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The Costs of Home Decarbonization in the US

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ABSTRACT

The upgrading of existing homes through electrification will play a critical role in the decarbonization of the residential building stock in the US. Currently, upgrade project cost is the key barrier that the buildings industry and homeowners are facing. These costs must be reduced in order for home decarbonization to scale. The buildings industry currently lacks relevant home upgrade cost data needed to aid in the planning and implementation of home decarbonization, as well as to engage in targeted R&D to lower upgrade costs. To address this, we gathered information on the total project and upgrade measure costs, along with the energy, utility bill and carbon savings from 1,739 energy upgrade projects across the US. We present analyses that summarize the measure and project costs together with estimates of cost variability and trends with key parameters. Our results will focus on electrification technologies and related decarbonization measures. We developed regression models to predict energy and carbon savings based on upgrade measure costs. The regression models were used to determine important factors impacting measure costs, as well as to estimate the costs required to meet savings targets for energy and CO_2. Our results show that there are currently no low-cost solutions capable of providing significant (>50%) energy and CO_2 savings for the US residential building stock. Carbon reductions of 50% or greater typically required investments of at least \$250/m^2 (\$23/ft^2) or \$40-\$50,000 per home.

Introduction

Upfront cost is cited as the major barrier when upgrading homes to reduce carbon emissions in industry surveys (Chan, Less, and Walker 2021; McIlvaine et al. 2013; EMI Consulting 2016). Yet, cost benchmarks for these upgrades are rare. Future efforts to scale decarbonization upgrades in the US housing stock will need cost benchmarks in order to guide strategies and priorities on cost reduction. Previous studies have estimated the cost of energy upgrades required for substantial energy savings. A meta-analysis of deep energy retrofit projects in the US (Less and Walker 2014) reported average project costs of \$40,420 ± \$30,358 (roughly \$47,000 ± \$36,000 in 2019 USD). A review of energy efficiency programs reported that deep energy retrofit costs were similar to other major home upgrades (Cluett and Amann 2014). Another ACEEE study indicated that there were significant challenges in obtaining accurate project-level savings estimates (Cluett and Amann 2016). Other R&D efforts focused on cold climate projects targeting exterior insulation reported even higher costs (Holladay 2012). High project costs combined with relatively cheap retail energy costs, and a focus on cost-effectiveness, have limited the large-scale implementation of critical energy upgrades in the US housing stock. There are existing cost databases in the US for energy efficiency measures (NREL 2018), however, the data for most of the upgrade measures relevant to home decarbonization have not been updated in many years, and they do not include price adjustments based on location or inflation.

Electrification will be a key tool in the decarbonization of existing homes. In order to determine the potential barriers to electrification at scale, we investigated the current costs for energy upgrades and decarbonization measures, and we investigated approaches that can be used to reduce costs. This study created a database incorporating household metadata (e.g., location, vintage), project and measure costs, measure performance data, and energy data. It has been developed as a basis for future residential energy upgrade data gathering activities by the US Department of Energy (DOE) and other agencies. Project data was obtained for 1,739 projects, from 15 states and 12 energy programs, with a total of 10,512 individual measures (including rebates). More details about the database are given in Less et al. (2021).

The project costs embody a wide range of diversity both geographically and in the year of construction (around 2010 to 2020). To provide consistency, the reported costs were adjusted to represent US national average costs for the year 2019, using inflation and location adjustment factors from RSmeans (Lane 2019). Reported energy data was translated into common units (kWh), and site energy values were converted into 2019 energy costs and carbon dioxide equivalent (CO_2e) emissions using statewide average retail energy prices (from the US EIA) and the carbon intensity of delivered electricity (from US EPA eGRID). See Less et al. (2021) for additional details on energy conversions.

The database has limitations. It is a sample of convenience from programs, agencies and individual contributors that were willing to share project data. Some of the data was provided for free, while other contributors required paid effort to gather and organize the desired information. Many projects provided only minimal information. Finally, many projects were not comprehensive energy upgrades or aimed at decarbonization, including less than three measures.

The final results cannot be generalized across all homes in the US or allow more detailed parametric breakdowns. For example, we did not break down project costs or CO_2e impacts by location. While the database in this study has insufficient data from each state in the US to examine state-to-state variability, it is important to consider how variability in energy costs and CO_2e content of electricity changes project outcomes. For example, a recent analytical study (Walker, Less, and Casquero-Modrego 2022) has shown that the variability in carbon impacts and energy costs of electrification of home heating can be large from state-to-state and that there are states where CO_2e savings from decarbonization are significant but may not be supported by energy cost savings. To perform a similar analysis using actual project data would require a much larger dataset than we have for the current study.

Database Summary

Figure 1 shows the number of projects in each state, together with summary statistics on the total aggregated dataset. The area and $ cost are the sum across all the projects. The database includes a wide-array of projects, ranging from single-measure HVAC upgrades to net-zero energy whole home remodels. Only 273 homes in our database changed fuels during the upgrade, so not all the data are explicitly about the costs of electrification projects. However, most projects included measures that would be used in electrification and their costs, energy savings and CO_2e reductions can be used in decarbonization analyses. Nearly all projects participated in some energy program at local, state or federal levels. All costs reported in this work are total gross costs excluding any incentives, unless directly stated otherwise.

