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Reducing the cost of home energy upgrades in the US: An industry survey

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ABSTRACT

Decarbonizing the US residential building stock requires a substantial acceleration in home energy upgrades. Numerous barriers exist to accelerating adoption of efficient and electric building technologies, but foremost among these is high upfront costs. This study uses an industry survey delivered to a sample of home energy professionals to examine promising cost reduction strategies across a range of project types, including HVAC, water heating, and envelope/insulation projects. The survey included quantitative and qualitative questions to collect evidence on the estimated cost reduction potential of these strategies and their likelihood of use in the construction industry. The 167 survey respondents included contractors, energy consultants, architects, manufacturers, and others with experience in delivering energy upgrades in single-family and multifamily buildings in the US. Results show that significant cost reductions are achievable by minimizing additional infrastructure costs (such as replacing electric panels), streamlining project planning/management, and deploying innovations that simplify installation. We find that for a typical deep retrofit project, including heat pumps for space and water heating in addition to envelope upgrades, the strategies could result in a total installed cost reduction of nearly 50 %, dramatically improving the customer economics of such a project. This research makes a novel contribution to the literature on strategies to reduce the costs of residential retrofits. We discuss how our study's insights on the highest-value cost reduction strategies for home energy upgrades can further accelerate their uptake in the US housing stock.

1. Introduction

In the US, the buildings sector accounts for around a third of energy-related carbon dioxide (CO_2) emissions (EIA, 2023). More than half of these are attributable to the 130 million housing units in the US (of which 68 % are single-family homes, 26 % are multifamily buildings, and 6 % are manufactured or mobile homes) [1]. While increasingly stringent building codes and appliance standards can drive down the CO_2 emissions associated with new construction, a substantial share of future residential buildings' emissions will be attributable to existing homes. Upgrading these via energy efficiency and electrification retrofits is thus a top priority for decarbonizing the US building stock.

While such upgrades can deliver numerous benefits to building occupants and to the broader energy system, they are still uncommon in the US — especially whole-building approaches that achieve substantial energy savings [2]. Rates of "deep renovations" that reduce building site energy use 75 % or more below a pre-retrofit baseline are currently well below 1 %, but these must accelerate to 3 % by 2040 to achieve net-zero targets by 2050 [3]. The practice of converting homes to lower carbon content fuels (primarily

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electricity) is in its infancy. Achieving the US DOE's building decarbonization goals of 65 % by 2035 and 90 % by 2050 [4] will require a massive acceleration in the pace of deploying building energy efficiency and electrification upgrades.

While numerous deployment barriers exist, the most prominent challenge is the high upfront or installed costs of these upgrades [5–7]. Less et al. [8] describe a database of project costs and energy savings for over 1700 single-family home energy upgrade projects in the US. The authors estimate required cost compression for these projects by comparing the present value of energy savings against reported project costs using a 30-year analysis period and 3 % discount rate. Comprehensive projects with more than 50 % energy and carbon savings had a median reported cost of $54,000, while the present value of their reported energy savings was only $34,000. The authors conclude that these projects must pursue strategies to reduce costs by an average of $20,000 in order to completely recover upfront costs through bill savings. Shorter analysis periods (e.g., 15- or 20-years) or higher discount rates would further increase the required cost reductions. To put these costs and required reductions into an affordability context, the median income for 2022 in the US was $74,580 per household [9]. Furthermore, median household savings in transaction accounts (e.g., checking and savings accounts) are only about $8000 [10], which means that most of these projects will not be affordable for US Households, even with large incentives such as those made available through the Inflation Reduction Act. A consistent finding in the literature is that home energy retrofits are technically feasible but that upfront costs present a significant barrier to implementation [11].

Determining the most promising opportunities for reducing the installed costs of home energy upgrades is an active area of research. Previous studies using industry surveys have noted strategies such as expanding market scale, heightening competition, improving the efficiency of delivery, and reducing project risks [6,12,13]. Building permit cost and time savings (i.e., time management from design to construction) have been clearly demonstrated for online, automated systems supporting solar PV installation in California and Arizona [14,15]. The impacts of market efficiency and industry familiarity can be seen for HVAC heat pump technologies by comparing costs in the US with those in other regional markets. Navigant Consulting Inc [16]. reports that ductless heat pump costs range from $800–2000 per unit in Asian Pacific, Latin American and European markets, compared with $3000–4500 per unit in the US. Their review attributes higher prices in the US to lower sales volume, more premium products, lack of retail distribution channels, and contractor unfamiliarity. Similar cost reductions associated with comprehensive manufactured retrofit solutions have been documented for the Energiesprong programs in Europe, delivering >50 % reductions in overhead and envelope measure costs in the Netherlands and UK [17]. Friedler & Kumar [18] report that costs per project in 2010 were 110,000€ ($117,000) but that these decreased to 74,000€ ($78,000) in 2018; the program is targeting 35,000€ ($37,000) per home by 2025. More recent results from Energiesprong indicate that cost reduction challenges still remain, with costs per unit in the 90,000–120,000€ ($95,000–127,000) range [19,20]. Egerter & Staengl [21] report on cost reductions in the Netherlands for varying project features between 2010 and 2019, including cost reductions for heat pump/PV packages (73 %), site preparation (44 %), and envelopes (37 %). LED lighting technologies have a similar cost trajectory [22,23]. Concerted R&D has also been directed towards reducing costs and finding efficiency practices for the exterior insulation of above grade walls [24–26], but those efforts have not gained market attraction.

Key surveys in the past decade have highlighted trends in the construction industry for residential upgrades. The NAHB-RC's 2001 Consumer Practices Survey (CoPS) emphasized the use of home equity for remodeling [27]. Redman [28] stressed the need for robust training for energy efficiency. Fuller [29] and McIlvaine [12] discussed motivations and challenges in energy retrofits, with Palmer [30] noting gaps in homeowner awareness and follow-through on audit recommendations. Camarasa [31] highlighted technical and economic factors in energy-efficient technology implementation, while Antonopoulos [32] and Biswas [33] found regional variations in decarbonization motivations across the US. Despite this growing body of evidence on cost reduction opportunities, to the authors' knowledge, there exist no established approaches for assessing these cost reduction strategies for their efficacy in terms of their potential cost savings and/or their likelihood of uptake among a diverse industry of home energy professionals.

To address this gap, we employ a detailed industry survey delivered to a sample of 167 industry professionals, from which we collect both quantitative and qualitative data on the potential of a wide range of strategies to reduce costs for typical home energy upgrade projects. Our primary aim in this study is to assess how likely our survey sample of industry professionals is to adopt these strategies and to quantify their cost reduction potential on a per-project basis. The strategies in the survey are specific to either types of home upgrades (e.g., HVAC, water heating, envelope/insulation) or project phases (e.g., customer acquisition, project delivery, and project close-out). These latter "soft costs" are especially important to consider given their contribution to overall project installed costs and their prevalence in the fragmented home energy upgrade industry in the US. We combine quantitative results from the survey with qualitative insights to provide a holistic view of the opportunities to accelerate the pace of home energy upgrades by reducing their upfront costs. While many previous studies have investigated strategies to reduce operational energy use and energy costs in residential buildings, this study is novel in its focus on reducing upfront costs and its use of primary data collection from a wide range of stakeholders with first-hand experience of the costs of home energy upgrades and opportunities to reduce them.

The paper is organized as follows: Section 2 discusses the survey design, data collection, and data transformation and analysis methods. Section 3 presents results for both the quantitative and qualitative portions of the survey, including an application of the study sample's estimated cost reduction potentials to prototypical home energy upgrade projects to demonstrate the magnitude of cost reduction that could be achieved. Section 4 discusses the study's recommendations for the home energy upgrade industry and for further research, and Section 5 concludes.

2. Materials and methods

The primary method employed in this study is an industry survey that was delivered to a sample of home energy industry professionals to assess their estimates of the cost reduction potential and feasibility of various cost reduction strategies. The survey was designed by the authors in consultation with several industry partners who helped pilot the survey in August 2022. It was launched in

December 2022 and kept open through January 2023. In order to obtain robust results, the survey included both quantitative and qualitative questions, allowing us to gather comprehensive data and to capture both numerical trends and detailed personal insights. It was developed in SurveyMonkey and was sent to prospective participants via email (or shared through collaborator email newsletters).

