs, such as customer acquisition or rapid HVAC sizing.

8.1 Business Models

The U.S. DOE's BBNP (discussed in Section 2.4.1), produced a detailed documentation of business models for the parties associated with whole home energy upgrade work, including Contractor/Retailer, Remodeling Contractor, HVAC Contractor, Home Performance Contractor, and Retailer business models (Better Buildings Neighborhood Program, 2012). For each of these business types, the report outlines the governance, financial model/structure, assets and infrastructure, service offerings, and customer acquisition/marketing. The report posits that the unique mix of these business model elements determines how actors in the Energy upgrade market will respond to incentives, regulations and fluctuations in the market. And also, it shows their capability to either grow their existing home energy upgrade services or expand into the energy efficiency upgrade market if they do not currently offer those services. The following sections (8.1.1 through 8.1.4) summarize the results of the BBNP.

8.1.1 Remodeling Contractor

The remodeler market is dominated by small companies where only 1% of total jobs are whole-home remodels. This is a very low number because few customers have the disposable income according to the BBNP (however, savings or access to capital and the fact that they are rarely offered by remodelers are likely also factors). Most of the remodelers are typically free to set prices and enter and exit new markets. The average which they operate are at around 45% gross profit (10% net of costs). Established firms generating more than $1 million in annual revenue are most likely to have the capacity to incorporate energy efficiency products and services into their businesses. Smaller firms typically do not generate enough cash flow to cover the cost of expanding their service offerings. Only 20% of remodelers currently offer home energy upgrade services, although an additional 40% are considering offering these services. 60% of remodelers are considering development of energy efficiency service. To generate revenues from home energy upgrades, remodelers may need to adjust their service offering strategy from longer, larger projects to shorter, higher-volume efficiency jobs. Based on the interviewed remodelers (Better Buildings Neighborhood Program, 2012) indicated they have about a 70 to 80% close rate on small jobs and only a 20% close rate on large jobs. Home energy upgrades are estimated to have about a 50% close rate when marketed by experienced home performance companies.

8.1.2 HVAC Contractor

An HVAC contractor is a specialized business model which is focused primarily around the installation, maintenance and repair of HVAC units. HVAC equipment is the largest energy user in a residential setting and it accounts for 54% of total residential site electricity use.

Due to the seasonality of the HVAC business, with the prime HVAC replacement and maintenance season lasting only seven months in many climates, HVAC contractors rely on lines of credit to cover their cash shortfalls. To maintain profitability, despite the seasonality of the industry, HVAC contractors rely on a pricing system for their jobs that builds in a high gross profit margin on equipment and that limits labor. The gross profit margin on equipment is approximately 45%, but the gross profit margin on labor is much lower. While material costs for a given type of job tend to be relatively consistent, labor costs are highly variable and drive down the overall profit margin on a job. Therefore, it is in the HVAC contractor's business model to generally limit the amount of labor hours on a job, focus on quickly completing the project, and move on to the next job. In general, HVAC contractors see home energy upgrade jobs as being more labor-intensive than traditional HVAC jobs and, therefore, less profitable. However, this thinking does not take seasonality into account. Home energy upgrade jobs can be done year-round, which could enable HVAC contractors to generate revenue and avoid using lines of credit to fund payroll and other fixed costs. Adding labor-intensive home energy upgrade services to a service mix primarily focused on material sales will require a shift in strategic thinking and may require additional sales training (from program administrators or manufacturers). Figure 29 shows a sample income statement for an HVAC contractor. The target operating income is approximately 12% for an HVAC contractor. This metric is calculated by dividing earnings before interest and tax by total revenues. Generally, 12% is a solid, average target that HVAC contractors will use as a measure of profitability when evaluating business opportunities. As seen in Figure 30, adding home energy upgrade services can allow an HVAC contractor to maintain its 12% target operating income margin while minimizing seasonality issues.

Sample Income Statement HVAC Contractor Year End 2011, $ Thousands	
REVENUES	
Sales	$2,000
Total Revenues	2,000
COST OF GOODS SOLD (COGS)	
Labor	220
Materials	740
Subcontractors	40
Others (Permits, etc.)	36
TOTAL COGS	**1,036**
GROSS PROFIT	**964**
OPERATING EXPENSES	
Marketing and Advertising	576
General and Administrative	144
Total Operating Expenses	720
OPERATING INCOME	**244**
OTHER EXPENSES	
Interest Expense	10
Total Other Expenses	10
NET INCOME BEFORE TAXES	**$234**

Variable costs that can be most influenced (Labor, Materials)

- Common profitability measure is gross margin per man-day: (revenue – COGS) ÷ average labor hours per day
- Target operating income/revenue is ~12% for general HVAC

Source: Industry interviews

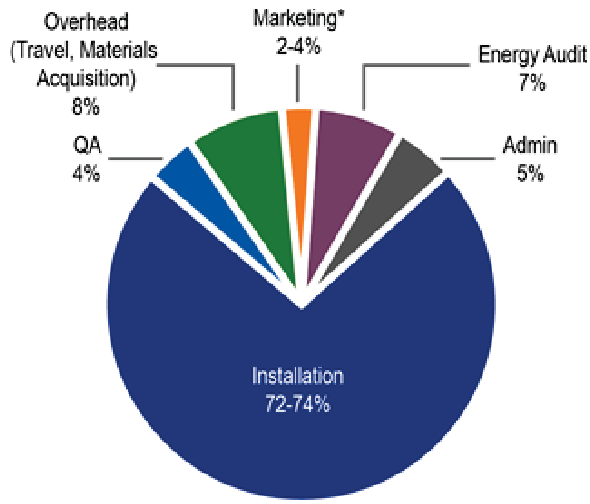
Figure 29 Sample HVAC Contractor Income Statement, (Better Buildings Neighborhood Program, 2012)

	Conventional HVAC Projects	Energy Efficiency Add-on Projects	Integrated Services
Jobs performed	670	60	730
Operable months	7	12	12
Total revenue	$2,000,000	$240,000	$2,240,000
Total expense	$1,760,000	$220,800	$1,971,200
Operating income	$240,000	$19,200	$268,800
Operating margin	12%	8%	12%

Figure 30 Sample job profitability analysis, (Better Buildings Neighborhood Program, 2012)

8.1.3 Home Performance Contractor

A home performance contractor is a company whose primary business is to deliver the full suite of home energy upgrade services to consumers directly. They have a dedicated business model that integrates all aspects of a home energy upgrade into one comprehensive service. Many home performance contractors that do not secure external funding to grow or work with an energy efficiency program administrator cannot grow beyond $1 to $3 million in revenue per year. For this reason, home performance contractors must develop an understanding of market demand and leverage partnership opportunities to reach their target revenue threshold and achieve sustainability for the business. Home performance contractors must continually examine their service offerings to identify ways to reduce associated labor costs and maximize their profit for each component of a home energy upgrade job, Figure 31.



Labor hours assumed equivalent % labor costs. $10,000 retrofit building size 2,500 ft^2.

Figure 31 Retrofit labor costs (by type), (Better Buildings Neighborhood Program, 2012)

8.1.4 Retailer

Retailers can be valuable partners in building a sustainable residential energy efficiency market. They have well-established brand names and central store locations that provide partner contractors and programs with credibility and better access to customers.

8.2 Gross Margins, Overhead and Profit in Residential Construction

The "gross margin" of a business is defined as the fraction of total sales revenue made up of business operations/overhead costs and profit. The remaining costs include equipment, materials and labor costs. High gross margins increase the cost of energy upgrade projects, because much of the revenue from each executed project is required to support new customer acquisition, industry training, specialized equipment, and traditional business expenses (e.g., marketing, office space). For smaller companies with fewer projects, these business costs can become particularly high relative to the actual labor and materials involved in construction works. Some have suggested that gross margins in home energy upgrade work are too high, substantially exceeding those of standard residential remodeling, due to the particular nature of home performance jobs (Andy Frank, personal communication, May 28, 2020). To assess these claims, we have examined the available literature describing typical gross margins in residential remodeling and construction, and we compare these against values reported from industry stakeholders in the LBNL Deep Energy Retrofit market survey (W. Chan et al., 2021). Typical values extracted from the literature are compared against the median values from the LBNL survey in Figure 32.

