Title

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ABSTRACT

Decarbonization of energy use in homes will be necessary for the US to meet its climate goals. Currently, very few homes are undergoing decarbonization upgrades and pathways are needed to scale up these efforts. This study combined a literature review, an industry survey and a project cost database in order to identify the key barriers and potential solutions to increased adoption of home decarbonization. We analyzed key cost-compression activities, together with the non-cost innovations needed by the residential buildings industry. We present pathways for home decarbonization based on these results, together with emerging technology innovations and market solutions that were identified during the project. The pathways include non-energy issues, such as health and comfort, as well as addressing related topics, such as financing and grid integration. These pathways identify where R&D efforts are needed and the innovations required to successfully implement decarbonization programs at scale.

Introduction

To examine the best approaches for decarbonizing homes in the US, we conducted a study with three parts. First, a literature review (Less, Walker, & Casquero-Modrego 2021) summarized the academic, professional, and energy program studies attempting significant energy reductions in homes. Second, an industry survey (Chan et al. 2021) was used to determine the industry perspective on home energy upgrades, identifying current barriers to decarbonization and potential ways to change the home energy upgrade market. Finally, cost and energy data from over 1,700 home energy upgrade projects were analyzed to find ways to make decarbonization more popular by addressing affordability and identifying optimum decarbonization strategies (Less, Walker, Casquero-Modrego, et al. 2021). The upgrades cost database is reviewed in detailed in a companion ACEEE Summer Study paper by Walker, Less, Casquero-Modrego, et al. (2022). This paper will focus on combining the results of these studies in order to develop pathways to decarbonize existing homes in the US.

A key issue we need to address is what do we mean by “decarbonization”? In this paper, we set a target of reducing carbon emissions by at least half. However, we acknowledge that this is probably not good enough and to go beyond this level of reduction will require electrification of all major end-uses in order to be able to use low-carbon content energy. Our future carbon reduction targets will likely be much more stringent, and we cannot get to zero emissions with efficiency alone – we will have to electrify and use renewables and other low-carbon energy sources. This would argue against using fossil-fuel powered appliances in our analyses, as these bake-in many years of fossil fuel emissions. Nevertheless, from a practical, near-term, viewpoint we will need strategies that strike an appropriate balance between carbon emissions, cost-effectiveness and practicality. We define “cost-effectiveness” as a comparison between a project’s actual costs and the present value of the project’s reported energy cost savings. Consistent with this, our analyses include fossil-fuel appliances and considers efficiency upgrades.

In electrifying all homes, we need to bear in mind the potential for increased energy bills for some occupants, and we also need to consider the varying carbon content of electricity throughout the US. While beyond the scope of this paper, a recent publication by Walker, Less, & Casquero-Modrego (2022) discussed the state-by-state heat pump performance required to break even from an operating cost and CO_2e point of view in each state. CO_2e represents the global warming potential of all emitted greenhouse gases converted to the equivalent global warming potential in tons of CO_2. Other sources (Alstone et al. 2021; Maguire et al. 2014) have also studied required heat pump water heater performance that account for this variability.

There are several ways to reduce carbon emissions from homes. For currently electric end-uses, a primary pathway is to reduce the carbon content of electricity by generating less of it from fossil fuels. Reducing electricity use (particularly in locations using fossil fuels to generate electricity) can also help, primarily this is from the use of higher efficiency appliances. Improved appliance efficiency must first focus on the big energy users (space and water heating) using high-performance heat pumps, with potential 3-4 fold reductions in site energy use. For homes with fossil fuel systems (heating, hot water, clothes drying and cooking), it is difficult to achieve carbon reductions through appliance replacement, because there are limited energy savings available from fuel-burning appliances. For example, a 96% efficient natural gas furnace cannot reduce its site energy use by factors of three through improved efficiency. If fossil fuel appliances are retained, the majority of carbon reductions have to come from substantial load reductions. The alternative is to replace fossil fuel appliances with electric equipment. This means using heat pump technologies for heating, hot water and clothes drying, and induction cooktops and electric ovens for cooking. This latter path can be referred to as “electrification”: i.e., households change the source of energy from on-site combustion (usually fossil fuels, but also including biomass) to electricity. It is also the only path that allows us to get to zero carbon homes. This paper will not include some important factors that will be essential as we move forward with home electrification, such as thermal storage for leveling out demand or how to integrate home EV charging. This is because the survey and cost data are from the current residential market and reflect actual costs and experiences of the industry to date.

At present, there a small number of leading contractors, utility programs and non-profits that are electrifying homes. There is no large established no industry doing this work, with no electrification-specific workforce or infrastructure. This study attempts to define a pathway, so that this industry can be created and rapidly scaled up to meet this challenge.

The State of Energy Upgrades of US Homes

In order to create a pathway to decarbonization, we need to know the state-of-the-art for energy upgrades (including electrification) in US homes in general. The literature review for this study (Less, Walker, & Casquero-Modrego 2021), investigated 161 scientific papers and technical reports from the past ten years and reached the following general conclusions about the energy upgrades market in the US.

- Current energy upgrades do not save enough energy (or carbon) – typically in the 30%-40% range.
- Projects focused solely on energy savings are not appealing to most households.
- Market interest and acceptance is low amongst homeowners.
- Costs are too high and improved financing mechanisms are a core need.
- Economic justifications are challenging and possibly inadequate. Low electricity and natural gas prices make financial payback arguments challenging.
- There is a lack of trained workforce with the necessary skills.
- There is a lack of real estate market valuation of energy upgrades.
- Upgrade programs are beginning to use emerging carbon-related metrics.
- Consumer demand and program support is increasing for solar PV and electrification technologies, while costly and time-intensive aggressive envelope upgrades are becoming less common.

