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Review

Home Energy Upgrades as a Pathway to Home Decarbonization in the US: A Literature Review

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Abstract: This work aims to characterize how home energy upgrade projects and programs in the US have evolved over the past decade. It also identifies what changes are needed to drive expansion of the US energy retrofit market in such a way that addresses carbon emissions from buildings, improves resilience and upgrades the housing stock. This review focuses on whole-home energy upgrades, targeting deep energy retrofit savings of >30%. The topics we cover include trends in home electrification, US and European home energy upgrade programs, energy upgrade measure costs, business economics, and health effects. Key changes in project design noted in this review include: (1) the electrification of dwellings with rapidly improving heat pump systems and low-cost solar photovoltaic technology; and (2) a shift away from high-cost building envelope strategies and towards more traditional home performance/weatherization envelope upgrades. Promising program design strategies covered include: (1) end-use electrification programs; (2) novel financing approaches; (3) the use of carbon-based program and project metrics; and (4) "one-stop shop" programs. Based on the existing market barriers, we suggest that the industry should adopt new project performance metrics. Additionally, market drivers are needed to spur widespread energy upgrades in the US housing stock. Costs must be reduced, and projects designed to appeal to homeowners and contractors.

Keywords: decarbonization; energy retrofit; energy upgrade; deep energy retrofit; electrification; policymakers; building stock; residential buildings; literature review

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1. Introduction

In recent years, the need to decarbonize home energy use has received increasing attention. With this has come a shift in the design and delivery of home upgrades that specifically target carbon emissions (CO_2) reductions, rather than solely focusing on energy savings. In addition, projects are designed to provide numerous co-benefits, including improved indoor environmental quality (IEQ), thermal comfort, resilience, home resale value, health, etc. Several factors have coalesced over recent years that have brought the US to the point where decarbonization of home energy use is not just acknowledged but can also begin to scale up in existing homes. These include: (1) increased affordability of on-site electricity generation; (2) ongoing decarbonization of the electric grid; (3) improved heat pump performance for space conditioning and hot water, particularly in cold climates and existing home applications; (4) increased knowledge of the health and safety concerns about burning fossil fuels in homes; and (5) increased consumer demand for electrification and decarbonization [1].

This review summarizes the state-of-the art in the energy upgrading of existing US homes, but it also should be broadly applicable to other countries facing the same decarbonization challenges. It focuses on programs and developments that have occurred subsequent to a prior review published in 2014 [2]. It also highlights where more research, engineering, or technology are needed, as well as new industry trends and innovations. This paper retains the prior study's focus on the existing building stock, rather than new construction, primarily because we will need to energy upgrade existing homes in order to achieve significant carbon savings in the residential sector.

The studies reviewed here were gathered from a combination of the published literature and from practitioners in conjunction with a US Department of Energy (DOE) study that included an industry survey [1] and a cost analysis/breakdown for home energy and carbon reduction upgrades [3]. In places where we refer to comments from specific individuals or companies, or refer to specific products by name, we are not intending any endorsement, but rather to provide clarity on sources of information. Additional background information and details of this literature review can be found in [4].

2. Home Energy Upgrades and Electrification in the US

Traditionally, energy upgrades have focused on load reduction, with the highest priority given to envelope improvements, followed by equipment, primarily space conditioning and hot water, and finally miscellaneous loads such as lighting, appliances and plugs. Generally, the idiom and governing approaches of the home performance industry have not caught up to rapid changes in the related realms of the electric grid, carbon reduction imperatives, smart technologies, and emerging trends in equipment cost and performance. PV systems, for example, have undergone dramatic changes in pricing, financing availability and customer experience over the past decade [5]. Much of the recent home electrification and decarbonization movements are born from the realization that the traditional home upgrade industry's focus on energy savings has not and will not deliver substantial carbon reductions, and that no practically achievable level of thermal envelope efficiency will lead to zero-carbon homes. In the subsections below, we discuss recent US developments in both traditional home energy upgrades and home electrification upgrades.