Overall, the gross margins reported by home performance professionals in the DER survey (median of 48%) are substantially higher than those for typical remodeling and construction. General contracting (commercial), construction services and renewable energy have the lowest margins (from roughly 10-25%), while standard residential remodeling gross margins are typically around 30-35%. Oddly enough, the DER survey data suggests that the primary difference between residential remodeling and home performance companies are that profit margins are higher in energy upgrade work, while business overhead is reported as only slightly higher. The soft costs that make up part of these overhead expenses are explored in more detail in Section 8.3. The sources of general construction and remodeling industry data are discussed in further detail below.

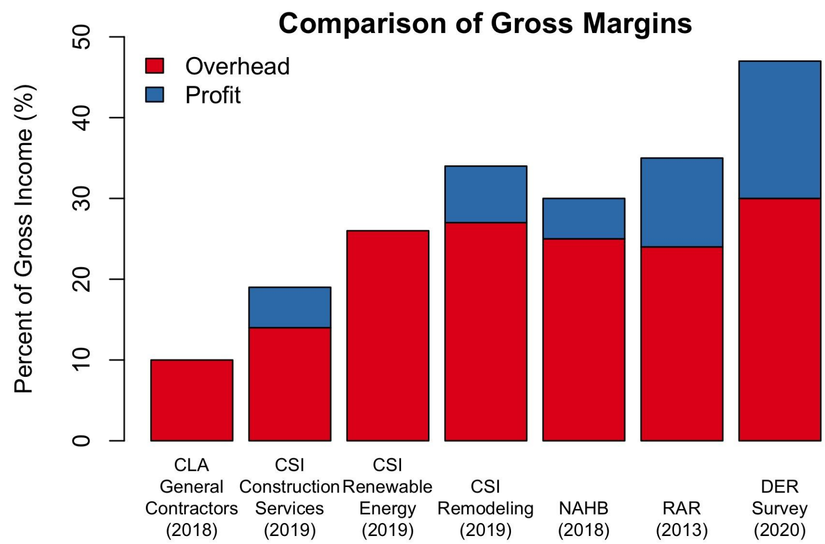


Figure 32 Comparison of gross margins in residential remodeling and energy upgrade works.

Table 43 Gross margins reported by CSI for construction services, home improvement and renewable energy. Source: (CSI Market, 2020)

	12-Month Trailing Gross Profit Margin (%)				
	2019, Q2	2019, Q1	2018, Q4	2018, Q3	2018, Q2
Construction Services Industry	18.1	18.4	18.2	19.6	19.6
Home Improvement	33.8	33.9	34.3	34.6	34.7
Renewable Energy Services and Equipment	25.9	20.4	26.4	25.9	24.7

The CSI Market provides business performance statistics across a variety of industries, including Construction Services Industry, Home Improvement and Renewable Energy Services and Equipment (CSI Market, 2020). The annualized gross margins for these three industries are shown in Table 43, from Q2 2019 to Q2 2018. Home Improvement gross margins were consistently 34% over this time period, while Construction Services and Renewable Energy companies maintained gross margins of roughly 18-19% and 20-26%, respectively. Over this same period, annualized net-margins (i.e., net-profits) for the Home Improvement industry averaged between 7 and 7.7%. Construction Services showed net-profits ranging from 4.8 to 6.4%, and Renewable Energy showed net-losses.

These gross margins from the construction services industry agree well with values reported by the 2018 CLA General Building construction Benchmark Report, which includes data from 229 contracting companies, including residential, commercial, industrial, multi-family, specialty and others (CLA, 2018; Jon Weston, 2019). General building contractors reported the lowest gross margins, averaging 10.1% in 2018, while civil, electrical/mechanical and specialty contractors reported averages of 16, 21.5 and 21.9%, respectively. The pie charts below, Figure 33 show the breakdown of revenue cost composition for general building contractors.

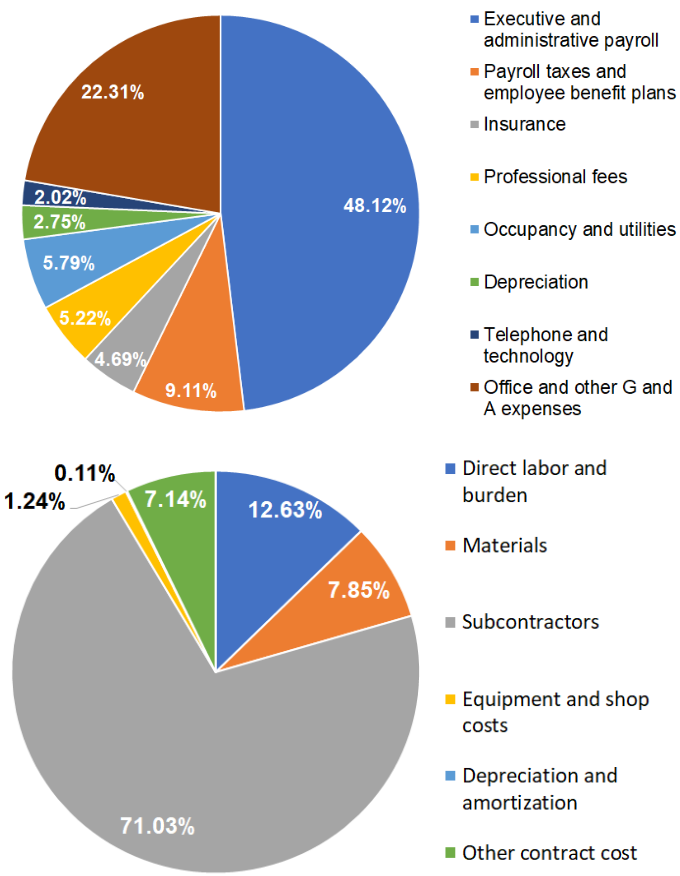


Figure 33 Revenue cost composition for general building contractors. Source: (CLA, 2018).

It is clear that within the larger construction industry, different business types have substantially different financials. In line with the reported values for home improvement above, the suggested margins vary from 34-42% for remodeling, 26-34% for specialty work, and 21-25% for new home construction (Stefan, 2020). In general, remodeling work entails higher gross margins than new construction. Some high-end remodeling companies actually design their business processes around maintaining much higher gross margins in the range of 40-60% (John Caulfield, 2005). These same companies also targeted higher than average net-profits. Below, we hone in on residential scale remodeling business financial summaries from the NAHB and Remodeling magazine.

In 2019, the National Association of Home Builders sent the Cost of Doing Business 2020 survey out to 3,700 remodeling contractors, and they got 60 responses including detailed business financials for calendar year 2018 (National Association of Home Builders, 2020). They summarize the business gross margins, net-profits and hard costs using the sample average, 25th and 75th percentile values based on the company's net-profit margin. "Top performing" contractors have the highest net-profit margins.

As shown in Table 44, the 2018 responses showed a remodeling industry average gross margin of 30.1%, which was marginally higher in the top 25% of respondents (31.4%) and marginally lower in the lowest quartile (29.8%). These differences were much starker in survey years 2011 and 2015, where high performing contractors had gross margins 8-12% higher than the lowest quartile. In 2018, the gross margins for general remodelers was 27.1% (22.2% overhead and 4.9% net profit; labor vs materials of 13.4 and 17.6%), while design-build remodelers had gross margins averaging 31.6% (26.2 and 5.4% overhead and net-profit; labor vs materials of 15.6 and 18.5%). Very little variability in gross margins and profit across US regions. The Gross margins have varied between 27 and 31% since 1993, operating expenses have varied from 22-25% over that same period, while net profits varied from 3-7%. Design-build remodelers finished an average of 53 jobs per year, while general remodelers finished 47. In general, top-performing remodelers completed fewer jobs, with similar numbers of jobs across a wide range of total project costs. The worst performing contractors did more jobs and nearly half of their work was jobs <$5,000.