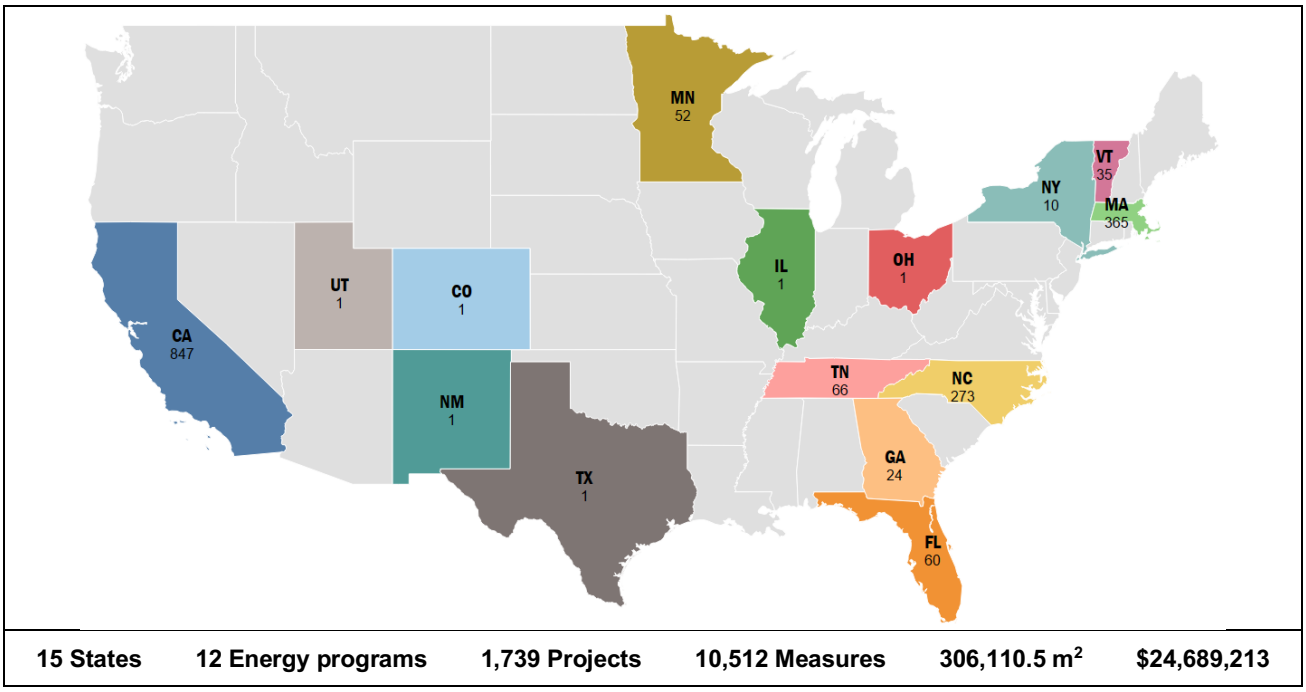


Figure 1. Map of project locations and overall summary statistics.

Table *1* summarizes some of the key characteristics of the projects in the database. The database covers a wide range of construction types and home characteristics. Many projects did not report some or all of these characteristics, so the tabulated values do not always add up to the total number of projects. Again, we must emphasize that this is a sample of convenience and any trends in these values simply reflect the data that was contributed. They do not necessarily represent underlying trends in the home upgrade market. In order to capture recent cost and performance data, upgrades were only included if they occurred within a decade of the project start date (i.e., 2010). The vast majority (84%) of projects occurred from 2018 onwards and the last ones were completed in early 2020, implying little effect from COVID-related construction price increases post May 2020 ("AGC 2021 Construction Inflation Alert" 2021). The project costs were all converted to 2019 values. The 1,739 projects were distributed (unevenly) over 15 states, representing diverse climate and economic regions. 76.7% of the projects were single-family detached buildings, 16.4% of manufactured homes, and 4.3% single-family attached buildings. The median conditioned floor area was 164.3 m^2 or 1,768.5 ft^2 (mean of 184.7 m^2 or 1,988.1 ft^2), which is lower than the median for single-family homes in the US of about 210 m^2 or 2,260.4 ft^2. Only 6 projects recorded a change in floor area during the renovation work, indicating that this is uncommon in the homes in this study. The homes of the study cover a range of vintages from 1800 to 2019, with most homes exceeding 50-years in age; mainly built between 1960-1979 (44.1%) and 1980-1999 (28.8%).

We subjectively characterized the projects by the type of upgrades they received. Each project could be assigned up to two retrofit types. The most common retrofit type was "Home performance upgrade" (n=1,061), which represents a project whose measures included both HVAC equipment and building envelope, and whose methods and materials are fairly standard and off-the-shelf. The

other most common upgrade types included Electrification (n=294), Individual measure[1] (n=251), HVAC-focused[2] (n=226), and Envelope-focused[3] (n=122). Retrofit types are in-part dependent on the energy programs that contributed data to the database and also depend on the energy objectives of the program, and do not necessarily represent all patterns or trends in US energy upgrades.

Table 1. Summary of Project Characteristics.

	PROJECT CHARACTERISTICS	NUMBER OF HOMES REPORTING
Construction Type	Wood Frame	399
	Concrete Masonry Unit	47
	Unknown	*1,293*
Foundation Type	Basement	316
	Slab	75
	Crawlspace	34
	Crawlspace and Basement	63
	Slab and Basement	51
	Unknown	*1,200*
Number of Stories	1	344
	2	254
	3	24
	1.5	45
	2.5	24
	Unknown	*1,048*
Number of Bedrooms	2	68
	3	316
	4	145
	Unknown	*1,210*
Number of Bathrooms	1	31
	2	104
	3	27
	Unknown	*1,577*
Home Vintage	Pre 1900	59
	1900-1960	274
	1960-1980	728
	1980-2000	476
	2000-2020	114
	Unknown	*88*
Project Year	2020	828
	2019	374
	2018	258
	2010-2018	*279*
Project Duration	< 1 month	855
	2 months	258
	3 months	110
	4 months	63
	5 months	31
	6 months	23
	>6 months	70
	Unknown	*329*

Massachusetts and Vermont had the most projects in the database labeled as Electrification projects. This is due to programs operating in those locations with strong decarbonization goals and with higher incentive rates. This included MA DOER – Home MVP and VT New Leaf Design - Zero Energy Now. The Zero Energy Now program had the highest median total project costs ($53,369), and this program included solely whole-home aggressive upgrade projects targeting

[1] i.e., projects with only one recorded measure
[2] Mostly upgraded duct, heating and cooling systems, with few envelope improvements
[3] Added insulation and air sealing to walls, attics, etc. with no heating/cooling appliance replacement.

>50% fossil fuel savings, with express electrification goals. Both of these Electrification-focused energy programs had the highest median incentive fractions (35% and 24% respectively), compared to the typical incentive fractions of other programs (14-18%). Incentive fractions were typically very high in the envelope-focused projects (60%), which were largely incentivizing deeper envelope upgrades, including exterior wall insulation, triple pane windows, and aggressive air sealing. HVAC-focused and Electrification projects had 29 and 25% incentive fractions, respectively. Electrification is an emerging trend, with new technologies still unfamiliar to most of the contractors and homeowners, and we might expect higher incentives in order to overcome this barrier. However, Electrification incentives do not appear to be higher than other project types.

Project Total Costs

While our data collection targeted projects exceeding typical weatherization performance, there were still many homes that could not be considered comprehensive decarbonization upgrades (i.e., targeting 50% or more reductions in energy and carbon emissions). The median savings across all projects reporting energy use data was 28-33%, depending on the metric used. Overall, this leads to projects with lower costs and fewer measures. This is reflected in the distribution of total gross project costs depicted in Figure 2. The median project cost was $8,740 (mean of $14,429), with a median floor area normalized cost of $4.95/ft^2. The median number of measures in a project was 3 (mean of 3.6). If projects are limited to those with three or more measures (n=923), the median project cost increased to $10,802 (mean of $19,649). Project costs were lowest in recently constructed dwellings (presumably built under improved building codes) and in milder climates, while project costs were substantially higher in older vintages of homes and those located in cold climates. 71% of projects reported receiving incentives to partly fund the energy upgrade work, with a median incentive of $1,327 (mean of $3,053; n=1,218), representing 21% of gross project costs. Incentives were highly variable depending on the program the project participated in. These incentives do not include federal or state tax rebates accruing to the individual homeowner (26% in 2021).