Survey respondents were all home energy professionals working in a range of roles, including contractors, consultants, manufacturers, distributors, program managers, and others. We sought insights and opinions on home energy upgrades in single- and/or multifamily buildings, focusing on home energy professionals' assessments of the potential to reduce costs for typical projects across a range of different project types and specific strategies.

The survey included closed-ended questions to obtain estimates of the cost reduction potential of various strategies that could be employed to reduce the costs of home energy upgrades, and it also asked open-ended/free response questions to collect more detailed data on the perspectives of individuals working in the home energy upgrade industry.

2.1. Survey design

To investigate the potential for cost reduction in home energy upgrade projects across a range of project types, project phases, and specific cost reduction strategies, we designed a comprehensive survey with four parts combined in quantitative and qualitative questions. The survey included 26 questions (15 of them were open-ended questions) and took around 15 min to complete. Fig. 1 provides a visual summary of the survey and its main components, including: 1) general questions that are applicable to all types of home energy upgrade projects, 2) questions specific to "soft costs" and potential reduction strategies, 3) questions specific to different types of upgrade projects (e.g., heat pumps or building envelope/insulation), and 4) respondent demographic questions.

The first set of questions asked general questions on which types of projects or specific upgrade measures had the greatest potential for cost reduction and the best ways to reduce costs (see Supplemental Information (SI) Fig. S11). The second set of questions, which were the primary focus of the survey, asked respondents to indicate 1) how likely they would be to adopt or use a given strategy, and 2) how much the strategy could potentially reduce costs for a typical project. Examples of these are provided in SI Figures S12–S13.

As shown in Fig. 1, these questions focused on "soft cost" reduction strategies, encompassing the "Customer acquisition", "Project delivery", and "Project closeout" phases of a project, as well as strategies that applied to specific types of upgrade projects, including "Heat pump upgrades", "Heat pump water heater (HPWH) upgrades", and "Envelope/insulation upgrades". Each of these had a list of distinct strategies that the authors developed based on previous research and in consultation with industry partners. Strategies specific to each category are shown in the Results section. Respondents used Likert scales to indicate their likelihood of adoption and selected from a range of values to indicate cost reduction potential.

The latter response options varied based on the question category — "Customer acquisition", "Project delivery", "Heat pump upgrades", and "HPWH upgrades" were assessed using dollar ranges, while "Project closeout" strategies were assessed using percentages of the total project cost, and "Envelope insulation/upgrades" were assessed on a $/ft^2 basis. We designed the survey to ask respondents to select a range of values rather than a single point value after piloting the survey and receiving feedback that ranges were easier for respondents to select. The ranges included in the survey were based on detailed measure cost data collected in a previous

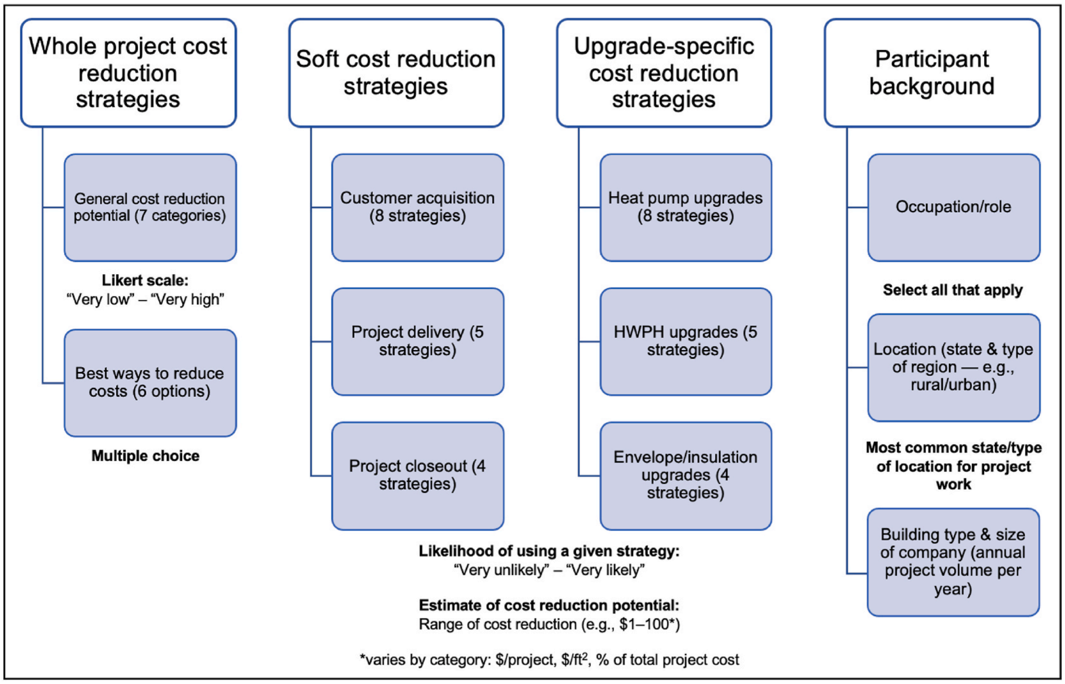

Fig. 1. Overview of survey categories and question types.

study of residential retrofit projects [8]. Ranges for each question type are available in SI (Figs. S1–S5).

Finally, each of the "Soft cost" and "Upgrade-specific" sets of questions included an open-ended response question that allowed respondents to submit additional strategies not included in the survey that would be effective in reducing costs (and to estimate the potential for cost reduction). See SI Figure S14 for an example of this type of question.

2.2. Data collection

We used the SurveyMonkey platform [34] to administer the online survey to participants over a period of about 6 weeks from mid-December 2022 to late-January 2023. We piloted the survey with several contacts in the home energy upgrade industry prior to the survey's launch and held semi-structured interviews with our pilot respondents to improve the design and legibility of the survey.

Survey participation was entirely voluntary. We provided an incentive to increase our survey response rate, offering the first 200 respondents a $50 gift card for completing the entire survey. Survey responses were kept separate from any personally identifiable information (PII) that was provided (e.g., to facilitate compensation for completing the survey) so as to ensure anonymity of responses. Respondents gave informed consent prior to participation, and all data collection procedures were conducted in compliance with human subjects research protocols.

To target the desired study population, we implemented a multifaceted survey outreach approach. It included sending traditional email invitations to individuals within our personal contact lists (collected from previous research investigating costs of single- and multifamily energy upgrade projects) and those with whom we have previously collaborated. These contacts then helped us distribute the survey to other response groups, and several companies and organizations assisted in recruiting respondents by promoting the survey campaign on their websites, newsletters, and other communication channels. We also made the online survey available on our research website (*homes.lbl.gov*).

2.3. Characteristics of survey respondents

Out of the 263 respondents who started the survey, 167 completed all the required questions. The respondents represent various professional categories, with the largest group being consultants (45 %), followed by contractors (34 %), program managers (30 %), energy raters (21 %), and engineers (16 %). Among those categorized as contractors ($n = 66$), 58 % were home performance contractors, 41 % were HVAC contractors, 35 % were insulation contractors, and 33 % were general contractors. Respondents reported working on home energy projects in 38 of the 50 states in the US, covering a broad range of climate zones across the country. The majority of respondents reported New York and California were the states in which they most commonly performed home energy upgrade work. In terms of type of location, 46 % of respondents reported working in suburban areas, while 34 % operate in urban settings, and 16 % in rural locations. Regarding building types, approximately 68 % of the participants most commonly worked on single-family building projects, while 22 % worked on low- and mid-rise multifamily projects (the remainder worked either on high-rise multifamily or manufactured housing projects). Approximately 35 % of respondents had a typical project volume of >50 projects per year, while slightly smaller shares completed 11–20 (21 %) or <5 (19 %) projects per year.