The literature review identified an increasing interest in home electrification, supported by other analyses that have shown home electrification to be financially beneficial under select local rate structures, fuel sources and dwelling types. One study (Energy and Environmental Economics 2019) focused on building electrification in California, concluded that electrification can lead to consumer capital cost savings, bill savings and lifecycle savings. This was the case for new home construction and for existing homes replacing air conditioners with high efficiency heat pumps. Griffith et al. (2020) highlight the importance of having low carbon electricity sources, reduced energy costs and improved financing. Other studies have reached broadly similar conclusions (Billimoria et al. 2018; Hopkins et al. 2018). Home electrification is also appealing due to health and safety concerns, because it reduces the risks from CO, NO_2, particles and other combustion-related contaminants of concern (Tan & Jung 2021). The literature review identified innovative technologies that address the costs of upgrading the electric panel, electric service and electric circuits in the home. This can be achieved through a combination of low-power appliances (e.g., 120V heat pump water heater), along with smart panels and circuit splitters that allow circuit sharing. These approaches have already been developed into guidance documents for use by practitioners (Redwood Energy 2020).

Affordability, Financing and Net-Monthly Ownership Cost

Cost analysis by Less et al. 2021 and Walker et al. 2022 showed that to achieve carbon reductions of at least 50% in existing homes typically requires at least $\$250/m^2$ ($23/ft^2$; \$40,000-\$50,000 per home) (2019 USD). Consistent with this, the industry survey by Chan et al. (2021) and past surveys reviewed in the literature review suggest that upfront costs are the main barrier to home decarbonization upgrades. Later in this paper, we demonstrate some pathways to reduce these costs at both the whole project and individual measure level. Yet, even with lower costs, the required home investment remains substantial and out of reach for nearly all US households, where median household savings were \$5,300 (in 2019), with a mean household savings of \$41,600. The vast majority of US households will need financing to decarbonize their homes.

Financing is relatively uncommon in both general residential remodeling (Guerrero 2003) and in other energy upgrade databases (Palmer et al. 2013). In our review of the literature, Less, Walker, & Casquero-Modrego (2021) found that energy upgrade projects often do not use financing, even when it is available. For example, of the 75,110 projects whose information was recorded during the DOE Better Buildings Neighborhood Program (BBNP), only 12,360 (16%) were financed using loans. There is some evidence in the review suggesting that use of financing is more common in projects that had greater energy savings. For example, in an analysis of Energy Upgrade California projects, those projects with the greatest savings used financing roughly half the time (49%), while projects with lower savings used financing much less frequently (30%). Similar results were observed for the BBNP program (Heaney & Polly 2015), where financed projects generally had higher savings and nearly double the investment in the upgrades. Of the 1,739 projects analyzed in the LBNL database, we confirmed that financing was used for 467 projects (27%), though that number may very well be higher, because many projects did not record financing information. Taken together with trends from the literature, we observe that financing is relatively uncommon in home upgrade work. Consumer preference and attitudes towards financing varies across sociodemographic variables like income, urban/rural location, language and cultural practices, etc. Some literature on energy equity and environmental justice suggests many residents may not understand the financing, believe the claims for energy savings offered by financing providers and/or contractors, or otherwise may have aversion to incurring debt (Bardhan et al.

2014). Nevertheless, the high cost of the required upgrades indicate that attractive and widely available financing will need to be provided to get to scale.

Using projects in the LBNL database, we performed a net-monthly assessment of ownership costs (i.e., balance of monthly loan cost vs. monthly energy cost savings) under a variety of financing scenarios representative of loan products available for home renovation/upgrades (i.e., 10-, 20- and 30-year loans at 0, 3 and 8% interest), with and without a hypothetical 25% federal rebate. In Figure 1, the net-monthly ownership cost is assessed for the 1,212 projects in the database that included both energy cost savings and total project costs. In this plot, positive values show increased net-monthly ownership costs (savings are less than loan costs), while negative values indicate reduced net-monthly ownership costs (net-cost savings). Under most financing scenarios examined, the median net-monthly ownership costs increase by between $6 to $59 per month due to upgrades. In other words, under these financing assumptions, household costs increased rather than decreased post-upgrade. For a program covering a portfolio of homes, these results are promising, because central values are near-zero. For individual homes on the high-end of monthly costs, this may present a significant barrier to energy upgrade adoption. To ensure net-savings in the majority of homes requires either 0% financing or very long loan terms (e.g., 30-years).