Table 44 Gross margins, net-profits and hard costs for residential remodeling. Source: (National Association of Home Builders, 2020).

	Share of Total Revenue (%)		
	2011	**2015**	**2018**
Labor	13.5	15.3	14.8
Materials	19.8	18.4	18.4
Trades/Subs	28.8	25.9	28.7
Direct costs – commercial	2.5	2.1	0.6
Direct costs – single family	5.5	5.4	3.0
Other	3.2	3.9	4.5
Total Cost of Sales	73.2	71.1	69.9
Gross Margin	26.8	28.9	30.1
Operating Expenses			
Indirect Construction	3.4	5.2	3.6
Financing	0.6	0.2	0.2
Sales and marketing	3.2	2.2	3.2
General and administrative	10.5	10.6	12.6
Owner's compensation	6.1	5.5	5.3
Total Operating Expenses	23.7	23.6	24.8
Net Profit	3.0	5.3	5.2

A similar benchmarking effort of remodeling industry business performance was built using the Remodelers Advantage Roundtable (RAR) members in June of 2013 (Freed, 2013). This cohort of remodelers includes a group of top-performing remodeling companies for the year 2013 that "follow best practices and strive for professionalism in all aspects of their business". A similar effort was also done in 2011, and those results are sometimes presented for comparison. The cost of goods sold averages 65% in this cohort, and the gross margin of 35% is split between overhead (24%) and net-profit (11%). Owner's compensation totaled 18%.

The RAR member cohort also provided useful data on the number, cost and source of leads, prospects and contracted work over the previous 6-months (Table 45). In this group of businesses, an average of 152 raw leads were reported (134 in 2011), and 59% of these raw leads became new prospects, with a 35% closing ratio (construction contracts / new prospect meetings; 33% in 2011). Overall, this suggests a 21% closing ratio based on raw leads. These raw leads cost an average of $299 in 2011 and $220.45 in 2013, which translates to $425.30 per new qualified prospect, and $2,455.64 for each contracted sale. This cost per sale averaged only $1,116 in 2011. Oddly, if we take the $220.45 cost per lead in 2013 and assess this using the 21% closing ratio, we calculate a cost per contracted job of $1,050. It is not clear how to compare this with the reported $2,455. These costs to acquire a project for general remodeling are roughly in-line with the costs quoted from home performance professionals for energy upgrade job acquisition (see Section 8.3.2, with job acquisition costs of $700 to 1,200 from one source and $1,000 to 1,500 from another source). These averages apply to 24 construction contracts per over a 6-month period. Their overall marketing costs were 2.45% of revenue. Referral or repeat customers made up 51% of raw leads, with the remaining raw leads split between media advertising and web leads.

Table 45 Operations and marketing benchmarks for residential remodeling. Source: (Freed, 2013)

Operations Benchmarks	
These averages are from the top 25% of all Remodelers Advantage Roundtables members, as June 2013	
Owner's compensation	18%
On track to meet X% of budget	115%
Cost of goods sold	65%
Gross profit	35%
Overhead expenses	24%
Net profit	11%
Quick ratio	1.37
Current ratio	1.70
% of raw leads to new prospects	59%
Close ratio	35%
Construction contracts	24
On track to meet X% of budget	111%

Marketing Benchmarks		
Avg. for top 25% of Remodelers Advantage Roundtables members, over 6 months	**2011**	**2013**
Marketing budget as a % of revenue	2%	2.45%
Total number of raw leads	134	151.91
Proactive outbound sales calls	24	79.17
Referral/repeat customers as a % of raw leads	55%	50.73%
Media advertising leads	16	38.71
Internet/website leads	18	44.75
Close ratio (construction contracts/new prospect meetings)	33%	35.35%
Construction contracts	30	23.59
Cost per raw lead	$299	$220.45
Cost per new qualified prospect	$475	$425.30
Cost per sale	$1,116	$2,455.6
2013 figures from the top 25% of RAR members, June 2013 2011 figures from RAR members, July 2011.		

A key point of comparison for business overhead and soft costs is the solar PV industry. Figure 34 from (Farnsworth et al., 2018) shows that the installed cost of residential PV systems is dominated by gross margins and supply chain, making up more than half of the installed cost. This exceeds the estimates provided above for residential remodeling and for energy upgrade businesses. Extending this further, Farnsworth categorized a full 68% of PV costs as "soft". Notably, this total includes in the "soft cost" category the installation labor and structural components of the system, which we would not consider soft costs in energy upgrade work.

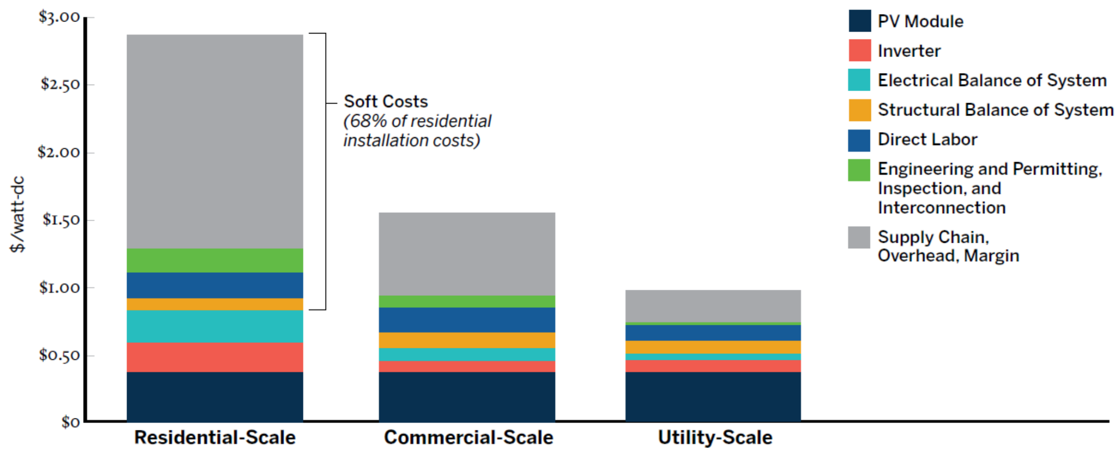


Figure 34 Cost stacks for solar photovoltaic costs, including gross margins and soft costs. Third Quarter 2017 (Source: (Solar Energy Industries Association (SEIA) and GTM, 2018))

8.3 Home Performance Soft Costs and Savings Opportunities

As noted above, gross margins are quite high in-home performance companies, and reducing these business operation soft costs offer an attractive means to potentially reduce energy upgrade project costs. These costs include all costs incurred by the contractor, program or homeowner that do not fall squarely under material/equipment and labor expenses. Soft costs can occur at the level of individual projects (e.g., diagnostic testing, lead testing) or for the business as a whole (e.g., training, conference attendance, specialized equipment). These soft costs are a potentially large contributor both to overall DER project costs and to the limited market penetration of energy upgrade projects.