2.1. Energy Upgrade Trends and Programs in the US

A previous study by *Lawrence Berkeley National Laboratory* (LBNL) [2] assessed the state of deep energy retrofit (DER) performance in the US using performance data on 116 home retrofit projects gathered from a range of publications. The value of the analysis for some metrics was hindered by data gaps and inconsistent reporting. The authors suggested that future analyses are needed using a larger, more fully developed dataset. These homes generally achieved good results, with average annual net-site, net-source and carbon reductions of 47%, 45%, and 47%, respectively. The variability was substantial with standard deviations of about ±20%. Despite these considerable airtightness reductions, mechanical ventilation was not installed in about 30% of homes. It was recommended that home energy-upgraded homes should comply with the US National Ventilation Standard: ASHRAE 62.2-2013 (now ASHRAE 62.2, 2019) [6]. The study concluded that the perceived risks regarding more advanced home energy upgrades needed to be better characterized through standardized retrofit packages and a better-trained workforce capable of delivering the quality of workmanship required in extensive retrofits. Several studies by the *American Council for an Energy Efficient Economy* (ACEEE) [7–9] have shown the following: that pilot programs have shown that greater than 50% savings are possible with existing technologies/materials, with costs about the same as those for a kitchen renovation or room addition. Both the energy savings and costs had wide ranges, with some project costs exceeding USD 100,000. These studies indicated that the greatest opportunities to reduce costs were to improve project management efficiency and to integrate energy upgrade measures with other renovation work.

In recent years, utility retrofit programs and emerging program/business models have led to whole-home energy upgrades becoming more common. Table 1 summarizes the US whole-home upgrade programs identified in this review, providing a limited summary of results and relevant citations. Notably, the programs reviewed do not include single-measure upgrades, such as the rebating of heat pump installation, for which there are numerous programs across the US (see recent heating electrification review by Cohn and Esram [10]). Overall, savings fall in the range of 30–40% for whole-home upgrades, which exceed those commonly reported for low-income weatherization, but they are not as substantial as those documented by Less and Walker [2,11] for extensive deep energy retrofits. Project costs reported by these programs ranged from USD 10,000 to USD 20,000 in most instances, but more ambitious programs with higher average savings reported costs as high as USD 50,000 per home. Paths to reducing these costs by optimizing approaches to home decarbonization have shown that increased carbon savings and reductions for similar, or lower, costs can be achieved through a combination of moderate envelope upgrades and the use of heat pumps and solar PV [12]. Other approaches tend to have lower carbon savings or higher costs [11]. Many of the newer generation of home energy upgrade programs are addressing and engaging with emerging issues and design trends, at both the project level and program level. These issues and trends include carbon reduction, electrification, resilience, healthy homes, grid interactivity and others.

We have identified in the literature the following three trends in US whole-home upgrade programs: (1) a shift away from superinsulation strategies; (2) programs designed around decarbonization and electrification strategies; and (3) "one-stop shop" program offerings that simplify the upgrade process for home occupants. Other notable program innovations observed in this review include innovative recruitment strategies (e.g., at the block or community level; using machine learning predictive modeling), project financing (e.g., property-assessed and on-bill strategies; bundling projects into securitized investments) and pay-for-performance incentive structures or savings guarantees for homeowners. While much work in the early 2010s was focused on "superinsulation" strategies (i.e., extensive insulation upgrades in cold climate homes) [13–16], superinsulation approaches have largely been deemed too expensive and impractical for widespread adoption [17]. Instead, we observe programs targeting substantial energy and carbon reductions that focus on more standard, moderate envelope upgrades paired with equipment electrification and solar PV. A home upgrade cost study [3] used clustering analyses of over 1700 deep retrofit projects in the US and reached the same conclusion regarding this lower-cost carbon reduction strategy. The only program reviewed that included extensive envelope upgrades was a small pilot community in Rhode Island and Massachusetts [13]. Consistent with this shift away from extensive insulation measures in upgrade programs, a recent survey of the home upgrade market rated exterior insulation retrofits and prefabricated panelized envelope upgrades as the least likely approaches to scaling extensive upgrades [1]. However, there are still research and development efforts to lower costs of very high-performance envelopes. For example, the US Department of Energy is currently engaged in efforts, as part of its *Advanced Building Construction (ABC) Collaborative*, to reduce the costs of extensive insulation upgrades through industrialized and automated construction practices [18].