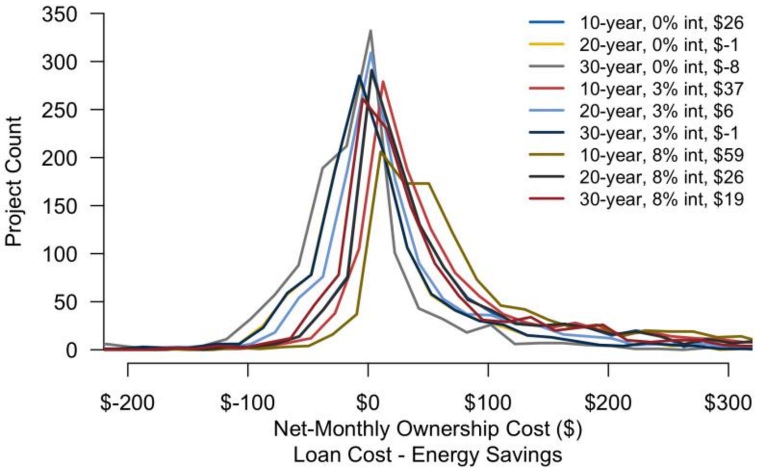

Figure 1. Net-monthly ownership cost under nine financing scenarios, including three interest rates (0, 3 and 8%) and three loan terms (10-, 20- and 30-year). Median monthly ownership costs are shown in the plot legend. Negative values indicate net-monthly cost savings post-upgrade, and positive values indicate net-monthly cost increases post-upgrade.

We repeated the monthly ownership cost calculations shown above including a flat 25% rebate across the gross costs reported for each project. The relative impacts of a 25% rebate on net-monthly household ownership cost depend strongly on the financing terms. More advantageous financing terms show little benefit to a 25% rebate, while the worst financing terms benefit substantially from a rebate. Comparing the impacts of financing terms against the impacts of a rebate, securing advantageous financing is more likely to benefit household's net-monthly ownership cost independent of the measures adopted in the project. For example, shifting from the 10-year, 8% to the 30-year, 3% loan terms reduce median net-monthly ownership costs by $60 (from $59 to -$1). This would represent a $60 per month benefit to homeowners. In contrast, the 25% rebate at most reduces net-monthly ownership cost by $27 (from $59 to $32). These results indicate that a combination of rebates together with long-term, no-/low-interest financing may be necessary to reduce the risks to homeowners of increased monthly costs. From an equity point of view, it is important to broaden eligibility for financing, and this will require adoption of financing mechanisms that are less dependent on an individual's credit history (e.g., on-bill repayment).

Levelized Cost of Saved Energy (LCOE)

The LCOE distributions for all projects in the database are shown for net-site energy (kWh), energy cost (USD) and carbon emissions (lbs. CO_2e) in Figure 2, assuming a 15-year measure life and 3% discount rate. This rate is based on guidance from the US OMB (*OMB Circular No. A-4* 2003) and others (Drupp et al. 2015) as a reasonable rate at which society discounts future consumption. The median values were \$0.11 per kWh, \$1.36 per project dollar, and \$0.21 per lbs. CO_2e saved. The net-site kWh values include all fuel types and do not represent solely electricity. While \$0.11 per kWh of site energy saved is competitive with the US average retail price of electricity in 2019 (\$0.1054 per kWh), the retail pricing for natural gas is typically much lower nationally (\$0.0359 per kWh). If we assumed a 6% discount rate, the LCOE median would increased to \$0.134 per kWh. For comparison, Goldman et al. (2020) analyzed a variety of energy retrofit program types, and they reported typical LCOE for whole house retrofit programs of \$0.069 per kWh, assuming a 6% discount rate. Whole home programs had the second highest LCOE in Goldman's analysis, while lighting and other single-measure programs had lower LCOE. According to Goldman, low-income energy programs had the highest LCOE of roughly \$0.10 per kWh.

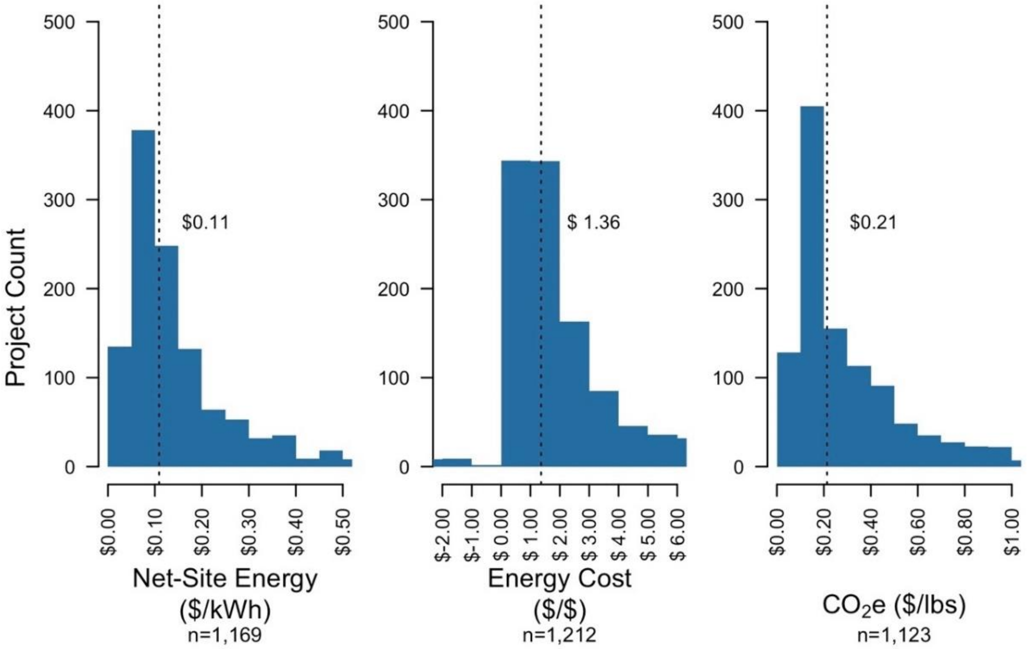

Figure 2. Levelized cost of savings. 15-year measure life and 3% discount rate.