Based on the analysis reported in Section 8.2, typical home performance gross margins are 48%, compared with 30-35% for residential remodeling, and 10-25% for general contracting and renewable energy. Home performance margins are higher, because the costs of doing business are higher in-home performance than they are in standard construction and remodeling. A large part of this gap are the numerous soft costs in this industry. In effect, the home performance industry currently has to charge much higher gross margins in order to remain profitably in business. Cost reductions might be achievable that would bring home performance gross margins in line with residential remodeling (e.g., savings of 15-20%). On top of that, improvements to the business processes and scale of home performance work could bring these businesses to levels more consistent with new construction and general contracting, where margins are even lower than in residential remodeling. Achieving a gross margin of 20%, for example, would reduce whole project home performance costs by 28% on average. This is the type of transformation that companies like Sealed (see Section 2.4.11) are attempting to develop, where many of the soft costs are handled more efficiently by an entity other than the boots-on-the-ground contractor.

The following is an incomplete list of soft costs incurred in typical energy upgrade work:

- **Common to both home performance and standard remodeling:**
    - General business overhead (office space, insurance, vehicles, etc.)
    - Permitting and inspections
    - Project management
    - Workforce retention
    - Marketing
    - Customer acquisition
    - Work scope development
    - Customer management
    - Travel to/from job sites

- **Unique to home performance:**
    - Program and/or rebate administration
    - Health and safety
    - Energy auditing/rating/inspection
    - Professional development, training and certification
    - Building energy simulation
    - Purchase use and maintenance of specialized equipment
    - HVAC sizing calculations

It is important to note that one's definition of "soft" costs can be quite different depending on one's role and perspective in the industry. Some costs, such as HVAC equipment sizing (load calculations), diagnostic testing, and commissioning may not be perceived as soft costs by contractors but might be by someone with a management perspective. Diagnostic testing and commissioning are likely considered part of the labor of an installation by those doing the work. Other costs, such as site cleanup and preparation are also not definitively categorized as being soft costs. Similarly, lead safe work procedures are often a requirement in older homes, but their categorization as "soft" or "hard" is unclear.

Despite, this variability in definitions, soft costs are greater in-home performance work, and they represent an opportunity for cost reduction. The ability to leverage and spread these soft costs out over many projects is often hampered by the small size of most home performance contractors that engage in energy upgrade work. On top of this, most contracting businesses are run in typical small business fashion, with limited resources and time for nuanced market analysis, customer targeting, technology deployment, etc.

Examples of strategies to reduce the soft costs of energy upgrade work include:

- Customer acquisition and support provided by large programs/entities, with dedicated staff and budget to leverage marketing and customer acquisition across many more projects. In this case, contractors do the field work, but are not responsible for the full burden of acquiring and managing their customers.

- Reduce or eliminate diagnostic testing to qualify or confirm work. Many programs have moved away from intensive test-in and test-out diagnostic approaches and have instead relied on deemed savings estimates or have focused efforts on checklist approaches that are critical.
- Remote approaches to customer engagement, work scope development and sales. While particularly relevant during the global COVID-19 pandemic, remote customer engagement provides an opportunity to eliminate many of the soft costs typically associated with planning and executing energy upgrade work in homes. We provide a more detailed example of remote engagement in Section 8.3.1 below.
- Rapid or automated HVAC sizing calculations.

8.3.1 Remote Energy Auditing and Assessment

One approach to reducing the soft-costs identified above is to remotely manage the process of customer intake, work scope development and sales. Broadly, this is called a "remote energy audit", and it is a newly emerging trend that existed prior to the COVID-19 pandemic, but which has accelerated due to social distancing requirements. Estimates have shown that remote audits can reduce auditing costs by 40% for individual projects, and by 60% for projects that proceed to implement the work scope. Proponents argue that this approach is critical to scaling home energy upgrades across the housing market, as it leverages internet technologies and sales expertise, rather than leading with building physics. The purported benefits of remote audits include: increased convenience and flexibility for customers, increased cost effectiveness (due to lower audit costs), reduced or eliminated travel time to/from jobsites, and improved conversion rates from audits to projects than traditional in-person visits. Below we highlight the experience of a New York company named Sealed[63] in its transition from traditional energy audits and customer acquisition to a remote-audit approach (Andy Frank, personal communication, June 2, 2020).

Sealed claims that in-home audits are expensive, disruptive and, in many cases, ineffective, with typical market costs of $200-$650 (3-5 hours of work, including travel). Since 2015, Sealed has transitioned from offering traditional in-home energy audit and project delivery services, to using an entirely remote-auditing approach starting in 2018. They claim that their remote audits quickly eclipsed the in-home audits by a factor of ten.

Sealed divides the goals of in-home audits into four main sub-tasks:

- Customer education
- Work specifications
- Health and safety
- Direct measure installs

[63] https://sealed.com/

While most programs have effectively required all four tasks to occur during a single home visit, Sealed argues that they can be separated and handled more effectively by different persons and at different times and places. Furthermore, the majority of these goals can be accomplished online and over the phone.

The following elements distinguish in-home compared with remote energy audit/sales procedures:

- Remote audits ask the customer to provide more information.
- Initial sales and outreach are delivered by persons with sales expertise (rather than by persons with primarily technical backgrounds).
- They leverage cloud technologies (Google maps, real estate websites) to produce initial cost estimates[64], which are sufficient to provide meaningful cost estimates that homeowners are willing to initially commit to.
- Limiting in-home "verification visits" only to those projects where homeowners have already agreed to the provisional scope of work (verbally and/or in writing). This is the key cost/time distinction between traditional in-home and remote processes, because many site visits are eliminated, and those that remain are much more likely to be converted to actual projects.

To illustrate the differences, Sealed used its past experience with both auditing/sales approaches to estimate the time required for each step of a traditional in-home vs. remote approach. For traditional in-home approaches, they estimate 5 hours per audit and 34 hours spent on the auditing process for each project actually implemented. Based on a lower fraction of site-visits and higher installation rates for homes visited, they offer an adjusted time per audit of 3 hours and 13 hours spent auditing per executed project. This represents a per project reduction of 40% (2 hours, $100 at $50 per hour), and a roughly 60% reduction in auditing time/costs associated with executed projects (roughly 20 hours saved and $1000 per executed project).

Remote auditing has recently been implemented by Energy New England for 19 public power systems in response to COVID-19 social distancing requirements[65]. They report that homeowner response has been overwhelmingly positive. The approach requires the homeowner to walk through the property as directed by an energy advisor and to then photograph and document any required details, which hare then entered into the SnuggPro system to produce their conventional audit report.

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[64] The project costs from these estimates have proven to be within 15% (on average) of final costs after a site visit. They have also found little correlation between accurate initial project pricing and the likelihood that project will be closed and executed.

[65] https://www.publicpower.org/periodical/article/energy-new-england-offers-remote-home-energy-assessment-option-mlp-customers

8.3.2 Customer Acquisition

Customer acquisition is clearly related to the discussion of remote auditing in Section 8.3.1, as most customers are ultimately acquired and onboarded through an audit-like process. Based on the analysis provided by Sealed above, they estimate the cost to acquire a customer (i.e., cost per audit divided by the fraction of audits that are converted to sales) at $1,690 (assuming $50/hour pay rate). The remote audit process led to customer acquisition costs estimated at $650. These estimates agree well with others provided by industry partners, which are discussed in further detail below. Overall, the cost of customer acquisition is estimated with well-honed best practices and using lower-cost labor to be around $700, while more typical practice leads to acquisition costs of $1,000 to $1,600 per customer, and potentially upwards of $2,500. Notably, the costs of customer acquisition for energy upgrade projects appear not altogether different from the customer acquisition costs reported for general residential remodeling (see Section 8.2), where typical acquisition costs ranged from $1,000 to $2,500 depending on how they are calculated (Freed, 2013). As noted above, the goal for home performance should be to beat the margins of the remodeling industry, not to meet or agree with them.

