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Energy Technologies Area
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# Challenges and Opportunities for Home Decarbonization


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**TABLE OF CONTENTS**

This report outlines new and innovative strategies needed to achieve substantial carbon dioxide ($CO_2$) reductions in the US housing stock. Rather than presenting a guide to home decarbonization that includes well-established approaches and technologies, this report is focused on challenges to enable decarbonization of large numbers of existing homes as soon as possible. This report identifies the key opportunities to overcome these challenges, with a particular emphasis on helping the US Department of Energy (DOE)'s Building Technology Office (BTO) achieve its vision of low/no carbon emission existing homes by 2050.

Decarbonizing the US housing stock is a complex and difficult undertaking. However, recent US federal government initiatives are providing considerable support by investing in buildings infrastructure. This report provides targeted guidance and background information to help residential building sector initiatives succeed. Actions identified in this report are selected based on the following overarching priorities:

1. **Develop solutions for all households**
   The US has 118 million households, which include single-family homes and multifamily units across seven distinct climate zones (US Energy Information Administration (EIA), 2015). These households also have varied needs in terms of efficiency, electrification, and remediation to decarbonize. Finally, these homes vary in terms of occupancy, ownership status, and access to capital based on homeowner income, savings, and credit. Decarbonization solutions are needed that are inclusive and flexible to these varying conditions and designed to leave no one behind.
2. **Make home decarbonization affordable**
   Because decarbonization retrofits have not yet achieved scale in the market, costs remain high – a previous Lawrence Berkeley National Laboratory (LBNL) study suggests, on average, $55,000 per home (Less et al., 2021). Reducing the technology and soft costs associated with home decarbonization retrofits will make these projects more accessible and appealing to more households.
3. **Support the US clean energy economy**
   DOE's Office of Energy Efficiency and Renewable Energy (EERE) has a mission to equitably transition the US to a net-zero greenhouse gas emissions economy by 2050. Combating the climate crisis through clean energy deployment presents an unparalleled opportunity to create millions of good-paying jobs and successful businesses, including in manufacturing and constructing emissions-free technologies for US homes.

With these priorities in mind, this report identifies key challenges preventing home decarbonization retrofits from scaling in the market today. These challenges and opportunities fit into three key categories: Technical, Cost, and Valuation.

| Challenge or Opportunity Category | Description |
|---|---|
| **Technical** | Areas where specific aspects of technology design, performance, specification, or interoperability may be improved to simplify residential decarbonization. |
| **Cost** | Areas where residential decarbonization project costs may be reduced to increase project affordability. Includes both hard and soft costs across project first costs, home operational costs, and cost of capital. The cost data used to support this work did not include rebates, tax credits or differences between utility rate structures and net-metering policies. |
| **Valuation** | Areas where the understanding, quantification, and communication of residential decarbonization project benefits can be improved to drive greater market demand for this work. Benefits include lowered energy costs, increased comfort, improved indoor air quality and health outcomes, increased home value, and reduced pollution. |

Although specific challenges may apply across these categories, for the purposes of this document, identified challenges have been placed into one best-fit category. The table below summarizes the identified challenges and opportunities discussed throughout this report.

<table>
<tr><th>Technical Challenges</th><th>Associated Opportunities</th></tr>
<tr><td rowspan="3">Limited product availability for power- and space-constrained homes. Limited supply options for the replacement of appliances upon failure</td><td>Develop new products: power-efficient appliances, more form factors, and transportable technologies.</td></tr>
<tr><td>Expand US manufacturing base for decarbonization technologies.</td></tr>
<tr><td>Develop products and technologies for temporary emergency replacement.</td></tr>
<tr><td rowspan="3">Some decarbonization projects require electric service and panel upgrades, which are costly, cause project time delays and can increase the need for ratepayer funded additions to the generation and distribution system</td><td>Develop storage and load-management products and technologies at a residential building scale.</td></tr>
<tr><td>Update electrical codes to support safe, power-efficient electrification that limits the need for site panel replacement and higher power electric service.</td></tr>
<tr><td>Perform field demonstrations of power-efficient technologies and power-limiting packages to avoid electric service upgrades in power-constrained homes.</td></tr>
<tr><td rowspan="3">Many decarbonization technologies are currently more difficult to purchase and install than business-as-usual alternatives</td><td>Standardize decarbonization solutions (e.g., electrify end-uses, install solar photovoltaics (PV), and seal and insulate ducts & envelope). Develop multi-trade workforce to implement packages.</td></tr>
<tr><td>Minimize remediation of structural, moisture, and other issues.</td></tr>
<tr><td>Support the development of a robust and profitable supply chain for decarbonization technologies in the US.</td></tr>
<tr><td>Energy efficiency metrics (e.g., site energy, energy ratings) are misaligned with decarbonization</td><td>Develop and standardize decarbonization metrics to be used in programs, financial decisions, software tools for project and policy planning, etc.</td></tr>
</table>

| Cost Challenges | Associated Opportunities |
| --- | --- |
| **Project costs are not affordable for many households** | Create prioritized strategies using existing technologies and staged/partial decarbonization approaches. |
| | Reduce costs of solar PV and develop rate structures supportive of decarbonization that ensure benefits for low income households. |
| | Integrate project financing, planning, and delivery as part of one-stop shop program models. |
| | Use affordability and monthly cost as new metrics, and develop new financing, payment, and ownership models. Create stacked incentives that get to cost parity with business-as-usual solutions. |
| | Explore delivery of comprehensive projects using direct install program structures. |
| **Address operational cost increases with electrification in areas with high electric rates** | Use load reduction and higher efficiency equipment to reduce potential bill increases. |
| **Low-income and renter households often cannot access decarbonization upgrades** | Develop solutions for renters. |
| | Improve renter protections. |
| | Analyze energy costs and fuel poverty issues. |
| | Characterize and address legal issues with rental leases that include landlord-paid heating or other energy services |
| **Lack of available workforce with residential decarbonization expertise** | Develop training and apprenticeships/mentoring programs. |
| | Develop DIY and plug-and-play solutions. |
| | Develop business practices and business models for contractors that improve project efficiency and profitability while reducing soft costs. |
| **High overhead in home energy upgrades** | Reduce project acquisition costs for contractors. |
| **Building codes and standards may add unnecessary cost burdens when they are misaligned with decarbonization** | Develop revisions to codes and standards barriers to home decarbonization. |
| | Provide leadership and technical assistance to standards and code bodies. |

| Valuation Challenges | Associated Opportunities |
| --- | --- |
| **Lack of accounting for increased home value due to decarbonization upgrades in cost-effectiveness metrics market-wide** | Support metrics to increase home value from decarbonization. |
| | Use metrics and framing that emphasize value over cost. |
| | Change economic justifications to base around affordability and easy access to financing. |
| **Key energy stakeholders do not always support residential decarbonization** | Conduct analyses to inform policy changes. |
| | Conduct workshops to bring key players together and develop consensus-driven policies. |
| **Home electrification/decarbonization is not a priority for homeowners** | Develop programs with phased approaches. |
| | Showcase benefits for energy reliability, performance, and costs. |
| | Determine homeowner needs/perspectives. |
| | Demonstrate comfort, health, and safety improvements from decarbonization. |
| | Include health, indoor air quality (IAQ), and other benefits in decarbonization programs and policies. |
| | Improve market understanding using industry surveys and stakeholder solicitations. |
| | Increase industry and public awareness – include collaboration with trusted partners. |

While the challenges to scaling residential decarbonization solutions are varied and current costs are significant, the benefits of taking on this work are immense. US residents spend a combined $200 billion on their home energy bills every year, leaving many struggling to pay for other necessities and to stay warm in the winter or cool in the summer.

- Homes with better access to decarbonization solutions can reduce these energy costs while improving indoor air quality and comfort to produce homes that are better to live in overall.
- The work it takes to deploy these solutions can jumpstart the economy in every county across America, supporting skilled workers in good-paying jobs with year-round employment.
- Decarbonized homes also improve outdoor air quality by reducing pollution from power production.

- Increasing our country's production and use of energy efficiency and renewable energy will support national security, energy affordability, and future-proof our economy.

Although this report focuses on costs and barriers and how to overcome them, it is worth noting that the costs of *not* taking action are much higher, including those associated with growing energy bills, aging housing infrastructure, lost revenue to overseas resources, and intensifying climate disasters. By taking on these research, development, and deployment tasks, DOE can help accelerate access to better homes, lower costs, and a better climate across the country.

The aim of this report is to identify the key challenges that stand in the way of a decarbonized US housing sector by 2050 and assess actionable solutions to these challenges. By beginning with this end goal, this report is forced to address a much wider array of issues and complications that may otherwise leave some homes behind. Through review (Less et al., 2022) and analysis (Walker et al., 2022c) of existing retrofit projects (Less et al., 2021a), emerging decarbonization pathways (Walker et al., 2022a), and the landscape of existing housing conditions (Walker et al., 2022b), the following three overarching priorities have emerged:

1. **Develop solutions for all households**

   Solutions are needed that focus on retrofitting the US's 118 million existing homes (EIA, 2015). Decarbonizing the US economy will require solutions that can be deployed across housing types, climate zones, and income levels. In particular, affordable solutions for disadvantaged, low-, and mid-income households are the key to successfully achieving our primary target of zeroing out housing emissions. There must be simple solutions that are designed to meet the needs of disadvantaged communities, multifamily housing residents, and renters. Some subsets of US households that may require significant support:

   - The 44 million households in rented accommodations (EIA, 2015). Although these residents pay into efficiency programs, they typically cannot access these programs themselves, and landlords typically do not experience adequate incentives to make decarbonization upgrades themselves.
   - The nearly 7 million Americans in manufactured homes, of which roughly a third live in homes that were built prior to any federal manufactured housing code. These households are disproportionately lower income and with fewer options for low-cost financing. They also have been shown to suffer disproportionately large energy burdens compared to the rest of US housing.
   - The 12 million homes needing health and safety mitigation before energy or decarbonization upgrades can occur (Graham, 2022).
   - Households with little/no savings or low/poor credit that prevents them from accessing savings or financing. In 2018, among applicants with incomes under $40,000, 37% were denied credit (Federal Reserve Board's Division of Consumer and Community Affairs (DCCA), 2019).

   Research and development (R&D) activities are needed to create simplified technology packages that can reach the diversity of US households. Affordability will also be a key component of making these solutions technically feasible and economically viable.

While many building code programs have focused on new construction, this sector is not the focus of this report. Since new construction is only a small fraction of the housing market (typically 1% or less in any given year), technical barriers to decarbonizing new construction are minimal, and in many cases, decarbonized new construction is already affordable, in part due to reduced gas distribution infrastructure costs. In contrast, homes with the most significant barriers to decarbonizing are typically older, in more extreme climates, and comprise lower-income households.

2. **Make decarbonization affordable**
   To get to scale, decarbonization of residential buildings in the US needs to become an easy option, which includes assuring it is affordable. LBNL recently completed a study, *The Cost of Decarbonization and Energy Upgrade Retrofits for US Homes,* that created a database on the costs and energy/carbon performance of over 1,700 home retrofits in the US (Less et al., 2021b). This study showed that reaching at least 50% carbonreductions currently costs about $55,000 for a typical single-family home. Expanding this to cover all homes implies that decarbonizing US housing would cost upwards of $5 trillion. At the same time, median US household savings are only about 10% of this cost (Board of Governors of the Federal Reserve System, 2019). Targeted activities to increase affordability are:

   - Reduce costs of $CO_2$ emissions avoided per home through improved and standardized project designs. Current approaches typically require customized solutions for each home, which increases overall project costs. Supporting the development of standardized technology and financial solutions can help reduce this cost burden.
   - Prevent efforts to reduce costs through reduction of worker wages by making home retrofits and technology deployment more labor productive. In the long term, improving the value proposition for workers in this industry can reduce costs by supporting a sustainable and skilled workforce.
   - Develop solutions that limit total power requirements and avoid upgrading the electric service, panel, and electric circuits in the home. This reduces upfront costs, project delays (e.g., some utilities have long wait lists to approve panel upgrades and upgrade service drops), and operating costs due to upgraded utility infrastructure, and helps with grid integration of new electric loads.
   - Reduce customer acquisition costs by making decarbonization projects not only affordable but a desirable and easy default option.

   Although the cost of full decarbonization may be high for some homes, there are many homes where decarbonization is an affordable and achievable outcome today. A key strategy for reducing costs for all homes will be supporting business innovation and deployment today to achieve economies of scale. In the short term, programs and incentives can focus on accelerating market scale, worker upskilling, and demonstrating decarbonization value to overcome some of the existing cost barriers.

Affordability also includes the cost of energy. The relative costs of different fuels can lead to increases or decreases in household energy bills after a home has been decarbonized. For regions of the US where electricity is expensive relative to other fuels, care must be taken to control operating costs. This can represent a significant decarbonization challenge, particularly for low-income households and multifamily buildings, where occupants are responsible for their individual electric use, but gas use is included in rent or other fixed fees.

3. **Support the US clean energy economy**

Combating the climate crisis through clean energy deployment presents an unparalleled opportunity to create millions of good-paying jobs and successful businesses, including in manufacturing and constructing emissions-free technologies for US homes. To do so, activities to decarbonize housing must fundamentally spur continued market demand for decarbonized housing. Without demand for decarbonization, there is no economic driver to spur job growth or business innovation. To successfully increase demand, solutions will need to be what homeowners and residents desire: readily available, affordable, easily financed, reliable, safe, and resilient.

As a result of the meager overall demand for home decarbonization, not enough businesses and contractors offer home decarbonization services such as heat pump installation, weatherization, and electrical upgrades. Some clean energy products, needed for home electrification and decarbonization, are not manufactured in the US.

As home decarbonization is scaled-up to meet climate goals, there is an opportunity for domestic manufacturers to support the goals and benefit. Money spent on climate mitigation should support the US jobs, businesses, and overall economy. This manufacturing opportunity goes beyond economics, considering controlling materials sourcing for products – such as web-enabled connected devices that allow remote control by occupants or that automatically respond to grid signals – introduces sensitive national and energy security considerations.

With these economic opportunities comes a significant potential for job growth in manufacturing, engineering, construction, and business services. As the market for home decarbonization grows, there is a need to ensure there are workers with appropriate skills to take on these tasks. While actions to support the residential decarbonization workforce are a key component of assuring economic growth, it is not the core focus of this report. Additional reports are available from DOE regarding specific actions to support the millions of workers in this sector nationwide.

## 2.1 Scope of the Decarbonization Challenge

To prioritize and develop decarbonization R&D strategies, it is important to recognize that some homes need more decarbonization than others and that there are considerable geographic variations in critical factors, such as climate, utility rates, and carbon content of electricity. Multiple strategies are needed for success. In addition, there are key divisions in the US housing stock, split into three groups:

1. First are the 25% of homes where all energy is supplied by electricity and where there is no fossil fuel-burning equipment on site. These homes do not need service upgrades or rewiring (unless adding substantial Solar PV or EV charging) but may lower carbon emissions through energy efficiency improvements, such as replacing electric resistance devices with heat pumps. If a home is located where the carbon content of electricity is high, the decarbonization end goal should be to use less electricity at the household level to reduce carbon emissions.
2. The second group is the 40% of homes that are not fully electric but are heated with electricity (Davis, 2020). These homes need to electrify existing fossil fuel end uses (hot water, clothes drying, and cooking) and upgrade electric resistance heating to heat pumps. Also in the second group are multifamily buildings with electric cooking and drying, but fossil fuels for space and water heating. These could be a challenge for electrification especially in multifamily buildings with limited electrical service or in cold climates with no air conditioning.
3. The remaining homes with non-electric heat will be the biggest challenge. They require the replacement of heating systems and the most challenging of them will use fossil fuels for other end-uses, such as hot water, clothes drying, and cooking. Some of these fossil fuel homes may be difficult to fully electrify if they are located in northern climates due to limited heat pump capacities in cold weather. They also may have significant costs associated with electric service/panel upgrades if they are older homes with insufficient electric capacity to support the transition to an all-electric home. The US DOE EAS-E prize is focused on these high gas use, hard to electrify, homes.

Figure 1 illustrates the geographical distribution of primary heating fuel. According to a University of California, Berkeley report, the primary driver of this variation is energy prices (Davis, 2020). The second important factor is that little heating is required in mild climates (in the Southeast), and this leads to the use of electric resistance heating that has a low initial capital cost. There are also parts of the rural US that lack gas infrastructure and use liquid petroleum gas (LPG), fuel oil, electricity or biomass (e.g., woodstoves). This distribution indicates that some locations will be more challenging to decarbonize than others - i.e., those that mostly use fossil fuels for heating. Furthermore, electric heating has been growing in the US, and any electrification program is simply an addition to this trend, as illustrated in Figure 2.

**FIGURE 1: GEOGRAPHIC DISTRIBUTION OF PRIMARY HEATING FUEL IN THE CONTIGUOUS US STATES**

Primary Heating Fuel (Plurality)

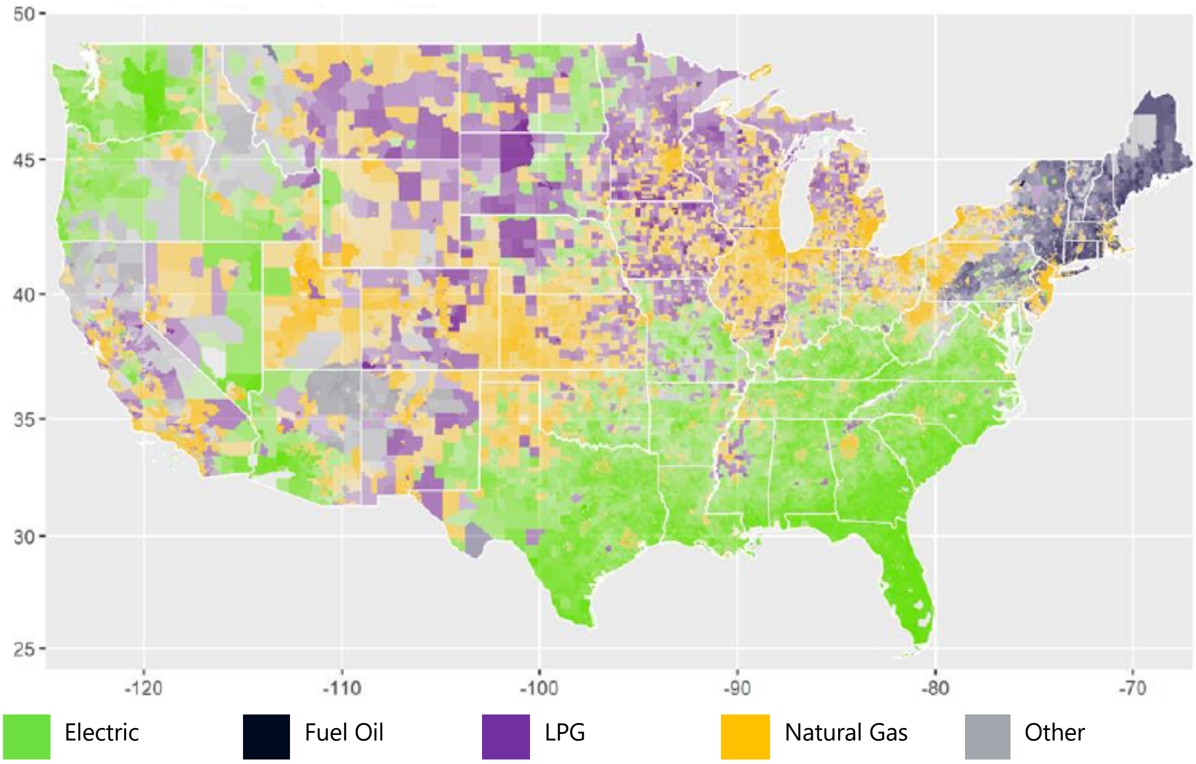



Figure source: The American Community Survey, (2016)

**FIGURE 2: GROWTH OVER TIME OF ELECTRIFICATION OF HEATING IN THE US**

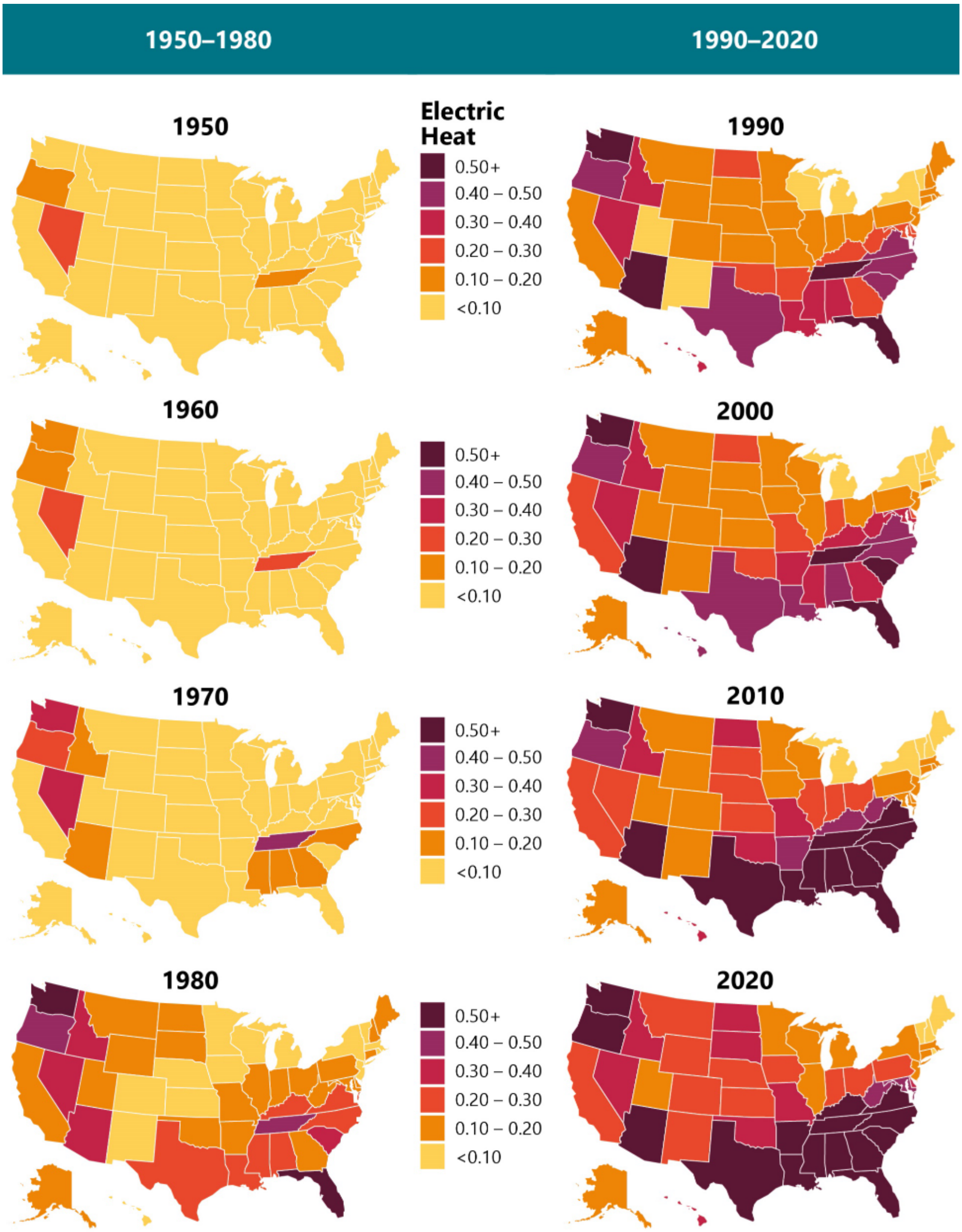



Figure source: Davis, (2020)

This geographic variability is further reinforced by an analysis of heat pump performance required to break even from a carbon and energy bill perspective (Walker et al., 2022b). As an example, Figure 3 shows how the coefficient of performance (COP) required for $CO_2$ equivalence to an 80% Annual Fuel Utilization Efficiency (AFUE) furnace varies from state to state due to the differences in the carbon content of electricity. Most locations in the US achieve carbon neutrality using heat pumps with COPs of around 3. Exceptions are states that use a lot of fossil fuel to generate electricity, such as Wyoming. As the electric grid decarbonizes over time, we expect the minimum COP for $CO_2$ neutrality to decrease from the values shown in Figure 3 that are based on current emissions reported in the US EPA eGRID data set. It should also be noted that the results in Figure 3 do not account for all sources of potential emisisons, such as methane or refrigerant leaks, or for embodied $CO_2$. Including these factors will require more comprehensive future analyses.