Overall, the LCOE in the deep retrofit database were substantially higher than those for whole-house programs assessed by Goldman et al. This may be because the LBNL upgrades are targeting higher levels of energy savings than in Goldman et al.'s past assessments. As savings targets are increased, typically the cost to save each additional increment of energy increases.

Indeed, the LCOE generally increased with greater project expenditures, but the relationship was weak ($R^2 = 0.13$), as a wide range of LCOE values were apparent at all levels of project cost. This weak correlation is likely due to other factors affecting the LCOE, such as climate, pre-retrofit condition of the dwelling, equipment/measure types (e.g., cellulose vs. SPF insulation) and project strategies. Energy upgrade project types that commonly saved >50% of net-site energy and carbon often had very high LCOE values of $0.18 to $0.39 per kWh saved, suggesting a substantial need for cost reduction.

Project Type Clustering to identify Lower Cost Approaches

To identify lower-cost pathways to reducing household carbon emissions by 50% or more, we applied clustering techniques to projects in the LBNL database using the measure costs for each individual project. Clustering is an unsupervised machine learning technique used to identify similar groups of objects in a dataset. In the existing scientific literature there are studies that have already used clustering techniques for representative building identification on dwellings (Famuyibo et al. 2012; Schaefer & Ghisi 2016). The details of the clustering analysis are covered in Less et al. (2021). A total of six distinct clusters were developed, ranging in size from 14 to 857 projects. Based on a subjective expert review, we assigned each cluster a short, human-interpretable name that represents some of its primary characteristics (see Table 1).

To inform research aimed at reducing retrofit costs, a cost stack was developed for each cluster. The typical distributions of project expenditures were applied to the median cluster costs in order to produce these summaries. The cluster cost stacks organized by Section are shown in Figure 3, together with the same cost stacks using on three cost categories—envelope, equipment and PV.

Table 1. 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., exterior wall insulation, triple pane windows, etc.) 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.

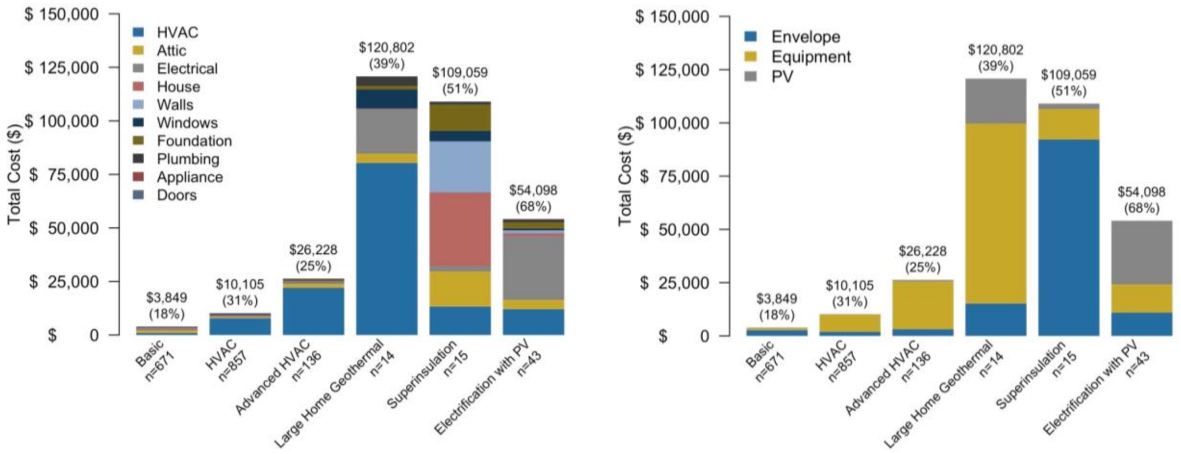

Figure 3 Cluster cost stacks by Section category and with reduced cost categories. Median values of total gross project cost and percent carbon reductions

Only two clusters had median CO_2e reductions greater than 50%: the Superinsulation and the Electrification with PV. Typical envelope insulation and sealing costs in the Superinsulation cluster were roughly $60,000, with total project costs exceeding $100,000. Electrification with PV is a combination of solar PV, comprehensive weatherization work, and electrification of end-uses with heat pump technologies. Envelope costs are still substantial ($12,000), but investment largely shifts to installing PV. This emerging approach is half the cost per square foot ($301 vs 614 per m^2 or $28 vs $57 per ft^2), the net-site savings are slightly greater (72 vs 64%) and the carbon emission reductions are substantially higher (68 vs 51%). Even with its lower costs, the net-monthly ownership costs of the Electrification with PV cluster remain substantial (+$90 per month) when financed using 30-year financing at 3% interest. The levelized cost of saved energy in these clusters exceeds utility rates in most of the country ($0.18 per kWh).

Required Cluster Cost Compression

While the Electrification with PV cluster represents a lower-cost pathway to increased carbon savings, it is not cost-effective. The present value of the energy cost savings are less than the reported project costs. Cost compression is the amount that costs must be reduced such that a project is cost-effective. This cluster requires cost compression in order for the savings to adequately offset the costs. In this section, we quantify the amount of cost compression required for each cluster to be cost-effective.