2.4. Data transformations

After collecting survey data, the next step was to transform the data to support our analytical objectives. Data transformation procedures include the following:

1. We adjust all estimated cost reduction potential responses in the survey to account for inflation (converted to 2023 $USD), and we apply location-based adjustments to ensure that cost reduction estimates from survey respondents located in different states are comparable. We apply adjustments based on location-based factors from the *2023 RSMeans* data provided by Gordian [35] that correspond to the state where each respondent reported conducting the majority of their work.
2. Given that our survey presented cost reduction potentials for various strategies using ranges (e.g., 0, $1–100, $101–500, etc), we convert these ranges to single point values for the purpose of applying adjustments as above and also to construct sample-wide estimates. Our method is to convert each range to a low, medium, and high point value (e.g., $1, $50, and $100, respectively for "low", "midpoint", and "high" for the range $1–100). In cases where a response option was framed as "greater than $" (e.g., >$3000), we simply use the value listed as the point value for those responses. This assumption will tend to yield more conservative estimates for average cost reduction potential across the survey sample given that, in some cases, a much larger value might be assumed by the respondent, but given the low frequency of these "upper range" responses across most survey questions, the effect of this decision is likely to be small.
3. When calculating sample-wise averages across individual survey questions and for categories of cost reduction, we exclude responses marked as "Not sure".
4. After applying adjustments and converting ranges to point values, we construct a weighted average cost reduction potential for each strategy in the survey where the weights are equal to the percentage of respondents selecting each response option.
5. For all cost reduction strategies, we calculate the percentage of respondents who indicated they are either "Very Likely" or "Likely" to adopt a given strategy for a typical home energy upgrade project. These estimates are used to represent the potential market uptake of a given strategy irrespective of the amount by which it might reduce typical project costs.

Fig. 2 presents an example of the transformation steps described above. This figure presents results for the survey questions related to the "Customer Acquisition" phase of a typical home energy upgrade project. Individual cost reduction strategies pertaining to this phase are shown on the vertical axis of the figure, and the shaded bars indicate the percentage of respondents who estimated a given range of cost reduction potential. After excluding the respondents who marked “Not sure” for a given strategy (the gray portion of each horizontal bar) and converting ranges to medians as described in step 2 above, we apply step 4 to calculate a weighted average, which is shown for each strategy in the red figure labels; the yellow labels indicate the share of respondents who are “Very Likely” or “Likely” to adopt. Fig. 2 is sorted based on the weighted average cost reduction potential across the survey sample.

As demonstrated in Fig. 2, some specific cost reduction strategies displayed a relatively large share of respondents marking “Not sure” in terms of the cost reduction potential. We posit two potential reasons for this: 1) in some cases the strategies are fairly new/ innovative (e.g., “Robotic or automated inspection of relevant building assemblies”) and may not be familiar to survey respondents, and 2) in some cases the variability across individual project types for a given strategy is large enough that respondents would not feel comfortable providing an estimate (or would find it difficult to do so). Across all survey questions related to estimating cost reduction potential, we find that the percent of “Not sure” responses ranges from 8 to 43 % with an average of 23 % of respondents. Figs. S1–S5 show figures for the other categories included in the survey.

3. Results and discussion

This section presents quantitative and qualitative results from the home energy upgrade survey. In section 3.1, we examine quantitative results that explore the most promising opportunities to reduce costs across project types, and we compare estimated cost reduction potential and likelihood of adoption for a range of project phases and specific efficiency upgrade project types. In section 3.2, we apply these estimated cost reduction potentials to existing project cost data to develop plausible estimates of compressed project installed costs. Section 3.3 presents a summary of qualitative survey results.

3.1. Quantitative survey results

3.1.1. Most promising cost reduction opportunities

The survey first asked respondents to identify which types of projects had the highest potential for cost reduction and which strategies would be most effective for those projects. Here we included a more expansive list of projects, including on-site renewables and energy storage projects, than is the subject of the rest of the survey (which focused specifically on building mechanical system/ envelope upgrades). Fig. 3 presents the distribution of responses from the survey.

The results show a range of responses, with over 60 % of respondents indicating that HVAC, solar PV, building envelope, and water heating projects have a “Very high” or “High” potential for cost reduction. Energy storage, home appliance, and electrical infrastructure projects were seen as having less potential for cost reduction (the last of these, electrical infrastructure upgrade projects, was reported to have “Very high” or “High” cost reduction potential by 30 % of the sample). Across all project types, however, an average of 57 % of respondents reported they have high cost reduction potential, signaling the opportunity for compressing costs across residential decarbonization project types.

Respondents were also asked to report which general cost reduction strategies have the greatest impact across project types. Over a third of respondents said the best strategy was to “Reduce the cost of goods sold (e.g., smaller heat pumps, cheaper spray foam insulation)” while a quarter said the best strategy was to “Improve the efficiency of labor” by, for example, improving the speed and ease of installation. “Reducing soft costs” was the top strategy reported by 15 % of respondents.

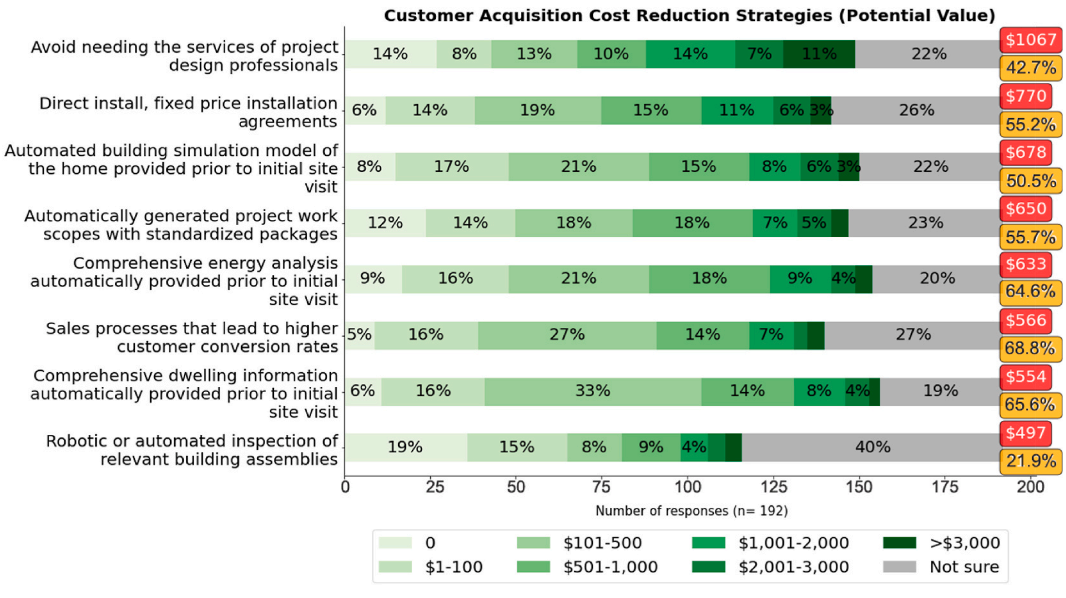

Fig. 2. Customer acquisition soft cost reduction strategies shown with response frequencies for the ranges provided on the survey (figure bars). Text annotations indicate the median cost reduction potential for each strategy (red label) and the percentage of respondents who are either “Very Likely” or “Likely” to adopt (yellow label) after removing “Not sure” responses. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

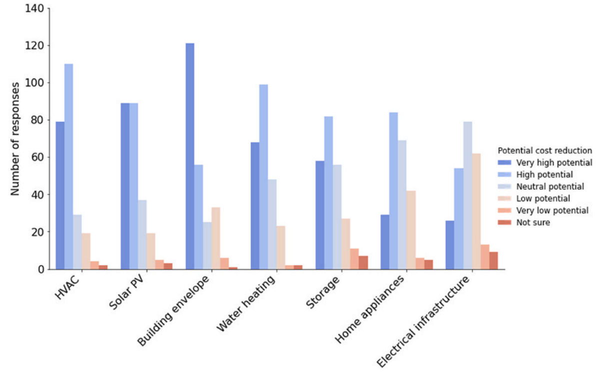

Fig. 3. Qualitative cost reduction potential by project type for full survey sample. Project types are ordered based on the total share of "Very high" or "High" potential responses.