The high costs of the current standard approach to customer acquisition in home performance is echoed in a blog post from Nate Adams of Energy Smart Ohio[66], in which he describes his shift from standard customer acquisition to a consultative approach where free consulting is not an option. The author notes that in an attempt to move beyond prescriptive and quick recommendations, his business began to spend way too many hours on each project, which increased the overhead required on each job, reduced project effectiveness and customer satisfaction, and limited professional growth as a business owner. He notes that his more thorough approach increased quote times from 1 hour up to 2-3 hours, which combined with 1-1.5 hours of drive time per site visit and 1-hour to write up a quote, meant that most quotes involved 5-6 hours of time. On top of this time, he notes the time-consuming email correspondence required with homeowners interested in more comprehensive work (anywhere from 5 to 20 emails), which increased job times by several hours. He estimates that all told, getting a job required 10-15 hours of his time as the business owner. At $50/hour and $100/hour pay rates, these estimates work out to acquisition costs ranging anywhere from $500 to $1,500. Unfortunately, the jobs averaged $2,500 and were executed by his crew in 1-day. On top of this, only 55-65% of quotes turned into executed jobs, which is actually a high rate. This conversion rate would increase the acquisition cost per executed job to a range of roughly $800 to $2,500. Nate Adams argued that the end result was way too many hours for each job, and jobs that were not satisfactory, due to the time pressure to find more work.

We received an additional estimate of job acquisition time and cost from Beanstalk Enterprises, a home performance company from Sonoma California, who was attempting to streamline their job acquisition process. They provide similar discouraging estimates of the time and effort required to generate actionable quotes or scopes of work. They estimated the time (in hours) required for each element of converting a job from initial phone call through scheduling of on-site construction. These steps included initial phone call, site audit and write-

[66] http://energysmartohio.com/radical-transparency/confessions-of-an-insulation-contractor/

up, energy model, customer proposal, program paperwork, final contract and scheduling. They then explored cost reductions through using higher or lower cost team members to do this effort. The highest cost team member (at $100 per hour) could complete this process using 12 hours at $1,200. All steps through the proposal delivery to a customer accounts for $800 of this total. A mix of lower- and higher-cost team members required more hours (14), but at a lower total cost $850. Finally, a high reliance on external subs could bring down the cost of $669. These values are for each job that gets executed. Some aspects would also be accrued for inspections and quotes that are not converted. In all, this supports the notion outlined by Andy Frank that site visits, proposal generation and customer management are substantial fractions of most home performance work.

8.3.3 Rapid HVAC Sizing

The vast majority of HVAC installations rely on quick rules-of-thumb for sizing equipment, rather than engineering calculations. The generally agreed upon result has been that most systems are substantially over-sized. Under this paradigm, there is no project cost savings available from improving HVAC sizing methods, because the dominant low-cost approach is "no method at all". Yet, many consider the sizing of HVAC equipment to be a critical element of high performing home retrofits that address occupant comfort and IAQ priorities. Traditionally, this has meant a detailed HVAC load calculation using the ACCA methods, including Manuals J, D, S, etc. This has generally been done with the WrightSoft software suite. These calculation procedures can be time-consuming and expensive, requiring detailed measurements of the home's geometry, duct layout, glazing, orientation, etc. Substantial cost savings may be achievable for properly sized systems, without sacrificing accuracy or performance.

Options are beginning to emerge for rapid HVAC sizing calculations, both through a new generation of traditional software-based tools, as well as data analytics-based methods that rely on internet connected thermostats and smart meter data to track equipment runtimes.

Example software tools that claim to drive down the cost and time requirements for HVAC sizing include:

- EDS HVAC Load Calculator[67]
- CoolCalc[68]
- Kwik Model[69]

These tools are all intended to make the data inputs fast, intuitive and useful. Some tools provide only a whole dwelling load based on gross geometry (i.e., block load), while Kwik Model provides traditional room-by-room loads and duct design. According to EDS, "A Comfort Advisor can perform a whole house block load calculation in under 5 minutes. This is possible by utilizing data from Google Earth, Zillow, and real estate databases along with a complex series

[67] https://www.eds.tech/products/hvac-load-calculator
[68] https://www.coolcalc.com/
[69] (Haverinen-Shaughnessy et al., 2018)

of algorithms and equations. The user interface and reports are elegant and streamlined. The original load calculations can be executed prior to a site visit, and then can be trued-up using information collected on-site. Kwik Model 3D uses a video game-based platform to allow users with no CAD experience to easily build 3-d models of a home, and the software then does all the take-offs necessary for a load calculation. The software is integrated with the EnergyGauge simulation tool from FSEC, and it performs manual J, D and S design calculations, including a fully specified and digitally rendered duct system. CoolCalc also offers easy geometry tracing from Google Maps, as well as tie-ins with HVAC manufacturer specification libraries.

Emerging methods based on data analytics from smart thermostats or smart meters might also provide an avenue for highly accurate and automated residential load calculations. These approaches would likely use maximum annual hourly runtime for the existing central system, combined with the current equipment output capacity to extract the in-situ peak load. Nate Adams of HVAC 2.0 has presented a non-automated demo of this kind of approach[70]. While not yet publicly available, this type of approach could in theory be fully automated for homes with internet-connected thermostats and smart meters. The HVAC installer would need to confirm the equipment capacity on-site and then use the automated run-time calculation to extract the effective peak load. Future research should seek to address how to adapt these methods of equipment sizing in the context of an energy upgrade project that substantially reduces the building loads through weatherization activities. Similarly, outcomes from these approaches should be compared against traditional sizing routines from ACCA.

[70] https://docs.google.com/presentation/d/12ThQRLVK0pPbTOO1hEkCXen1B76IVBnTIl4Ybw-r_z4/mobilepresent?slide=id.g13f20136c3_0_481

9 Health Benefits of Energy Efficiency Retrofits

There is ample evidence that housing interventions, including efficiency measures, can have positive impacts on occupant health, both physical and mental, as long as they are carried out using best practices. The evidence is strongest for home warmth interventions, and for interventions targeted towards susceptible populations, namely children, the elderly, and those with pre-existing respiratory issues, including asthma, COPD and ILD. These impacts are most likely to be positive when programs are designed with IAQ/health as equal considerations with efficiency measures, and when energy and health interventions are interwoven. Examples of this include the reduction of asthma triggers during home assessments by efficiency professionals and referencing clients in-need to community health organizations that perform home visits to manage chronic health conditions (e.g., asthma, COPD, and ILDs).

The health impacts mentioned above, which have substantial documentation in the research literature, are largely for acute health conditions and events, including asthma attacks, emergency room visits, allergic rhinitis, etc. These conditions can be measured using current epidemiological methods with sample sizes in the hundreds or thousands of participants, which are achievable in the best of studies. These health outcomes can both manifest and disappear rapidly depending on the surrounding conditions. For example, when allergens are removed from the environment, a rapid impact can be ascertained on allergy sufferers. The same follows for asthma triggers, for inadequate warmth, etc. These are the only “health” outcomes currently being measured in studies assessing the association of energy efficiency or housing improvements with health, which typically occur over periods of weeks or at most 1-2 years. Health outcomes discussed in the paragraphs below are almost exclusively referring to these acute health outcomes and symptoms.

Acute health outcomes (like those discussed above) very rarely occur due to changes in the measured concentrations of contaminants in indoor air, unless those contaminants are at extremely high levels, above which acute health outcomes can be evident. Most contaminant measurements are longer-term (e.g., 24-hours or 7-days), and they represent changes in the average concentration in a space. If there are any health outcomes associated with changes in long-term contaminant exposure, they are chronic (i.e., long term) health outcomes. These longer-term risks are for conditions like cancer, endocrine disruption and other outcomes that are effectively impossible to observe (and therefore measure) with studies of the size (and statistical power) typically used to assess efficiency programs/interventions. If lifetime cancer risk increases by 10 in 100,000 people due to increased formaldehyde exposure (for example), those cancer cases will never be observed in an energy efficiency study that conducts measurements one-week before and after the interventions (nor one-year before and after).