In the states requiring COP greater than three, or where cold weather heat pump performance cannot deliver a seasonal average COP of 3, additional measures will be needed to achieve cost neutrality – such as specifying high-performance heat pumps, on-site generation using PV, or load reduction with envelope and duct air sealing and insulation. There are substantial R&D efforts underway to improve cold climate heat pump performance to help address this issue, including efforts from DOE,[1] but other complementary efforts are still needed. Figure 4 illustrates the COP required for operating cost neutrality in which the variability in required COP reflects the ratio of gas to electricity prices. The variability in $CO_2$ intensity and fuel costs imply that decarbonization programs and priorities will need different approaches in different parts of the country. These results also imply that optimum strategies will often need to include load reduction and DOE's Building Technology office has programs for both Windows[2] and Opaque Envelopes[3] that are undertaking R&D efforts to reduce heating and cooling loads. There are also DOE reports (Harris, 2021) that outline DOEs plans in this area, and DOE's Advanced Buildings Construction program[4] is a key DOE R&D activity supporting reduction of envelope loads.

[1] https://www.energy.gov/eere/buildings/residential-cold-climate-heat-pump-challenge

[2] https://www.energy.gov/eere/buildings/windows

[3] https://www.energy.gov/eere/buildings/opaque-envelope

[4] https://www.energy.gov/eere/buildings/advanced-building-construction-projects-building-envelope

**FIGURE 3: MAP OF MINIMUM HEAT PUMP COP REQUIRED FOR CARBON DIOXIDE EQUIVALENT EMISSIONS NEUTRALITY IN EACH US STATE, COMPARED WITH AN 80% AFUE NATURAL GAS FURNACE, USING 2019 EGRID AVERAGE EMISSION FACTORS**

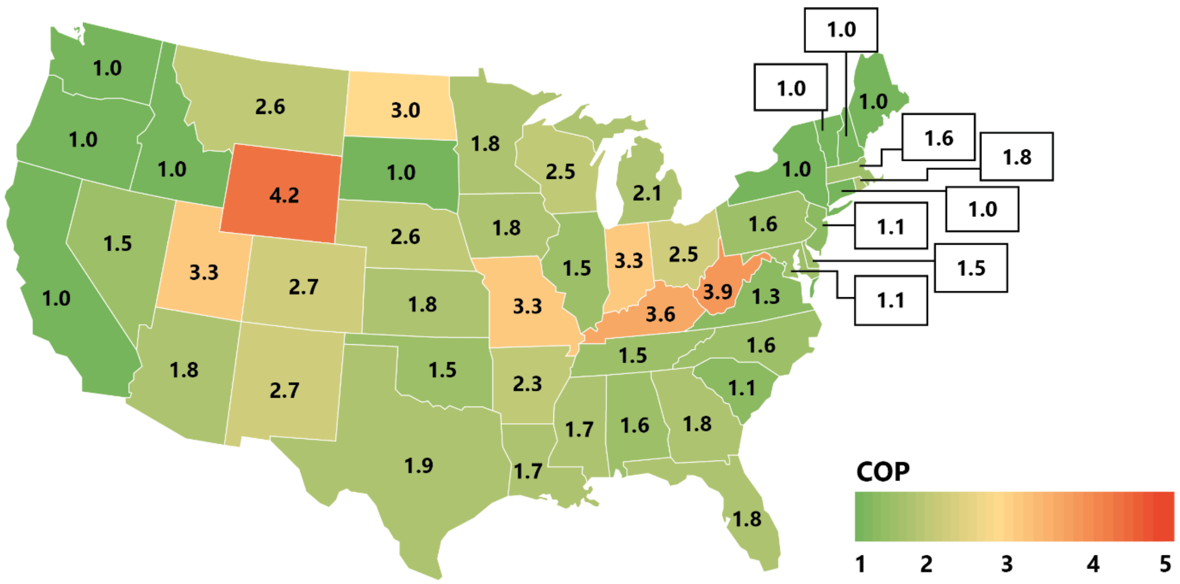



Figure source: Walker et al., (2022b)

**FIGURE 4: MAP OF MINIMUM HEAT PUMP COP REQUIRED FOR ENERGY COST NEUTRALITY IN EACH US STATE, COMPARED WITH AN 80 AFUE NATURAL GAS FURNACE**

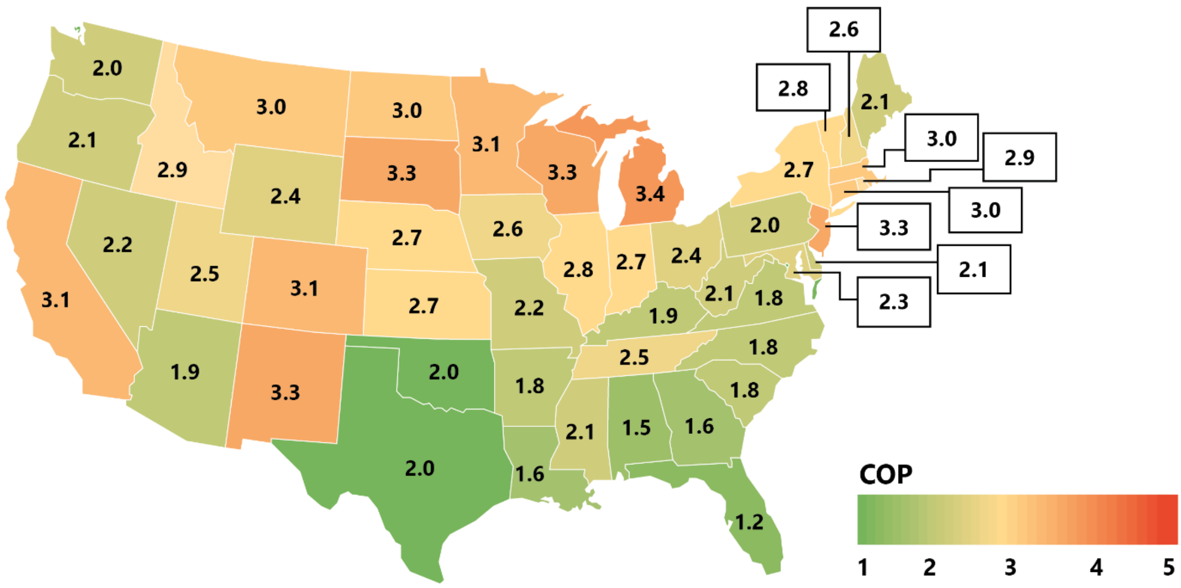



Figure source: Walker et al., (2022b)

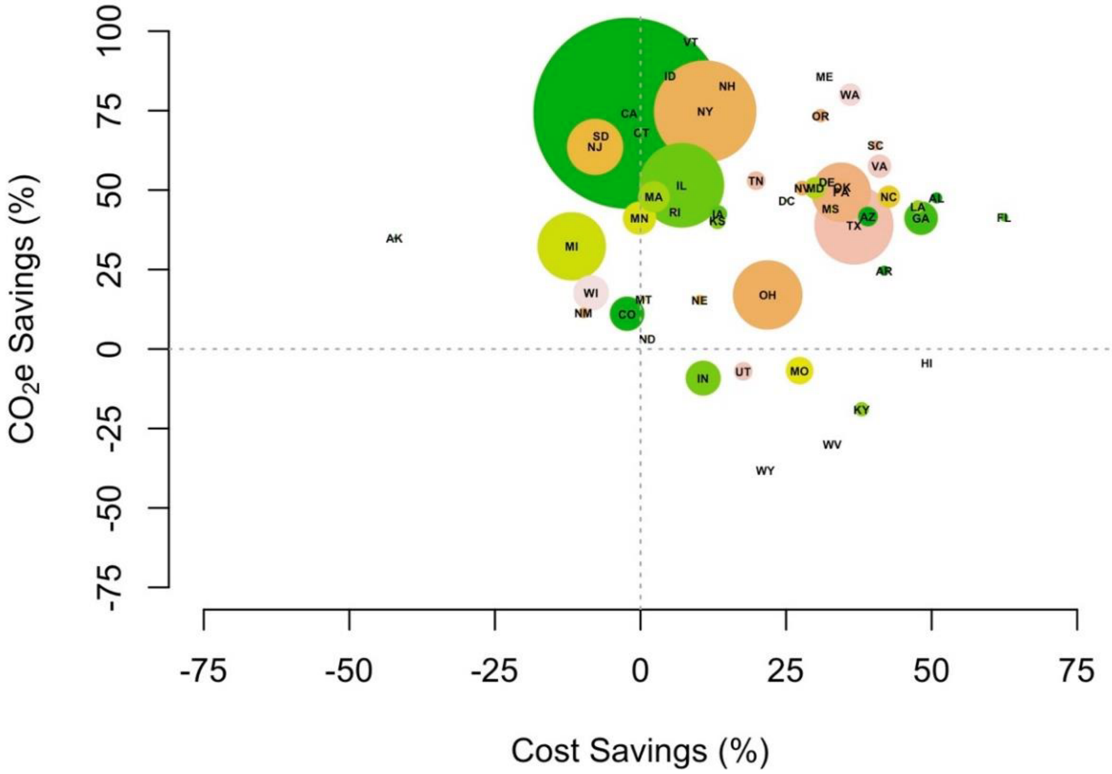
The 80% AFUE was chosen for comparison because it is common in many homes. Historical shipment data from the EIA up to 2014 (*Residential End Uses: Historical Efficiency Data and Incremental Installed Costs for Efficiency Upgrades*, 2017) shows that more than half of shipped new units from 2004 to 2014 were 80% efficiency. Before 2004, it would be an even greater fraction at 80% or lower, so using 80% AFUE is the most reasonable comparison. The same analysis for an older 65% AFUE furnace shows that only two states (Wyoming and West

Virginia) need a COP greater than 3 to have lower $CO_2$e emissions, and a COP of 2.7 makes all states at least cost neutral.

When compared to high-efficiency condensing furnaces (95% AFUE), the geographic trends remain the same, as seen above in Figures 3 and 4, but higher seasonal COPs are required in larger portions of the mountain west for carbon neutrality, including Montana, North Dakota, Colorado, New Mexico, and Nebraska. From an energy cost perspective, 45% of states need a seasonal average COP greater than 3, and a few (2%) require a COP of 4. These states comprise nearly the entire Northern section of the US (excluding Washington, Oregon, and Maine), along with a few states in the desert southwest (New Mexico and Colorado) and California. Additional US geographic maps for the AFUE 95 comparison are shown in Appendix A.

It can also be useful to look at $CO_2$ and cost savings together and to weight the results by the number of appliances that need to be changed out. This comparison between $CO_2$e and cost savings for an 80 AFUE furnace is shown in Figure 5, where the size of the balloon is proportional to the number of furnaces in each state. This shows that many of the states with large numbers of gas furnaces are close to cost-neutrality while having substantial $CO_2$e savings. These results for a 95 AFUE furnace are shown in Appendix A.

**FIGURE 5: PERCENT SAVINGS FOR $CO_2E$ AND ENERGY COST IN EACH US STATE, WHEN REPLACING AN 80% AFUE FURNACE WITH A COP 3 HEAT PUMP USING 2019 EGRID AVERAGE EMISSION FACTORS AND STATE AVERAGE RETAIL ENERGY COSTS FROM EIA**




Notes: Points are scaled according to the count of natural gas space heating appliances in each state. Color coding is for visual separation only.

Figure source: Walker et al., (2022b)

## 2.2 Current State of Home Energy Upgrades and Decarbonization

The rate and the scope of energy efficiency retrofits are insufficient to meet our carbon reduction goals. A summary of deep energy upgrade programs in the US (Less et al., 2014) showed that current deep energy retrofit (DER) programs have typical energy savings of 20–40%. A recent literature review for DOE (Less et al., 2021a) showed that programs aiming for deep savings typically save 25–30%, with the very best saving 40–60%. While the relationship between energy and carbon savings is not exact, these savings ranges provide useful estimates of carbon savings for these projects. While a significant contribution, these reductions of 25-30% are not enough to achieve reductions in carbon emissions that meet the US federal government's goals of halving all carbon emissions by 2030 vs. 2005 levels and DOE goals of low/zero carbon emissions for the buildings sector will require electrification of end uses to reduce $CO_2$ emissions.

DOE's 2021 study on *The Cost of Decarbonization and Energy Upgrade Retrofits for US Homes* showed that, to have at least 50% carbon reductions, current projects require about $55,000 per home. However, this could be reduced by $10,000 or more by shifting to archetypal projects that avoid higher-cost energy and carbon-saving measures. These archetypal projects reach over 60% carbon reductions through upgrades such as moderate envelope improvements and the installation and use of heat pumps – alongside solar PV – to provide heating, cooling, and domestic hot water (DHW). Such upgrades likely have a minimum cost of about $40,000 per home. This cost could be reduced in more modern homes that are already well-insulated and have low air leakage (such as the 3-5 ACH50 specified in codes) and may need little envelope upgrading. In locations with very low carbon content electricity (or, as the grid becomes less $CO_2$ intensive in the future) it may be possible to avoid the cost of installing Solar PV, although this may be offset by a need to increase home and grid resiliency, increase the total renewable generation at larger grid scales and lower the load on the grid by integrating energy storage.

R&D efforts are required to reduce the cost of achieving these deeper carbon savings, and guidance needs to be created for the industry to encourage the use of more affordable solutions. In addition to the carbon emission reductions during operation, there is a need for R&D on embodied carbon in measures specific to existing home decarbonization (e.g., in the production of insulation, replacement windows, HVAC equipment, solar PV systems, and the GHG potential of refrigerants). This will be an essential part of the long-term decarbonization of the construction industry. From an embodied carbon perspective, upgrading existing homes rather than replacing them means that much of the carbon-intensive infrastructure (such as concrete foundations) is retained.

Almost all previous studies have focused on single-family homes, so much of the background for this report and the resulting challenges and opportunities are based on insights from that market segment. DOE is currently funding cost, carbon, and energy performance studies for multifamily dwellings so that they can be better represented in future planning activities. Some key complications associated with multifamily buildings (and other rental properties) are not addressed in this report. For example, in many cases tenants are responsible for electricity bills, while gas bills for heat or hot water are often included in rent or other fixed fees. Heating electrification would shift those costs from the landlord to the individual tenants, increasing their monthly costs or necessitating large-scale re-negotiation of leases and contracts.

### 2.2.1 Pioneering Programs

Efforts are underway in some parts of the country to ease the transition to decarbonized homes. California, Vermont, and New York are leading this effort.

- In California, San Mateo County administers a pilot program providing homeowners with electrification plans to help homeowners with the transition. There are also non-profit organizations leading the transition to low-carbon housing. The state's Bay Area Regional Energy Network (BayREN) runs outreach programs to a variety of audiences, including community organizations, individual homeowners, architects, contractors, and others. One exceptional program is TECH clean California[5] program that offers incentives, pilot activities, technical assistance, and training to address barriers associated with clean space and water heating technologies across California homes. It is also making data summaries publicly available. These data provide a great resource for updating the TECH program in the future and as guidance for other program developers. A key takeaway from the first year of the TECH program was that there is much more interest than anticipated and there was rapid participation growth.
- In Vermont, the Vermont Energy Investment Corporation (VEIC) and Efficiency Vermont are not only decarbonizing homes but are involved in workforce training programs, publicizing success stories, developing programs for low- and mid-income households, and expanding to include non-residential buildings (such as grocery stores).
- In New York, NYSERDA has created resources to help building owners and operators develop cost-effective decarbonization strategies; a carbon-neutral buildings roadmap; funding mechanisms for carbon-neutral communities; and significant funding for competitions, such as the Global Innovation Challenge, to decarbonize New York City Housing Authority buildings using new heat pump electrification technologies.

Nationally, many more local non-profit, advocacy, and community organizations are ready to engage residential communities. Stakeholder engagement with these organizations -

[5] https://techcleanca.com/

particularly to address affordability and equity issues – is a key opportunity to achieving decarbonization goals and has been identified as a key strategy by DOE. Examples include the BBNP evaluation Spotlight on Key Program Strategies from the Better Buildings Neighborhood Program (Research Into Action, 2015) or Better Buildings Residential Network Voluntary Initiative: Partnerships Toolkit (*Voluntary Initiative: Partnerships Toolkit*, n.d.), and other DOE resources[6].

### 2.2.2 Scaling Challenges

The residential buildings sector is uniquely challenging to decarbonize at scale due to the extremely high rate of decision-makers per unit of $CO_2$ compared to any other sector. Getting to scale requires reaching a significant number of decision makers: More than 100 million individual households and tens or hundreds of thousands of contractors, wholesalers and retailers, program managers, local code officials, and others. Furthermore, these constituents hold a wide range of perspectives on the need to decarbonize buildings, their personal interest in improving homes, financial status, and range of acceptable risks, among other concerns.

These sector-specific realities make decarbonizing residential buildings a particularly difficult challenge. Therefore, this report will focus on various approaches that will reach and impact most households (such as using heat pumps) while recognizing multiple disaggregation factors such as building type, climate zone, and occupant needs, including factors other than solely carbon reduction as motivators for change.

### 2.2.3 Industry Perspectives

A recent survey (Chan et al., 2021) (Casquero-Modrego et al., 2022) sought input from a group of industry experts, primarily practitioners: contractors, energy consultants, and utility program managers. The results (examples are shown below in Figures 6 and 7) showed that lack of demand and workforce issues are key barriers to implementing projects, coupled with unforeseen home conditions that require remediation measures[7] prior to project completion and considerable project-specific problem-solving.

"Lack of consumer demand" represents at least two distinct household types: those with little or no interest in decarbonization and energy-saving projects and those with the desire to decarbonize but where other issues prevent action (primarily due to cost or lack of perceived value). For those households interested yet unable to pursue projects, industry experts shared that increasing demand for decarbonization and energy-saving projects would require addressing project costs, providing easy access to financing, and valuing non-energy aspects of projects, among other responses. Reaching the remaining households with little

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[6] https://rpsc.energy.gov/handbooks/program-design-customer-experience-identify-partners

[7] For example, structural and moisture issues, asbestos/lead abatement, and replacing knob-and-tube wiring.

to no interest in decarbonization proves to still be a long-term challenge that requires as-yet unidentified solutions.