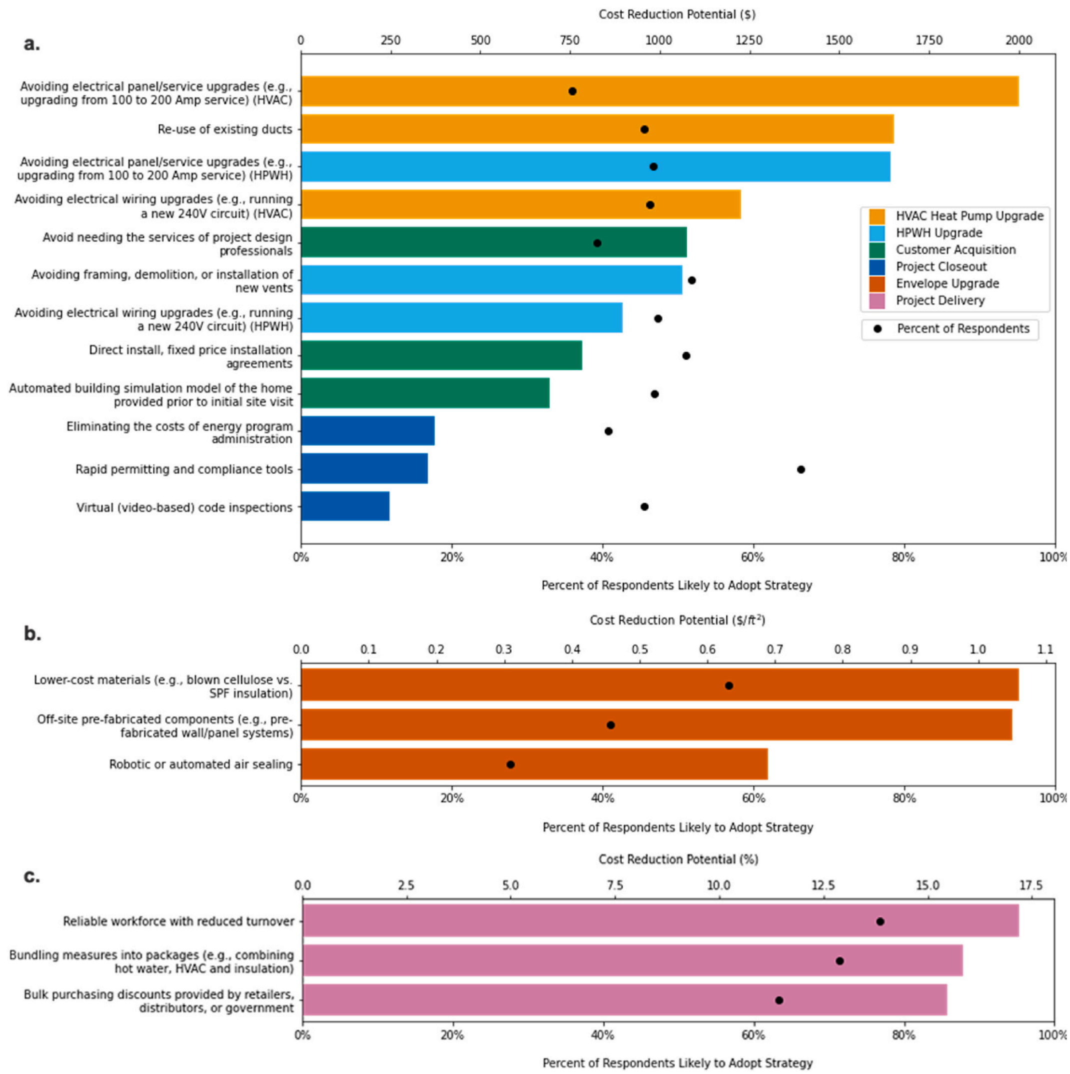

Fig. 4. Top three cost reduction strategies by project type or project phase (for soft cost reduction strategies). Bars show the median estimated cost reduction potential for specific strategies across the full survey sample (excluding any missing data). Colors represent different project types or phases, and black dots indicate the median adoption likelihood (%) reported across the full survey sample. Results are plotted separately for survey categories that had scales measured in $USD (a), $USD per square foot of building floor area (b), or percentage of total project cost (c). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.1.2. Cost reduction potential and adoption likelihood by project phase or type

The remainder of the quantitative part of the survey focused on asking respondents to estimate the cost reduction potential of a variety of strategies that were specific to either soft costs that could be reduced across distinct phases of a typical home energy project or specific to a given type of project (as shown in Fig. 1).

Survey respondents were asked to assess 17 cost reduction strategies addressing three phases of project administration: a) customer acquisition (8 strategies); b) project delivery (5 strategies); and c) project closeout (4 strategies). *Customer acquisition* and *project closeout* strategies were assessed according to total project cost ($ per typical project), while *project delivery* strategies were assessed based on percentage of the project cost (%).

Next, survey respondents were asked about a total of 17 cost reduction strategies specifically relevant to three home energy upgrade project types: 1) HVAC heat pumps (8 strategies); 2) heat pump water heaters (5 strategies); and 3) envelope upgrades (4 strategies). The two heat pump upgrades were assessed according to total project cost ($ per typical project), while the envelope upgrades were assessed on a floor area-normalized basis ($\$/ft^2$). Data were transformed following the steps explained in section 2.4 prior to analysis.

Fig. 4 shows cost reduction potential and likelihood of adoption for the top three strategies specific to different types of upgrade projects as well as for given phases of a typical project. Due to differing scales used for the categories included in the survey, separate panels show strategies that use these different scales, and bar colors indicate the categories these strategies belong to.

As shown in the figure, survey respondents indicated a range of estimated cost reduction potential for strategies across project types and phases (bar lengths), but the median likelihood of adoption of those strategies (black dots) showed less variance across these categories. Strategies with the highest likelihood of being adopted by the survey sample are all related to the "Project Delivery" phase of a project, suggesting the potential ease of implementing these strategies and/or their potential benefit to installers and project developers.

Table 1 includes results for all strategies included in the survey, along with the averaged low, midpoint, and high estimated cost reduction potential across the survey (as described in step 2 in section 2.4). The remainder of this section describes and discusses these findings.

3.1.2.1. Soft costs: Customer acquisition. Estimated soft cost reduction potentials for *customer acquisition* strategies were, on average, around 2.2x greater than those estimated for *project closeout*. In fact, every single soft cost reduction strategy for *customer acquisition* was rated as having higher potential than all the strategies in the *project closeout* category (the *customer acquisition* strategy with the lowest cost reduction potential was $505 per project while the *project closeout* strategy with the highest potential was $374 per project). Robotic or automated inspection of building envelopes was estimated to be lower ($505 per project). In contrast, automated provision of dwelling information ($575), energy modeling ($692), and generation of work scopes ($662) were estimated to be higher. These findings suggest that strategies aimed at optimizing project time and management could be promising opportunities to achieve reductions in customer acquisition costs. Direct install program designs were estimated as having high cost reduction potential ($783), while sales processes with higher customer conversion rates were estimated to have somewhat lower cost reduction potential ($585). Both are intended to streamline inefficiencies in the process of acquiring customers, by either outsourcing the process (direct install) or increasing the likelihood that site visits become contracted work.

3.1.2.2. Soft costs: project delivery and closeout. Most project delivery strategies were estimated to have similar cost reduction potential (14–17 % of the final cost of the project). Of these, the highest was using a reliable workforce with reduced turnover, followed by bundling multiple measures into a single upgrade package and then bulk purchasing strategies. An important outlier was the use of lower-cost, entry-level workers, which was estimated to have low reduction potential (9.5 %).

Survey results indicate that acquiring detailed information about the building's current state before initiating the design and energy upgrade process is crucial. This approach saves time and money during the construction process of the energy upgrade, but it also helps mitigate potential unexpected issues that could increase final project costs. The strategy of avoiding diagnostic testing ($242) had the lowest estimated potential across soft cost categories.