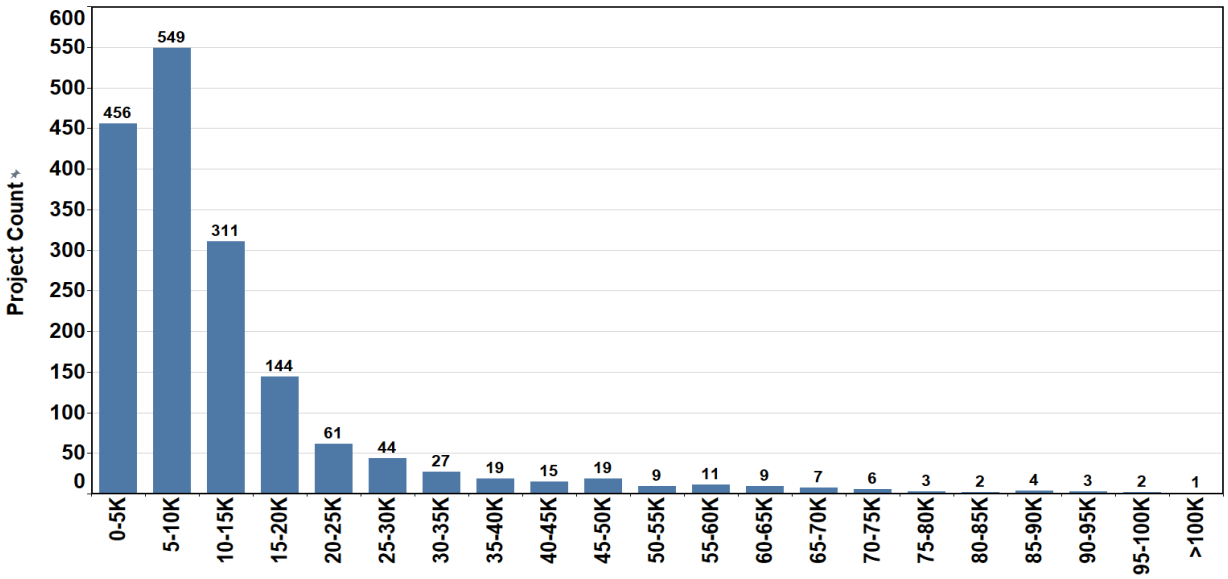


Figure 2. Distribution of gross project costs ($).

Project Measure Costs

The 6,165 retrofit measures that included cost data were subdivided by section into counts in Figure 3a, and into total recorded costs in Figure 3b. The most frequent measures were recorded in the HVAC, followed by House and Attic sections. By far the greatest expenditures were recorded in the HVAC section ($14.2 million). The next greatest expenditures were recorded in the Attic, House and Electrical sections. When all building envelope-related sections are added together, they total 1,742 measures compared with 2,298 HVAC measures. When envelope-related costs are summed, they total $5.3 million compared with $14.2 million for the HVAC section. These results demonstrate the dominance of reported HVAC work in current energy upgrade projects and programs, particularly in terms of expenditures. The House section is mostly building envelope and air sealing upgrades, which explains the prevalence of measures in this section. The Electrical section includes both lighting upgrades and PV installation. Almost all project cost data submitted fell under the total cost category, with effectively no detail provided on labor/material breakdowns or related work (e.g., electrical work for heat pump installation). This is an important limitation when considering where best to put cost reduction efforts, because we do not have clear information on what element of an upgrade drives measure costs.

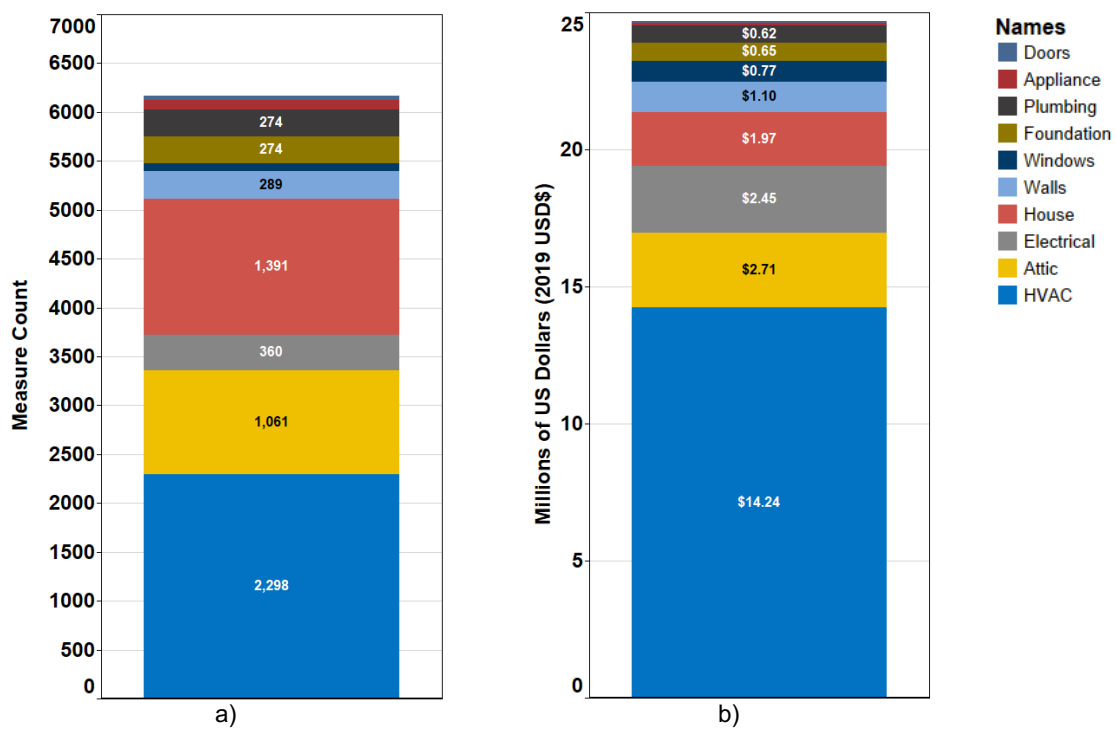


Figure 3. a) Count of recorded measures by section; b) Total recorded expenditures by section.

The median installed costs (total and normalized by floor area) and interquartile ranges are shown for the most frequently installed measures in Figure 4. Measure costs per m^2 of dwelling floor area are shown in parentheses for each measure data label. Each measure is represented by the Section (what part of the house), Action (what was done) and Component (specific element or type addressed). The error bars show the interval between the 25th and 75th percentiles. The frequent measures with median costs exceeding $5,000 per project were solar PV, HVAC equipment and window replacement. Mid-tier measure costs (from $1,000 to $5,000 per project)

were identified for installation of HVAC ducts, water heaters, wall insulation, attic framed floor and roof insulation, foundation framed floor and basement wall insulation, and refrigerators. Lower cost measures ($250 to $1,000) included envelope and duct air sealing, band joist insulation and installation of mechanical ventilation. The lowest cost upgrades (<$250) were lighting and smart thermostats. These figures show the range of costs between measures, while also showing the variability within each measure. The range of costs for almost all measures is very large and is indicative of how building condition, climate and other variables can dramatically alter the costs. This variability within measures has implications for business and homeowner risk acceptability. Measures that have better controlled costs, i.e., less variability, are likely to be more attractive due to reduced uncertainty.