**FIGURE 6: BIGGEST BARRIERS FACED BY STUDY RESPONDENTS WHEN PERFORMING DEEP ENERGY RETROFIT (DER) PROJECTS**

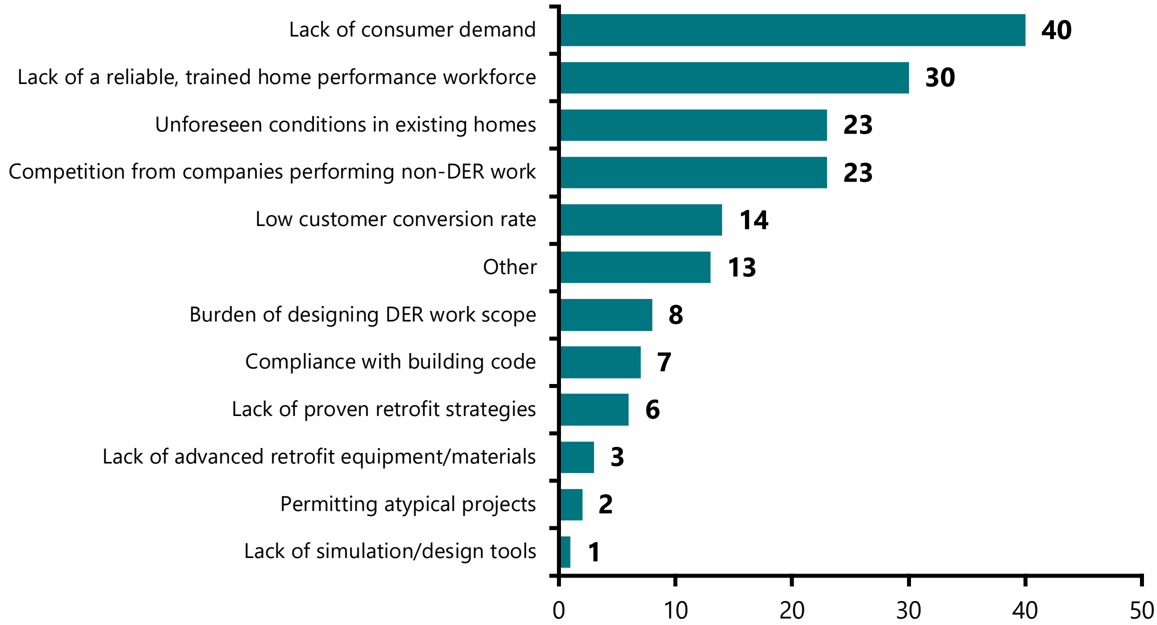


Figure source: Chan et al., (2021)

**FIGURE 7: EFFECTIVE WAYS TO INCREASE CUSTOMER DEMAND FOR DER PROJECTS**

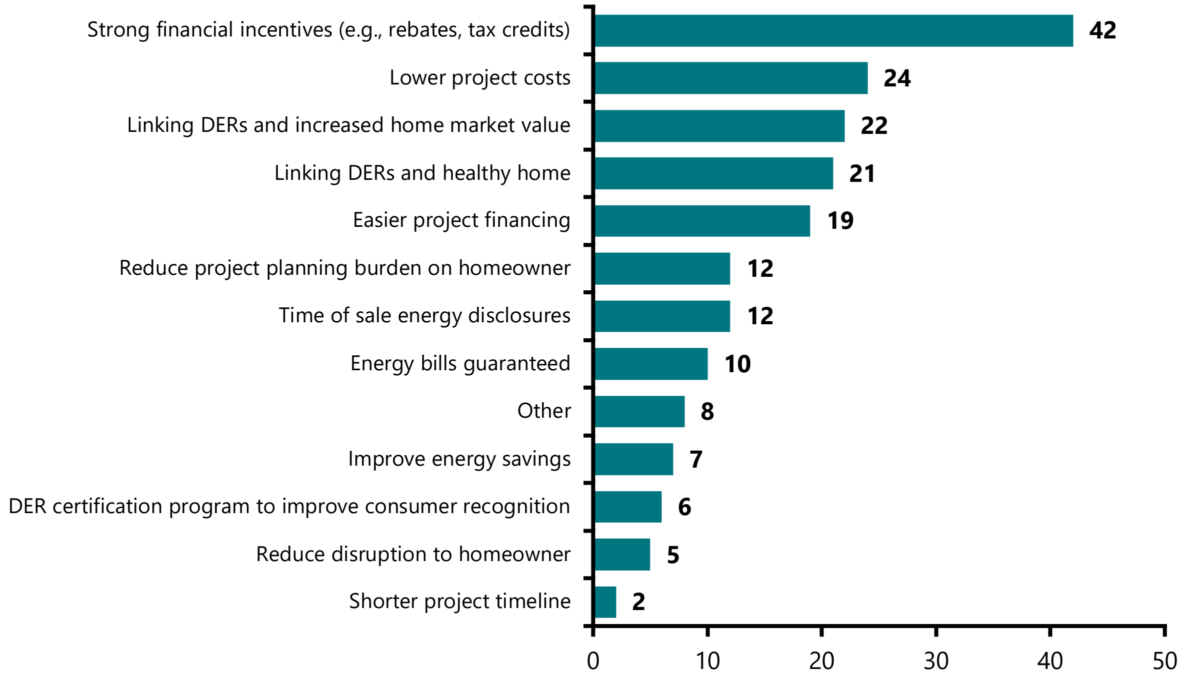


Figure source: Chan et al., (2021)

### 2.2.4 Identifying Key Actions and Opportunities

Based on the current state of home decarbonization efforts, the following actions will need to be taken to address at-scale decarbonization challenges and identify key opportunities:

1. **Showcase solutions today**
   Delaying action will result in higher costs and unavoidable future emissions. Ramping up activities now will help grow the market from where it is today into what it will need to be to achieve full-scale decarbonization. Programs and incentives that continue to support the deployment of efficient fossil fuel equipment and appliances in homes with the ability to electrify major end-uses will make future decarbonization more challenging.

2. **Increase demand**
   Without demand for decarbonization, there is no economic driver to spur job growth or business innovation. To successfully increase demand, solutions will need to be what homeowners and residents desire: readily available, affordable, easily financed, reliable, safe, and resilient. There are many strategies that can increase demand that generally fit into one of two categories: reducing cost or increasing perceived value. Rebates are a proven way to increase demand by reducing costs. Strategies to increase value include demonstrating comfort and health benefits or elucidating the benefits of decarbonization to augment home value. It will be critical to support demand by incorporating and valuing upgrades in real estate transactions and lending practices and supporting public awareness campaigns.

3. **Lower risk**
   Deploying existing, off-the-shelf technology allows for quicker scaling and reduces real and perceived risks for program implementers, contractors, and homeowners. Homes that are more difficult to decarbonize may require new products with technology innovations optimized for application instead of performance using current technology foundations (e.g., heat pump water heaters (HPWHs) that fit in the same space as current water heaters). Decarbonization projects should also reduce risks for home residents by addressing resiliency, affordability, occupant comfort, indoor air quality, and safety.

4. **Expand workforce**
   Today, not enough businesses and contractors offer home decarbonization services such as heat pump installation, weatherization, and electrical upgrades. In addition, as demand for home decarbonization grows, there are not enough skilled workers in the residential building industry to take on this work. There is a tension that needs to be resolved between reducing the cost of decarbonization projects while also assuring good pay, benefits, and working conditions to attract workers to the industry.

5. **Increase affordability**
   Affordability represents the balance between upfront and operational costs and how together they impact household budgets. Median US household savings only cover about 10% of the current cost to substantially decarbonize a home. As such, the residential decarbonization industry cannot rely solely on consumer savings to scale effectively. Along with lowering project costs, consumers and their contractors will also need access to simple, low-cost financing combined with rebate programs. This includes developing approaches that spread decarbonization upgrades and costs over time, pursuing community and state-level efforts to retrofit groups of homes simultaneously, and other ways to reduce transaction costs and leverage economies of scale.

6. **Include equity and accessibility**
   Create solutions that are designed to meet the needs of disadvantaged communities, multifamily housing, and renters. This includes technical and policy approaches focused on solutions for actual housing types, resident needs, and financial conditions.

## 2.3 Key Topics in Home Decarbonization

Policies, programs, and building regulations reducing home energy use or increasing home energy efficiency have been around for about 50 years. However, specifically reducing carbon emissions (decarbonization) from homes is a relatively new endeavor. Furthermore, the scale of change required and the need to include all households in fair and equitable ways requires additional considerations. These issues of novelty and scale raise the following key topics for consideration compared to past programs and initiatives.

### 2.3.1 Upgrading Home Electric Systems

To increase the affordability of residential electrification projects, avoiding the costs of upgrading the electric service to the home, the main electric panel (to make space for more circuits), and wiring within the home – particularly for high-power circuits associated with heat pumps and cooking – is critical. Emerging technologies are coming to market that reduce or remove the need for these upgrades. They include:

- Smart circuit splitters that allow sharing of circuits – typically between two high power demands: electric vehicle charging and clothes dryers. Controls are implemented that curtail car charging when the auxiliary load is being actively used. The same devices could be used to run an electric water heater alongside another appliance.
- Programmable subpanels that control loads below panel total capacity can achieve some of the same load management outcomes, but without sharing receptacles at the appliance level, and by allowing load sharing across more than two end uses.
- Utility meter collars that allow the addition of higher power end uses (such as electric vehicles, solar PV, or heat pumps) without disturbing or upgrading the electric panel of the home.
- Power-efficient appliances that use fewer watts and/or use existing 120V circuits in a home. Manufacturers are developing power-efficient appliances that can operate using existing 120V outlets throughout a home, most importantly for HPWH and heat pump space conditioning. Plug-in 120V HPWHs are being tested by the Advanced Water Heating Initiative[8] in collaboration with utilities and manufacturers, and at least one product is now available.[9] 120V plug in heat pumps are also finding niches in multifamily buildings, both for existing and new construction as replacements for gas wall heaters. More portable heat pump systems are becoming available and are increasingly using more efficient compressor technology.

[8] https://www.advancedwaterheatinginitiative.org/120v-field-study

[9] https://www.prnewswire.com/news-releases/rheem-introduces-120-volt-proterra-plug-in-heat-pump-water-heaters-301587523.html

An inexpensive, quick, and simple technology advancement would require that all cooling heat pumps add the required valves and controls to operate in heating mode (i.e., all air conditioning systems would also be able to heat the house). While some of these systems can take up too much space and can be considered unattractive and noisy, more consumer-attractive solutions from other countries are beginning to become available in the US. There is a need to make 120V plug-in heat pumps that are more efficient, smaller, quieter, and both heat and cool become the norm and readily available, particularly from US manufacturers.

### 2.3.2 DIY, Drop-In, and Transportable Technologies

To quickly get to significant $CO_2$ reductions, technology pathways are needed that do not always require addressing every need of every home. Measures addressing individual end uses can engage many more households, including renters and low-income households. Furthermore, there is currently a lack of workforce available to complete all necessary aspects of home decarbonization.

Therefore, there is a need to quickly develop do-it-yourself (DIY) and drop-in technology replacements. This could allow the millions of households who would otherwise lack access, ability, or interest to participate in decarbonizing their homes. This is particularly helpful for disadvantaged communities (DACs), where households already engage in DIY solutions, and enables community-building efforts, where communities organize their fellow neighbors to do the work by and for themselves. In addition, these technology solutions target renters by enabling solutions that are transportable in the event of moving, as well as if the renter has no legal control over changing the physical aspects of their residence. This puts solutions in the hands of those who need them most and allows participation from households historically excluded from energy efficiency and decarbonization. Key technology targets include:

- **Heating and cooling**
  Instead of replacing an entire central system, create smaller-scale solutions. Heat pump-based heating and cooling solutions that are efficient, quiet, compact, and easy to use are needed. We want to make electrification an easy and simple option to quickly reach all homes.

  These small-scale solutions should be considered similar to existing devices, such as window-mounted air conditioners, which should not require an electrician or a contractor. They should be simple plug-and-play using standard 120V outlets found in most homes. They should be considerably cheaper (target <$250) than replacing a central system. These should be expandable solutions, such that a household may purchase one device at first to heat/cool the main part of a home, allowing households to purchase another device as needed. Drop-in replacements are required for gravity floor furnaces, wall furnaces, and fireplace inserts. These existing systems will all have greater carbon reduction opportunities than other heating systems due to their lower efficiency and would benefit lower-income households the most as they live in the homes where these poor-performance devices are most common.

- **Hot water**
  This is more complex than heating and cooling because plumbing connections may be required if the device is integrated into central plumbing. One option found in other countries would be individual end-use water heaters, such as for shower heads. A key technical difficulty in the US compared to some other countries is the low voltage/low power distribution used within homes, which limits the power that can be used for these in-line end-use water heaters.

- **Lower-power/one or two-burner induction hot plates/cooktops**
  In addition to $CO_2$ reductions, induction cooking improves indoor air quality due to eliminating $NO_2$ emissions from burning gas and some particle emissions compared to both gas and electric resistance cooking. These public health benefits could be significant, particularly in DACs, which suffer disproportionately from health issues related to poor indoor air quality.

  Some performance standards may need developing because consumers have found that some units can be noisy (from fans and electronics) or are sensitive to the type of pots and pans used. While lower-power one/two burner options currently exist and would be sufficient for many households (particularly for smaller apartments/homes with limited kitchen space), there is a need for options with three or more burners. Some lower-power options are currently in development and may be available within the next couple of years. Irrespective of the number of burners, all technologies could also include integrated controls for load management, such as limiting the total power draw of the appliance by dynamically balancing the burners as needed.

- **Window treatments**
  Interior storm windows require technology development to upgrade performance (for example, using multiple thin panes of glass similar to the thin triple pane replacement windows that have recently come to market) and to make them more flexible regarding window size. There may be insurmountable issues for interior storm windows due to the change in window sizes from home to home as renters move. However, this technology would still be useful as a lower-cost alternative to window replacement.

- **Portable PV**
  The target for portable PV is to provide some resiliency for DACs during power outages while also providing some renewable power for simple plug loads, such as

phones, laptop devices, lights, or cooling fans. These would be lower-capacity portable units designed with a standard 120V outlet to power a single device. These should be small enough to fit on a porch, a balcony, or the ground, and possibly integrate a battery to increase power output or have the ability to shift when energy is used. Some of these technologies exist already (e.g., for camping or living in tiny homes or vans), but others – such as solar window films – need more development.

US manufacturers are critical audiences to engage in these technology developments. Currently, many high-performance, quiet, and appealing devices are manufactured overseas, and US manufacturers have shown little to no interest in this market segment. It is important to build up US abilities in this area to catch up with the rest of the world and to not solely depend on foreign-based industries when meeting our decarbonization targets.

### 2.3.3 Soft Cost Reduction Strategies and Business Economics

Efforts are being made to reduce the administrative and code compliance burdens that drive soft costs so high in home decarbonization. Solar PV is one key example of high soft costs, as the use of solar PV is much more expensive per watt in the US than in other countries (by factors of two to three; see discussion in Griffith et al., 2020). The National Renewable Energy Laboratory (NREL) SolarAPP+[10] is aiming to reduce the code compliance burden for solar PV installations in the US, but there is still a need to reduce installation costs.

Similar efforts should be made to address code compliance and permitting issues with other energy upgrade measures, including those for HVAC systems, electrical panels, and battery systems. Program and rebate administration has also been identified as being time-consuming and, therefore, costly (Chan et al., 2021). Simplified and digital approaches to permit, inspection, and rebate processing could significantly reduce residential decarbonization soft costs, supporting the goal of making decarbonization projects more affordable for consumers.

DOE's recent literature review (Less et al., 2021a) found that gross margins (i.e., soft costs, overhead, profit) were higher than residential remodeling industry averages for home performance contractors – 47% on average.[11] This gross margin is compared with other construction industry benchmarks in Figure 8, below. 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 at 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%, a 14% reduction in overall project cost.

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[10] https://solarapp.nrel.gov/

[11] This is for market-rate work, and may not represent programs such as the DOE's Weatherization Assistance Program.

To reduce gross margins in energy upgrade work, it is necessary to understand what is driving soft costs. A recent deep retrofit market survey (Chan et al., 2021) reported typical soft costs in deep retrofit projects, including design costs and testing (see Figure 9, below). The survey showed that, while not common to all projects, professional services from architects were 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 and envelope leakage measurements (<$200 each per home).

The survey also reported average labor rates for different energy upgrade soft cost activities, and the reported values ranged from $90 to $138 per hour. Typical hours spent on each soft cost category were also estimated, and these varied from roughly one hour (including diagnostics for combustion, ventilation flow, and infrared (IR) imaging) to up to 12 or 13 hours per project (including travel to/from a job site and project management). The data presented in Figure 9 suggest that streamlining project management, planning/design, and delivery likely have a high potential for cost savings, whereas diagnostics, testing, and permits likely have relatively lower potential due to their already low costs.

**FIGURE 8: COMPARISON OF GROSS MARGINS (OVERHEAD + PROFIT) FOR DEEP RETROFITS COMPARED WITH OTHER CONSTRUCTION SECTORS**

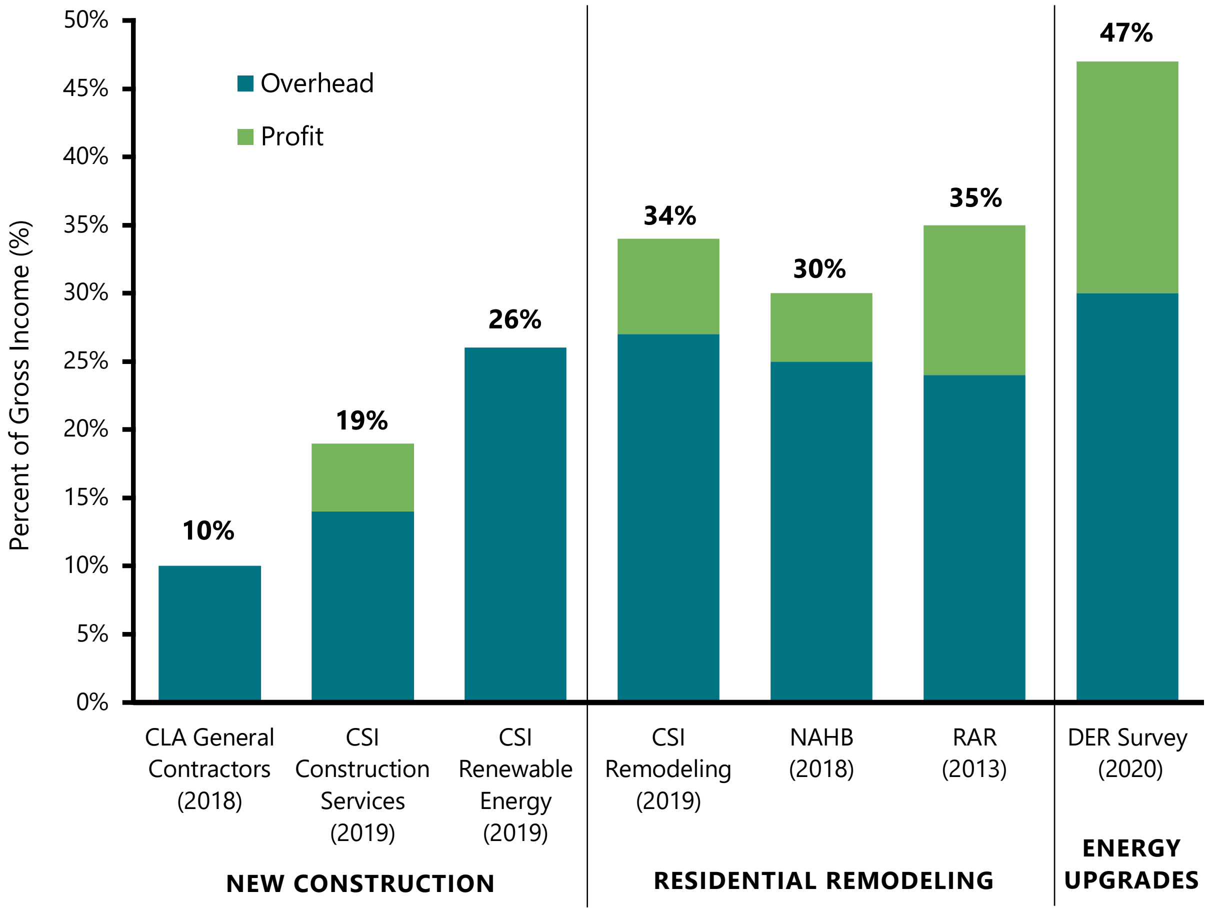


Figure source: Less, (2021a)

**FIGURE 9: AVERAGE PROJECT SOFT COSTS REPORTED IN DEEP RETROFIT INDUSTRY SURVEY**

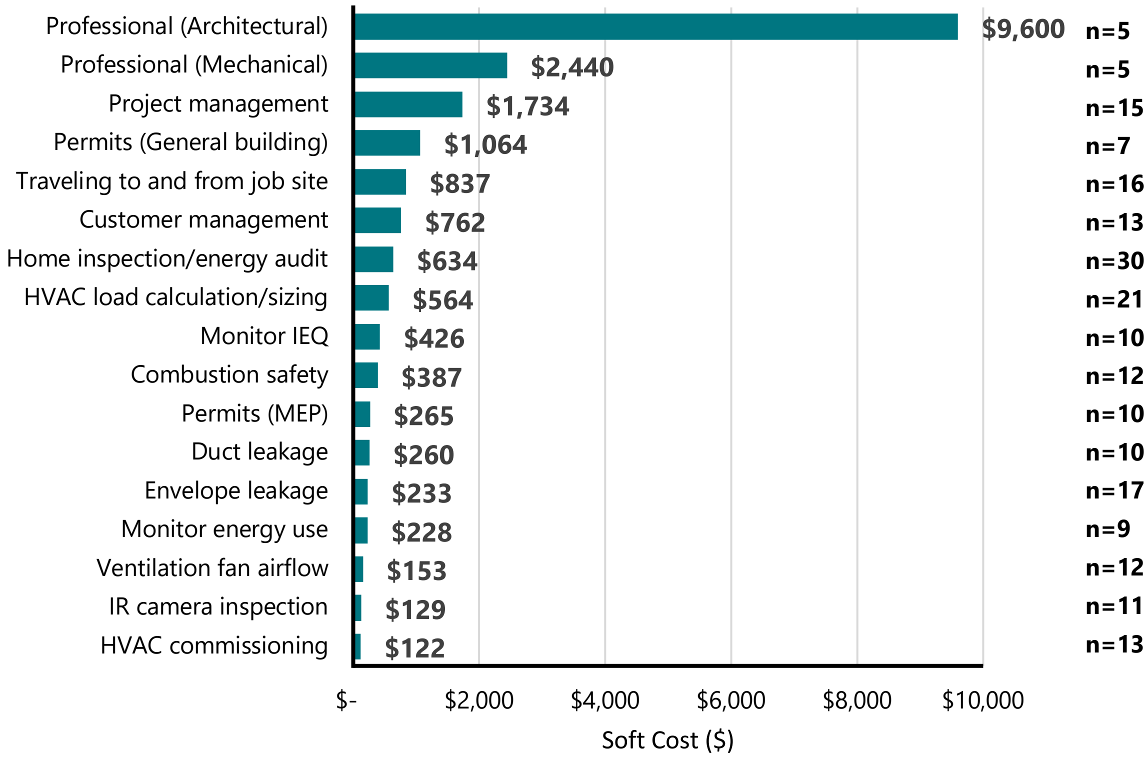


Figure source: Chan et al., (2021)

Survey respondents reported that the most time-consuming non-construction tasks were the efforts required to acquire customers and scope projects. This is a significant contributor to higher soft costs. This burden could be significantly eased by supporting program development that connects customers and contractors via online portals (some of which exist at the local level), supports standardized packages, and offers easy financing. Energy labeling programs can also support more sustained market demand for energy upgrades as consumers gain a greater understanding of energy features, and energy information becomes better integrated into real estate market understandings of home value.