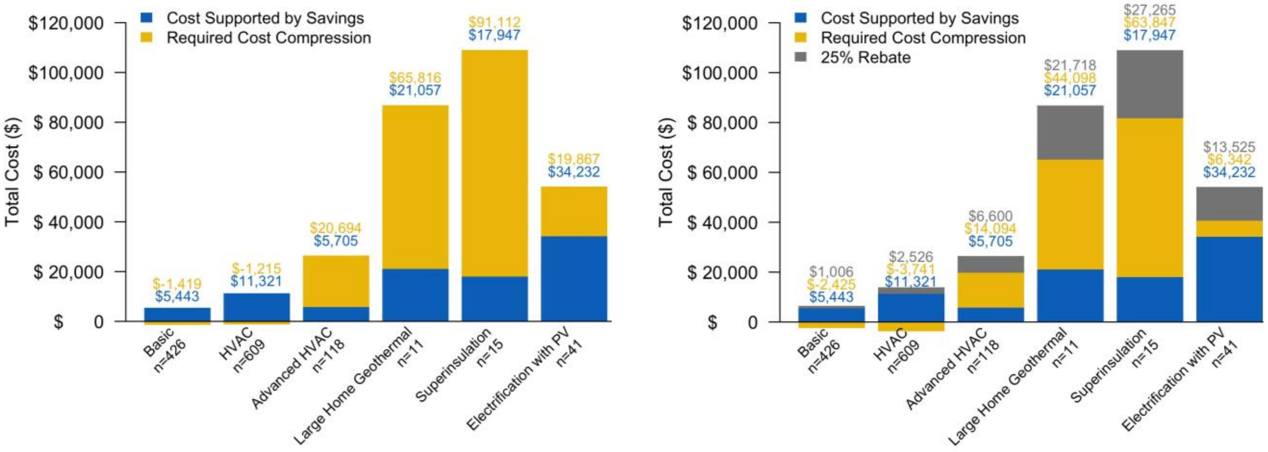

Figure 4. Required cost compression for each project cluster. 30-year, 3%. Without (left) and with (right) hypothetical 25% rebate.

The median present value of the energy savings (blue) and required cost compression (yellow) are shown for each project cluster in Figure 4, assuming a 30-year loan with 3% interest rate. A hypothetical 25% federal rebate (grey) is included on the right-hand plot. Based on these assumptions, the first two clusters are already cost-effective, because the actual projects cost less than the loans that could be supported by the energy cost savings. For these projects, we expect the net-monthly ownership cost to be positive (i.e., the savings are greater than loan costs). The remaining clusters, including all clusters with >50% average carbon savings, require substantial cost compression in order to be cost-effective. The required compression ranges anywhere from $20,000 to $91,000 in cost reductions. The Electrification with PV cluster is nearest to being supported by the energy cost savings, with a required 37% percent reduction in project cost ($20k). With a 25% rebate, the required cost compression for this cluster would be only $6,342. Upgrade projects achieving the level of cost savings reported for the Electrification with PV projects could cost-effectively support a project costing roughly $34,000 ($48,000 with 25% rebate). The Superinsulation and Large Geothermal projects require much greater cost compression of seven to ten times that of the Electrification with PV approach.

Optimizing for Carbon Reductions using Archetypal Projects

We also developed novel project approaches in an effort to reduce costs even further for decarbonization projects. To do this, we created archetypal projects representing an example dwelling that matches the typical characteristics of homes in the database: floor area of 164.3 m^2 (1,768 ft^2), single-story, wood framed, single-family dwelling with a basement foundation[1], built in 1970. The archetypes for this example home were assembled from the bottom-up using combinations of measures in each of three categories: Envelope, Equipment and Solar PV. The measures considered within each category were:

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[1] The basement foundation determines the insulation used for the foundation, it is not used, for example, as a default for duct location.

- **Envelope**: None, Weatherization (Wx), Home performance (HP), Deep Energy Retrofit (DER). The DER has more envelope air sealing, better foundation/wall insulation and replaced windows compared to HP.
- **Equipment**: None, Electrification (Elec) and Gas (Gas). “Gas” includes only space and water heating, no cooling.
- **PV**: None, Small, 3.35 kW, Medium, 6.7 kW, Large, 10 kW

More detailed measure specifications and costs in each category can be found in Less, Walker, Casquero-Modrego et al. (2021). The costs for each individual measure were either predicted using random forest regression models built for each individual measure, or they were predicted using the median cost recorded in the energy upgrade database. The costs for each category are summarized in Figure 5. This figure includes a Gas+Cooling category under Equipment, which is not included in the broader archetypes analysis. This is included in the figure simply to show a comparison of predicted costs for gas versus electric equipment when also replacing air conditioning.

Project costs and percent CO_2e savings were predicted using regression models for each of 48 archetype projects. We focus our remaining discussion on the archetype projects with regression-predicted CO_2e reductions of 60-70% (see Figure 6). Those archetypes are sorted according to the predicted total project cost. We do not include the predicted carbon savings, because the accuracy of our regression model is roughly +/-14%, so any specificity within the 10% range from 60-70% is unreliable. Bear in mind that these archetypal costs could be higher or lower depending on the specifics of the home being retrofitted. The costs and savings are predicted using regression models and do not represent engineering estimates. For example, from an engineering perspective, we know that larger PV systems would lead to greater savings, but this is not adequately reflected it in our results.

We note the following general trends:

- Minimum cost identified for 60% carbon savings was ~\$40,000 (\$23/ft^2 or \$244/m^2).
- All of these projects include PV systems to offset on-site consumption.
- The most expensive projects always included aggressive DER envelope upgrades.
- If PV was included, either gas or electric equipment upgrades were compatible with substantial carbon reductions, but electric equipment projects were twice as likely to be in the group of lowest cost projects achieving 60 to 70% savings.