Because of this, changes in measured indoor air contaminant concentrations have generally not been associated directly with measurable health effects. For example, both (Purcell, 2018) and (Haverinen-Shaughnessy et al., 2018) failed to associate changes in indoor contaminants with the acute health effects that both studies also observed. Due to the difficulty in measuring health outcomes for chronic, long-term health conditions (e.g., cancer, endocrine disruption), the impacts of changes in indoor contaminant concentrations instead must rely on estimates of concentration response functions estimated in the literature, largely based on pollutant measurements in outdoor air. This does not make the potential health impacts of changes to indoor contaminant concentrations resulting from energy retrofits any less real, it simply means that they are much more difficult, if not impossible to accurately measure/observe with current methods. In order to understand or estimate long-term, chronic health outcomes of energy retrofits, we must rely on long-term changes in contaminant exposures in those spaces (paired with concentration-response functions), and we should not expect to observe chronic health outcomes directly.

9.1 Review Articles

(Maidment et al., 2014) performed a meta-analysis that pooled together the results from 36 past studies of the health effects of energy efficiency, for a total sample of over 33,736 participants. On average, interventions had a small, but significant, positive impact on residents' health (overall mean improvement of 8%). Maidment noted that larger health effects were observed in more recent studies, and that effects on some specific medical conditions (e.g., respiratory health) were greater than those observed for general health. Overall, Maidment's review agreed with past assessments reporting modest physical health improvements from housing interventions (Liddell and Morris, 2010), as well as more mixed though mainly positive outcomes in other past reviews (Thomson et al., 2009; Hilary Thomson et al., 2013; H. Thomson et al., 2013).

(Denson and Hayes, 2018) authored an ACEEE review of: (1) exemplary programs in the US working on these issues; (2) trends across programs; and (3) sharing of best practices and recommendations. ACEEE sought nominations nationally for exemplary programs that combined energy efficiency and health, and they used a national panel of public health and efficiency experts to rank and assess the programs. Overall, the best programs with documented health and energy benefits targeted buildings/households where people suffer from chronic respiratory illnesses, and the interventions they provided were multi-faceted. They combined: (1) health/asthma management education using actual community health professionals; (2) helped directly address sources of asthma irritants (e.g., dust mite mattress covers, HEPA vacuums, etc.); and (3) also improved the energy efficiency and thermal performance of the dwelling with traditional weatherization type audits and work scopes, which can reduce heat/cold stress, lessen fuel poverty, etc. The best programs also offered referrals to related agencies serving specific needs that are not within the scope of the energy efficiency/health program. In these situations, meaningful and measurable improvements were possible for both energy use and health outcomes, such as asthma-related hospitalizations, sick days from work/school, etc.

In 2016 the US DOE published a report (Wilson et al., 2016) that reviewed the available evidence on the relationship between health and home performance. This review was conducted primarily by representatives from the National Center for Healthy Housing (NCHH), along with other individual contributors. Forty studies were reviewed and are summarized in the white paper. The reviewed works were categorized by the type of intervention (e.g., basic weatherization, green renovation, ventilation intervention, etc.). They report that interventions at all levels improved occupant health and had positive impacts.

E4TheFuture published a report in 2016 (E4TheFuture and Tohn Environmental Strategies, 2016) that summarized potential health benefits of energy efficiency programs and developed a roadmap for future efforts. Figure 35 from this report provides a summary that is common across the literature. This document also provided an estimate of the monetary value of health improvements and noted that states are increasingly recognizing such co-benefits in cost-effectiveness practices (Woolf et al., 2013) (e.g., RI, DC, MD (Itron, 2014), CA, MA, NY). Monetary estimates of household health benefits ranged from $3 to over $900/household unit/year for residential energy retrofits. Other studies have estimated that health improvements represent as much as 75% of the total return on the investment for these interventions (Grimes et al., 2012).

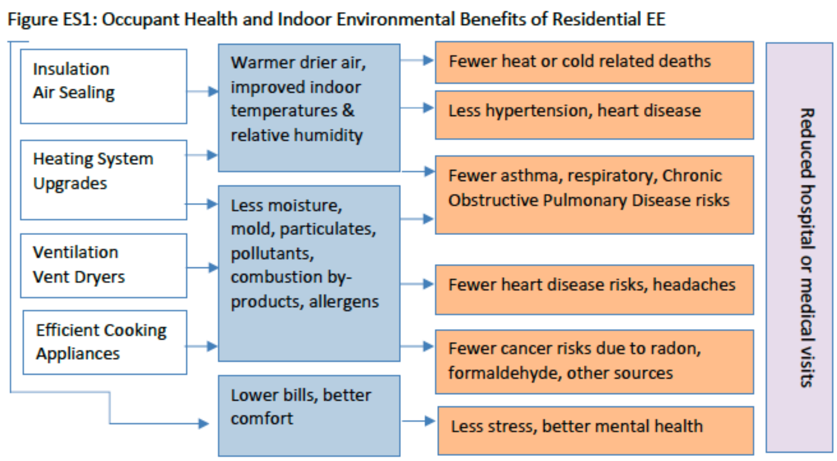

Figure 35 From the E4TheFuture publication “Occupant Health Benefits Residential-Energy Efficiency” (E4TheFuture and Tohn Environmental Strategies, 2016)

The IEA has produced a document (IEA, 2014) that outlines the multiple benefits of energy efficiency, with a chapter dedicated to the health benefits of energy efficiency. Their key findings were: improving energy efficiency in buildings creates conditions that support improved health and well-being for occupants. Positive health outcomes are consistently strongest among vulnerable groups, including children, the elderly and those with pre-existing illnesses, health improvements at the individual level generate indirect social impacts and relieve pressure on public health budgets (an estimated savings to the European public health budget of USD 99 billion per year in 2020), and health benefits represent up to 75% of overall energy efficiency program benefits.

The most recent study we found for this literature review examined evaluations of the influence of residential energy efficiency retrofits on indoor environmental quality conditions and self-reported thermal comfort and health (Fisk et al., 2020). A total of 36 studies were reviewed, with most studies focused on low-income homes in Europe or United States. Overall, these studies found that indoor radon and formaldehyde concentrations tended to increase after retrofits that did not add whole-house mechanical ventilation, however, other contaminants, such as nitrogen dioxide and volatile organic compounds other than formaldehyde increased and decreased with approximately equal frequency. Average indoor temperatures during winter typically increased after retrofits, usually by less than 1.5 C. Dampness and mold, usually based on occupant's reports, almost always decreased after retrofits. Subjectively reported thermal comfort, thermal discomfort, non-asthma respiratory symptoms, general health, and mental health nearly always improved after retrofits.

9.2 Recent Studies

There have been several recent studies in other countries that found a variety of results[71]. Some found that retrofits were associated with occupants reporting an absence of upper respiratory symptoms, as well as reduced absenteeism from school/work, whereas others found that retrofits had less direct health effects and were instead were associated with improved indoor warmth and reduced financial stress associated with paying utility bills and improved subjective well-being and feelings of belonging.

The research literature suggests that when energy retrofits are paired with mechanical ventilation, IAQ can be maintained or improved, though there is also a risk of increasing levels of contaminants of outdoor origin. For example, (Francisco et al., 2017) provided compelling evidence for the IAQ benefits associated with mechanical ventilation during energy retrofits, where the higher airflow mechanical systems delivered statistically significant reductions in indoor formaldehyde, VOCs and CO_2, and non-significant reductions in radon. Furthermore, children experienced fewer headaches, eczema, and skin allergies after weatherization and adults had improvements in psychological distress.