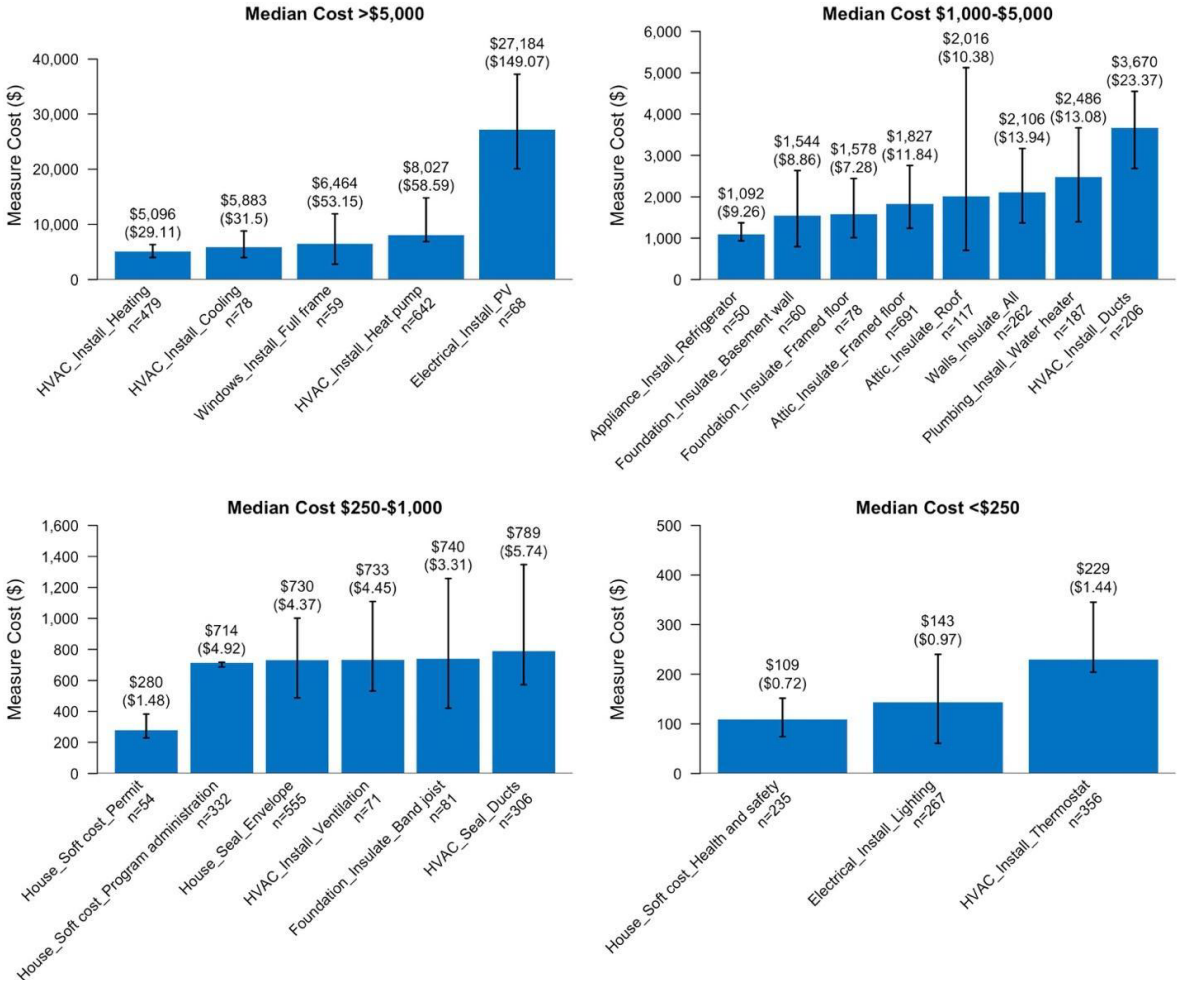


Figure 4. Most frequently installed upgrade measures, median installed costs (per square meter in parentheses) and interquartile ranges (vertical lines).

Energy and CO_2e Use and Savings

1,239 out of 1,739 projects of the database, reported energy data. Net-site energy savings accounted for the contribution of on-site solar systems, though these were quite rare (n=68). Net-site savings was reported by 1,185 projects, largely made up of modeled (66%) and deemed (28%) savings, with small fractions of actual (5%) and unknown data types. The pre-retrofit data had a

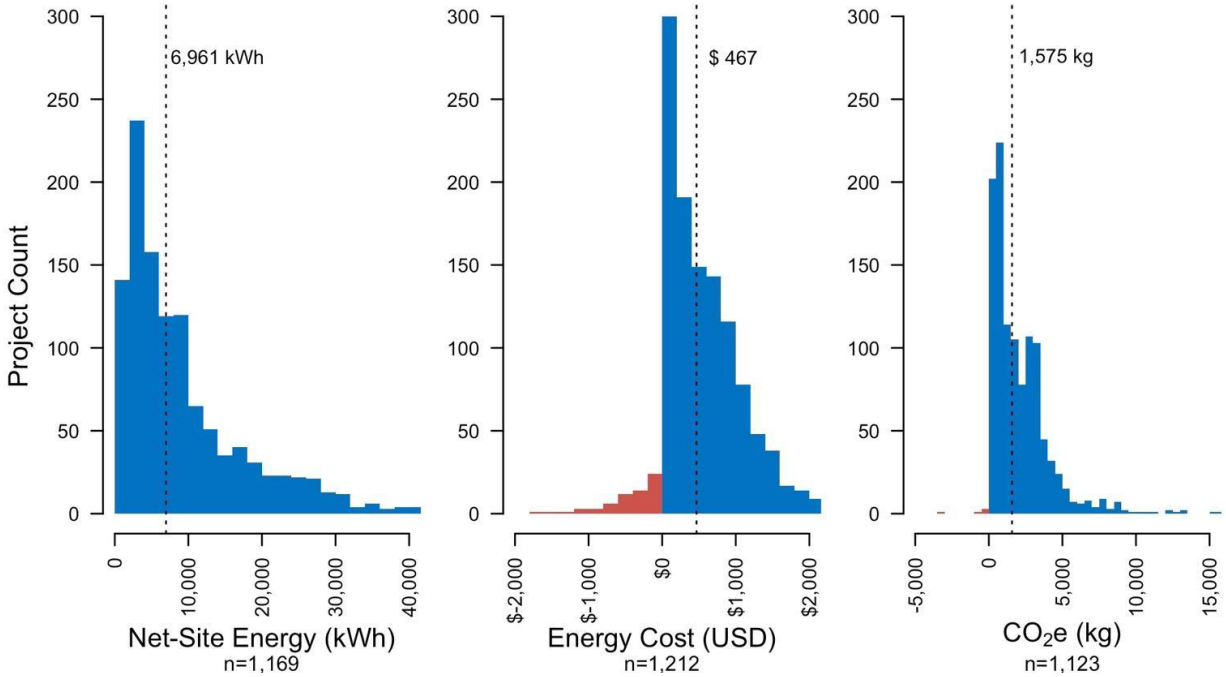
much higher fraction of projects reporting actual energy use (46% vs. 54% modeled).