The analysis of soft costs in the *Cost of Decarbonization and Energy Upgrade Retrofits for US Homes* study suggested the following opportunities and estimates for reducing soft costs in home performance upgrades:

- **Outsource customer acquisition to programs with marketing and sales expertise**
  Customer acquisition typically costs $1,000–1,600 per project, and up to $2,500. With the use of program design best practices and aggregating efforts for greater amplification, this cost can be reduced to around $700 per project.
- **Reduce diagnostic testing and commissioning**
  Combustion safety testing averaged $387 per project, but electrification of all end uses could eliminate the need for this testing.

- **Use remote approaches for customer acquisition, management, and sales, and effectively eliminate full-scale on-site audits**
  Remote audits can reduce audit costs by 40% for individual projects and 60% for projects that execute the work scope. These types of audits are estimated to save 20 hours and $1,000 per executed project. Note that there is some risk with this approach in reducing conversion rate because either the audit is less effective (for any reason) or because more homeowners sign up for this with no real intention to follow through on home upgrades. In addition, care must be taken to avoid confusion regarding work scopes and other details for installing contractors when working from remote audits.

  Even simpler would be to eliminate audits and rely on fixed, standardized work scopes. Standardized work scopes would also reduce the need for on-site management and sales – effectively commoditizing the work and allowing third parties to employ the advantages of scale to marketing and customer acquisition. Some existing programs already use this approach, where contractors only complete installs while program staff perform other activities contributing to high overhead costs. For market rate work, this could be provided by market integrators.

- **Automated, rapid HVAC equipment sizing**
  Current HVAC sizing costs are typically $564, which can currently be reduced using rapid, block load software programs. In the future, there is potential for further reduction through an automated smart meter or connected thermostat data analytics.

While gross margins are roughly half the total project costs in a deep energy retrofit, there were few soft cost details gathered in the database. These were limited to program administration, permitting, and health and safety work. Program administration costs were the most expensive, at $714 per project. These costs vary significantly by program. Building permits were relatively low-cost, with typical permitting costs of $280, ranging from $100 to $600. Health and safety measures are primarily combustion safety testing, with median costs of $109 per project. For comparison, the *DOE Deep Energy Retrofit Cost Survey* reported that permit costs were $1,064 for general building versus $264 for mechanical, electrical, and plumbing permits and $387 for combustion safety testing costs (Chan et al., 2021).

This large variability in soft costs reflects ranges in project scopes and local permitting fees associated with the two studies combined with differences in how contractors and programs disaggregate these costs. Health and safety measures listed in the database may have been for programs with different testing requirements that were less detailed and time-consuming. While still ensuring occupant safety, reducing such testing requirements is one way to reduce project soft costs. An example of achieving this aim would be to electrify a home’s heating and hot water, thus removing the need for a combustion safety test.

Although highly variable, any efforts to reduce these soft costs would certainly help improve project affordability.

The *DOE Deep Energy Retrofit Cost Survey* identified customer acquisition and work scope/proposal development as time-consuming and costly. Reducing these cost burdens could significantly reduce the soft costs of a project. Survey respondents identified "one-stop shop" program models (encompassing energy audits, work scope, financing, permits, construction, and testing) as being a good approach to deal with this issue.

### 2.3.4 Equity and Resilience

The need for home electrification and energy upgrade programs to provide access to everyone – not just relatively wealthy homeowners – is essential. There are important implications in developing decarbonization approaches when energy is used for sufficiency rather than excess, which may lead to different solutions for different segments of the population (Fournier et al., 2020).

For example, to break the classic "split incentive" problem between owners and renters, technologies that belong to the occupant rather than the homeowner are needed. This implies transportable technologies from home to home that do not require expert installation, as explained earlier. Examples would include advanced portable heat pumps (and making all portable AC units into heat pumps), putting batteries directly into appliances rather than the home, window treatments for thermal control, etc.

There is also a need to develop inexpensive "drop-in" technologies that require minimal effort to install and may be suitable for do-it-yourself (DIY). Examples include heat pump replacements for floor and wall furnaces (or fireplaces). Another benefit of transportable units is increasing consumer knowledge, interest, awareness, and comfort with new technologies. Another approach to addressing split incentive problems is through mandatory building improvement programs, such as Building Performance Standards or rental licensing programs.[12]

#### Health Equity

There are currently very few programs integrating "health into home" energy upgrades and decarbonization. Recently, several organizations have been using health and safety rationales for home electrification. The key points are that removing combustion devices from the home reduces risks of fire, carbon monoxide poisoning, gas cooking-related emissions of $NO_2$, and particles (Seals et al., 2020 and the Environmental Law Institute, 2021). Other efforts are being made to combine healthcare and home performance (Ortiz et al., 2019).

One concept is to use healthcare funds to improve indoor air quality in homes, thus reducing collective healthcare burdens (e.g., from reduced hospital visits for uncontrolled asthma).

[12] For example, the City of Boulder, CO has mandatory energy efficiency requirements for rented properties (https://bouldercolorado.gov/smartregs-guide).

While currently rare, this concept may significantly scale home energy upgrades through a new funding stream for upgrades. This could also better distribute upgrade resources to vulnerable populations with health-related problems living in the poorest quality housing.

To justify the funding of upgrade activities by health insurance companies for medical reasons, there must be a robust connection established between upgrade activities, particularly electrification measures, and associated general, mental, respiratory, and cardio-pulmonary health outcomes. It is possible that healthcare dollars might be leveraged to partially support upgrade work, funding only those elements most directly associated with improved health outcomes (e.g., cooking electrification, air/duct sealing, whole home air sealing, and mechanical ventilation). The remaining end uses could be electrified through more traditional utility or low-income program methods.

If other health-related improvements (e.g., better vacuums[13]) are bundled with decarbonization efforts, decarbonization may become more appealing to a wider range of households. Because indoor comfort can lead to higher levels of productivity (Bueno et al., 2021), the increase in comfort in an upgraded home has additional value. Also, health improvements in upgraded homes can lead to improved school attendance and its associated improvement in life outcomes (*The Relationship Between School Attendance and Health*, 2016*)*.

## Resilience

Resilience has become much more of a concern for homeowners in recent years, with increasing extreme weather events and natural hazards or disasters such as wildfires. In particular, 40% of rental units are located in areas with at least moderate risk of weather and disaster-related loss (*America's Rental Housing 2022*). While hugely burdensome to homeowners and residents, these issues can spur more investment and funding streams going to residential decarbonization.

Homeowners may seek to improve their home's performance and increase its "passive survivability" – meaning their homes can maintain livable environments even when power is in short supply. Homeowners may also become more interested in off-grid power capabilities, such as solar PV and batteries that can function even when the power grid is unreliable, and reducing or eliminating smaller fire hazards from fossil fuel heating equipment that can turn into bigger community disasters (especially in earthquake-prone regions).

There are currently no standards in place to assess the resilience of our homes in terms of providing basic services such as heating/cooling, hot water, lighting, and plug power,[14] and future work is needed to extend this to develop design guidelines and metrics. After

[13] Slipstream and CLEAResult did this work in Michigan under their Healthier Homes program, blending energy efficiency and health care initiatives.

[14] There are programs, such as FORTIFIED, that focus on structural resilience.

disasters strike, there can also be opportunities for insurance companies and disaster recovery efforts to rebuild decarbonized homes – ultimately with the goal that this work can reduce the likelihood of worse disasters in the future.

Heat waves and cold snaps present significant equity issues for low-income households, who tend to live in poorer-quality homes with less insulation and air sealing. These poor-quality homes require more energy to heat and cool in regular weather conditions, conditions that are further exacerbated during extreme weather events. Envelope improvements, heat pumps, and solar PV can help by providing more efficient heating and much-needed cooling, especially for those households who do not currently have cooling or have inefficient cooling that is expensive to operate.

#### Billing Equity

Renters face significant housing and energy cost burdens. Stabilizing these costs for households living in poor and inefficient housing by decarbonizing through equipment upgrades (heat pumps), envelope upgrades, solar PV, and battery storage can provide predictability in household expenses currently lacking for many families. Through these changes in our built environment, households can start to reduce financial stress, leading to additional well-being benefits. Additionally, the development of building labeling and disclosure policies for rental properties can give cost estimates to prospective renters and home buyers prior to move-in. These disclosures need to be based on sound engineering principles from a trusted third-party, such as the DOE, the Environmental Protection Agency (EPA), or other entities that have previously developed labeling schemes.

### 2.3.5 Avoiding Rewiring and Panel Upgrades

Electrification projects often require electrical panel upgrades in situations where the amperage is insufficient to support substantial new loads. There is a range of reported costs for a 200 amp electrical panel upgrade with a range of about $1,000–5,000 from RS Means (Lane, 2019) and other sources.[15] The upgrade costs for each dedicated circuit run to new electrical appliances range from $200 to $500. In addition to these costs, practitioners are reporting considerable delays, often several months, in utility availability to implement upgraded services. Beyond individual project costs, limiting home power draw reduces the impact of wide-scale electrification on the electric grid, reducing the need for upgrades to distribution systems and peak generation infrastructure.

To avoid these costs, new project designs and technologies can enable electrification with appliances that operate on 120V circuits and within existing panel and service power limits for the home; see Figure 10 for examples. An example of this is the “Watt Diet” approach used by Redwood Energy (Armstrong et al., 2021), which shows how to electrically power a home using the existing panel/electric service. Such projects will need to be designed to

[15] https://www.fixr.com/costs/install-electrical-circuit-panel-upgrade

operate within the amperage budget provided by existing electrical infrastructure inside and outside the home. Emerging technologies contributing to this change are:

- HPWHs: The leading manufacturers of 240V HPWHs introduced 120V HPWHs in 2023.
- Window and through-wall packaged heat pumps, which are popular in other countries, are coming to the US, with several already on the market.[16] These are higher efficiency devices than those typically found in window-mounted applications in the US and can be powered by a regular 120V circuit. They also eliminate long refrigerant lines and the associated larger amounts of refrigerant, which can help address existing issues with refrigerant charge, leakage, and end-of-life disposal, which are important due to the high global warming potential of the refrigerants. In addition to the electric infrastructure cost savings, the installation costs savings for these devices compared to a central forced air system can be significant. Some of these new devices also have improved form factors – for example, rather than blocking a whole widow, a small saddle goes over the window sill[17] and the heating/cooling unit sits below the window, or they use window frame integration to conceal through the wall ducting.
- For cooking, smart induction cooktops are available that use up to three burners to share a single 120V circuit (or, in some cases, two low-power circuits). Induction hot plate burners also provide an alternative that can travel with occupants. This type of transportable technology may be especially important for renters, who do not have direct control over the appliances and features of their homes. There are also cooking products coming to market with integrated batteries that can operate off a standard 120V socket and use less than 1,800W. In addition, they have an electric outlet allowing them to not only cook in the event of power failure, but also to power other essential devices.
- Heat pump clothes dryers (some integrated with clothes washers) are available that also have the advantage of not requiring a vent through the wall.
- Smart electric panels, circuit splitters, and plugs that allow circuit sharing between major end uses that otherwise required dedicated 240V circuitry (see Figure 11). For example, a 240V circuit can be shared between a clothes dryer and an EV charger.
- Most panel upgrades are currently driven by EV charging requirements or to handle the output of large PV systems. For EV charging, the impact can be reduced by using less powerful chargers that are sufficient for the vast majority of users and/or controllers that manage multiple chargers and can modulate charging power to

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[16] One example is this device that includes serval mounting alternatives: https://ephoca.com/aio-wall-mounted-pro

[17] There is an example from a US manufacturer that is planning to bring this device to market in 2022: https://www.gradientcomfort.com/

avoid tripping the main breaker. . Solar PV is treated as a load in the National Electric Code NEC which limits back-fed solar power to 20% of the main breaker rating. There are several solutions to avoid this limitation:

- De-rating the main breaker. e.g., from 200A to 180A, allows 20A more of solar.
- Install solar ready main panel that avoids back-feeding the solar circuit through the busbar.
- Use a line-side connection that does not use the busbar by connecting upstream of the service disconnect - one example is the "meter collar" that bypasses the main panel. Each utility regulates these interconnections differently.

FIGURE 10. LEFT PHOTO IS OF A METER COLLAR FOR BYPASSING THE MAIN PANEL FOR SOLAR PV OR EV CIRCUITS. RIGHT PHOTO IS OF AN INDUCTION RAGE WITH A BUILT- IN ~4KWH BATTERY. PHOTO CREDITS: CONNECT DER AND CHANNING STREET COPPER.


In addition to these technology approaches, there also needs to be a better understanding of the NEC requirements. A key issue is that the decision to upgrade panels and electric service is driven by the NEC requirements rather than efforts to minimize homes tripping main breakers. Many existing homes have capacity- and space-limited panels that cannot accommodate the new loads according to current rules in the NEC.

In NEC Articles 220.83 (Existing Dwelling Unit) and 220.87 (Determining Existing Loads), there is some leeway for adding new loads that could reduce the need for panel upgrades, but this flexibility often remains unused by electricians due to unfamiliarity and lack of clarity in the code language. The draft 2023 version of the NEC explicitly allows the use of load control technologies (NEC Article 750), and the current NEC Articles 625.40 (EV Branch Circuit) and 625.42 (Rating) explicitly allow load controls for EV charging without forbidding their use for other loads. The industry needs to have a better understanding of the NEC requirements, and the NEC itself needs updates to better accommodate existing home electrification.

#### FIGURE 11: POWER-EFFICIENT APPLIANCES

| | **LG WM3998HBA**<br>4.5 ft$^3$ Condensing Washer/Dryer Combo | **GE GeoSpring**<br>Heat Pump Water Heater | **Innova HPAC 2.0**<br>Low-Amp Window Heat Pump | **LG LS-120HXV**<br>120V Mini-Split Heat Pump |
|---|---|---|---|---|
| |  |  |  |  |
| **Maximum Rating** (Amps, Watts) | 10A, **1200W** | 8.3A, **1000W** | 6.3-15A, **~1400W** | 10.4A, **1090W** |

Figure source: Sean Armstrong/Redwood Energy (Armstrong, 2021)

#### FIGURE 12: SMART CIRCUIT SPLITTERS AND CIRCUIT SHARING

| | **BSA Electronics**<br>Dryer Buddy | **NeoCharge**<br>Smart Splitter | **EV-PowerShare**<br>EV-PS Smart | **SimpleSwitch**<br>240V/EV Circuit Switch |
|---|---|---|---|---|
| |  |  |  |  |
| **Cost** | $200–$365 | $450 (smart splitter)<br>$500 (dual car splitter) | $375 | $575/$675 |
| **Description** | Plugs into a 30A circuit (which is common dryer plug) and allows for vehicle charging while dryer is not in use.<br><br>It has a digital display that shows the draw of each load. | Provides Level 2 EV charging without rewiring or panel upgrades.<br><br>Pauses EV charging for other large loads.<br><br>Also has a "dual car" option, allowing users to charge two EVs at half power or fully charge one at a time. | Plugs into a NEMA 10-30 or NEMA 14-30 high-voltage wall socket.<br><br>EV service equipment should be set to 24 amps (24 amps max is recommended continuous load for 30 amp circuit).<br><br>High voltage appliance should be plugged into the left socket, while the electric vehicle supply equipment (EVSE) should be plugged into the right socket. | One load is the "primary" load and the other is the "auxiliary" – if the primary load comes on, the auxiliary load will shut off.<br><br>EV version is EVSE.<br><br>Useful for short/long-load sharing, such as electric baseboard heating with overnight EV charging. |

Figure source: Sean Armstrong/Redwood Energy (Armstrong, 2021)

### 2.3.6 Electric and Thermal Storage and Demand Flexibility

As more homes are electrified, there will be increased loads put on the current electric grid infrastructure. This may be intensified by increased reliance on sustainable electricity generation that has variable and periodic output. The key issue is not just *how much* energy is used but *when* it is used.

To reduce stress on the grid, time-shifting technologies are needed. Both electric battery and thermal storage are currently in their infancy but will be an essential part of managing grid loads and adding resilience to homes. Thermal storage has the potential to significantly reduce costs compared with battery technology as a much more sustainable (from a resources point of view) and reliable long-term option. Thermal storage technologies are just coming to market for residential scale, and R&D efforts are needed to evaluate them.

As utilities move towards billing schedules that vary with time of use and include demand charges, at-home storage may significantly change the economics of home electrification and home energy upgrades in general by providing the opportunity to significantly reduce energy bills. Similarly, some end uses can have time flexibility, such as DHW (Alstone et al., 2021) and dwelling ventilation (Young et al., 2020), allowing for reduced electricity use at peak times. Demand flexibility may be enhanced by developing and deploying heat pumps (and their related controls) that can receive and respond to grid signals that allow customers to reduce bills and helps shift energy use to when emissions are lower. This can also help grid operators by reducing the afternoon ramp, which makes the grid more controllable. DOE's *National Roadmap for Grid-Interactive Efficient Buildings*[18] has more analyses and guidance on this topic. Some specific examples of load flexibility programs are already under development, such as CalFlexHub (Piette et al., 2022).

Some technologies provide automated control of building loads to reduce carbon emissions or grid stress. One important example is automated emissions reductions (Auto AER) from WattTime, a control strategy that leverages internet-connected end uses along with real-time estimates of electrical grid carbon intensity to automatically operate existing appliances in a way that reduces carbon emissions. Analysis from the Rocky Mountain Institute (RMI) suggests that, using current technologies, automated load reduction can achieve a 5% $CO_2$ reduction for cooling equipment and a 12–15% reduction for HPWHs or electric cars (Mandel et al., n.d.).

Similar smart devices may be able to schedule energy-using appliances during off-peak hours, which can substantially reduce household energy costs if a good time-of-use (TOU) rate is available. Other automated controls in homes can respond to peak demand events. An example of this capability is provided by Ohm Connect,[19] which compensates participants for shedding electrical load during select periods of grid stress. Numerous smart devices –

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[18] gebroadmap.lbl.gov

[19] https://www.ohmconnect.com/

including smart plugs, internet-connected thermostats, and others – can be integrated and centrally controlled during load shed events. In addition, including some of these low-cost technologies in retrofit packages can augment carbon and cost savings opportunities for consumers and better guarantee realized savings.

### 2.3.7 Plug Loads

Many homes have substantial plug loads for various household appliances. None of the measures in the *Cost of Decarbonization and Energy Upgrade Retrofits for US Homes* home retrofit database explicitly included plug-load reduction. However, there are well-developed, readily available existing technologies, such as smart power strips, timers for lights and fans, occupancy sensors, etc. Components of this, such as standby power for audio-visual equipment and computers, have been addressed by appliance standards, but more effort is needed, including ideas around behavioral changes (e.g., in-home energy displays[20]) and/or smart technology that turns itself on or off without user intervention.