The Pierce County Healthy Homes Partnership (PCHH), with funding from the Weatherization Plus Health program (WSUEP, 2019) delivered integrated healthy home and weatherization services to 53 low-income households with 78 occupants that had pre-existing respiratory conditions, including asthma (71%) and COPD (29%). The results showed improved respiratory/asthma control, scores for COPD also improved, but without reaching statistical significance. 7 in 10 respondents reported improved quality of life, and there was a net-decrease in missed school/work days due to illness across all clients

Recent research in Europe has pushed the boundaries with improved methodologies that include long-term study periods (years as opposed to months) and have sufficiently large sample sizes to support robust statistical analysis. Some of these find remarkable positive health outcomes from upgrading existing social housing to new standards, (Ortiz et al., 2019).

[71] The INSULATE project that retrofitted multifamily buildings in Lithuania and Finland (Haverinen-Shaughnessy et al., 2018); The Arbed program, an energy retrofit program in Wales between 2013 and 2015 (Grey et al., 2017); National housing quality standards in public housing in Carmarthenshire District in Wales, UK (Rodgers et al., 2018a, 2018b, 2016); The Glasgow GoWell public housing study (Curl et al., 2015); Social Housing and Adult Asthma in Cornwall, UK (Sharpe et al., 2015).

In conclusion, the studies and results summarized here, and the various programs that are the source of these evaluations have indicated that it is certainly possible to integrate heath and energy efficiency – but substantial efforts are still needed to make this commonplace.

This past work has focused on the actual impacts of energy efficiency interventions on human health and IAQ outcomes. In the US, a different approach has emerged recently, where the weatherization and public health/healthy homes professions have begun combining their efforts, with the understanding that health outcomes are improved further when both interventions are leveraged. This approach is less concerned with attributing health outcomes to certain measures or interventions, and instead the focus is on simply and efficiently improving the health outcomes of as many households as they can touch. These coordinated efforts allow weatherization crews to connect occupants with healthy homes services and vice versa, which improves recruitment for programs and outcomes for the homeowners.

10 Summary and Conclusions

10.1 The Last 10 Years and the Next 10 Years

This review has shown that DERs are well beyond the demonstration phase. The materials and methods are well established and have been shown to perform appropriately in most cases. The work of much of the second decade of the 2000s has been to bring energy upgrade design and construction principles to a broader market, generally as part of utility- and market-based programs.

The key conclusions from LBNL's previous 2013 DER meta-analysis were:

- Complex technological solutions lead to poor performance and energy savings and their higher perceived risk does not lad lead to further adoption.
- Using models to predict energy savings is still very difficult for individual homes, but may still be a useful tool for program evaluation averaged over many homes.
- Costs and performance not well correlated. A combination of occupant behavior, the starting point of the home, and inclusion of measures whose energy performance is not reflected in their cost or are done for non-energy reasons (e.g., window replacement).
- Most DERs are performed in pilot programs at small scale and not clearly contributing to a larger market transformation.
- Behavioral changes should not be overlooked – they can offer 10% savings for little or no cost – particularly if implemented with direct occupant feedback, e.g., from Non-Intrusive Load Monitoring.

However, much has changed since our first meta-analysis of DERs, with substantial impacts on how DERs can (or should) be designed, implemented and marketed. Critical changes include the following:

- Electrification as a core strategy to achieving deep carbon reductions in buildings and vehicles.
- Rapidly improving heat pump systems, particularly for cold climates and water heating, are leading to increasing adoption of heat pump technologies in previously fossil-fueled applications.
- A shift in DERs away from high-cost super-insulation strategies, with increasing recognition that traditional weatherization/home performance strategies are adequate for most dwellings.
- PV is becoming an integral part of efficiency upgrade work due to drastic reductions in the cost of solar PV and a desire for home owners to have PV systems.
- Low electricity and natural gas prices make financial payback arguments challenging. This can often shift project focus towards addressing thermal comfort, IAQ, resilience, environmental or aesthetic goals.
- Emerging smart home technologies are facilitating the ability to manage, reduce and communicate about energy use.
- Increasing awareness about the importance of when homes use energy, and what type of energy they use and from what source. This pairs with emerging technologies for

electricity storage and thermal storage integrated into home energy systems and the use of lower-power appliances.

Programs are still needed to promote DERs, and are experimenting with some innovative approaches to overcome the barriers to energy upgrades, including:

- Neighborhood or street-level recruitment.
- Working with community organizations to engage homeowners, particularly for low income/disadvantaged communities.
- Multi-fuel or fuel agnostic programs.
- Electrification of heating and hot water end-uses.
- Financing from the program using local networks of lenders.
- Novel financing approaches, including Pay As You Save (On-Bill) and PACE funding mechanisms, which provide some novel economic benefits.
- Use of vetted contractor networks.
- Pay-for-performance program structures.
- Emergence of one-stop-shop program types that integrate financing, project management, design and support services into making the experience easy for homeowners.

10.2 New Metrics for Home Energy Upgrades

New energy performance metrics are becoming increasingly important, including: (1) peak demand, (2) time at which energy is used (for both carbon and cost reasons), and (3) CO_2 emissions per unit energy for electricity and other fuels. In addition, metrics for energy storage, both for electricity and thermal storage, are poorly developed and are required in order to assess resiliency and responsiveness to electric grid demands. Home energy upgrades must be designed to meet these emerging performance metrics if they are to continue to be relevant in addressing carbon emissions of the housing stock and upgrading homes for the 21st century.

These new and changing home upgrade performance metrics include:

- CO_2 (and other Green House Gas) emissions.
- Peak demand and the ability of a home or technology to time-shift to optimize use of renewables, respond to variable energy costs, and support electric grid reliability.
- Assessments of health and IAQ associated with home energy upgrades. This is particularly important for electrification, because it removes the hazards associated with combustion of fossil fuels in the home: emissions of particles, NO_2, CO and various aldehydes. This can make homes more safe for occupants, while also reducing program costs that no longer require combustion gas leak detection or combustion safety testing.
- Home safety metrics such as fire risk and CO that are increasingly being recognized by the home-improvement industry, builders and contractors.
- New ways to assess the cost of energy upgrades. These include:

- *Monthly net cost of ownership:* i.e., a cash-flow approach more akin to traditional home mortgages.
- *Affordability:* Like selling a car the home upgrade industry needs to do better at sales and closing deals by selling retrofits in the same way as leasing and financing of automobiles. For this to work the industry needs easy access to finance. The automobile financing industry demonstrates that interest rates do not even have to be particularly good if they are a tool to get people what they want.

10.3 Key Barriers for Getting Home Energy Upgrades to Scale

Barriers to the scaling of home energy upgrades that address the metrics described above are varied, ranging widely from individual homeowners and contractors, up to whole utility systems, program managers and financial institutions. We have identified the following key barriers or opportunities:

- Projects focused solely on energy savings are not appealing. The past focus on energy efficiency or annual site energy savings is not enough. There is a need to emphasize other metrics including health, resilience, affordability, maintenance, and environmental aspects. Energy upgrade projects must address the actual needs and goals of homeowners, and these projects must be profitable and enjoyable for the contractors and trade workers implementing them.
- The workforce remains inadequate. Despite market development efforts over the past decades and the presence of many dedicated and very skillful companies, the general workforce is inadequate to implement complex projects at scale. The emergence of new technologies, metrics and processes make this inadequacy even more evident, as no centralized databases exist of contractors who have experience with electrification or low-carbon projects, for example.
- The costs remain too high. Finding the lowest cost way to save energy and reduce carbon emissions is likely to include PV, thermal storage, simple weatherization and electrification, rather than high-cost envelope upgrades. Other novel approaches may include leaving existing heating systems in place and augmenting with higher-performance systems to save the cost of existing system decommissioning. Another aspect of cost control is to invest in technologies that can more reliably reduce energy use (or CO_2 emissions) in homes to reduce financial risks for homeowners and post-retrofit home performance risks for contractors. Across the industry, soft costs are a substantial fraction of the total, and efforts are needed to reduce these soft costs to levels equivalent to or less than the general remodeling industry.
- Economic justifications are challenging and possibly inadequate. Due to low energy costs and the failure to appropriately price carbon emissions, the direct financial benefits of home energy upgrades are difficult to prove using simplistic methods, such as the number of years it takes to payback an investment. Other approaches, such as net-monthly cost and Pay-As-You-Save programs are making progress in this area, but more work is needed to incorporate health and environmental costs that are typically ignored. We also need to recognize that for many homeowners, their

motivation and decisions regarding home energy upgrades are not purely based on simplistic financial analyses.