Fractional savings distributions were quite consistent across each of the three-energy metrics, with 28% median savings for carbon and energy cost, and 33% median net-site energy savings. These results imply that most current programs and retrofits are not aggressive enough to have substantial impacts on meeting climate goals, such as net-zero emissions by 2050[4]. For each metric, the maximum apparent savings were around 80%, though 14-25 projects saved >80% depending on the energy metric. For comparison, a past meta-analysis of US deep energy retrofit projects (Less and Walker 2014) found higher median site energy and cost savings (47% and $1,283, respectively), suggesting that projects were on average achieving and aiming for lower energy savings in this database compared with projects in the 2014 review.

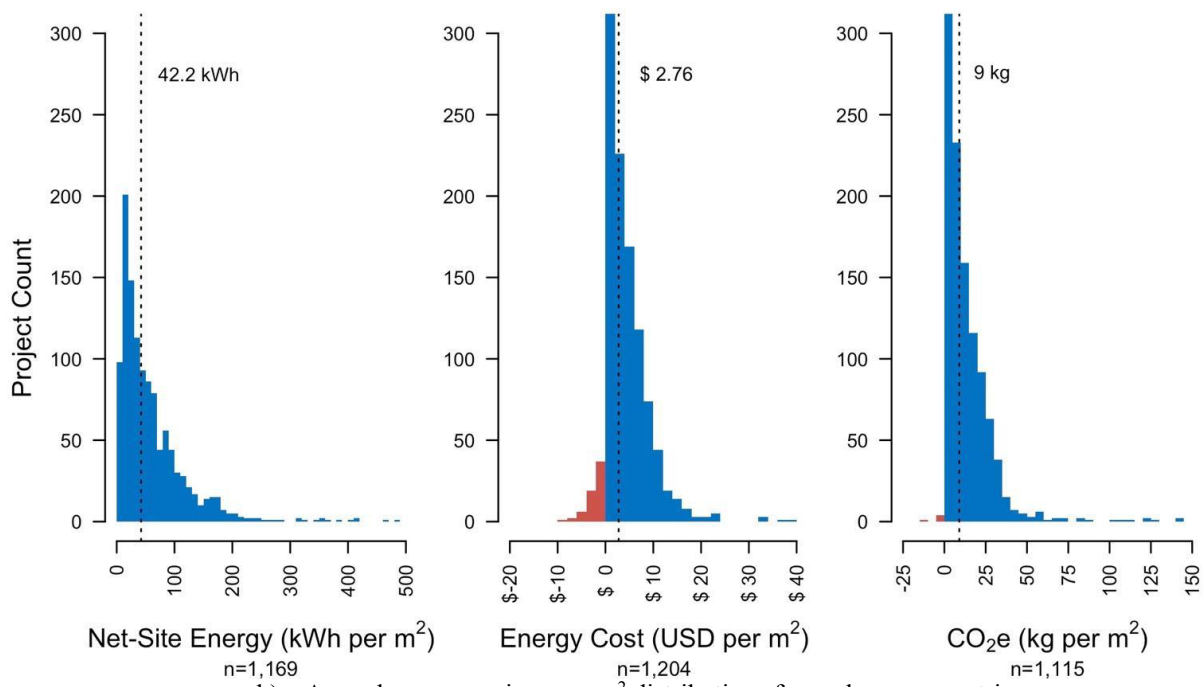
Figure 5 shows the distributions of energy savings for each of the key metrics across all the homes in the database. Median project savings for net-site energy, energy cost and carbon emissions were 6,961 kWh (42.2 kWh/m^2), $467 ($2.8/m^2), and 1.6 metric ton CO_2e (9 kg CO_2e/m^2), respectively. In total, the 1,228 projects reporting energy use recorded a combined annual energy cost savings of $835,622, with annual net-site energy savings totaling 13 million kWh and an annual reduction of 2,600 metric tons (almost six million pounds) of CO_2e emissions. Figure 5 shows savings distributions that are approximately log-normal, with most projects having modest savings and a select few saving lots of energy. A substantial minority of homes increased their energy costs post-upgrade (bars colored red in Figure 5). These were almost exclusively the result of fuel-switching in regions where the cost per unit energy is much higher for electricity than for natural gas, for example, in the states of Massachusetts ($0.184/kWh), California ($0.169/kWh), Vermont ($0.154/kWh) and New York ($0.143/kWh) (US Energy Information Administration (EIA) 2019). This highlights the importance of careful consideration of fuel sources and unit energy prices when electrifying end-uses in home upgrades. Despite this, almost all homes saw carbon reductions.

To confirm the role of Electrification in the energy cost increases observed in Figure 6, we compare the distribution of energy cost savings for the 273 electrification projects with cost savings data, to the savings reported for all other upgrade types (Figure 6). The tendency for electrification projects to increase post-retrofit energy costs in some projects is evident in comparing the distributions, by as much as $1,000 per year in some cases. But we also observe that many electrification projects achieved high reductions in annual energy cost. This is most likely in homes with high pre-retrofit energy bills, such as those heating with propane or fuel oil.

[4] Executive Order 14008, "Tackling the Climate Crisis at Home and Abroad," January 27, 2021.



a) Annual energy savings distributions for each energy metric.



b) Annual energy savings per m^2 distributions for each energy metric.

Figure 5. Annual energy savings distributions.