In the results, we observe a pressing need to simplify and possibly standardize the administration process for home energy upgrade projects. Respondents indicated that improving speed of permitting and eliminating the cost of energy program administration both had moderate potential to reduce costs ($354 and $373, respectively).

3.1.2.3. Upgrade type: HVAC heat pump and HPWH upgrades. For the heat pump upgrade projects, the strategies with the highest estimated cost reduction potential include the avoidance of electrical upgrades for main service panels and for wiring upgrades. Potential cost savings associated with avoiding electrical upgrades were higher for HVAC heat pumps ($1999) than for heat pump water heaters ($1643), while avoiding electrical wiring upgrades were estimated at $1226 and $898 for HVAC heat pumps and heat pump water heaters, respectively. Strong potential cost reductions were also reported for re-use of existing ductwork for HVAC heat pumps ($1654) and for avoiding demolition, framing, and new vent pipe work associated with heat pump water heater installation ($1062). To avoid these costs, 120 V HPWHs can be used that can plug into existing low power circuits. Similarly, HPWHs with smaller tanks, higher water temperatures, and tempering valves are not only lower cost but also more likely to fit into the constrained spaces sometimes found in existing homes. For both types of equipment, replacement of service panels or utility service interconnections can be avoided through use of alternative electric code compliance pathways in the *National Electric Code* (e.g., such as using metering data in Section 220.87), specification of lower-power appliances and equipment, or use of active load controls.

Other measures had lower reported cost reduction potential, but they were identified as being very likely to be used by respondents. Examples of these included automated load calculation and equipment selection tools for HVAC heat pumps, as well as innovations to make installation easier and to use offsite pre-fabricated components ($744 and $772, respectively). These strategies may have broader impact across the market, whereas avoiding electrical upgrades noted above may apply in a smaller subset of existing dwellings (e.g.,

Table 1
Range of cost reduction potential and likelihood of adoption by strategy. Cost reduction strategies are ranked by a combination of each strategy's median estimated cost reduction potential (of the midpoint of the range) and likelihood of adoption. Strategies relevant to soft cost reductions for each phase of a typical upgrade project are shown first, followed by strategies relevant to specific types of upgrade projects.

Cost Reduction Category	Cost Reduction Strategy	Mean Cost Reduction Potential Across Full Survey Sample			Percent Likely to Adopt Strategy [%]
		Low (bottom of survey range)	Medium (midpoint of survey range)	High (top of survey range)	
Soft cost reduction strategies by project phase					
Customer Acquisition	1. Avoid needing the services of project design professionals	$996	$1076	$1437	39 %
	2. Direct install, fixed price installation agreements	$530	$783	$976	51 %
	3. Sales processes that lead to higher customer conversion rates	$404	$585	$808	60 %
	4. Comprehensive dwelling information automatically provided prior to initial site visit	$403	$575	$859	58 %
	5. Comprehensive energy analysis automatically provided prior to initial site visit	$526	$647	$973	51 %
	6. Automatically generated project work scopes with standardized packages	$489	$662	$924	50 %
	7. Automated building simulation model of the home provided prior to initial site visit	$550	$692	$990	47 %
	8. Robotic or automated inspection of relevant building assemblies	$304	$505	$599	23 %
Project Delivery	1. Reliable workforce with reduced turnover	14 %	17 %	20 %	77 %
	2. Bundling measures into packages (e.g., combining hot water, HVAC and insulation)	13 %	16 %	19 %	71 %
	3. Bulk purchasing discounts provided by retailers, distributors, or government	12 %	15 %	19 %	63 %
	4. Mature supply chain	12 %	14 %	17 %	55 %
	5. Lower-cost, entry-level workers	8 %	10 %	12 %	35 %
Project Closeout	1. Rapid permitting and compliance tools	$280	$354	$468	66 %
	2. Eliminating the costs of energy program administration	$284	$374	$458	41 %
	3. Virtual (video-based) code inspections	$171	$249	$335	46 %
	4. Reduction of diagnostic testing (e.g., not testing air leakage)	$161	$242	$308	21 %
Project Cost Reduction Strategies by Upgrade Type					
HVAC Heat Pump Upgrade	1. Re-use of existing ducts	$1164	$1654	$1981	46 %
	2. Avoiding electrical panel/service upgrades (e.g., upgrading from 100 to 200 Amp service)	$1638	$1999	$2557	36 %
	3. Avoiding electrical wiring upgrades (e.g., running a new 240 V circuit)	$955	$1226	$1679	46 %
	4. Innovations that make installation easier (e.g., snap-together refrigerant line set fittings)	$451	$744	$1000	61 %
	5. Off-site pre-fabricated components (e.g., stands/ mounts for outdoor units, plenum and registers)	$556	$772	$1135	56 %
	6. Automated load calculations	$301	$447	$706	60 %
	7. Automated equipment selection tools	$256	$411	$640	53 %
	8. Lower efficiency equipment	$617	$854	$1073	18 %
HPWH Upgrade	1. Avoiding electrical panel/service upgrades (e.g., upgrading from 100 to 200 Amp service)	$1373	$1643	$1935	47 %
	2. Avoiding framing, demolition, or installation of new vents	$814	$1062	$1355	52 %
	3. Avoiding electrical wiring upgrades (e.g., running a new 240 V circuit)	$629	$898	$1160	47 %
	4. Smaller tank size with mixing valve (e.g., 50-gallon vs. 80-gallon)	$343	$565	$774	46 %
	5. Lower efficiency equipment	$429	$550	$701	10 %
Envelope Upgrade	2. Lower-cost materials (e.g., blown cellulose vs. SPF insulation)	$0.8 ft2	$1.06 ft2	$1.47 ft2	57 %
	3. Off-site pre-fabricated components (e.g., pre-fabricated wall/panel systems)	$0.84 ft2	$1.05 ft2	$1.31 ft2	41 %
	4. Robotic or automated air sealing	$0.46 ft2	$0.69 ft2	$0.92 ft2	28 %
	5. Robotic or automated insulation removal and/or placement	$0.47 ft2	$0.69 ft2	$0.89 ft2	26 %

those lacking current air conditioning or with outdated main service panels).

Respondents reported low likelihood of using lower efficiency equipment as a means for cost reduction. In fact, these strategies had the lowest likelihood reported for the entire survey. For HPWH upgrades, respondents estimated this strategy would have the lowest cost reduction potential ($550 per project).

We find that solutions associated with avoiding additional infrastructure, such as replacing electrical panels or upgrading wiring, or refraining from demolition, installation, or reusing existing structures, are estimated to have high potential for cost reduction (ranging from $898–$1654). Historically, the construction industry has tended to minimize interventions in a building as much as possible during an upgrade. Our results highlight the challenges and inherent costs of upgrades that are due to the risk of encountering unexpected issues during the construction phase. However, the percentage of respondents likely to adopt these strategies is slightly lower than strategies that focus on using automated solutions to gather more information about the building before the construction phase. As mentioned before, anything related to time-saving and improved project management carries significant potential in terms of cost reduction.