Automated smart meter data analysis and end-use disaggregation provide valuable outputs, which can be used by homeowners or automated "assistants" to actively reduce their loads. Smart meter analyses can also be useful for in-home energy assessments and upgrade project design. Future efforts should be directed toward making this information readily available to both homeowners and contractors.

Some programs have successfully shown significant savings based on household operational changes that were made in response to behavioral and retro-commissioning feedback generated in part by automated smart meter analytics, along with input and suggestions by remote coaches. For example, a study of more than 1,400 homes enrolled in the Home Energy Analytics HomeIntel program in California's Bay Area showed energy reductions of 10% at little to no cost. These approaches have the ability to substantially increase the performance and outcomes of more comprehensive energy upgrade projects.

### 2.3.8 Emergency Equipment Replacement

Most heating and DHW equipment is replaced at the time of failure. Particularly for heating, equipment failure can be an emergency, where immediate replacement is vital. These emergency replacement situations have insufficient time to arrange and execute home electric system upgrades. In addition, the selection of replacement equipment is restricted to that which is readily available (on a time scale of hours) to installers.

To overcome these issues, there is a need to develop temporary equipment that can be used while the home's electric infrastructure can be upgraded and equipment is procured. This temporary equipment could use the existing fuel supplying the home, although lower-power

[20] These are common in other countries where energy providers include or require an energy display so that customers can see the impact of different appliances on their energy use. However, studies have shown very limited impact on long-term energy savings.

devices that could be plugged into existing 120V outlets would also be an option. The same idea could be used for clothes dryers and cooking, where temporary devices are used until the home electric systems are upgraded. Alternatively, there are 120V options for clothes drying and cooking that could be used if they were made available via the distribution network serving local contractors and installers.

For clothes dryers, this means promoting and putting incentives in place for heat pump dryers. For cooktops, a high priority is to address the demands of users. For example, some households will not be satisfied with a two-burner cooktop and will want three or even four burners. There are three-burner induction cooktops that run off low power, and other low-power cooktops are in development. Furthermore, a cooktop will require a junction box to be installed. While this might not be as much effort as adding a new 240V circuit, there is still a significant cost for this. It is possible that a temporary two- or three-burner induction cooktop could be used that plugs into a kitchen outlet while the necessary home wiring upgrades are completed.

### 2.3.9 Integrating Personal Transport into Homes

As the primary power source for personal transport moves from internal combustion engines to electric systems, the convenience of home charging will directly combine household energy use with transportation energy use. For most homes, electric vehicle charging will become the biggest electric load in terms of power requirements and needs to be managed appropriately. Fast charging of vehicles at home is not a good solution because it requires a lot of service upgrades, and the peak power requirements will be challenging for the electric distribution system to deal with. It is possible that if utilities introduce residential demand charges, this will put financial pressure on consumers to use lower power home charging.

A more scalable solution would be to limit home charging to 7.2 kW or less and introduce circuit sharing (e.g., have an EV charger share a circuit with another large load, such as a clothes dryer). In the future, when EVs are commonplace, non-residential EV infrastructure will be necessary to limit the impact on home power draws and allow people to charge at work or other parking areas. This will be helpful in terms of grid demand management as it shifts the EV charging load to the daytime when solar power is at its peak and may help to reduce the "duck curve" and renewable curtailment issues for utilities associated with excess power generation from solar PV (Kintner-Meyer et al., 2020).

Rapid charging will remain a key technology for highway networks and some local superchargers. This non-residential infrastructure development will also help people who do not have off-street parking at their homes, which is an important equity issue because lower-income people and renters generally have less access to off-street parking or the ability to install an EV charger.

## 2.4 Metrics to Assess Home Decarbonization

To assess, evaluate, and better describe home decarbonization, there needs to be a shift from traditional metrics that focus on energy use and savings to new metrics focused on $CO_2$ emissions and other metrics that are directly useful in making decarbonization decisions. The following is a list of the metrics that need to be considered.

### 2.4.1 $CO_2$ Content of Energy

$CO_2$ emissions are based on the $CO_2$ emitted directly from on-site combustion and the $CO_2$ associated with delivered electricity. Generally, $CO_2$ emissions are rated on an annual basis. They can be normalized by the floor area of a home to get an efficiency metric. This normalized metric should be restricted to comparing different approaches for the same home. Allowing larger homes to emit a lot of $CO_2$ but at a low rate per square foot will not lead to reduced $CO_2$ emissions.

For fossil fuel combustion, $CO_2$ emissions are estimated from standardized calculations based on combustion chemistry. For electricity generation, there are multiple factors to account for that require several metrics. The main factor is that the $CO_2$ content of electricity is not constant and depends on the source of electricity, which varies by location and over time. The steady decline in the $CO_2$ content of electricity (Wiser et al., 2021) means that projections based on current $CO_2$ content underestimate future $CO_2$ savings. The sources used change seasonally and with short-term demand. The classic example is the use of gas-powered electric generation used at peak times that increases the $CO_2$ content of electricity on peak.

Typically, metrics use short or long-run marginal emission rates – although there is considerable debate over which of these (if any) is the most appropriate. Average emission rates are a good alternative, which can be directly related to the electricity generation mix at any point in time, whereas marginal emissions require models and predictions of what generation sources would be dispatched at any given moment based on changes in demand. Emerging efforts by DOE and others to define appropriate carbon metrics for buildings are trending toward the use of hourly, long-run marginal emission factors from the NREL Cambium tool.[21] These are appropriate for assessing building operations at the design phase, using simulation or analysis tools. Real-time marginal carbon emission rates are provided by WattTime[22] for use in operational building controls and related grid services.

### 2.4.2 Site Carbon Emissions and Energy Costs to the Resident

Metrics for energy use are typically annual energy use and costs and energy use normalized by floor area. However, net-zero carbon (and energy) goals require more emphasis to be placed on absolute use rather than normalized by the square footage of a home. This is

[21] https://cambium.nrel.gov/

[22] https://watttime.org

because climate goals are related to the quantity of carbon emissions and energy use rather than efficiency.

The DOE Home Energy Score tool, which evaluates energy consumption for existing home projects and retrofits, does not normalize by floor area. Large homes emit a lot of carbon and use a lot of energy, even if their floor area normalized values are low. Thus metrics that assess absolute emissions are better indicators for meeting low or zero carbon/energy targets. Normalization and efficiency approaches should be restricted to comparing homes of the same floor area. Similarly, homes are not billed per square foot – the bills are for the actual energy used. When considering household energy bills, it is therefore necessary to use absolute metrics, not ones normalized by floor area.

Other carbon metrics are related to reductions in carbon emissions after home upgrades. As with overall carbon emissions, the metrics can be absolute as well as normalized – typically by floor area. In addition, a valuable metric in assessing homes is the carbon reduction expressed as a fraction of the pre-upgrade carbon emissions. This allows a reasonable balance between small and large homes and high and low-carbon emitting/energy-using households. With the increasing availability of smart meter data, both carbon and energy performance metrics could be based on actual consumption data (with appropriate conversion to carbon content) rather than currently common modeling approaches. All these metrics need to be designed to allow the offsetting of energy use by on-site generation. Guidelines need to be produced to develop metrics that account for dedicated offsite generation, such as community solar projects or renewable power purchases.

### 2.4.3 Embodied Carbon

Generally, it is very difficult to determine the embodied carbon involved in home upgrades, including decarbonization efforts, and embodied carbon metrics are seldom used. Some information is available from Environmental Product Declaration (EPD) sheets, which include standardized assessments of the embodied energy and carbon associated with selected products. There are publicly available databases – such as the Embodied Carbon in Construction Calculator (EC3)[23] – but they are not integrated with design processes or assessment tools in residential construction. Extending this analysis beyond manufactured products and into upgrade activities themselves (e.g., job site travel) is even more difficult. More work is needed to simplify the assessment of embodied energy and determine how such metrics might be applied in actual projects.

For example, if a homeowner needs to replace a natural gas water heater, and they go to the home improvement store, they can choose another natural gas water heater or a heat pump water heater that are in stock then differences in embodied carbon need to be considered and product labeling of embodied carbon would help with consumer decision making. Another example is when considering early retirement of equipment, i.e., not waiting until a

[23] https://www.buildingtransparency.org/

water heater or furnace fails before it is replaced. There will be embodied carbon in the old appliance that still has some useful working life remaining. The GHG potential of the refrigerant in the heat pump should also be considered. Unless we can guarantee that this refrigerant is retrieved at end of life, some fraction of the refrigerant charge should be included in any lifetime GHG emissions estimates. Embodied energy analyses can be used in policy decisions, such as deciding which appliances to promote or subsidize. There also needs to be a consideration of how well energy-using equipment, appliances, and devices can be reused or recycled.

### 2.4.4 Financial

A problem for any financial analysis is that the environmental and social cost of emitting $CO_2$ is not included in energy prices. Metrics using energy costs may be useful to understand program impacts on occupant spending on energy but have limited use beyond that application. Many policy and programmatic assessments remain tied to these billing costs, which are not a suitable metric for making investment decisions around decarbonization. Furthermore, their continued use distorts any discussion with homeowners, severely hampering our ability to get to scale.

For example, homeowners are given the impression that it is sophisticated to use metrics such as payback when making home energy upgrades and decarbonization decisions. However, these metrics are not applied to any other home upgrade decisions. Most home upgrades do not break even or provide a return on investment, but offer quality-of-life improvements – a perspective that could be adopted for home decarbonization. In addition, homeowners often express payback time limits in the 1- to 5-year range that represent extremely unrealistic investment strategies. It may be necessary to limit using payback metrics in discussions with homeowners and in any analyses aiming to get to large-scale, mass-market decarbonization. Currently, the following metrics are being used to frame financial discussions:

- **Energy cost** is typically a total annual energy cost ($), although the cost per unit floor area ($/ft2 or $/m2) is sometimes used. Total annual (or monthly) energy cost can be used to assess the energy burden that is a significant issue for lower-income households, together with low-income energy bill support programs.
- **Simple payback**, where the energy bill savings and decarbonization project costs are used to determine how long it takes to pay off the investment in home upgrades. This is a metric that investors use to assess investment opportunities.
- **Levelized cost of saved energy** based on normalized costs per kWh of savings, lbs. $CO_2$ savings, or initial cost. Measure life and discount rates are used to support comparisons across a variety of measure types and programs. This metric is more useful for assessing programs and policies than for individual homeowners.

- **Net-monthly cost of ownership** based on household cash flow. Typically, this metric compares energy bills to the monthly cost of financing home electrification and is a metric that is suitable for use by homeowners.
- **Affordability** is a new metric being used by some industry pioneers (such as BlocPower and Sealed) and is related to the net-monthly cost of ownership. Affordability is framed as an acceptable monthly expense in return for living in a better-performing home. This may be a way to broaden financial analysis approaches to reach larger market segments.

### 2.4.5 Health, Resilience, Comfort, and Safety

In feedback from industry surveys (e.g., Chan et al., 2021) (see Figure 7) and other sources, it is becoming clear that decisions regarding home energy upgrades are inspired by a wide range of issues not captured in current evaluation metrics that focus purely on simple financial analyses, energy use, and $CO_2$ emissions.

Health and safety impacts resonate with homeowners and are an important part of the homeowner decision-making process. Metrics that are currently being used or considered include indoor air quality (IAQ)-based health impacts, such as the reduced risk of respiratory-related health problems or improved kitchen safety. There is considerable literature on the impact of gas cooking on health, particularly for children. There are efforts underway to use health as a reason to upgrade from gas to induction cooking, including changes to California building codes that have more stringent code compliance paths for homes cooking with gas.

While comfort and utility (i.e., the ability to use space fully due to conditioning improvements) add to home value, and the “feel good” factor of living more sustainably may resonate with homeowners, it is far from clear how to capture these in a quantifiable way that could be used to assess home energy upgrades. Given that they are essential and can be dominant in the decision-making process, efforts to develop metrics and assessment procedures for these criteria are needed.

Comprehensive resilience metrics currently do not exist. They would need to account for comfort, health, and other effects related to how well a home performs when faced with challenges, such as heat waves, cold spells, energy infrastructure failures, wildfires, flooding, and more. These challenges are diverse and represent a significant difficulty in developing metrics to account for them individually or bundled together. Some efforts have investigated potential benefits to utilities and regulators in quantifying reliability and resilience benefits (Mims Frick et al., 2021).

From a safety perspective, removing gas from a home removes concerns about carbon monoxide poisoning; fire safety is improved because there are no naked flames; the risk of burns is lower for induction cooking due to much lower-temperature cooktop surfaces; and, at a larger scale, the risk of gas explosions and post-earthquake fires is reduced. Accounting for all these safety effects may be impractical from a metrics development point of view, yet they may be important factors to embed in project recommendations when encouraging homeowners to decarbonize.

### 2.4.6 Emerging Metrics

Other new metrics are needed that will be important for successful electrification and decarbonization.

#### Household Peak Power

The impact of peak power needs to be considered for both individual appliances and the whole home. For individual appliances, changes to home wiring and electric service requirements may be necessary, while whole home upgrades may require panel/service changes that have implications for the electricity distribution system.

For individual end uses, peak power (kW) is an appropriate metric. Whole house metrics are more difficult as they must account for the diversity of loads. However, methods to address this are readily available; for example, current electric codes already allow for assumed diversity when sizing circuits and panels. Some practitioners have developed extensive guidance on how to limit peak power requirements that show how this metric can be effectively utilized (Armstrong et al., 2021). It is likely that these existing methods will need to be updated as the industry increasingly focuses on managing peak power for all-electric homes.

Metrics need to be developed that allow for the rating of smart panels and switches that allow multiple end uses to share electric circuits and include the use of thermal and electric energy storage. Home charging of EVs is an additional load that needs to be accounted for in peak power analyses. Vehicle-to-grid and vehicle-to-home technologies are emerging that allow vehicle batteries – typically many times the kWh capacity of home battery solutions – to discharge energy to the home or the grid. This feature is an important way to increase home resilience in case of power outages or to serve to manage and separate when energy is delivered to the home versus when it is used in the home. Controlling household peak power requirements can have substantial energy costs and grid benefits.

#### Time-of-Use of Energy

Knowing not just *how much* energy is used but *when* it is used is vital for successful large-scale home electrification for efficient integration into the grid and to manage billing costs, which may include demand and time-of-use charges. Currently, there are very few examples of time-of-use energy metrics used in the home upgrade industry that assess or grade home upgrade projects on when and how much they use energy rather than monthly totals. One exception is the time-dependent valuation (TDV) energy metric used by the California Energy Commission, and there are examples of calculation procedures that attempt to capture time-of-use effects (Frick et al., 2022).

Both peak power and time-of-use metrics need to include the contribution of PV and thermal and electric storage to determine the maximum power consumed by the home and put into the grid at times of low demand for the home. The peak power and energy available from storage systems need to be assessed to evaluate resiliency and grid impacts. Therefore, the following metrics are also required.

### On-Site Power Generation Capability

Existing metrics for PV are peak power output (kW) and annual energy (kWh). The calculation of these metrics generally includes local solar availability, shading, and installation geometry.

### Energy Storage Capacity and Peak Power Delivery for Both Electric and Thermal Storage

Metrics are needed for energy storage (both thermal and electric) to account for changing cost per kWh and $CO_2$ content of electricity with time. Simple metrics exist, such as the capacity of a battery or thermal storage device or its maximum power capability (for both charging and discharging). It is likely that integrated metrics are needed that combine energy storage directly into $CO_2$ emissions and operating costs, together with related guidelines on how much thermal storage is needed for a given thermal/electric system. Example metrics would be storage capacity as a percentage of annual loads or a percentage of peak power consumption.

### Non-$CO_2$ Global Warming Potential Metrics

Beyond $CO_2$ there are two other climate-related decarbonization concerns. First is the high Global Warming Potential (GWP) of many refrigerants used in heat pumps, that, if released, can have climate impacts – in which case a metric favoring lower GWP refrigerants (such as $CO_2$) may be appropriate. A UK study (Eunomia Research & Consulting Ltd & Centre for Air Conditioning and Refrigeration Research, 2014) estimated that 10% of household heat pump installations leaked, with median leakage of 35% of the initial refrigerant mass (annualized losses of 3.5%). Over 90% of leaks were "catastrophic" in which more than 50% of all refrigerant mass was released. A second is the emissions of $CH_4$ (methane) associated with the gas distribution system. Currently this is about 2-3% of production, but due to the much higher GWP[24] of $CH_4$ could represent a large fraction of the global warming from using natural gas in homes ( (Alvarez et al., 2018) estimated that emissions across the supply chain, per unit of gas consumed, results in roughly the same radiative forcing as does the combustion of delivered natural gas over a 20-year time horizon). It is possible that $CO_2$ metrics be replaced with GWP metrics that would include the impact of $CH_4$ and refrigerant leakage.

[24] $CH_4$ is estimated to have GWP of 28-36 over 100 years according to the US EPA (https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#Learn%20why) and 21 over 100 years according to the IPCC Second Assessment Report.

To address the challenges related to getting to scale with home decarbonization, we can identify opportunities and key actions that need to be taken. This report is not a comprehensive list of all possible actions; instead, it is focused on areas requiring the most effort or where there is the least knowledge rather than more well-established approaches.

Many of the actions required to decarbonize the US residential building stock address several barriers at once and impact different parts of the larger effort to decarbonize the US economy. While acknowledging these cross-cutting effects, to make clear links between challenges and opportunities, the key barriers to home decarbonization are split into three categories:

1. **Technical challenges**
   Specific technical elements of upgrade projects, including appliances, insulation, HVAC equipment, and construction methods.
2. **Cost challenges**
   First costs, operational costs, and project financing.
3. **Valuation challenges**
   Limited understanding, quantification, and communication of various comfort, health, home value, and energy cost benefits of home decarbonization projects.

In each of these categories, this report identifies opportunities of broad interest as well as specific opportunities for the DOE.

Figure 13 and Figure 14 illustrate some of the technical challenges for home decarbonization that would lead to cost reductions needed to have the costs recouped through potential bill savings. This will be important in getting to scale with widespread decarbonization, and cost and valuation goals as applied to current home decarbonization best practices. The target cost was chosen such that energy bill savings would support this level of investment over a 30 year period. The reductions in overhead and profit assume a drop from the very high levels currently reported in the industry (see Figure 8). The reductions show here will require development of business practices to reduce overheads and increase efficiency, such as outsourcing of customer acquisition and management to third-party aggregators.

**FIGURE 13: ILLUSTRATION OF THE TECHNICAL CHALLENGE OF COST REDUCTION FOR DECARBONIZATION PROJECTS**

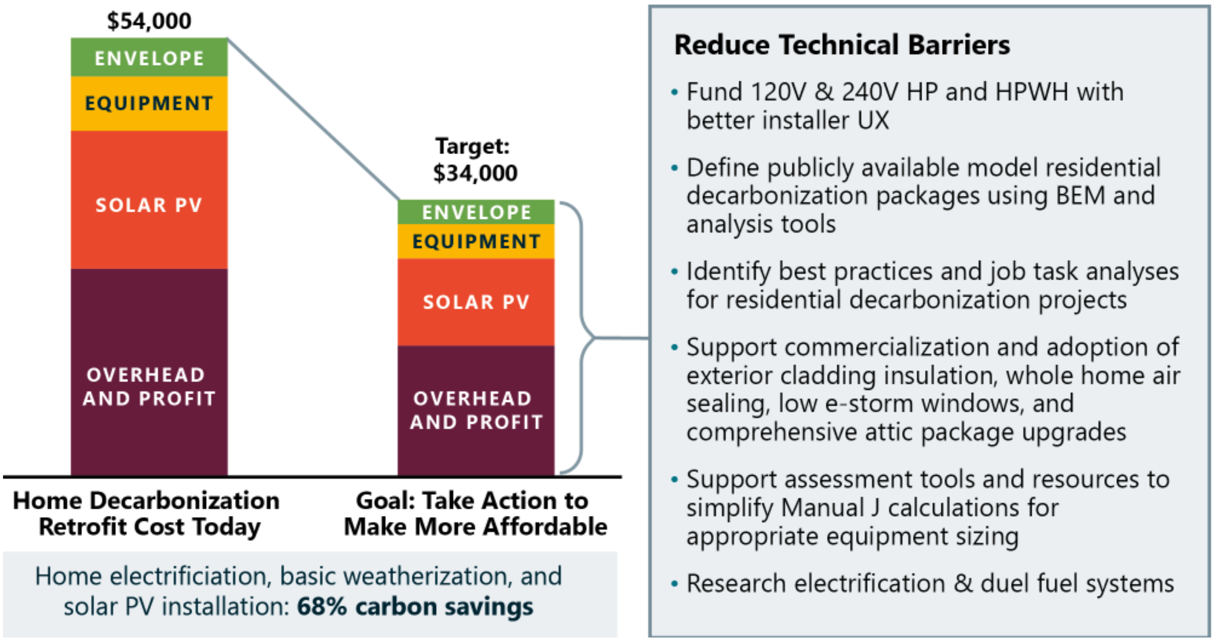
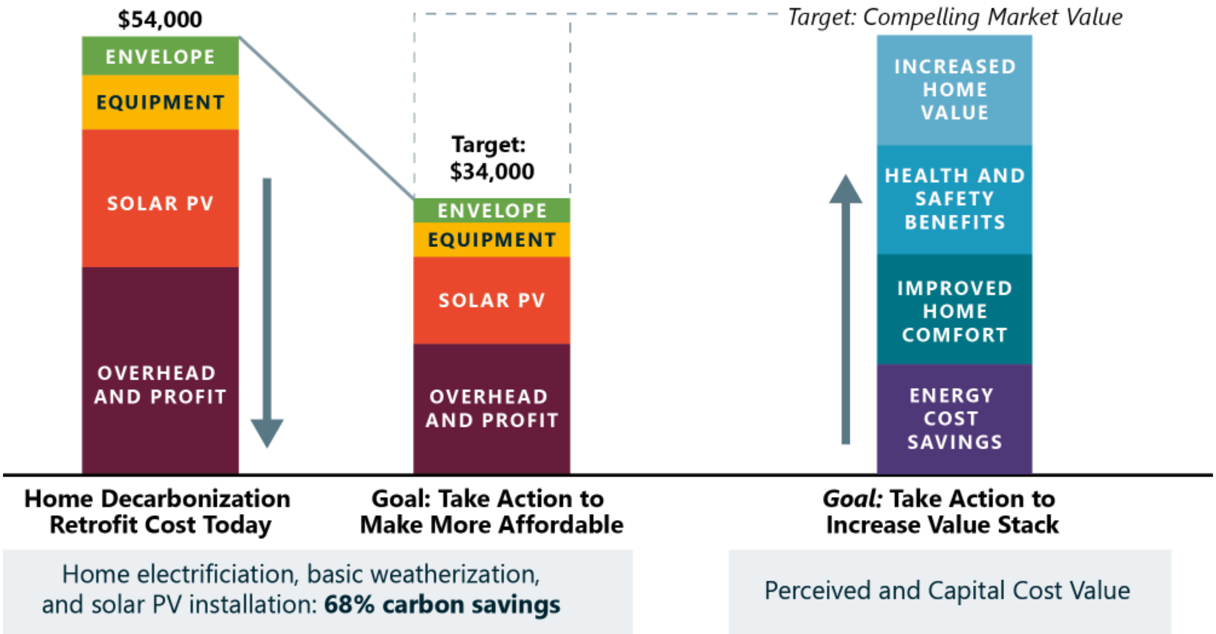



**FIGURE 14: ILLUSTRATION OF COST AND VALUATION GOALS**



# 3.1 Technical Challenges

## 3.1.1 Limited Product Availability

While readily available off-the-shelf products for home decarbonization exist for many applications, there are several product gaps. These are gaps that generally do not need any basic technology development; several examples are given in the table at the end of this section.