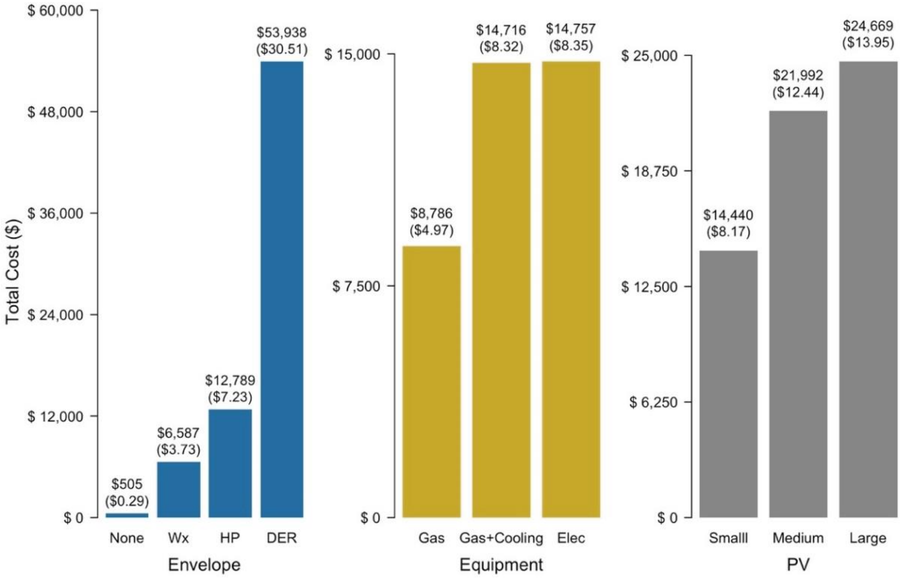

Figure 5. Archetypal project costs in each category (Envelope, Equipment and PV) for each set of archetypal retrofit measures. Costs per ft^2 are shown in parentheses.

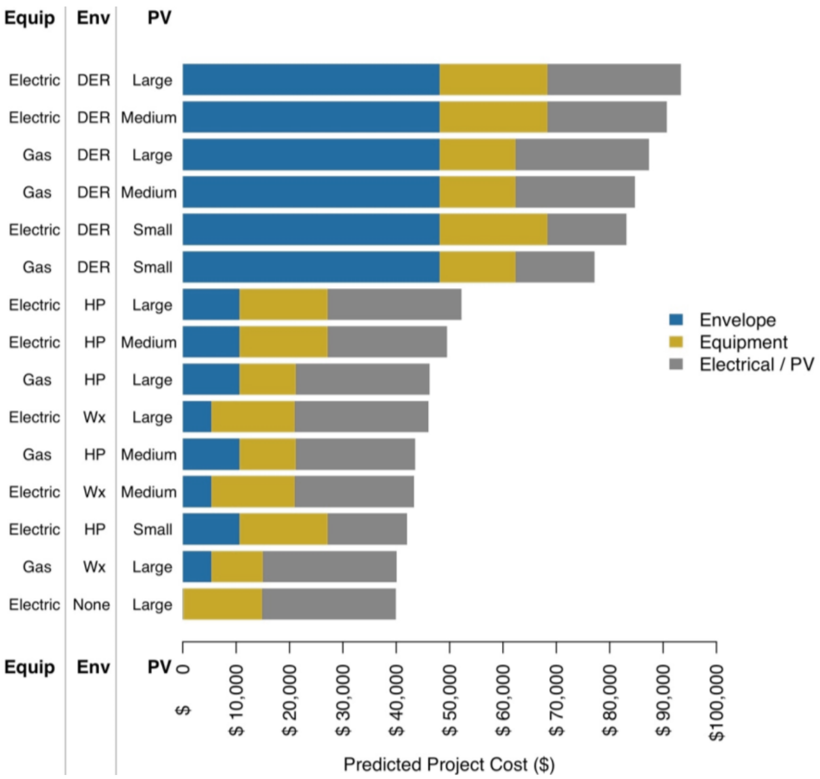

Figure 6 Archetypal upgrade projects predicted CO_2e savings >60%.

Cost Compression Pathways for Individual Technologies

The clustering and archetype analyses presented above suggest how project design at the whole house-level can be optimized to reduce costs. Here, we offer explicit though hypothetical examples of how individual measure-level costs might be reduced. Example waterfall plots showing estimated cost compression pathways for ductless heat pumps and heat pump water heaters are shown for illustrative purposes in Figure 7. Each technology starts as the median cost recorded in the LBNL database, and estimated cost reduction opportunities are plotted as per ton or per unit savings until reaching a compressed cost. These targets are the cumulative impact of all the example cost reductions listed in figure. The target numbers are not based on cost-effectiveness or technical potential. Each cost reduction in these waterfall plots is based on our best estimate of the potential, but the values require further validation. The cost reduction pathways illustrated in these waterfall plots address some of the primary cost drivers in this industry, including soft costs (e.g., customer acquisition, HVAC sizing or diagnostics), supply chain issues (e.g., bulk purchasing), and the difficulty of making electrical upgrades in existing homes.