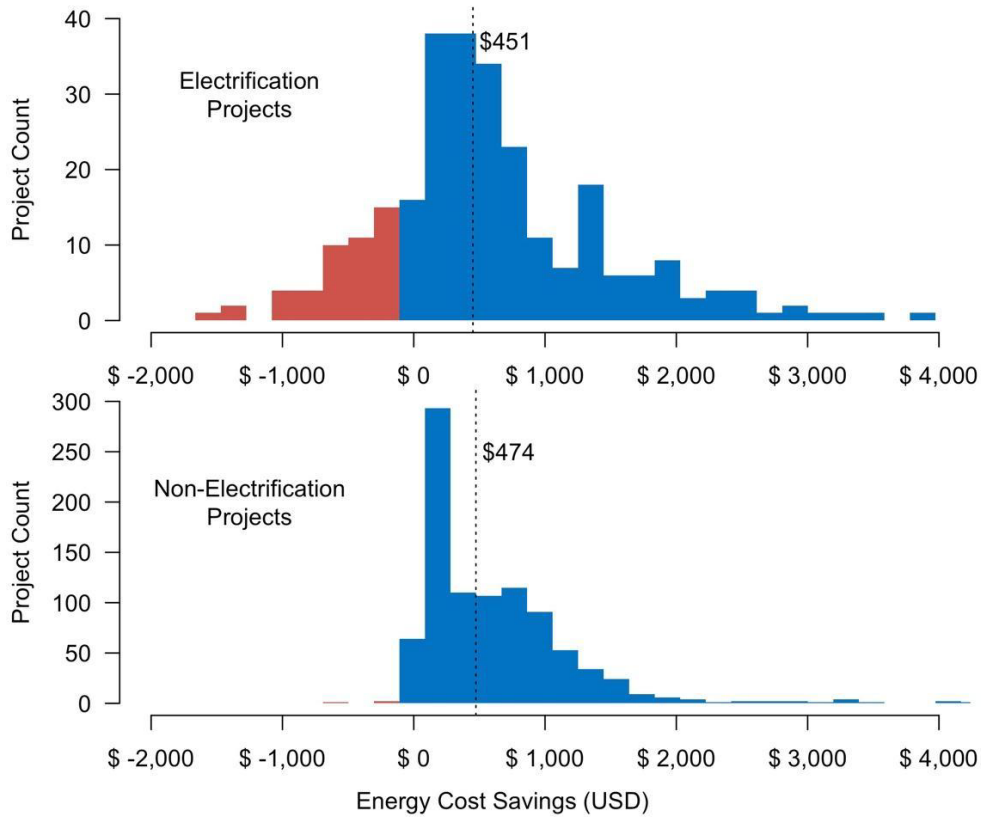


Figure 6. Comparison of energy cost savings distributions for Electrification and non-electrification projects.

Regression Modeling of Energy and Carbon Savings

The study conducted a regression modeling analysis to determine the most important project features associated with changes in savings, as well as to predict savings for new, novel projects. Random forest regression models were built to predict the percent net-site energy savings and the carbon emissions reductions for each project, based on the project characteristics. The cross-validated (10-fold, repeated 5-times) prediction root mean squared errors (RMSE) averaged 12.2% (adjusted R^2 0.578) for the net-site energy model and 15% (adjusted R^2 0.437) for the carbon savings model. These models suggest that typical errors for predicting savings for projects that were not used in building the regression models were 10-15%, and that roughly half of the variance in the data is explained by the model inputs. For both energy savings and carbon reductions, the strongest predictor variables were by far the total gross project costs. This was followed by the number of measures in the project. Taken together, these indicate that energy and carbon savings increase with additional effort and funds invested in the project. When looking at individual measures, expenditures in the HVAC, heat pump and PV systems were most strongly associated with changes in energy and carbon savings. Other common project measures amongst the highest ranked for predicting energy and carbon savings were wall insulation, water heater installation, attic framed floor insulation, envelope air sealing and lighting upgrades. Note that these results are not a cost-effectiveness assessment. Rather, they indicate which elements (such as which measure, number of measures, project cost) of the projects had the greatest impacts on

energy and carbon savings.

As the gross project cost was the strongest predictor in both energy and CO_2e savings regression models, the correlation between total gross project costs per m^2 and CO_2e savings are shown in Figure 7 (the correlation for net-site savings is very similar). This correlation shows a rough, linear relationship between project costs per m^2 and reported carbon savings in the database. This basic analysis suggests that projects targeting greater than 50% carbon savings can currently be expected to spend at least \$250/m^2 (23/ft^2 or about \$40,000-\$50,000 per home). Notably, some lower-cost projects also reported 50% carbon savings (e.g., a minority of projects in the \$200-250/m^2 category), while many more costly projects saved less than 50%. Many fixed characteristics of a home have lower correlation with carbon savings, implying that the ability to save energy and carbon has more to do with what is installed than what cannot be changed about a house.

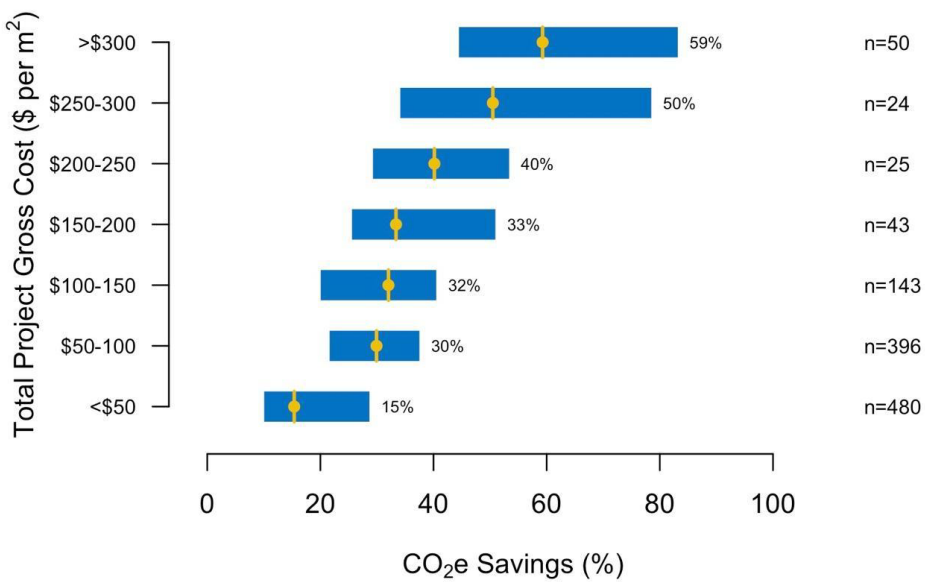


Figure 7. CO_2e savings percentage dependence on gross project costs per m^2.

Prototypical Project Cost Stacks

An analytical tool used in previous technology development to lower costs is the "cost stack" (e.g., US DOE's Sun Shot solar PV program), where the total cost is broken down into components to better observe where efforts should be made for cost reduction. In this study, we developed cost stacks for different projects together with energy and carbon savings estimates. To be manageable and useful for R&D and program/policy planning efforts, we used a k-means clustering analysis to identify six prototypical project types. Clustering is an unsupervised machine learning technique used to identify similar groups of objects in a dataset. The six distinct clusters range in size from 14 to 857 projects. Clustering was performed using cost data for each Section (e.g., total cost recorded in Attic section), and it did not include project meta-data (e.g., location, vintage, etc.), measure performance (e.g., heat pump efficiency or R-value) or energy performance. More details on the clustering analysis can be found in Less et al. (2021).

Table 2 describes the six clusters. For each resulting cluster, we developed a cost stack that was representative of how money was spent across Section categories. These do not represent specific measures, but aggregate costs recorded in the Section. Figure 8 summarizes the cluster

cost stacks and also shows the median CO2e reduction for all of the projects in each cluster. The only clusters with carbon savings greater than 50% are those that used either Superinsulation approaches or Electrification with PV. The Superinsulation approach had lower carbon reductions (51 vs. 68%) for roughly double the cost ($109k vs. $54k), largely because of the high cost of envelope upgrades to the house, walls and attic. Electrification with PV projects were more commonly located in states with low-CO_2 electricity, this, combined with end-use electrification and on-site renewables, tended to increase their carbon savings. The Electrification with PV approach had smaller (though still substantial) envelope upgrades (~$12,000). These projects used more basic insulating approaches, such as filling wall cavities and upgrading attic insulation. All Electrification with PV projects included installation of heat pump HVAC technologies, but these projects were clearly dominated by solar PV costs recorded in the Electrical section. Notably, the measure life of mechanical upgrades (e.g., heat pumps or solar inverters) is commonly considered to be much less than envelope upgrades, so it is important to recognize that this assessment is based solely on upfront costs, and not on longer time horizons that might include periodic equipment replacement. While the Electrification with PV approach offers substantial cost reductions relative to Superinsulation upgrades, it remains far too costly for widespread adoption, at $54,000 per home.