10.4 Guidance for DOE for Scaling Home Energy Upgrades

10.4.1 Make DERs Appeal to Home Owners

The survey performed for this study and other previous surveys all share some common conclusions regarding driving demand for home energy improvements:

- It is not enough to provide information; programs must sell something people want, e.g., affordable, tangible solutions.
- Partner with trusted messengers.
- The language to discuss energy improvements is powerful.
- Contractors are program ambassadors.
- Make it easy, make it fast.
- Rebates, financing and other incentives create demand.
- A well-qualified workforce and trustworthy work are vital.

Surveys have shown that the people currently undertaking DERs want tangible assets that go beyond saving money and energy and include green/sustainable attributes. The primary instance of this is solar PV where studies have shown significant increases in home value (on the order of $10,000-15,000). This needs to be revisited in the light of reduced solar costs and increased public interest in PV. IAQ, health and safety are also key aspects of increasing interest and demand for DERs. Finally, the industry needs to adopt more positive terminology for use in messaging to the general public and to those engaged in public policy For example, instead of “Home Energy Retrofit”, use “Home Performance Upgrade”, etc.

10.4.2 Develop A Standardized Set of Strategies that Apply to the Many Home Archetypes in the Country

One benefit of the trend towards electrification and PV, and away from very aggressive envelope upgrades, is that these approaches are less dependent on the condition and/or archetype of the home being upgraded. This opens up opportunities for reducing customization and design costs, because the upgrades can potentially be more standardized. Customized projects require expertise and are costly, which are key barriers. Variability will remain due to the wide array of existing conditions in US homes, but effort should be made to reduce the variability in projects as much as possible. Homes encountered that already have insulation or upgraded windows, or where electrical upgrades have already occurred, can simply install the remaining elements of a standardized approach. Ideally, any such package should be available to homeowners at little-to-no upfront cost, and with effectively no need to shop around to identify appropriate contractors or sources of financing.

Any standardized approach to upgrading US homes must be adapted to the evolving paradigms of the energy and housing industries in the US. They cannot simply address, as they have in the past, site energy savings, or utility bill reductions and improved occupant comfort, health and aesthetics. They must be designed to provide the numerous personal and grid/societal services that are required of our buildings in a decarbonized future. In order to help the industry scale, there will be a need to share success stories and document good projects. We suggest something along the lines of the The Lower Energy Building website[72], that DOE could use as a template for archiving project cost data and case studies for demonstrating to contractors how deep retrofits are accomplished for different house types in in different climates.

The key emerging topics in this industry that must be incorporated into any standardized home upgrade process should include:

- Decarbonization and electrification of housing and personal vehicles.
- Demand-responsive technologies including electric batteries and thermal storage.
- Heat pump technologies.
- Grid connectivity.
- Smart technology and web-connectivity.
- Resilience to natural and manmade disasters.
- Health and safety.

10.4.3 Investigate Key Topics of Importance to the Industry That Are Currently Poorly Understood

- **Real estate market valuation of DERs/home upgrades**. While there are tangential references to added home value and data for specific measures (such as adding PV systems), we could not find publicly available studies evaluating the added value from both homeowner and real-estate industry perspectives. There are published values for many home upgrades, (e.g., kitchen remodel) but they do not include improved energy performance.

- **Solutions for driving the lack of consumer demand**. While the literature does point out that lack of consumer demand is a limiting factor, there is little information on how to address this. Surveys have suggested that there is increasing homeowner desire to make homes sustainable and incentives are helpful, but a better understanding of potential solutions is needed. For example, how might carbon taxes or time-of-sale requirements change people's perspectives.

- **Workforce solutions.** A common theme is the lack of a suitable workforce to undertake DERs. Some people advocate simplifying retrofits in order to use entry-level talent and make DERs less complex, so you do not need to be an engineer to do one. Others advocate for a more skilled workforce. Probably both are needed. The current situation is a chicken/egg problem. Until the industry grows, it is hard to attract a workforce, but

[72] https://www.lowenergybuildings.org.uk

without a readily available workforce, the industry cannot grow. Furthermore, there is some industry skepticism regarding investing in training and other workforce development because, historically, government and utility support were not consistent, with large programs being developed, only to be disbanded after a few years.

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13 Abbreviations

AHUP	Advanced Home Upgrade
ASHP	Air Source Heat Pump
ACEEE	American Council for an Energy Efficient Economy
BBNP	Better Buildings Neighborhood Program
BPI	Building Performance Institute
BPPA-VT or BPPA	Building Performance Professionals Association of Vermont
CPUC	California Public Utilities Commission
CERT	Carbon Emission Reduction Target
CHT	Champlain Housing Trust
CESP	Community Energy Saving Programs
CATI	Computer-Assisted Telephone Interviewing
DER	Deep Energy Retrofit
DERPA	Deep Energy Retrofit Planning Analysis
DOE	Department of Energy
DIY	Do-it-yourself
DHW	Domestic Hot Water
EV	Electric Vehicles
ER	Electrical Resistance
EEC	Energy Efficiency Certificate
EED	Energy Efficiency Directive
EEIX	Energy Efficiency Information Exchange
EBC	Energy in Buildings and Communities
EPC	Energy Performance Certificate
EPBD	Energy Performance of Buildings Directive
EUC	Energy Upgrade California
EIFS	Exterior Insulation Finish System
EIFS	external insulation and finishing system
EEM	Extreme Energy Makeover
FHA	Federal Housing Administration
FSEC	Florida Solar Energy Center
GWP	Global Warming Potential
GSHP	Ground Source Heat Pump
HP	Heat Pump
HPWH	Heat Pump Water Heater
HRV	Heat Recovery Ventilation
HVAC	Heating, Ventilation and Air Conditioning
HEA	Home Energy Analytics
Home MVP	Home Energy Market Value Performance
HIRL	Home Innovation Research Labs
HPXML	Home Performance eXtensible Markup Language
HPwES	Home Performance with ENERGY STAR
HUP	Home Upgrade
IAQ	Indoor Air Quality
IEA	International Energy Agency

IOUs	Investor-Owned Utilities
LZC	Low / Zero Carbon
MA DOER	Massachusetts Department of Energy Resources
MVHR	Mechanical Ventilation with Heat Recovery
MSHP	Mini-Split Heat Pump
NCHH	National Center for Healthy Housing
NILM	Non-Intrusive Load Monitoring
PG&E	Pacific, Gas & Electricity
PV	Photovoltaic
PCHH	Pierce County Healthy Homes Partnership
PACE	Property Assessed Clean Energy
RENs	Regional Area Networks
RAR	Remodelers Advantage Roundtable
RFF	Resources for the Future
RfF	Retrofit for the Future
RMI	Rocky Mountain Institute
SMUD	Sacramento Municipal Utility District
SAP	Standard Assessment Procedure
SEAI	Sustainable Energy Authority Of Ireland
TSB	Technology Strategy Board
TVA	Tennessee Valley Authority
TBS	Thermal Break Shear
TXV	Thermal expansion valve
US EPA	U.S. Environmental Protection Agency
ULE	Ultra-Low Energy
ULEB	Ultra-Low Energy Building
UEF	Uniform Energy Factor
VEIC	Vermont Energy Investment Corporation
ZEB	Zero Energy Buildings
ZEN	Zero Energy Now