It is notable that manufacturers are recognizing deficiencies in this product sector. During the development of this document, new products have been developed that are newly available or will be available within 12 months. These include advanced low-power portable heat pumps from Gradient and Midea (and many new models of in-room portable heat pumps with inverter-driven compressors and other efficiency improvements), 120V HPWHs, electric ranges/cooktops with power management systems, and batteries to limit maximum power draw (Impulse and Channing Copper). Other recent innovations include the development of Smart Meter Collars that allow easy addition of solar PV and EV charging without panel upgrades or even opening the electric panel.

**Guidance and market transformation investments are needed to assist manufacturers in the development of new products, together with technical performance analysis and evaluation, to support the use of these advanced products in energy programs, rating certifications, and future codes and standards.**

#### Develop Low-Cost "Transition" Solutions

Install what is currently practical with the aim to fully upgrade later. Leave legacy systems in place that only operate at peak times. This approach is particularly useful in very cold climates that may struggle to meet heating loads using heat pumps. Perform field studies to develop system controls algorithms and ways to best integrate the legacy systems with heat pumps.

#### Develop Standardized Solutions for Multifamily and Manufactured Housing

A few basic packages using the same components and installation could be easily applied to almost all manufactured homes. Multi-family homes can use centralized heating and cooling, DHW, and other services that similarly lend themselves to development of solutions that are unique for that housing type.

#### Analyze Maintenance and Durability

Investigate maintenance/durability issues (including workforce development) associated with electrification technologies through field studies and industry surveys.

#### Performance Analysis and Evaluation for New Products

Support the use of these advanced products in energy programs, ratings certification, and future codes and standards.

## Opportunities

### EXPAND TECHNOLOGY AVAILABILITY

The US should prioritize scaling domestic production and supply chains for key residential decarbonization technologies. The US Federal government is planning steps (such as invoking the Defense Production Act) to support manufacturing of certain technologies, such as solar panels, heat pumps, and transformers for the electrical grid.

### DEVELOP NEW POWER-EFFICIENT PRODUCTS MORE SUITABLE FOR INSTALLATION IN EXISTING HOMES

For heating/cooling and DHW systems, there is a need for products with lower power requirements, preferably operating off existing 120V electric circuits and with low amp draws. Products need to be developed that integrate storage (either electric or thermal) that can meet end use demands while having small input power. Active development in this area includes ranges and cooktops with integrated batteries and domestic hot water/heating heat pumps with integrated thermal storage. A significant issue in current decarbonization projects is finding space to fit heat pumps for heating and DHW, so products are needed in a wider range of form factors. Furthermore, due to restrictions on available building locations, new products are needed that are much quieter than existing models – particularly for DHW.

SUMMARY OF KEY PRODUCTS REQUIRING DEVELOPMENT AND EVALUATION

| **Power-Efficient Appliances** |
| --- |
| 3,400 W Heat Pump Dryer standard sized (7.4 cu ft)<br>• Preferably 120 volts |
| 7,200 W 36" induction cooktop[25] |
| 2,500 W unitary HPWH<br>• Kigali compliant<br>• Quiet<br>• Available in a range of form factors to fit in restricted spaces |
| 2,500 W split HPWH<br>• Available in a range of form factors to fit in restricted spaces |
| Drop in heat pump replacement for gas wall/floor furnaces, fireplaces, and mobile home furnaces<br>• Preferably 120V |
| **Power Control Devices** |
| Batteries/thermal storage to limit peak power requirements<br>• Integrated with high-power devices: heat pumps, cooktops, ovens, and ranges<br>• Meter collars and other power management devices to allow easy addition of PV and EV to homes without adding panel load and allow flexibility for adopting heat pumps and electric cooking |
| **Transportable Technologies for Renters** |
| Portable heat pumps[26]<br>• More efficient – variable speed inverter driven<br>• Higher capacity, given the same input power from a 120V 15A outlet |
| 120V induction 3-burner cooktop |

## COLLABORATE WITH THE INTERNATIONAL COMMUNITY

As other countries also tackle the issues related to decarbonization – specifically related to housing – international collaboration will be essential to share successes and failures and give people a sense that the global community is investing in change. Other countries have already developed integrated solutions to home energy upgrades that could be adapted to address new carbon reduction metrics and used as a model for developing similar US programs. There are also technology approaches that have resulted in far lower installation

[25] Low power 1800W ranges with integrated batteries are coming to market in 2023.

[26] As this report was going to press, several new high efficiency portable heat pumps became available and there is much manufacturer interest in this product segment.

costs; for example, the cost of PV installations in the rest of the world is much less expensive (by factors of 2–3) than in the US.

International agencies for collaboration include the IEA, the European Commission on Energy, and the Joint Research Centre (European Commission). International partnerships will help US industry to learn from others' successes and mistakes, bring technologies to the US (such as $CO_2$ and other low GWP heat pumps, low capacity/power heat pumps, heat pump clothes dryers, etc.), and challenge US companies to create similar – or better – devices. Furthermore, ensuring products can be used in multiple markets helps to achieve economies of scale.

#### EMERGENCY REPLACEMENT

This is an ideal time to replace a gas appliance with an electric one. However, most installers and contractors (and therefore households) are constrained by local and immediate availability of the appropriate appliances. Collaborating with distributors and big-box home retail outlets is an opportunity to change this paradigm. This needs to be done in conjunction with the development of temporary replacement technologies that allow continued service using gas while any home electric upgrades that are needed are carried out (e.g., adding a new electric circuit for a heat pump, HPWH, or range).

#### PURCHASE PRODUCTS IN BULK

Bulk purchasing may be a key strategy to adopt to encourage private-sector investment. It also provides local programs and contractors with buffers against supply chain issues.

### 3.1.2 Increased Electricity Demand

There is a need to limit peak loads to reduce the need for electric upgrades for the home and grid upgrades by utilities (that are ultimately passed on to consumers through increased rates). Technology development is needed for low-power consumption devices, thermal storage, and automated controls. These controls can manage capacity within a home and/or coordinate with the grid. **These solutions will also be helpful in avoiding large energy bill increases from demand charges, allow flexibility in places with time-of-use rates, and maximize the benefit of on-site generation.**

**Develop Load Management Technologies**

Develop and field test solutions for different dwelling types and service levels, including 50A (manufactured homes and apartments), 100A (many older homes), and 200A (typical new homes).

## Opportunity

### GRID-RESPONSIVE SOLUTIONS

Load management technologies are needed to control extreme loads on the grid and to increase home resilience (i.e., the ability to function when utility supply has failed) with onsite stored energy. Collaboration with utilities is needed to fund and develop R&D programs, in part because utilities will be the biggest beneficiaries. Exercising more control over home energy demand load shapes could dramatically reduce coincident demand on the energy grid. Storage technologies are needed at several scales (from large to small):

- **Utility/regional level**
  While important, this scale will be somewhat separate from home decarbonizing efforts.
- **Community level**
  One example is the EcoBlock project,[27] which aims to upgrade homes at the city block level rather than one home at a time. The project also includes block-scale storage. Another major investment by DOE is the Connected Communities[28] initiative. Benefits of community-integrated approaches include reduced $CO_2$ emissions, increased affordability, and better grid integration and reliability (Nemtzow et al., 2022).
- **Whole building level**
  Storage technologies for whole buildings already exist and are increasing in popularity despite their high costs because they give homes a level of grid independence, resiliency, and the ability to avoid potentially high electric tariffs and penalties for solar PV.
- **Device integration level**
  This smallest scale builds on smartphones, tablets, and computers that already have built-in batteries, as a matter of course. Expanding these battery-integrated devices to include appliances such as refrigerators, televisions, and DHW would allow some easy automation and built-in resiliency to power outages. There are already some lighting solutions with battery-integrated LEDs for homes.

The three non-utility scale storage levels are vital to limit the costs of upgrading the distribution grid (e.g., local substations and transformers) and to improve home resilience. Research is needed to find the right thermal/electric battery mix for a range of homes, retrofit applications, and climates and to develop appliances that fully integrate storage (e.g.,

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[27] https://ecoblock.berkeley.edu
[28] Connectedcommunities.lbl.gov

thermal storage for hot water). For low-income and multifamily applications, there is a need to develop community-scale shared storage, likely integrated with solar PV.

### 3.1.3 Costly Electric Service Upgrades, Panel Replacements, and New Circuits

The cost to upgrade electric services and rewire homes to provide heating, hot water, clothes drying, and cooking is commonly several thousand dollars and contributes significantly to high costs. **Technology development is needed for low-power-consumption devices, thermal storage, and automated controls, and the development of guidelines and changes to electric codes for electrifying homes without service upgrades.**

**Demonstrate Power Efficient Technologies**
This can be done through field demonstrations of solutions that limit power increases for electrified end uses.

**Update the National Electric Code**
Coordinate with the NEC committees and make proposals to the NEC that simplify decarbonization efforts. Help the residential construction industry to have a better understanding of the alternatives pathways already in the NEC that can be used when renovating existing homes through training and information campaigns.

**Develop a Power Efficient Appliance Program**
This program would invest in the R&D necessary to assist US manufacturers in developing new low power products. A key application is cooking, where the current high efficiency of induction systems is used to create very high performance rather than acceptable performance (e.g., matching a gas burner for time to boil a pot of water).

**Develop a New DOE/EPA "Power Star" Rating and Label for Power Efficient Appliances**
Lower power is the key to decreasing the cost and effort required for electrification. It allows the use of existing infrastructure in the home and makes electrification at scale grid-friendly.

#### Opportunities

##### UPDATE BUILDING/ELECTRIC CODES AND CREATE NEW INDUSTRY STANDARDS

Guidelines need to be developed for the residential construction industry to have a better understanding of the alternative pathways already in the NEC that can be used when renovating existing homes, as well as developing decarbonization packages that reduce the need for electric service/panel upgrades. For example, the Watt Diet used by Redwood Energy (Armstrong et al., 2021) guides users through NEC requirements and appliance selection to reduce the need for panel replacement and service upgrades. R&D is needed to develop change proposals for the NEC that better reflect the power usage patterns in decarbonized homes. This effort must be coordinated with standards-setting bodies as well as code officials and contractor training.

#### DEVELOP TECHNOLOGIES AND GUIDANCE FOR LOWER CONNECTED POWER

The total power requirements for a home can be reduced by selecting lower-power devices. Examples include heat pump clothes dryers and smaller capacity heat pumps. For heat and hot water, heat pump power limits can be offset by integrating thermal storage for use at peak load. The feasibility of power-efficient technologies needs to be shown through field demonstrations to reduce the perceived risks of adopting these new products and technologies. Solutions need to be developed for different dwelling types and service levels, including 50A (manufactured homes and apartments), 100A (many older homes), and 200A (typical new homes).

#### DEVELOP LOW-COST LOAD REDUCTION SOLUTIONS

In addition to the big individual loads of heating, cooling, and DHW, there are low-cost solutions that address smaller end uses. These low-cost approaches are currently often implemented using direct occupant feedback, but in the future may also include automatically controlling plug loads, lighting, and development of direct current, low-power options for key safety and communications services to enhance resilience.

## 3.1.4 Develop Products That Are as Easy to Purchase and Install as Business-as-Usual Solutions

Products and technologies related to decarbonization need to be readily available and easy to install and service. They need to be the easy choice for consumers. For rapid scaling, decarbonization-related products and technologies need to match or improve current approaches related to installation time, lead time, maintenance, product life, product availability, and install/repair availability.

**There is a need to develop products and home upgrade approaches that make decarbonization the obvious choice.**

### Opportunities

#### STANDARDIZE DECARBONIZATION PROJECTS

Simple envelope load reduction (air sealing and insulation) combined with PV and end-use electrification was shown to be the least costly approach for deep $CO_2$ savings in the *Cost of Decarbonization and Energy Upgrade Retrofits for US Homes* study. These projects produce high energy savings and carbon reductions, use readily available technology, and employ a workforce and infrastructure familiar with almost all the products required (one exception is the reluctance of some contractors to adapt to heat pump technologies). Furthermore, an industry survey has shown that the addition of solar PV is appealing to homeowners (Chan et al., 2021) and easier for contractors to sell, allowing them to reduce the overhead costs of closing contracts. The cost compression required for this path of envelope upgrades and electrification is much less than trying to reach the same carbon savings using envelope upgrades alone – as shown in Figure 14. Note that that utility bill savings from onsite solar PV may be reduced in the future as utility net-metering policies change. This will make the economic justifications for decarbonization an even greater challenge.

FIGURE 15: REQUIRED COST COMPRESSION FROM DIFFERENT PROJECT TYPES

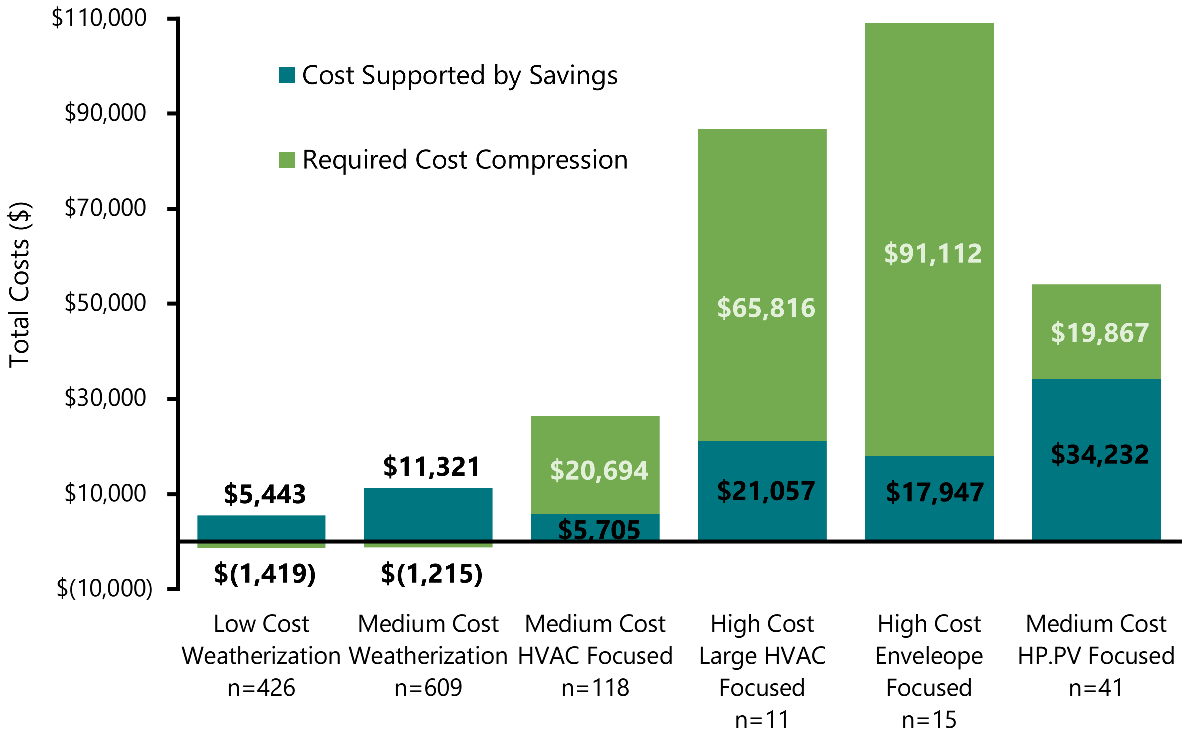


Figure source: Less et al., (2021a)

## USE EXISTING TECHNOLOGY

Existing technology is already being manufactured, has distribution platforms, has a proven track record, and has an industry that is familiar with it without retraining. Pilot tests and community-scale demonstrations of off-the-shelf electrification solutions are needed that would serve as examples to the industry and for home occupants as to the viability of electrification. Some examples of relatively easy solutions are:

1. Electrify heat and DHW in every home that has air conditioning. These homes are unlikely to need a new electric panel or upgraded electric service and represent some of the lowest-cost opportunities.
2. For all-electric homes, replace resistance heat for heating and DHW with heat pumps.

3. Develop AC to heat pump packages of reversing valves and controls to convert existing AC units to heat pumps. Develop policies that ensure that all AC units are also heat pumps.
4. Determine how to halve the cost of PV to bring it into line with the rest of the world – mostly through efforts to simplify design and installation requirements.

#### MINIMIZE REMEDIATION

The poor infrastructure conditions of existing housing can often present a significant barrier to decarbonization. Homes with outdated electrical panels and wiring, asbestos, lead paint and pipes, mold, and water damage can present technical and health and safety barriers. Packages need to be developed for electric capacity-limited homes to avoid panel upgrades, including the evaluation of smart panels/circuits. Approaches that rethink/reanalyze asbestos removal requirements or knob-and-tube limitations would be very helpful. This needs a coordinated effort with building codes and standards organizations and local code authorities. It is unlikely that getting to scale with home upgrades can avoid all infrastructure issues, such as mold and moisture remediation or lead pipes. Therefore, decarbonization programs will have to have the flexibility and budget to allow homes with these limitations to be decarbonized and not deferred while at the same time recognizing decarbonization of the nation’s housing stock cannot fix all injustices or address all legacy health and safety risks in US housing.

### 3.1.5 Misaligned Metrics Between Energy Efficiency and Decarbonization

Energy efficiency metrics are misaligned with decarbonization. Traditional energy efficiency metrics are often not appropriate for decarbonization, and alternative metrics need to be standardized to better evaluate barriers and solutions. R&D is needed to assess current metrics and to integrate these metrics into program and technology development and financial mechanisms. Examples of alternative metrics are:

- Peak power – for both individual appliances and the whole home. Whole house metrics that account for diversity and that account for the use of smart panels and switches that allow multiple end uses to share electric circuits
- Time variability of the carbon content of electricity and related time-of-use of energy
- On-site power generation capability, normally solar PV
- Energy storage capacity and peak power delivery for both electric and thermal storage
- Embodied carbon, including the ability of products to be re-used or recycled
- A metric that integrates all the power and energy issues into one that is suitable for real estate transactions

- Health, resilience, and comfort impacts of decarbonization
- Affordability as a replacement for current financial metrics

### Standardize Metrics

R&D is needed to ensure that metrics are robust and reliable. Industry surveys and stakeholder meetings are needed to ensure that metrics are relevant and usable by the buildings industry.

## 3.2 Financial Challenges

### 3.2.1 Unaffordable Project Costs for Many Households

Cost data from the *Cost of Decarbonization and Energy Upgrade Retrofits for US Homes* study shows that current single-family home upgrade projects achieving 50% carbon or net-site energy savings cost about $30 per square foot, or about $50,000 for a typical home. Idealized archetypes from this study suggest that the costs to reach 50% savings could be reduced to $20,000 to $30,000, or roughly $11 to $17 per square foot. These costs still exceed the direct energy savings that would only support investments of $14,000 to $19,000 based on national average energy costs. They also far exceed the median household savings in the US of $5,300 (Board of Governors of the Federal Reserve System, 2019).

Local net-metering policies and energy costs vary greatly, and the idealized archetypes may be cost-effective in some places and not others, and it is likely that optimum decarbonization approaches, utility programs, and government policies will have regional variations. The disparity between costs and savings has been shown in literature reviews (Less et al., 2021a) and previous studies (Less et al., 2014) that about half of home upgrades currently do not have enough energy bill savings to offset costs.