Table 2. Description of clusters for cost stack analysis.

Cluster Name	Description
Basic	Low-cost, basic projects with mostly envelope and limited HVAC work.
HVAC	HVAC projects with standard equipment (~1/2 heat pumps), including some envelope work.
Advanced HVAC	Advanced, higher-cost HVAC projects (>2/3 heat pumps), including some envelope work.
Large Home Geothermal	HVAC-focused projects in large homes with geothermal heat pumps (90%) and some envelope and PV work.
Superinsulation	Comprehensive deep retrofits focused on aggressive envelope upgrades (e.g., double-stud walls, added exterior wall insulation with re-siding, R60 roofs,, triple pane windows, etc.), extensive air sealing, with some gas equipment and little or no PV
Electrification with PV	Equipment electrification projects that include moderate envelope upgrades and PV in all cases.

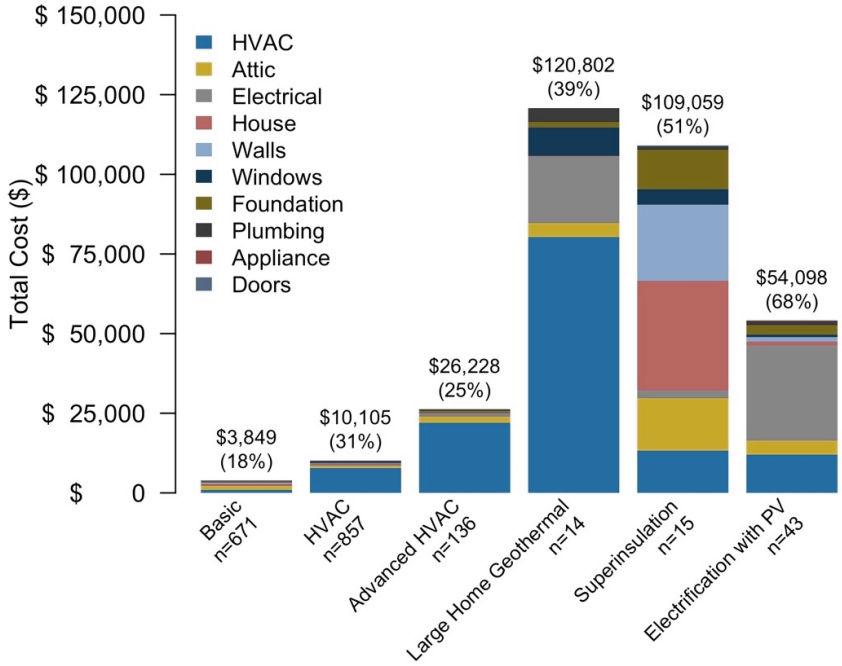


Figure 8. Costs stacks for six project clusters. CO_{2e} savings in parentheses.

Comparison with NREL Measure cost database

Prior to this effort to catalogue the cost of energy and decarbonization home upgrades, the primary source for retrofit cost information used in home energy analysis and optimization was the NREL efficiency measure data base (NREL EMDB (NREL 2018)). The NREL EMDB is used in tools, including BEopt, Home Energy Score, ResStock, and others. Due to its widespread use in analysis tools, we collaborated with NREL to compare a subset of the measure-level costs reported in our database to those currently in the EMDB. We have focused here on comparing common measures that were reported frequently in our dataset (e.g., heat pumps, air sealing), along with measures representing important elements of home energy upgrades (e.g., ventilation equipment). Across most upgrade measures, the costs in the NREL EMDB are lower than those reported for projects in our database. In many cases, by substantial fractions, ranging from 25 to >50% lower. We show some examples of differences in typical measure costs in Figure 9. The most notable exception is envelope air sealing, where the NREL data suggest higher costs than reported in the LBNL database. Some measure costs are similar between the two sources, including 50-gallon heat pump water heaters, programmable thermostats, wall cavity insulation, attic framed floor insulation (depending on the type of insulation material), refrigerators and windows.

Costs in the NREL EMDB may be lower for a number of reasons. First, most of the measure costs were based on data gathered by NREL and its partners in the period from roughly 2005 to 2010, and there are no automatic mechanisms in the database or analysis tools to adjust these costs to the current value of the US dollar. Relative to the year 2019, which is the assumption used for all LBNL energy upgrade costs reported in this paper, RSmeans historical cost adjustments suggest that 2010 dollars can be converted to 2019 dollars by multiplying by 1.266 (1.532 for 2005 costs). By this logic, if the $2,200 80-gallon heat pump water heater cost was

recorded in 2010, it would be adjusted to $2,785 in 2019 USD$, which is still much lower than reported in the LBNL data ($3,828). Adjusting for inflation gets many measure costs closer to one another, but by no means comparable. Similarly, there may be cost differences between typical or standard practice (NREL data), compared with more comprehensive upgrade projects (LBNL data). Deep retrofit and decarbonization contractors or programs may have higher overhead and project management costs, and they might also perform more robust work (e.g., diagnostics, commissioning, HVAC sizing, etc.). In the future, some of the new data from this study will be used to support revisions to the NREL database. In addition, more data collected from projects after May 2020 may be added to assess construction cost increases associated with COVID and other supply chain issues.