3.1.2.4. Upgrade type: envelope upgrades. Respondents estimated high potentials and adoption likelihoods for envelope upgrade cost

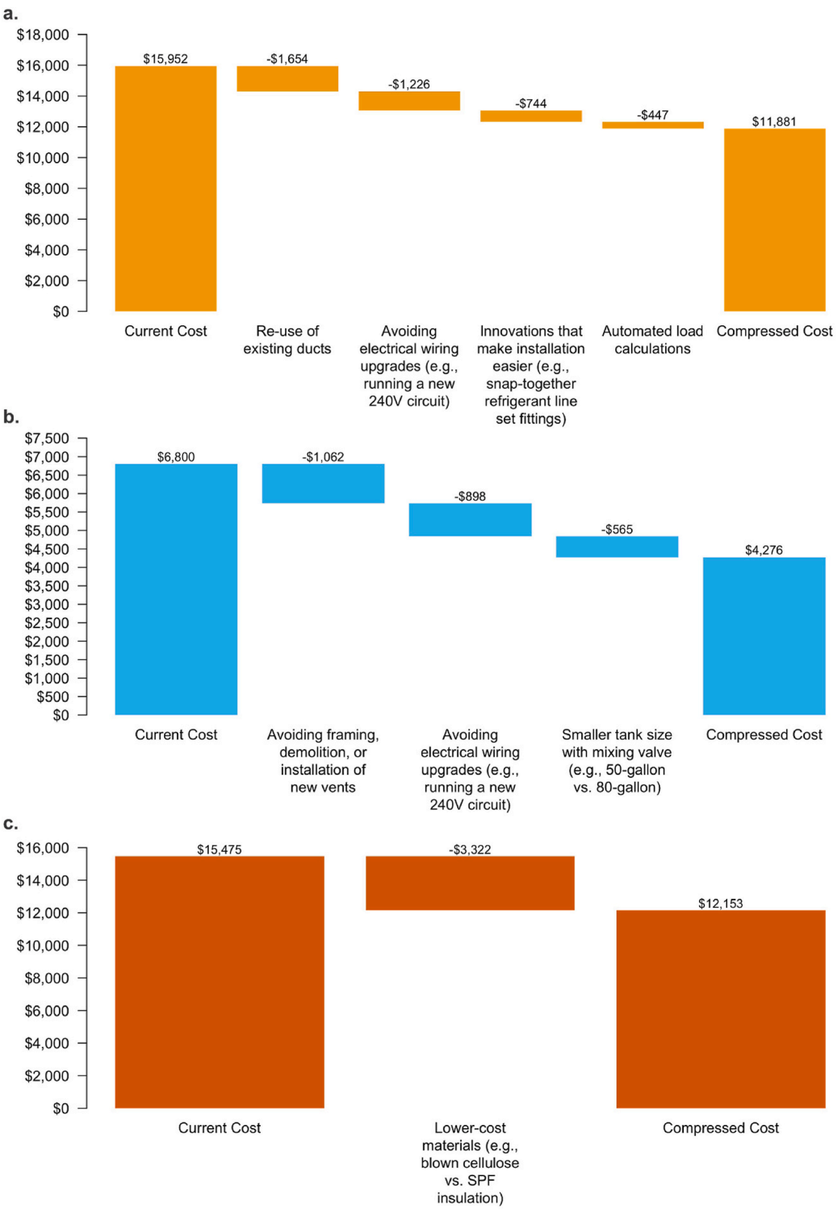

Fig. 5. Cost reduction waterfalls for HVAC heat pump (a), heat pump water heater (b), and envelope upgrade projects (c), using medium cost reduction potentials estimated from the survey sample and applied to adjusted project costs from Less et al. [8]. Note: these estimates do not include soft cost reductions associated with customer acquisition, project delivery, or project closeout.

reduction strategies with which they were familiar or had market experience. For example, respondents reported high likelihood of using lower-cost materials for envelope upgrade work and estimated average potential savings of $1.06 per ft^2 of treatment area. For a typical 1800 ft^2 dwelling requiring attic framed floor insulation, this would translate to a cost reduction of $1908. This is similar in value to the potential cost savings from avoiding main service panel upgrades during HVAC heat pump projects. Off-site pre-fabricated components, such as factory-built insulated wall panels, had similar estimated cost reduction potentials ($1.05 per ft^2), but the likelihood of use was much lower. Lower cost materials (e.g., cellulose insulation) are common in the market and well known to insulation contractors, whereas offsite, prefabricated components are a new technology currently under development and without meaningful market penetration in existing home upgrades. SIPS panels are becoming more common in new construction but remain uncommon as a strategy for existing homes. This lack of market maturity is reflected in the low likelihood of use and in relatively low cost reduction estimates for offsite pre-fabricated components. This trend is even more pronounced for robotic or automated strategies for either air sealing or insulation removal and placement ($0.69 per ft^2 and 26–27 % adoption likelihood).

3.2. Application of cost reduction potential to project cost data

This section provides an illustrative application of the results presented in the previous section to individual upgrade measures as well as whole-building retrofit projects with the aim of showing how estimates of cost reduction potential can inform future installed costs for various types of projects.

Current costs for upgrade measures were derived from Less et al. [8] and were updated from 2019 to 2023 $USD using the Consumer Price Index [36]. The resulting costs were further increased for the HVAC heat pump and heat pump water heater measures in order to account for recent cost increases not reflected by the CPI, as observed from programmatic data sources of heat pump installations in California homes [37]. These further cost increases were included in order to align our estimates with current measure costs observed in today's home upgrade market. Drivers of these increases likely include higher hardware costs from original equipment manufacturers and distributors, as well as higher labor rates in the construction industry in general. Measures include an HVAC heat pump (inflation-adjusted from $11,879 to $14,374 and further increased to $15,952), an 80-gallon heat pump water heater (inflation-adjusted from $3800 to $4598 and further increased to $6800) and comprehensive envelope upgrades (inflation-adjusted from $12,789 to $15,475). Using these baseline costs, we derived cost reduction curves for the combined impacts of multiple cost reduction strategies from the results presented in the previous sections. These curves show potential cost reductions as reported by survey respondents based on the median cost reduction estimates from Table 1. Cost compression plots are shown for each measure in Fig. 5a–c. These measure cost reduction estimates exclude potential savings associated with soft cost categories, including customer acquisition, project delivery, and project closeout, and only include strategies from the upgrade-specific categories in the survey. The resulting potential reductions are substantial, at 26 % for HVAC heat pumps ($4071), 37 % for heat pump water heaters ($2524), and 21 % for envelope upgrades ($3322).

A limitation of this approach is the potential that some cost reduction strategies and reported reductions may not be additive or able to be combined into a single project. In order to address this issue, we filtered the set of cost reduction strategies to include only those that were not mutually exclusive (e.g., using lower-cost materials or pre-fabricated components, but not both) and that we expect may be additive. This process led to combining several of the automation-related strategies into a single strategy. We also excluded cost reduction strategies that were rated unlikely to be used by survey respondents (e.g., robotic interventions). Some cost reduction categories required adjustment from the raw survey results. Project delivery cost reductions were reported by survey respondents as a percentage. In order to convert to a dollar value, we applied the percentage to the remaining total project cost after all other cost compression activities were deducted from the "Current Cost" value. The envelope upgrade cost reductions were reported as $ per treated surface area. We converted these to total dollar values using the surface area assumptions from the archetype building used by Less et al. [8] in their costing analysis, which were 1768 ft^2 and 1366 ft^2 for attic framed floor and above grade wall surfaces, respectively.

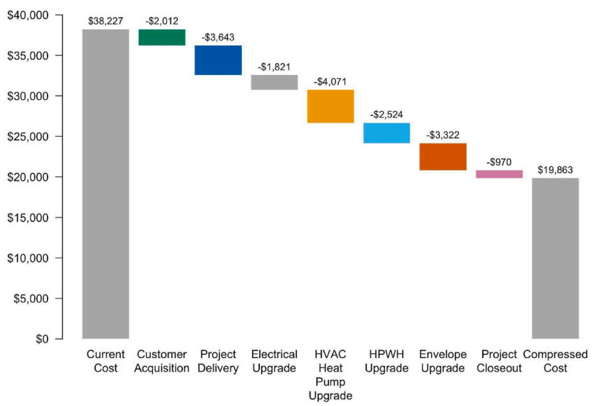

Fig. 6. Whole-dwelling upgrade cost compression waterfall including all cost compression categories evaluated in the industry survey. Medium cost reduction estimates from Table 1 are used. Total project costs are based on an archetypal project from Less et al. [8].

Many dwellings require a combination of several upgrade measures in order to improve performance and substantially reduce home energy use. In Fig. 6, we show a cost reduction waterfall plot for a whole-building upgrade that includes three primary measures–HVAC heat pump, HPWH, and envelope upgrades. This comprehensive project is based on a prototypical retrofit evaluated and assessed for costs in Less et al. [8]. For each individual upgrade, we apply the relevant cost reduction strategies while avoiding duplication (e.g., avoiding panel upgrades counted only once), and then we additionally apply the soft cost reduction estimates from Table 1 to the project as a whole. The resulting waterfall plot shows cumulative savings potential across a comprehensive, whole-building upgrade that leverages many cost reduction opportunities.