Based on these examples, ductless heat pumps have a path for reducing typical per ton costs from around \$4,400 today to \$3,100 (29%), while heat pump water heaters can be reduced from \$2,242 to \$1,318 (41%). In both of these examples, the greatest savings come from avoidance of new electrical circuits through use of power efficient technologies that use 120V instead of 240V. Not transparent in these waterfall plots is the substantial value of using smaller equipment for both space and water heating. We have included the potential to save the cost of doing a load calculation, but not the savings associated with buying and installing smaller capacity equipment based on that calculation. Similarly, the biggest savings for heat pump water heaters may very well be installing a 50-gallon instead of an 80-gallon tank unit.

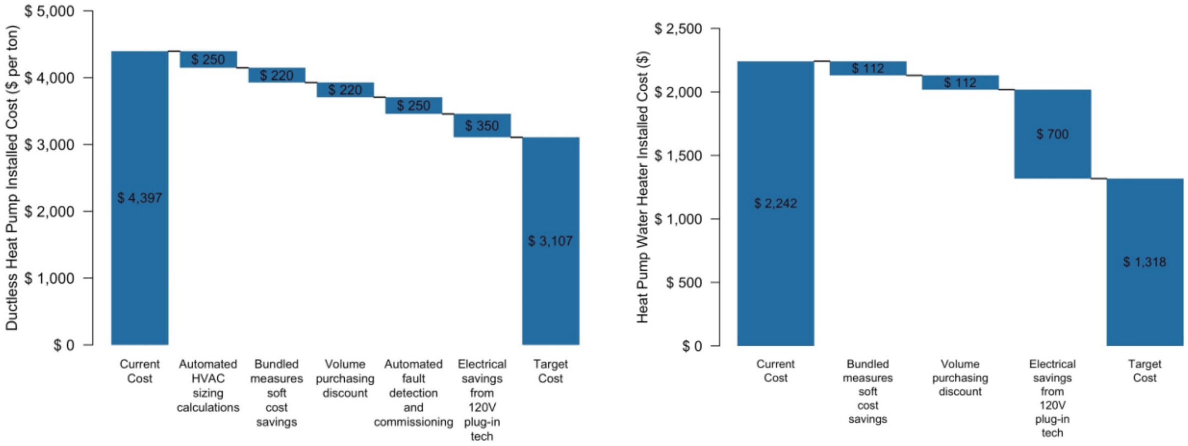

Figure 7 Example cost compression of ductless heat pump and 50-gallon heat pump water heater technologies. Estimated, non-validated cost reductions pictured.

Business Economics, Soft Costs and Market Interventions

The companion literature review to this study (Less, Walker, & Casquero-Modrego 2021) paired with the industry survey (Chan et al. 2021) found that gross margins (business overhead plus profit) were higher than industry averages for home performance contractors: 47% on average. This gross margin is compared with other construction industry benchmarks in Figure 8. Three of the benchmarks represent standard residential remodeling, with an average gross margin of 33% (CSI Market 2020; Freed 2013; NAHB 2020). The non-residential or new construction benchmarks are considerably lower: 10-26%. This suggests that if energy upgrade businesses were to reduce gross margins to the level of standard remodeling, overhead and profit costs could be reduced from 47 to 33%, representing a 14% reduction in total project costs. The potential for reduced costs is evident, but the pathway is not clear. One possibility is to reduce soft costs that are unique to upgrade projects (e.g., diagnostic testing, energy program administration). Another path is increasing market demand and the availability of skilled trades, which can also support improved market efficiency and reduced overhead for each individual upgrade.

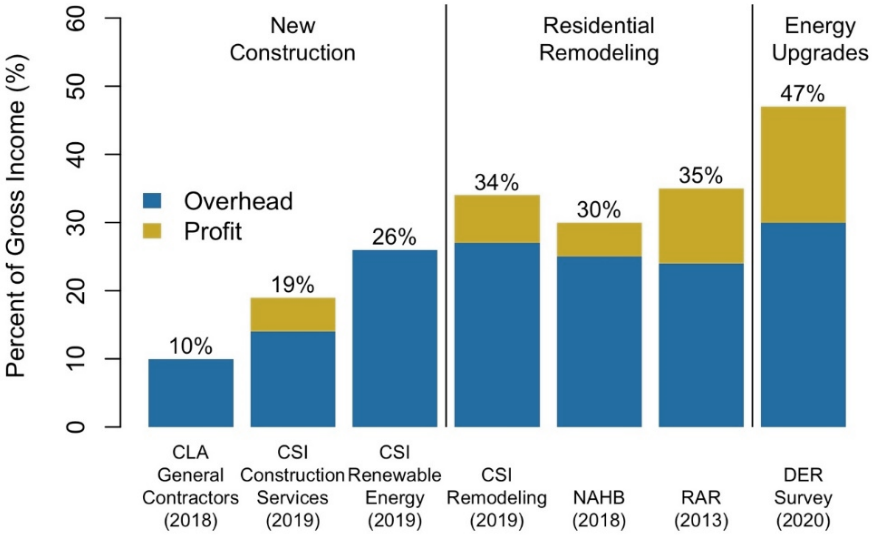

Figure 8 Comparison of gross margins (overhead + profit) for deep retrofits compared with other construction sectors.

To reduce gross margins in energy upgrade work, it is necessary to understand what common soft costs are and how much they typically cost. In our market survey, Chan et al. (2021) reported typical soft costs in deep retrofit projects, including design costs, testing, etc. The survey showed that, while not common to all projects, professional services from architects was a very high cost item (nearly $10,000 per project). More commonly reported items were home inspections/energy audits and HVAC load sizing (about $600 each per home); travel and customer management (about $800 each per home); and less expensive items, such as HVAC commissioning, building permits and envelope leakage measurements (<$200 each per home). Similar building permit costs were reported in the LBNL database, with typical permitting costs of $280, ranging from $100 to $600.