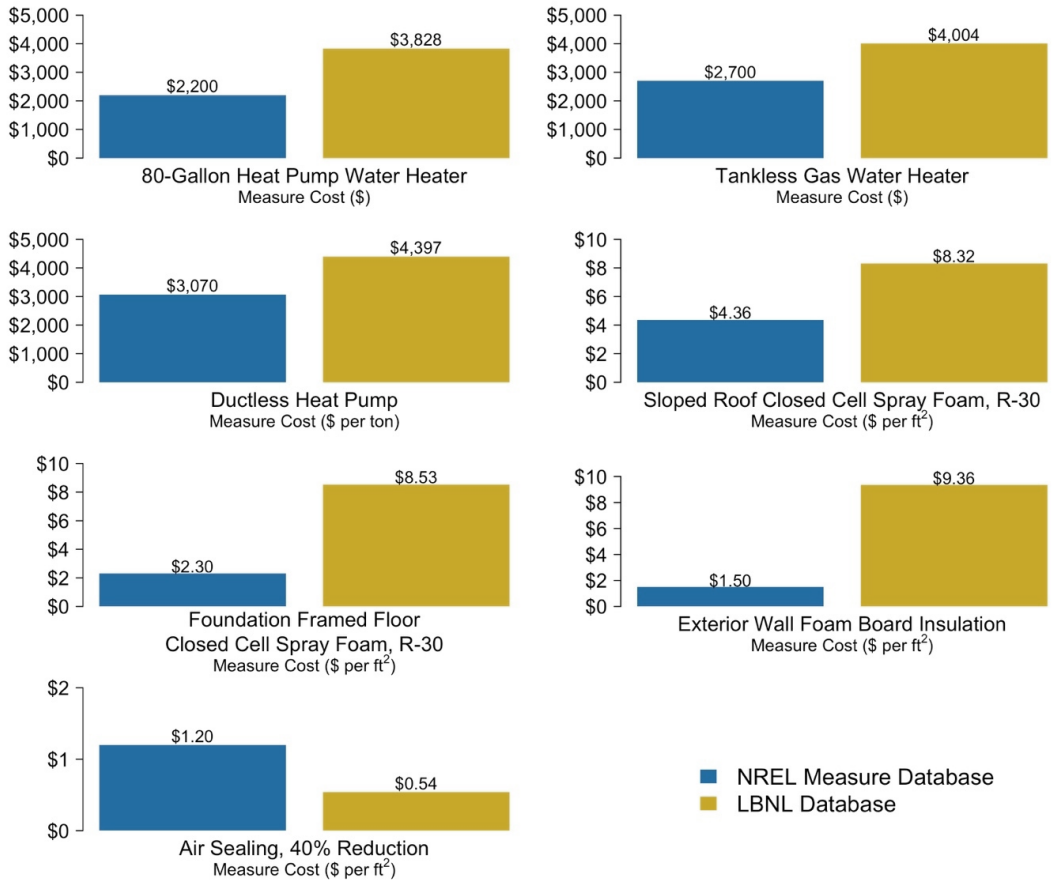


Figure 9. Comparison of typical measure costs between the LBNL and NREL efficiency measure databases.

Concluding Remarks

To develop cost benchmarks to guide future R&D efforts and program plans for scaling the residential energy upgrade market, we compiled a database of project cost data, household meta-data, and energy data. Project data was obtained for 1,739 projects, from 15 states and 12 energy programs, with a total of 10,512 individual measures (including rebate/incentive measures). The most common (and most costly) measures were HVAC system, envelope insulation and electrical upgrades that included installation of heat pump and PV systems. Median annual project savings for net-site energy, energy cost and carbon emissions were 6,961 kWh (42.2 kWh/m^2),

$467 ($2.8/m^2), and 1.6 metric ton CO_2e (10 kg CO_2e/m^2), respectively. There was large variability in savings due to the large range of projects covered by the database. We note that a minority of projects had increased energy costs post-upgrade, likely due to switching from cheap natural gas to more expensive electricity, which offset savings from reduced energy consumption. Median project costs were only $8,740 (mean of $14,429), or $53.3/m^2, and most projects did not have the energy savings or carbon reductions required to meet climate goals. To consistently reach reductions of 50% or greater, project costs had to be at least $250/m^2 ($23/ft^2), or about $40,000-$50,000 per home. These results show that in order to scale home decarbonization, significant cost reductions are needed. In addition, incentives need to increase to be more aligned with the real-world cost of completing these projects, and R&D should be focused on reducing costs for the measures most impacting CO_2e reductions. Financing can improve project affordability and scalability, so future efforts must go beyond the current energy program practice reflected in the database. For both energy savings and carbon reductions, the strongest predictor variables in regression models were by far the total gross project costs. The range of costs for almost all measures is very large. This is indicative of how building condition, climate and other variables can dramatically alter the costs. Comparing to the NREL EMDB that is used in economic analyses for setting policy, program and R&D planning, we found that costs reported in the present database were about 25-50% higher, depending on the individual measure being assessed, indicating that the NREL efficiency measure database should be updated. Efforts are underway to include the new data in the NREL EMDB. A clustering cost-stack analysis showed that the lowest-cost approach to achieve significant CO_2e savings included moderate envelope upgrades together with electrification and PV. However, even this approach was likely too expensive for getting to scale, at an average of $54,000 per home.

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References

"AGC 2021 Construction Inflation Alert." 2021. Associated General Contractors of America.

Chan, Wanyu R., Brennan D. Less, and Iain S. Walker. 2021. "DOE Deep Energy Retrofit Cost Survey." Berkeley, CA: Lawrence Berkeley National Laboratory. https://doi.org/10.20357/B7MC70.

Cluett, Rachel, and Jennifer Amann. 2014. "Residential Deep Energy Retrofits." A1401. Washington, D.C.: American Council for an Energy Efficient Economy (ACEEE).

Cluett, Rachel, and Jennifer Thorne Amann. 2016. "Scaling Up Participation and Savings in Residential Retrofit Programs." A1605. Washington, DC: American Council for an Energy Efficient Economy (ACEEE). https://community-wealth.org/sites/clone.community-wealth.org/files/downloads/Scaling%20Up%20Participation%20and%20Savings.pdf.

EMI Consulting. 2016. "Energy Upgrade California – Home Upgrade Program Process Evaluation 2014-2015." Final Report. San Francisco, CA: Pacific Gas and Electric Co. http://www.calmac.org/publications/EUC_Home_Upgrade_Process_Evaluation_Report_Draft_2016.08.24_%28CLEAN%29.pdf.

Holladay, Martin. 2012. "The High Cost of Deep-Energy Retrofits | GreenBuildingAdvisor.Com." 2012. http://www.greenbuildingadvisor.com/blogs/dept/musings/high-cost-deep-energy-retrofits.

Lane, Thomas. 2019. *Contractor's Pricing Guide: Residential Repair & Remodeling Costs with RSMeans Data 2020.*

Less, Brennan D., and Iain S. Walker. 2014. "A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S." No. LBNL-6601E. Berkeley, CA (United States): Lawrence Berkeley National Lab. https://doi.org/10.2172/1129577.

Less, Brennan D., Iain S Walker, N. Casquero-Modrego, and Leo Rainer. 2021. "The Cost of Decarbonization and Energy Upgrade Retrofits for US Homes." Lawrence Berkeley National Laboratory (LBNL).

McIlvaine, J., S. Saunders, E. Bordelon, S. Baden, L. Elam, and E. Martin. 2013. "The Next Step Toward Widespread Residential Deep Energy Retrofits." FSEC-CR-1954-13. Cocoa, FL: BA-PIRC/Florida Solar Energy Center. http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1954-13.pdf.

NREL. 2018. "National Residential Efficiency Measures Database (Version 3.1.0)." 2018. https://remdb.nrel.gov/.

US Energy Information Administration (EIA). 2019. "State Electricity Profiles." 2019. https://www.eia.gov/electricity/state/.

Walker, Iain S., Brennan D. Less, and Núria Casquero-Modrego. 2022. "Carbon and Energy Cost Impacts of Electrification of Space Heating with Heat Pumps in the US." *Energy and Buildings* 259 (March): 111910. https://doi.org/10.1016/j.enbuild.2022.111910.