These results suggest that with all-of-the-above cost reduction strategies applied to all facets of the upgrade, roughly a 50 % cost reduction is feasible (from $38,227 to $19,863). This is roughly equivalent to the $20,000 cost reduction identified by Less et al. [8] required in order to achieve cost-effectiveness in comprehensive home upgrades saving more than 50 % of energy and carbon. This estimate presumes that almost the entire process of designing and delivering a comprehensive home energy upgrade is altered from current practice. Customer acquisition is automated through programs or web services, project discovery and design are supported by automated data collection processes, panel replacements and new wiring are reduced or eliminated, permitting is expedited, and lower cost options are used for each individual measure in the project. These changes would require the development of new tools capable of supporting automated data collection and project design by contractors and of upgrade delivery mechanisms that streamline customer acquisition, increase economies of scale, and reduce administrative burdens.

3.3. Qualitative results

3.3.1. Summary of qualitative responses

Introducing open-ended questions to the survey allows participants the flexibility to express their opinions, providing us with detailed insights. It also allows for capturing information and perspectives that quantitative questions may miss. Additionally, respondents tend to be more engaged in responding to qualitative questions, offering a more comprehensive view of their perspectives.

This section explores responses to 15 open-ended questions on the survey, for which we received 1364 total responses. We conducted a narrative analysis in which we manually identified patterns in the text by grouping content into words, concepts, and themes. For each question key themes were identified together with the fraction of respondents expressing each theme. We also manually categorized the themes into categories based on what project phase (for soft cost-related responses) or upgrade measure type they referred to. Detailed results are presented in Table S1 in the SI. Additionally, we grouped the major themes together into the following categories: 1) the reduction of fossil fuel use and emissions, 2) workforce improvement, 3) customer awareness and communication, 4) financing, costs, and incentives, 5) process simplification, and 6) business development. In this section, we provide a brief discussion and include illustrative quotes from survey respondents.

- Availability and cost of products for home decarbonization: When asked to define "home decarbonization" in their work in one short sentence, the respondents' answers demonstrate a clear understanding of the concept, but their answers also indicate a concern about a lack of suitable products. They emphasize the importance of using high-efficiency equipment because the added costs are small and the savings are higher. However, respondents expressed skepticism about some efficiency options. For example, they considered that panelized or pre-fabricated systems would likely increase costs due to the need to adapt them to the complexities inherent in existing homes. Another significant but less mentioned topic is the importance of improving existing products, such as HWHPs, to address the complexities they encounter during project execution (e.g., space or noise constraints). Also important is ensuring that the selected products will perform optimally so that customers will not experience an increase in bills. One respondent noted "legitimate design concerns about heat pump water heater placement, especially in multifamily buildings in cold climates. Still requires engineering design and analysis, not a drop-in solution."
- Workforce improvement: Respondents emphasized the urgency to accelerate training to meet the customers' needs. One respondent summarizes the challenge as follows: "One of our biggest challenges is finding people with the necessary skills and abilities and paying them a fair wage." Another states: "There is still a significant learning curve for most skilled trades involved in the work. Thus, enhancing training to improve productivity becomes crucial." Responses suggest that a better trained and educated workforce allows for better time management, leading directly to cost savings.
- Customer awareness and communication: Respondents recognize that effective communication plays a pivotal role in ensuring project success. However, there is the prevailing issue of inadequate communication between contractors/installers and customers. Customers often lack the necessary knowledge about the project, making it time-consuming for contractors to work with them. While acknowledging this challenge, respondents did not offer suggestions for who should undertake the task of educating customers nor how it should be done. However, they are well aware of the benefits of customer education for cost reduction. One respondent noted, "Educating the general public on energy savings would decrease the overall cost of energy program administration." Another respondent mentioned that it is not just about education but also effectively marketing the benefits of home energy upgrades to customers: "Our customers don't purchase home energy upgrades. They purchase home renovations and improvements in which we incorporate improvements in comfort, operational cost, and durability (i.e., our customers are not making decisions based upon efficiency improvements)."
- Reducing material and labor costs: On this topic, opinions varied substantially across respondents. Some caution against reducing material costs through selection of lower performing equipment, while others suggest exploring standardized solutions that would allow for bulk purchasing discounts and reduction in project planning effort. Cost reductions through reducing labor costs are elusive, as one respondent notes, "There is very little that can be reduced here. It's mostly labor which can't be reduced without severe quality issues." Simply reducing labor wages is not thought to be a promising strategy; however, it may be possible to reduce

labor costs through improving the efficiency of jobsite activities and logistics planning. Respondents view bulk purchasing as an effective way to reduce costs without compromising on labor and material expenses (although some expressed concerns about the costs of storing bulk materials). Some respondents provided new ideas on how to facilitate bulk purchasing: "Neighborhood installations could be conducted in bulk using IRA funding, making sales more streamlined. These sales could be organized geographically in batches to minimize travel costs."

- Reducing material costs through supply-chain optimization: Respondents noted the importance of supply chain optimization to reduce material costs: "State-side manufacturing, again. Everything is currently foreign. We'll never meet demand unless we produce locally for ourselves. It still needs to be competitive. High quality local manufacturing should bring costs down, or at least keep costs from soaring as demand grows." Additionally, some respondents emphasized the need for market innovation, where an efficient supply chain can play a crucial role: "Create programs that support market innovation in this area. We don't have enough options for small load buildings and our product market is not mature yet." Furthermore, there is a widespread awareness and concern among respondents regarding the CO2 emissions associated with project-related transportation. "With transportation being primarily done with fossil fuel; the more it can be reduced, the better." Reducing transportation during a project is seen as not only reducing CO2 emissions but also contributing to overall cost reductions due to saving time driving to and from work sites, offices, distributors, and storage locations.
- Importance of available rebates: Many respondents concur on the significance of having rebates available (both for customers and contractors) to offer competitive prices and create customer demand. One respondent says, "Any rebate programs or tax incentives that can be applied to reduce the cost of these upgrades will have a very profound effect on the overall goals of reducing our carbon footprint in the global community." As was noted earlier, rebate programs involve excessive administrative requirements, so simplifying rebates, for example, by applying them at the point of sale rather than post-installation, could be implemented more easily to reduce costs. Some respondents highlighted the possibility of unexpected or hidden problems in existing buildings, which could result in undesirable cost increases. Having a comprehensive understanding of the current condition of the building is thus important and can minimize the risk of encountering unforeseen, cost-increasing issues during the construction process.
- Process Simplification: Frequently mentioned issues pertained to the simplification of bureaucratic processes, including permitting, rebates, and project closeout procedures. It is important to make these easy and efficient, as it saves installers valuable time and money because it allows for, in one respondent's words, "More efficiently performing solution design and permitting." Other related suggestions included automated online permitting and paperwork reduction for rebates and subsidies. Occasionally, there were contradictory responses. For example, some respondents commented that diagnostic testing was essential to maintaining quality installations, whereas others wanted much less testing.
- Business Development: Improving business operations was a recurring topic, which is reported as crucial for controlling costs, achieving project goals, and satisfying customers. There is a pressing need to improve efficiency in project management to ensure project success, as one respondent notes, "To have really good help there must be really good ethics in the company at all levels. Too many companies have trouble with the staff because there is trouble with the management."

4. Discussion

4.1. Summary of findings

Our results show that there are a range of project soft cost reduction opportunities that can reduce the costs of home energy upgrade projects. Those estimated to be the most promising are primarily customer acquisition strategies, such as improving public awareness around energy use, avoiding the need of project design professionals, fixed price installation agreements, and obtaining comprehensive dwelling information and energy analysis prior to site visits. Having a more reliable/better trained workforce, measure bundling, bulk purchasing, and simpler permitting/rebate tools were also reported as high-value strategies. Rebates and tax credits were stated to be strong incentives and contribute to more effective marketing.