Less, Walker, & Casquero-Modrego (2021) suggested the following opportunities and estimates for reducing soft costs in home performance upgrades:

- **Outsource customer acquisition from contractors to programs or private companies with marketing and sales expertis**e. Customer acquisition typically costs $1,000 to $1,600 per project, and up to $2,500. With lower cost labor and use of best practices, this cost can be reduced to around $700 per project.
- **Reduce or automate diagnostic testing and commissioning.** One example would be combustion safety testing that is typically $387 per project, but electrification of all end-uses could eliminate the need for this testing. Another would be automatic self-testing for charge and airflow for HVAC systems.
- **Use remote approaches to customer acquisition, management and sales.** Remote audits can reduce audit costs by 40% for individual projects, and by 60% for projects that execute the work scope. Estimated at 20-hours and $1,000 saved per executed project. Less, Walker, & Casquero-Modrego (2021).

- **Automated, rapid HVAC equipment sizing.** Current HVAC sizing costs are typically $564, which can currently be reduced using rapid, block load software programs (Less, Walker, & Casquero-Modrego 2021). In the future, there is potential for further reduction through automated smart meter or connected thermostat data analytics, or improved heuristics-based sizing (i.e., rules of thumb).

Other notable potential cost reduction pathways in the market include the following:

- **Direct install program structures**. For example, the Sacramento Municipal Utility District (SMUD) direct install program for heat pump water heaters.
- **Direct-to-consumer or retail sales structures**. Examples include Mr. Cool and Project Solar.
- **Bulk purchasing strategies**. This approach may become an increasingly important service provided by energy programs or local governments in order to avoid time delays associated with decarbonization technologies, and as a resource to overcome emergency replacement with fuel-burning appliances.
- **Do-it-yourself (DIY) upgrades**. Examples include Mr. Cool and Project Solar. DIY solutions are often designed with ease of installation in-mind, which also benefits trade professionals.

Summary and Conclusions

The path to home decarbonization at scale includes interventions at the market, project and measure levels. As project cost is the most substantial barrier to home decarbonization, the pathway we outline will be focused on cost reductions.

At the market level, the required changes along a path to decarbonization at scale are numerous and potentially most difficult to overcome. These include: alternative business models to reduce soft costs/overheads (helped by utility and energy efficiency programs driving awareness, credibility and volume of projects or contractors), low-cost long-term financing, larger scale programs to even out the risks and extra costs for homes that are hard to decarbonize, and streamlining of the supply chain to reduce mark ups and time delays, potentially through increased domestic manufacturing. Rebates are also needed to offset both the real and perceived impact of project costs.

At the project level, the most promising approaches include moderate envelope upgrades, electrification of end-uses and inclusion of solar PV. These upgrades are most likely to occur at the time of existing system replacement. Programs and business models are needed that offer low-cost, all-electric alternatives that can be rapidly installed at time of replacement that likely require an integrated approach to provide temporary services while homes are upgraded. In terms of time and cost, they must offer households a compelling alternative to overcome the tendency to simply replace failing equipment with in-kind fuel-burning equipment. Soft costs and project overhead should also be targeted for reductions at the project level, this can be attained largely by streamlining and improving the productivity of contractor efforts, namely those associated with customer acquisition, program compliance/documentation, HVAC sizing and specification, diagnostic testing, and code compliance (e.g., electrical requirements in the National Electrical Code).

At the measure level, key technical innovations include electrical upgrade requirements associated with electrification measures, along with improved cold climate performance for heat pump technologies. Example breakthrough technologies could include packaged cold climate window heat pumps that use an existing 120V plug. This would allow renters and low-income households electrification options that also reduce or remove installation and commissioning issues. Another example innovation would be the development of advanced methods for low-power electrification without panel or service upgrades. Integrated equipment that contains space conditioning, hot water, ventilation and electrical upgrades (i.e., mechanical pods) in one unit could also disrupt current costs at the measure level. In many cases, substantial cost reductions may also occur as markets mature.

Many interventions may be critical but have not been otherwise covered in this paper; these include: improving consumer and contractor awareness and trust in electrification technologies, workforce training and development, carbon and energy transparency in real estate transactions, and leveraging industrialized construction for rapid retrofitting. Ultimately, market forces may be insufficient to rapidly scale home electrification, and new public policy may be required (e.g., local or state funding of electrification programs). Project economics are currently limited by the generally low cost of natural gas and by the high price of electricity in regions currently supporting electrification. It is critical in this context that electricity rate structures are designed to encourage equitable electrification, and be supportive of both on-site renewables, energy storage and the electrification of transportation. Pricing of carbon emissions may be an alternative way to align the market's economic interests with the long-term interests of humanity.

Alongside cost reductions come opportunities for benefit expansion which may be critical in the market uptake of decarbonization strategies. Critical decarbonization benefits can include improvements in indoor air quality and health from elimination of indoor combustion, increased property value, improved thermal comfort, and disaster resilience. In the future, valuing and characterizing these decarbonization benefits should receive equal attention to proposed cost reduction strategies. While this work has improved our understanding of the decarbonization costs for single-family homes, we almost entirely lack similar cost data for multi-family and manufactured housing. This should be a focus of future efforts. In addition, all of the proposed cost reduction pathways require real world validation to overcome industry and consumer risk perceptions.

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