High costs are linked to overcoming a lack of demand, high equipment costs, problems addressing other non-energy issues in homes, and contractor business models that have high overheads. LBNL's recent study showed that there are home upgrade strategies that can significantly cut project costs. DOE's BTO is funding work to extend these analyses to include multifamily buildings to identify how single-family and multifamily building costs may differ and if there are multifamily-specific strategies that may offer cost-cutting opportunities.

Costs can be reduced by increasing affordability through easy access to financing, rebate programs, guidance for simplified installations, and focusing upgrades on the most effective carbon reduction strategies. Including electrification/decarbonization in real estate market valuation may be a strategy that works for some homeowners. Technology development is needed for low-power consumption devices, thermal storage, and automated controls. These solutions will minimize the costs of heat pumps due to lower capacity requirements and the need for costly electric service, panel, and home wiring upgrades.

#### Opportunities

##### COMPRESS HARD COSTS

Solutions are needed that use the existing electric infrastructure in homes (e.g., smart panels and 120V appliances). Demonstrations are needed for consumers and contractors to show that these technologies can reliably provide the required services. Analysis is also needed to evaluate the user experience and identify barriers to use. Expensive, complex upgrades – such as highly insulated envelopes or HVAC/DHW equipment requiring expensive and time-consuming one-off designs and installs – should not be prioritized as a primary path for most homes.

A better approach for envelopes is to focus on simple and inexpensive upgrades for which there is already a contractor base (e.g., basic air sealing and insulating, as is often done in current weatherization programs). It is possible to control costs that have high (>50%) energy savings by using readily available insulation, lighting, appliance, DHW, and HVAC solutions that have a local installation and maintenance/repair infrastructure. Recent work analyzing the cost of home upgrades that reached this performance level from the *Cost of Decarbonization and Energy Upgrade Retrofits for US Homes* study has shown that no additional package refinements are needed.

The least cost approach to at least halve carbon emissions and energy use is to replace gas furnaces, boilers, and water heaters with heat pumps, add onsite PV, and do basic air sealing and insulation. Replacing gas clothes dryers and cooking is a lower priority because they consume a lot less energy and emit a lot less carbon; these items can be re-prioritized for decarbonization at the time of appliance replacement – thus reducing the hard upfront costs. Staged, partial decarbonization strategies are a key way to spread out costs to make them more acceptable to consumers.

### REDUCE THE COSTS OF SOLAR PV

Although solar PV costs are much too high in the US,[29] efforts to bring solar PV costs more in line with the rest of the world are already underway – such as the SolarAPP[30] program to streamline the permitting process. Other measures are needed to bring costs more in line with the rest of the world by following their business and installation practices.

### INTEGRATE PROJECT FINANCING

Currently, paying for major decarbonization projects is usually presented as a single, large, upfront cost for which many households lack savings to cover. This introduces marketing challenges due to "sticker shock" and outright inability to pay. Other concepts from banking and financing, such as return on investment (ROI), have longer-term outlooks (10 years or more) that do not correspond to the financial time horizons of most households that are on the order of a year or two.

Better ways of presenting the finances of energy and carbon savings to a broader audience are needed to get to scale. The experience of some successful home energy savings and decarbonizing businesses has shown that there are better ways to approach financial aspects using cost metrics more suited to household economics. One example of this is monthly net

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[29] In Australia, solar PV costs are AU $0.66 to 1.20/W (US $0.46–0.84) (https://www.solarmarket.com.au/residential-solar/solar-systems-pricing/), compared to the US at about $3/W (https://www.seia.org/solar-industry-research-data).

[30] https://solarapp.nrel.gov/

cost of ownership (i.e., a cash flow approach more akin to traditional home mortgages), an approach already used in pay-as-you-save programs and "efficiency-as-a-service" models.

There are several examples – used to market expensive products in other sectors as more affordable – that can be used as guidance and that will enable the industry to better market decarbonization and reduce the soft costs associated with getting homeowners to commit to decarbonizing their homes. The first example is in automobile sales, where dealers automatically present financing deals for loans and leases at the time of sale. Another example is smartphones, where the cost of the phone is bundled into a monthly bill by service providers. A final example, from the buildings industry, is solar PV, which got to scale by having installers also offer financing and leasing options directly to customers.

A key point is to emphasize affordability – and improving lives and homes – rather than solely trying to show that decarbonization can be done for free or at a lower cost. To get up to scale, the building industry needs to work with financiers as well as equipment and materials manufacturers to provide financing models that are standard practice and automatically offered as part of the sales process.

### 3.2.2 Lack of Access to Decarbonization Upgrades for Low-Income and Renter Households

Solutions are needed that will meet the needs of renters, low/moderate income households, and disadvantaged communities. Under the New Deal, the first wave of electrification 100 years ago that electrified rural parts of the US was funded federally because access to energy was recognized as a public good for households, even if there was not a strong business case for utilities to build out supply. Similarly, today the decarbonization of households is a public good that is needed to mitigate the worst health, economic, and environmental outcomes of fossil fuels, regardless of where these households are located or their level of individual wealth. Solutions need to be accessible in multifamily, low-income, and rental applications where the benefits accrue to everyone, not just property owners.

Financing, billing, and energy subsidy solutions need to be combined with lower-cost (and possibly lower $CO_2$ reduction) approaches that do not overburden households with higher energy costs where fossil fuel energy is cheaper than electricity. For example, Figure 4 shows that, in some places, it will be difficult to not increase energy bills without also reducing loads or finding ways to subsidize low-income households. An additional complication for renters is that sometimes occupants get an individual electric bill, but gas use is built into rent or other fixed fees (this is also sometimes true for condominiums). This adds to post-decarbonization bill uncertainties and risks.

Another key barrier faced by renters is the fear that significant building upgrades – such as those associated with decarbonization – can be used as a reason for landlords to increase rents post-upgrade and possibly lead to existing tenants leaving or facing eviction. There are also often restrictions in leases on what occupants can install/use in rented accommodation that may apply to some decarbonization technologies. While beyond the scope of this report, policies are needed to protect renters and low-income households during the decarbonization transition.[31]

#### Develop Solutions for Renters

Develop solutions that renters can take with them when they move and would be acceptable to landlords. Simple 120V/limited power solutions that plug into a standard wall socket and transportable technologies that renters can own and move from home to home will be essential. Deploy the first generation of simple plug-in devices and monitor their energy performance and include IAQ monitoring and record user feedback to ensure that performance is acceptable. Focus on disadvantaged communities, public housing, and other affordable housing operators.

#### Analyze Energy Costs and Fuel Poverty Issues

Determine fair and equitable ways for utilities to charge customers as provision of energy changes from unit energy billing to energy management (e.g., peak loads, time-of-use).

## Opportunities

### UPDATE PROGRAMS BY IMPROVING CONSUMER AFFORDABILITY

Due to combined health, comfort, and economic benefits, residential decarbonization programs should include basic air sealing and insulation in projects. Programs need to be put in place to protect the most vulnerable from very high energy bills that expand upon or are similar to existing programs (e.g., low-income home energy assistance programs and programs that stabilize monthly energy bills throughout the year). Programs that provide energy bill assistance should be integrated with home upgrade programs to better support households. Risk should also be assessed across aggregates of households rather than on a per-household basis so financing will prove feasible across a wider range of household incomes. Existing low-income energy bill assistance programs could be expanded to include electrification elements.

There needs to be an effort to provide technical support to utility commissions and utilities to wind-down gas infrastructure without overly burdening remaining gas customers, and low-income support programs need plans for minimizing these infrastructure wind-down issues. Analyses are needed to assess stranded asset values.

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[31] Federal, state, and local agencies and other nonprofits are working on solutions to these issues that are somewhat beyond the scope of DOE activities. However, looking at ways to reduce upfront and operating costs discussed in this report have a major role to play in reducing these impacts and support DOE's Justice40 program.

Some analyses (Grubert, 2020) have already looked at this, and the values are low because the assets are old and have had very little investment for many years.[32] There are also equity issues for on-site generation, as renters cannot install rooftop solar PV themselves and may be reluctant to invest in this infrastructure that is tied to property they do not own. Furthermore, many multifamily buildings lack enough roof space to install enough solar PV to supply all units in a building – particularly for high-rise buildings.

These factors imply that community-aggregated solutions are needed – such as investments in community PV and PV on community buildings (such as schools, libraries, and post offices).

### DEVELOP AFFORDABLE DECARBONIZATION SOLUTIONS FOR THE WEATHERIZATION ASSISTANCE PROGRAM (WAP) AND OTHER LOW-INCOME PROGRAMS

There are several existing and emerging technologies that could contribute to lower-cost approaches tailored to WAP and other low-income assistance programs. One approach is to use low-power appliances to avoid costly panel upgrades and rewiring (e.g., three burner 120V induction cooktops that include a set of new pots/pans for low-income households, 120V washer/dryer combinations with heat pump dryers, 120V HPWH with thermal storage). WAP implementers need guidance on how to set WAP-recipient homes on a track for decarbonization within current program structures.

One possibility is to leave legacy systems in place that only operate on peak load, but 95% of the time, the house performs as "all electric." When using this approach, controls need to be used that integrate the operation of the two systems so that operation is transparent to occupants. This can save on removal costs, asbestos issues, etc., and is particularly suited to very cold climates where even cold-climate heat pumps may suffer from restricted capacity to heat a home.

Some practitioners who are working to decarbonize low-income households have developed packages of appliances that are low cost but can effectively electrify all the gas end uses. Most, if not all, of these devices can be transported by renters and do not tie the electrification upgrade to the home. Currently, these devices are very rare, but if this market could be developed, then there may be more choices available to programs and homeowners. An example package would consist of:

- High-performance (inverter-driven compressor) portable heat pumps (about $600). These also allow homes to be cooled – a significant improvement in resiliency and occupant comfort
- A couple of 120V induction hotplates (about $200)
- A countertop 120V oven (about $200)

[32] For graphical representations, see emilygrubert.org/energy-transition and emilygrubert.org/plant-age

- Compact 120V water heater with a small storage tank (about $200–400, with 7–19 gallons of storage)

#### IMPROVE RENTER PROTECTIONS

Renters have important concerns regarding home upgrades for decarbonization. Key issues are the fear of eviction while temporarily displaced as upgrades are carried out and rent increases after decarbonization efforts are completed. Policies, legislation, and programs should be required to protect and support renters during this decarbonization transition. Guidelines have been developed, many of which are specifically aimed at low-income/affordable housing – such as those in the Greenlining Institute's 2019 report, *Equitable Building Electrification* – and further efforts are needed.

For example, a summary of efforts in California has been assembled by the Build It Green non-profit (*Equitable Electrification Handout*, 2022) and other non-profit organizations, such as American Council for an Energy-Efficient Economy (ACEEE), are working on further studies of how to protect renters and low- or middle-income households and ensure these households receive the benefits of a decarbonized residence.

### 3.2.3 Lack of Available Workforce with Residential Decarbonization Expertise

Even if someone wants to electrify their home, it is very hard to find a contractor to do it. Many millions of homes need upgrading to reduce their carbon footprint every year. There is insufficient infrastructure to support millions of homes being decarbonized because home performance and renovation contractors are already busy, and there are not enough plumbers and electricians to do all the existing work, let alone a dramatic increase in market scale.

Furthermore, residential building workers are paid less than their counterparts in commercial construction and have much poorer benefits packages, making recruitment and staff retention difficult. Workforce considerations need to be aware of the tensions between lowering project costs (that are mostly driven by labor) and developing a well-compensated workforce.

In the short term, developing DIY and plug-and-play technologies will allow many more homes to electrify while addressing some of the equity issues for renters and less wealthy homeowners. The longer term requires engaging the home performance and renovation industry in changing their practices such that projects require fewer labor hours to perform. This may include compensating training programs for workers and developing better business practices for contractors.

## Opportunities

### EDUCATE AND TRAIN RESIDENTIAL WORKFORCE ON DECARBONIZATION

Employers must make a compelling value proposition to workers and showcase decarbonization technologies as a valuable commodity, similar to solar PV. Longer term, workforce development will require coordination between DOE, the Department of Labor, community colleges, labor unions, community organizations, youth corps, other non-governmental organizations (NGOs), and leading industry contractors.

### DEVELOP DIY AND PLUG-AND-PLAY SOLUTIONS

Where the jobs today are low-wage and unappealing, decarbonization solutions are needed that do not require professional labor. Giving consumers more options for decarbonization and flexibility to try out technologies can help accelerate adoption. This can reduce pressure on lower-wage jobs where the workforce is in low supply and help consumers gain familiarity and comfort with new technology.

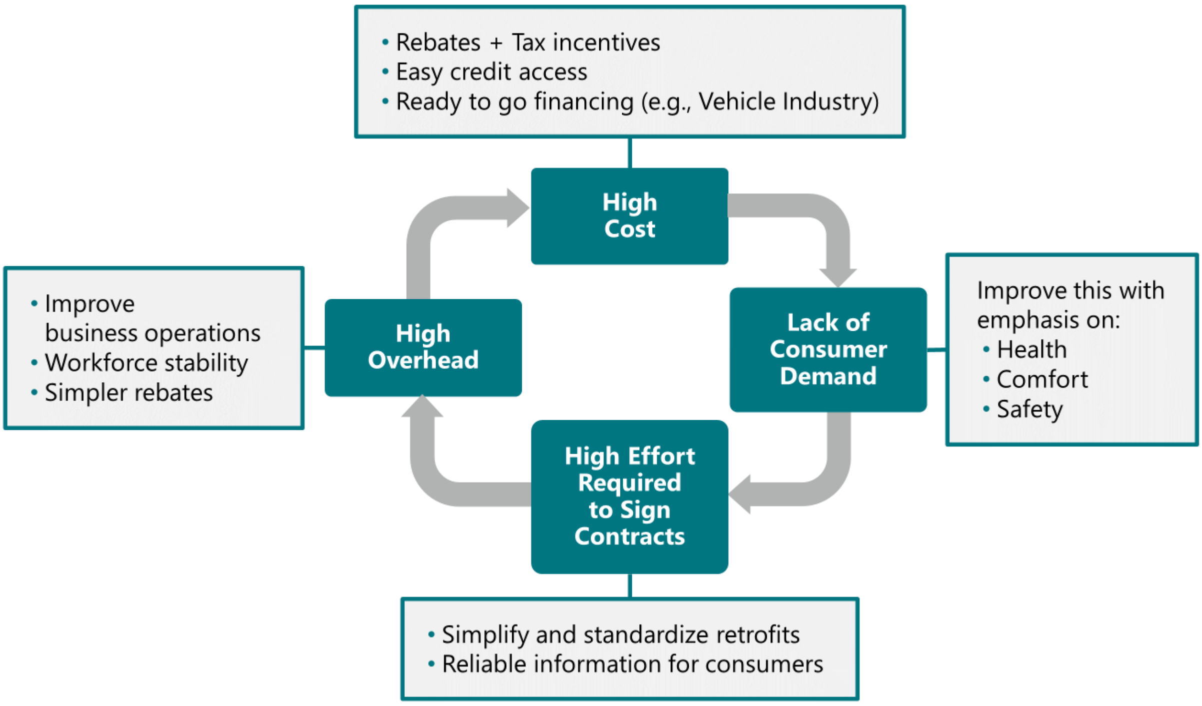
### DEVELOP BETTER BUSINESS PRACTICES AND BUSINESS MODELS FOR CONTRACTORS

The home performance industry is dominated by small businesses that lack the scale required to plan and organize projects more efficiently. Programs that assist these businesses are required that do not alienate the existing contractor base and allow them to reduce the labor hours required for each project. This could be done in coordination with national and local contractor organizations.

## 3.2.4 High Overhead in Home Energy Upgrades

As illustrated in Figure 15, for a contractor, the lack of demand means a lot of overhead is required for each project, which contributes significantly to project costs. This figure illustrates the vicious circle of how high costs lead to a lack of demand, making sales difficult and time-consuming and, in turn, significantly increasing costs.

FIGURE 16: ADDRESSING "LACK OF DEMAND" ISSUES FOR CONTRACTORS




## Opportunity

### REDUCE PROJECT ACQUISITION COSTS FOR CONTRACTORS

Addressing demand and reducing costs result in lower overhead and further cost reduction. As reported in a survey of industry professionals for DOE (Chan et al., 2021), educating homeowners and other professionals such as realtors is unlikely to be a solution in itself to move the market, but a lack of reliable information for contractors and the public is a barrier. Simplifying and standardizing home retrofits to reduce time spent on work scope and customer acquisition activities was seen as a key approach that could reduce overheads. Some programs are starting to not visit a house until the homeowners express their intent to proceed. These efforts need to be expanded to support the industry. Another potential change is to reduce the effort spent on whole-house energy assessments/audits and re-think how projects are designed and delivered.

While the whole-house consultant model is a technically sound approach and a viable business, it is unlikely to scale across the market and can lead to higher customer acquisition costs. Getting to scale will require more standardization and less customization and optimization. For example, single upgrade measures (e.g., water heater insulation blanket) have historically been deployed successfully and at low cost through direct install programs, with prescribed work scopes and program-wide contractually negotiated costs. The same approach must be tested and validated for delivering both decarbonization technologies (e.g., HPWH) as well as more integrated, whole-house projects.

Another example is the release of standardized upgrade work scopes in June of 2022[33] that WAP grantees can choose to apply in their work, which targets reduced administrative burdens associated with project planning and demonstrating cost-effectiveness. To support this and other deployment strategies, the market needs innovations, analyses, and demonstrations of these streamlined approaches.

### 3.2.5 Compliance with Building Codes and Standards

Most significant decarbonization work (including envelope, heating/cooling, solar PV, EV Charging, new electric panels, and DHW upgrades) requires a permit and an inspection for code compliance. Currently, building code requirements and their interpretations by industry and code authorities add unnecessary cost, time, and complexity to many home decarbonization efforts. There is a need to revise code requirements and provide training for code enforcement authorities that simplifies the process and makes home decarbonization/energy-saving upgrades easier to perform.

Building codes and standards can also be great drivers of industry changes. One recent example is the Washington state energy code that changed in 2018 to give a compliance path using electric heat and hot water, resulting in new construction changing from 20% to 88% electric primary heat (Bean et al., 2022).

#### Opportunities

##### IDENTIFY AND DOCUMENT CURRENT CODES AND STANDARDS BARRIERS TO HOME DECARBONIZATION

Industry surveys and stakeholder outreach is needed to identify current codes and standards barriers to decarbonization efforts. Some example topics are knob-and-tube wiring replacement, electric circuit sharing, and compulsory remediation (e.g., lead and asbestos).

##### UPDATE BUILDING CODES AND STANDARDS

R&D is needed to provide the technical background to support codes and standards changes. In addition, coordination with and participation on codes and standards committees is necessary to remove current barriers and enable the use of new approaches/technologies for decarbonization. One particular example is the NEC, which could become more flexible when considering electric upgrades to existing homes and has had recent revisions to adapt to new technologies, including solar PV, EVs, and energy management systems. Together with these updates, there is a need to make industry practitioners and professionals aware of how to better use existing codes. Using the NEC as an example, again, there are pathways within the NEC that can be very helpful when

[33] See Weatherization Program Notice 22–8: Streamlining the Energy Audit Process–Optional Regional Weatherization Priority Lists (https://www.energy.gov/eere/wap/articles/weatherization-program-notice-22-8-streamlining-energy-audit-process-optional).

electrifying homes that are rarely used by electricians due to a lack of familiarity and perceived risks when doing work that they are not familiar with. Examples, demonstrations, and training can help to improve industry flexibility and resulting cost and time reductions.

### Gather Information to Inform Policy

There is a need to gather more information on decarbonization costs and how to reduce them. A coordinated effort is needed to reach out to industry to get more detailed cost breakdown data on key electrification costs, particularly for multifamily and manufactured homes

### SUPPORT INDUSTRY TRANSITION TO DECARBONIZATION

Longer-term efforts are needed as the industry transitions to all-electric homes to work with industry organizations and standards-setting bodies to create codes and standards compatible with and/or supporting the decarbonization of homes. Examples include:

- Providing technical updates to NEC to allow for easier, less costly home electric upgrades.
- Develop equipment ratings for devices that integrate thermal and battery storage including industry collaborations, such as ASHRAE TC6.9.
- New HVAC sizing manuals to include thermal and battery storage in collaboration with ACCA.
- Work with RESNET (and possibly other rating organizations, such as LEED) to get thermal and battery storage included in energy performance ratings and to build on RESNET's new $CO_2$ index.
- Develop design guides that include thermal energy storage.
- Develop communication protocols and standards to allow real-time grid response for residential applications.
- Provide technical support to building energy codes and standards developers (e.g., RESNET,[34] IECC, and CEC) to shift from energy to carbon assessments of home performance.
- Provide technical support for utility planning/policy changes that will arise from electrification (e.g., how to phase out fossil fuel infrastructure in an equitable, lowest cost way, or how to create fair and equitable rate structures that reward homes that decarbonize without severely impacting late adopters, renters, and DACs).

[34] RESNET has recently introduced home ratings that reflect CO2 emissions: https://www.resnet.us/about/resnet-carbon-rating-index/

- Incorporate real-time, location-specific operational carbon emissions into analysis tools used to support both individual projects (e.g., SnuggPro, TREAT) and policymaking (e.g., ResStock, Scout).
- Support the development of decision-making and planning tools that include the assessment of embodied carbon. Also provide simplified guidance to practitioners of simple strategies for reducing embodied carbon (e.g., use of cellulose insulation versus spray polyurethane foam; or use of polyisocyanurate versus XPS foam board).
- Develop installation requirements and guidance that are more flexible and allow for easier installation in existing homes. This would also help to make code compliance easier.