Our survey also explored upgrade-specific cost compression avenues. High-value strategies in this category involve avoiding electrical panel replacements for heat pump projects, reusing existing infrastructure, minimizing framing/demolition work, and implementing innovations that simplify installation. Some respondents also pointed out that while some products need performance improvements (such as HPWH in cold climates), the use of high efficiency equipment is recommended due to low incremental costs over standard equipment and the potential to reduce installation costs, due to smaller physical size and reduced electric infrastructure needs. When applied to a typical whole-dwelling energy retrofit project, these strategies could potentially compress installed costs by nearly 50 %, with HVAC heat pump installation strategies offering the greatest cost reduction opportunity.

The results presented here underscore opportunities to reduce costs through standardization and simplification across all stages of home energy upgrades, from design and permitting to construction and incentive administration. The construction industry's focus on time management and efficiency is evident throughout the qualitative responses, with a reluctance to cut labor or material costs due to quality concerns. Instead, the emphasis is on client satisfaction and strategies that reduce project delivery time. This underscores the need for standardization and simplification across all stages of home energy upgrades, from design and permitting to construction and incentive administration. Consequently, the strategies that appear most effective revolve around efficient time management, including practices like purchasing in bulk, minimizing site visits, and streamlining the permitting process.

4.2. Limitations

This study is subject to limitations, including in its data collection and analysis procedures. Regarding the former, this study uses a survey instrument that primarily relies on participants estimating the value of cost reduction strategies by selecting a "range" of dollars or percentages. Given that ranges are not uniform across the survey and are wide in some cases, they are likely to both under- and over-estimate actual cost reduction potential. Further, the potential for cost reductions is subjective and likely to be biased by respondents' past work experience, type of role (e.g., contractor vs. program designer), expertise/knowledge, location, and other factors. We attempt to address this limitation by collecting data on respondents' occupation/role, location (e.g., urban vs. rural), type (e.g., single- vs. multi-family) and volume of projects, and other demographic data. We adjust all cost reduction estimates based on the state respondents listed on the survey as the location where their project work primarily occurs (and then apply state-level adjustment factors from *RSMeans*). Despite these efforts, there is uncertainty in the cost reduction estimates reported in this survey, and the reported estimates should not be treated as precise values. Our use of state-level adjustment factors potentially obscures important intra-state differences between, for example, urban and rural areas. Uncertainty is also magnified by our data collection approach, which was non-random and relied on recruitment via the authors' existing contacts and networks. For this reason, our results are not necessarily representative of, or generalizable to, the home energy upgrade professional population.

Regarding data analysis, our approach to determine low, medium, and high estimates of cost reduction potential using the ranges provided in the survey is a limitation. Cost reduction ranges rather than precise values were used based on feedback from pilot survey respondents. Our method for working with these ranges was necessary to aggregate data across respondents and simplify interpretation of results. Our approach likely *underestimates* the cost reduction potential of solutions, given we collapse the upper-bound of the range (e.g., ">$3000" is coded as $3000). We expect this effect to be small, because very few respondents selected the highest range for most strategies on the survey.

Our application of estimated cost reduction potentials for measure-specific strategies to the costs of prototypical projects also has some limitations. It is likely that many of the strategies applied in this part of the analysis have some overlap, so we cannot rule out double-counting of potential cost reduction even when attempting to select strategies that are categorically different. Similarly, it is possible that the strategies included are not collectively exhaustive, so it is difficult to say whether this part of our analysis over- or under-estimates cost reduction potential at the "whole project" level.

4.3. Recommendations and avenues for future work

Despite the limitations noted above, this work constitutes an important contribution to the literature on compressing costs for home energy upgrade and decarbonization projects. Our collection of primary data from a geographically and occupationally diverse range of home energy professionals on a pressing but not well studied area of research can provide important insights and recommendations for the construction/home energy upgrade industry and policy community.

First, at the highest level, time is money in home repair and remodeling work. Strategies that reduce the time requirements to deliver a project will lead to cost reductions. Time spent on customer acquisition, sales discussions, rebate administration, paperwork, permit applications, inspections, project design, energy analysis, travel, installation labor, and more all contribute to unnecessarily high upgrade costs. If all cost reduction strategies explored in this survey share one common theme, it is that they facilitate reductions in time to deliver projects. This must be done in a way that does not unduly compromise project quality, contractor profits, or end-user experience, otherwise the industry will rightly refuse to adopt these approaches. This core principle should guide future efforts in this space.

Second, there is a clear need to promote workforce training and education programs tailored to meet evolving industry needs. Streamlining bureaucratic processes is essential because it offers potential for significant time and resource savings. Enhancing project management practices is another critical area for improving cost control. Moreover, the industry should consider encouraging bulk purchasing and implementing accessible rebates and financing options to mitigate project costs. Prioritizing customer education (and providing customers with appropriate decision making and guidance tools) is critical to ensure informed decision-making by clients. Lastly, exploring opportunities for supply chain optimization and promoting local manufacturing initiatives could further enhance efficiency and contribute to cost reduction.

Third, lack of communication is a problem. We have observed a communication gap between the construction industry and homeowners, as well as issues within contractor networks stemming from imperfect information and challenges in conveying the benefits of higher-cost solutions. From previous studies, we know that addressing customer demand and reducing costs result in lower project overhead and further cost reduction.

Fourth, from a policy perspective, we stress the importance of deploying more lucrative and less burdensome incentives for home energy upgrades to assist homeowners and contractors in reducing high upfront project costs. The structure of these incentives can be as important as their dollar values. For example, midstream incentives at point-of-sale can address some of the challenges and complexity associated with taxation-based incentives (e.g., tax credits or deductions). Addressing the unique challenge of accelerating home energy upgrades requires a strategic approach centered on cost reduction through standardization, simplification, and the integration of incentives.

Finally, pursuit of any one cost reduction strategy alone is unlikely to resolve the cost challenges faced by the industry. Upgrade costs are high, projects often involve multiple upgrade measures, and survey respondents reported relatively modest cost savings for most individual cost reduction strategies. Based on these results, we believe that a multi-faceted suite of cost compression strategies will need to be applied in parallel to have substantial, meaningful effects on project costs. This multi-faceted approach likely demands too much time and effort for implementation by individual practitioners. Furthermore, many of the cost reduction strategies cannot be implemented directly by practitioners and must instead come from product manufacturers, utilities, energy programs, regional and national governments (e.g., online code compliance tools, simplified energy programs, and rebate administration). Instead, practitioners will need improved tools, methods, training, and pathways for project delivery to support them in remaining profitable while delivering lower-cost and effective home upgrades.

5. Conclusions

This study presents results from an industry survey on promising and high-value opportunities to reduce costs for home energy upgrades. It sheds light on the complex challenges faced by the construction industry in this domain, which necessitate a coordinated effort to enhance workforce skills, streamline project delivery processes, and optimize supply chains. The findings of this study are motivated by prior research on home energy upgrade projects, which emphasize the persistent issue of high upfront project costs as a barrier to more accelerated and equitable deployment.

The industry survey conducted in this study provides important evidence on the strategies that are promising from both an industry adoption and monetary value perspective. This evidence can support the home energy upgrade workforce in scaling up approaches to reduce costs for numerous types of energy efficiency and electrification projects, which will scale up adoption of these projects, thus providing a boon to the home energy upgrade industry while also delivering substantial progress on US residential decarbonization efforts.

Future research should focus on documenting these cost reductions in practice for projects implementing these strategies. Field evaluations will validate cost reductions, reduce uncertainty in their estimated value, and support industry adoption. Unfortunately, this form of data collection is often time-consuming and expensive. Given the variety of market actors involved in scaling home energy upgrade programs, future research should focus on subsets of the industry and conduct more detailed case studies of how the strategies explored in this study could be employed, including barriers or important considerations for their use.

CRediT authorship contribution statement

Aven Satre-Meloy: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Núria Casquero-Modrego:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Brennan Less:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Iain Walker:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Data statement

Anonymized survey data that were collected and analyzed in this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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