## 3.3 Valuation Challenges

### 3.3.1 Lack of Accounting for Increased Home Value and Cost-Effectiveness Metrics

There is a need to capture other benefits of electrification with a focus on home health/safety as well as increases in property values and home resiliency. **Valuation justifications need to change to include additional health, safety, comfort, and resiliency benefits.**

**Determine Increase in Home Value**

Analyze home sales to determine if there is any premium when selling an upgraded home – similar to analyses already done for PV systems. This will require collaboration with the real estate industry and other partners, such as the EPA.

### Opportunity

**EMPHASIZE VALUE OVER COST**

There is a need to shift expectations so that home decarbonization is not expected to be completely cost-neutral in terms of energy costs. This framing might make sense in the context of direct utility investment but makes less sense when considering the values and motivations of homeowners, who see benefits – including additional cost savings – from indoor air quality improvements, greater comfort, increased home value, and other perceived benefits. Rather than framing these investments in a narrow view of energy cost-effectiveness, activities need to support increased affordability along with greater clarity on value.

Energy payback is less relevant in a paradigm of affordable decarbonization packages that deliver high-value solutions to households and residents. This is the approach successfully being used by several industry leaders (e.g., BlocPower and Sealed) who change the language and marketing approach for decarbonization and talk about affordability rather than payback. This approach is successfully being used by selling affordable comfort and energy solutions with readily available financing arrangements, established contractor networks, and sophisticated, polished, and efficient marketing and customer acquisition. The biggest solar companies sell financial products as much as they sell solar through easy financing and leasing programs, and this model could be adapted to whole building decarbonization strategies.

### 3.3.2 Lack of Support for Residential Decarbonization Among Influential Energy Stakeholders

Some utilities are proposing to massively increase the costs of decarbonization efforts. Examples include large fixed monthly charges for a grid connection, large fixed monthly charges for on-site generation, and removal of net-metering capability. Collaborative activities are needed with utilities to ensure that they are partners in decarbonization. This includes improved techno-economic analyses, the development of grid-interactive technologies, and utility rate structures that allow for the decarbonization of homes.

**Analyses to Support Utility Policies**

Analyze impacts of power efficient decarbonization efforts and distributed generation and storage to support development rate structures, rebates, etc. that support decarbonization efforts, particularly for lower income households and community groups.

#### Opportunity

**BRING KEY STAKEHOLDERS TOGETHER**

There are key roles for various industry stakeholders to play in residential decarbonization. Manufacturers need to build the required products (and get distributors and big-box retailers involved in promoting decarbonization); banks need to provide financing; utilities and local communities need to work on deployment efforts; and unions, community colleges, and others need to develop a workforce. There is also a need to get utilities to support decarbonization. Some utilities are proposing highly punitive tariffs for standing monthly charges for grid connection and on-site generation – even if a house has electric storage (Frank et al., 2021). These would add up to about $100–125/month for a typical home and make decarbonization unaffordable for all but the very wealthiest of households. It will be essential to work with utilities and their oversight bodies to develop policies that are supportive of decarbonization for billing, rate structures, rebates, etc..

### 3.3.3 Home Electrification/Decarbonization Is Not a Priority for Homeowners

Projects focused solely on energy savings are not appealing to enough people, and many contractors and homeowners see the primary technologies – namely, heat pumps – as being high-risk. They are concerned, for example, that heat pumps will not be able to maintain thermal comfort or provide enough hot water or that they will not be able to find someone to fix a system if technology breaks. However, contractors say that some aspects are easy to sell. One example is solar PV, which is more appealing to homeowners because it is a tangible thing that consumers can see. In addition, solar PV is attractive despite the cost due to a combination of marketing and easy one-stop financing (no money down and low payments over several years). Demand can be increased by increasing affordability through easy access to financing, rebates, and demonstrations that reduce perceived risks.

**Demonstrate Comfort, Health, and Safety Improvements**

From a health and safety point of view, there is currently a focus on combustion safety, primarily related to kitchens and emission reductions of contaminants related to health (such as $NO_2$) that are reduced for electric/induction cooking compared to gas (Environmental Law Institute, 2021). In the future, this could be extended to include furnaces, boilers, water heaters, fireplaces, and unvented heaters. An additional consideration is for low-income households that do not use their primary heating source to avoid expensive utility bills and instead use devices like their oven to heat a single room. Beside indoor air quality improvements, some studies have identified significant outdoor air quality impacts on public health through electrification (Zhu et al., 2020).

levels, and allow for lower cost heating compared to electric resistance.

## Opportunities

### DEVELOP PROGRAMS OF PHASED APPROACHES

For some homes, the most cost-effective or otherwise preferred approach will be to decarbonize in phases by installing aspects of a full decarbonization package when equipment fails or during a partial remodel. Ideally, there will be ways for consumers to pursue this within programs that simplify communications and financing and with guidance from energy professionals.

### UNDERSTAND HOMEOWNER NEEDS AND PERSPECTIVES

The industry survey results (Figure 6 and Figure 7) and existing successful business models (e.g., BlocPower and Sealed) have provided insight on how best to motivate people to decarbonize their homes. A substantial portion of homeowners currently pursuing deep energy retrofits cite reducing carbon emissions as one reason for their projects. While recognizing and promoting this benefit, broader appeal for comfort, health, safety, home value, and affordability need to be centered to engage at the mass-market level needed to meet our decarbonization goals.

Strong financial incentives (including rebates and tax incentives) are cited by industry experts as the most effective way to currently increase demand. Rebates and tax credits are a good marketing tool, as reported in the *DOE Deep Energy Retrofit Cost Survey* (Chan et al., 2021) (see Figure 7). A rebate should never be hidden. For example, if rebates are provided at the manufacturer or distributor level, they should be very clearly promoted in product literature and marketing materials to the consumer. While tax credits are less useful for low-income/disadvantaged households who do not have a large tax burden and therefore cannot take the tax credit, they can still be an effective tool for many households.

Homeowners are often interested in how any upgrades may affect their home values. There is some evidence of price premiums for solar PV (Hoen et al., 2015), heat pumps (Shen et al., 2021), and energy ratings/green labels (Cespedes-Lopez et al., 2019) with typical increases of 4–7% in home value and reductions in mortgage delinquencies (Pigman et al., 2022). There is a need to link upgrades specifically about decarbonization to increased home value. Working on data aggregation, home labeling and certification, and education for real estate and appraisal industry professionals will be key to achieving this outcome.

Homeowners and contractors have expressed concerns about the reliability and comfort performance of heat pumps in cold climates. Demonstrations, third-party performance evaluations, and improved project design and installation guidance are needed to overcome these concerns.

### IMPROVE PUBLIC AND INDUSTRY KNOWLEDGE ABOUT DECARBONIZATION

Because the buildings industry does not currently support home decarbonization as a sector, solar PV is the only current aspect of home decarbonization that is readily available with a strong, competitive industry. With no infrastructure to deliver decarbonization solutions to customers, there is little demand. With little demand, it is too risky to invest in the infrastructure. Currently, there are homeowners who want to decarbonize and cannot find anyone to do the work, while the industry says there is no demand.

To get to scale, ways are needed to both improve the demand for decarbonization and help the industry to make decarbonization available. This requires the development of large-scale programs that bring potential customers, contractors, and financial agencies together. There is a need to develop infographics and informative websites, work with trusted partners (e.g., EPA ENERGY STAR), and provide technical support to organizations with good media and government connections (e.g., Rocky Mountain Institute, American Council for an Energy-Efficient Economy, and Rewiring America). Technical support should be provided to the industry for the development of standardized visible markings, such as product labels and status symbols, to be developed to help the public become more familiar with these products and for best practices for operating new heat pump technologies (i.e., "set and forget" and reduced setback temperature differences).

### IMPROVE MARKET UNDERSTANDING

Industry surveys and stakeholder solicitations are needed to better understand market needs and approaches for getting to scale, and consumer and contractor attitudes towards electrification technologies and strategies. These activities should target consumers who have installed heat pumps to get their feedback or who have chosen not to electrify, and develop best practices for overcoming negative attitudes toward electrification.

### INCLUDE HEALTH, INDOOR AIR QUALITY, AND RESILIENCY IN DECARBONIZATION PROGRAMS AND POLICIES

Provision of adequate ventilation and indoor air quality is an essential building service. While air sealing and insulation will often be necessary to reduce the load for electrified homes, this can spur the need for mechanical ventilation. Mechanical ventilation systems have been required in DOE weatherization programs for many years, but are less common in non-government sponsored projects and were found to be rare in the home energy upgrade literature (Less et al., 2014) (Less et al., 2021a) (Less et al., 2021b). Home upgrade programs have had building envelope tightness limits for a long time, and there are calculation procedures in the US national standard for ventilation (ASHRAE 62.2, 2019) to assess if a home needs mechanical ventilation.

In terms of envelope leakage, homes above about 7 ACH50 (Air Changes per Hour at 50 Pa) meet the minimum ventilation requirements with natural infiltration. The typical weatherization and home performance projects in LBNL's project cost study averaged 8.2 ACH50 post-retrofit. The same study showed that more aggressive envelope sealing in deep energy retrofit projects averaged 5.9 ACH50 post-retrofit. Therefore, many homes likely do not need dwelling unit mechanical ventilation in order to comply with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard. However, it is important to examine all homes to determine their mechanical ventilation needs, and it is recommended that compliance with the ASHRAE Standard for dwelling unit ventilation be met when decarbonizing homes.

In addition to whole-house mechanical ventilation, bathrooms and kitchens need exhaust systems to remove odors, moisture, and other contaminants (such as $NO_2$ from gas cooktops and ovens, and particles from cooking). These systems should be installed in homes no matter how leaky. In addition to IAQ issues, there are improvements in home resiliency from better envelopes, provision of cooling, onsite generation, and energy storage that are often part of decarbonization efforts. These additional benefits are considerable and need to be emphasized in programs and policies.

## Overview and Future

This report has summarized the technical, cost, and valuation challenges facing the US in its efforts to reduce $CO_2$ emissions from residences, and identified key opportunities for overcoming these challenges. While the challenge is great, recent US federal government infrastructure programs represent a great opportunity to achieve considerable advancement towards decarbonization of the building sector and fulfill DOE's goals of low/no carbon emission homes by 2050.

The technical challenges are mainly focused on developing new products using proven technologies that make home decarbonization easier and more practical. This includes finding ways to electrify homes that currently are predominantly fossil fuel users and may not have much capacity to expand their electricity consumption. The technical challenges recognize that preserving a reliable electric grid means going beyond consideration of how much energy is used to include strategies for controlling when energy is used, and this is one area where new storage and control technologies are needed.

The primary cost challenge is that homes requiring a high degree of increased electrification require a considerable investment that is beyond the savings and potential credit of most households. Addressing this through better financing approaches, efforts to reduce one-off costs, and tackling issues for renters and low-income households is essential. Related to costs is the need to develop a workforce to carry out home decarbonization and working with codes, standards, and regulatory bodies to remove barriers currently faced by homeowners.

The valuation challenges recognize that getting to scale requires appealing to households beyond the desire to save energy and reduce carbon emissions. This means that metrics and economic considerations need to include changes in home value and address affordability and access to financing. Efforts are also needed to recognize other attributes of decarbonized homes, including improved indoor air quality and health and increased home resiliency through the provision of cooling, onsite generation, and energy storage that are often part of decarbonization efforts.

This report has a strong focus on single-family homes, mostly because the background information is more readily available – including previous efforts funded by the DOE. In the future, similar work is needed for multifamily buildings and manufactured homes that have their own unique challenges and associated opportunities. From a social equity point of view, these other home categories must be prioritized because they house the lowest income and most disadvantaged households.

This report represents a snapshot in time (late 2022), and the authors recognize that the home decarbonization industry is rapidly evolving, with significant innovations as well as the discovery of new challenges and barriers. It is highly likely that over the next few years, many of the barriers identified here will be obsolete and that new analyses will be needed to prioritize not just DOE's efforts but those of the buildings industry.

While this report has emphasized R&D opportunities for DOE, it also recognizes that DOE alone cannot achieve the scale required to significantly reduced $CO_2$ emissions. Success will require collaborations between the US DOE and other government agencies at the federal, state, and local levels, where many initiatives are already underway. There is a need to bring together key stakeholders – including manufacturers, contractors, trainers, utilities, consumer advocates, regulators, financiers, and others – to develop a consensus on what to do and coordination on how to do it. Furthermore, reducing carbon emissions is an international effort. Coordinating and collaborating on an international stage, where countries learn from each other's successes (and mistakes) and share pathways to large-scale decarbonization, will be essential.

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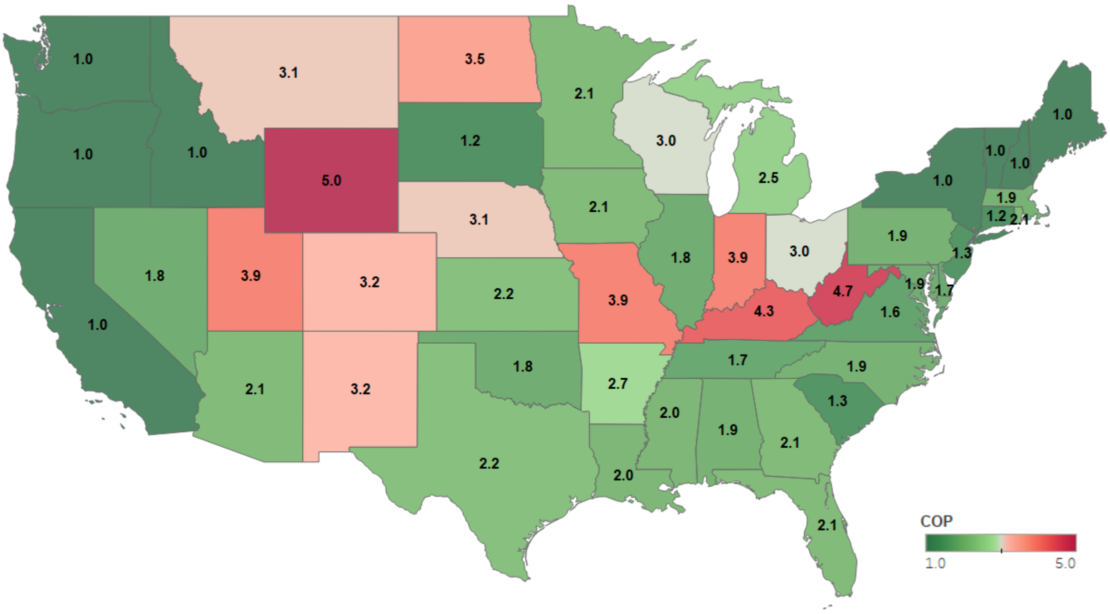
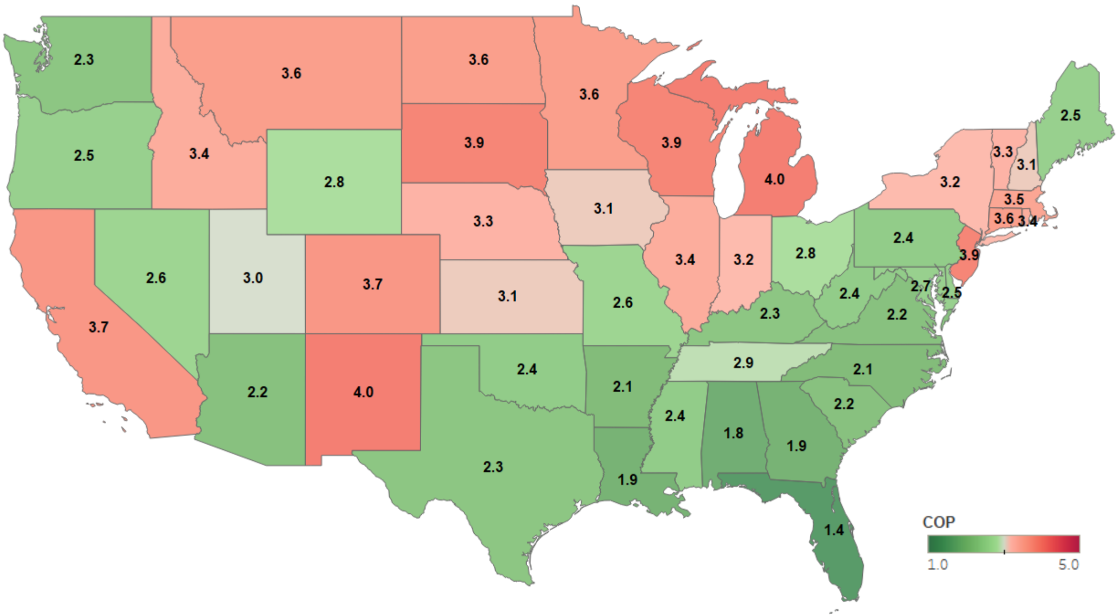



**FIGURE A1. MAP OF MINIMUM HEAT PUMP COP REQUIRED FOR CARBON DIOXIDE EQUIVALENT EMISSIONS NEUTRALITY IN EACH US STATE, COMPARED WITH A 95 AFUE NATURAL GAS FURNACE, USING 2019 EGRID AVERAGE EMISSION FACTORS (WALKER, LESS, AND CASQUERO-MODREGO 2022)**




**FIGUREA2. MAP OF MINIMUM HEAT PUMP COP REQUIRED FOR ENERGY COST NEUTRALITY IN EACH US STATE, COMPARED WITH A 95 AFUE NATURAL GAS FURNACE (WALKER, LESS, AND CASQUERO-MODREGO 2022)**

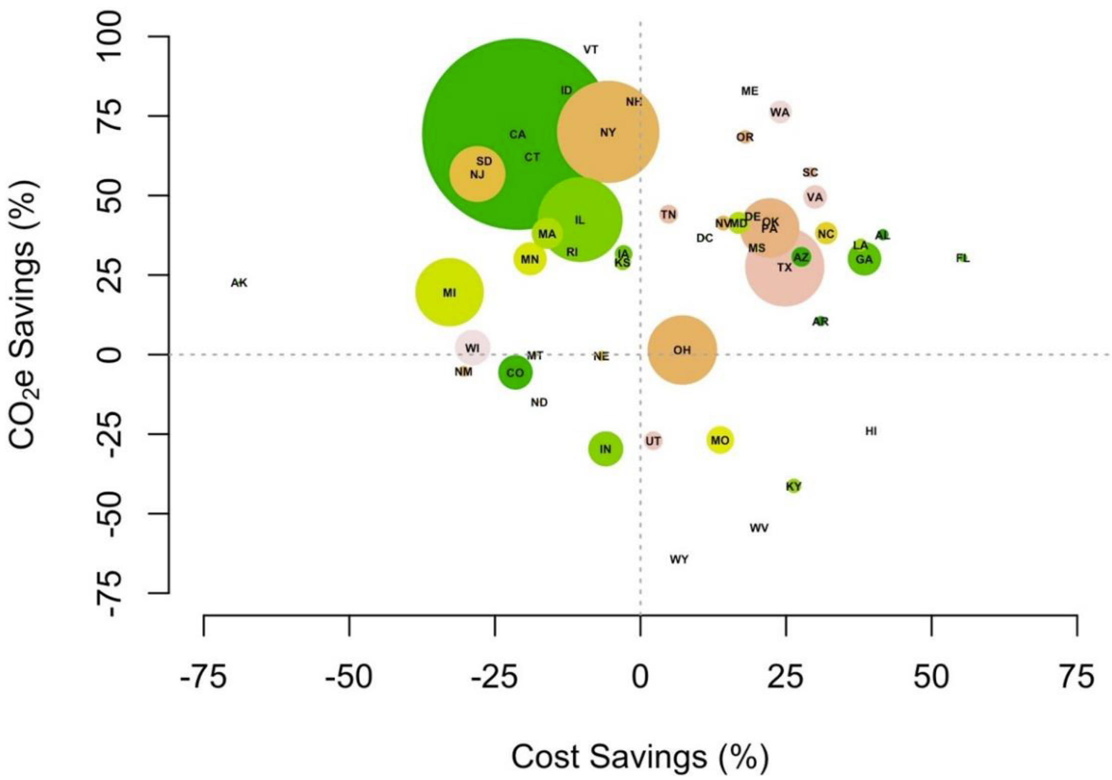



**FIGURE A3. PERCENT SAVINGS FOR $CO_{2E}$ AND ENERGY COST IN EACH US STATE, WHEN REPLACING A 95 AFUE FURNACE WITH A COP 3 HEAT PUMP. POINTS ARE SCALED ACCORDING TO THE COUNT OF NATURAL GAS SPACE HEATING APPLIANCES IN EACH STATE. COLOR CODING IS FOR VISUAL SEPARATION ONLY, USING 2019 EGRID AVERAGE EMISSION FACTORS AND STATE AVERAGE RETAIL ENERGY COSTS FROM THE EIA (WALKER, LESS, AND CASQUERO-MODREGO 2022).**

Note that the figures in Appendix A are based on 2019 average emission rates reported in the eGRID data set. In the future, as the grid decarbonizes, we expect the $CO_2$ content of electricity to go down. This would reduce the heat pump COP required to break even and increase the $CO_2$ savings for any given heat pump COP.