Table 1. Cost saving for programs included in the review conducted by Less et al. The table is reproduced from [4].

Program Name	Number of Homes	Average Cost (USD)	Average Site Energy Savings	Notes
Better Buildings Neighborhood Program–US [19,20]	50,102	USD 4910	Average predicted source energy savings in each quartile: 11%, 26%, 43%, 94%	Roughly $\frac{1}{2}$ of savings estimates are based on annual simulations, while another $\frac{1}{4}$ are deemed savings. Remaining $\frac{1}{4}$ are unknown. Comparison with actual utility bill savings in small subset of homes suggests substantial overprediction of savings by simulation models and deemed approaches.
Energy Upgrade California–CA [21,22]	20,000	USD 6300	274 kWh, 16 Therms	Actual bill savings. Predicted savings were typically much higher.

Table 1. *Cont.*

Program Name	Number of Homes	Average Cost (USD)	Average Site Energy Savings	Notes
Zero Energy Now–VT [23]	24	USD 54,500	39% delivered site energy savings; 64% fossil fuel and grid energy savings; 60% energy cost savings	Weather normalized savings from utility bills and fuel delivery invoices. Most projects electrified, including insulation, heat pumps and solar PV.
Home MVP–MA: Deep [24]	66	USD 49,126	48%	Predicted energy savings.
Home MVP–MA: All [24]	341	USD 21,675	33%	Half were electrified.
Extreme Energy Makeovers–TN [25,26]	3420	USD 9000	35% (4900 kWh)	Deemed energy savings; affordable housing.
National Grid Deep Energy Retrofit Pilot Community–MA and RI [13]	60	USD 34.59/ft^2 (USD 371.39/m^2)	55% 43% source energy savings	For 29 comprehensive projects.
FSEC DERs–FL [27–29]	10	USD 14,323	38%	Energy upgrade increment was USD 7074; affordable housing.
FSEC DERs–FL [30]	70	USD 16,424	30%	Energy upgrade increment was USD 3854; affordable housing.
EnergyFIT Philly–PA [31]	67	USD 14,257	36% gas; 22% electric	Affordable housing.
EnergySmart Ohio–OH [32]	11	USD 30,173		-
Sealed–NY [33]	338	USD 10,000	20% heating; 5% electricity	-

Several programs reviewed include explicit decarbonization goals, either by incentives for electrification technologies (e.g., heat pumps), not having incentives for combustion technologies, supporting fuel-switching, or by structuring program goals around carbon or fossil fuel reduction metrics. Programs using these metrics tended to be more recent, reflecting the increased activity around decarbonization and electrification. Key whole-home programs with a decarbonization focus included the *Zero Energy Now* pilot in Vermont, the *Home MVP program* in Massachusetts, and the private company *Sealed* operating in New York.

Finally, several programs are employing a relatively new method of project delivery called "one-stop shop", where financing, project design, a vetted contractor network and ongoing maintenance and support are provided by the program. The intention is to make project delivery faster, easier and cheaper by shifting some of the planning and administrative burdens from the contractor and homeowner to the program. For these reasons, in a recent survey of the home upgrade market, "one-stop shop" was identified by far as the most promising approach for scaling extensive energy upgrades in existing homes [1]. This approach has been contrasted with current home energy upgrade project delivery by comparing key business model components, including value proposition, customer interface, financials and government [34]. Brown et al. [34] argued that project delivery will have to move towards more integrated offerings in order to scale home energy upgrades. In addition to its focus on decarbonization, the *Home MVP program* in Massachusetts provided 0% interest financing and a validated contractor network. Other programs have utilized some but not all of these "one-stop shop" strategies, such as *Energy*

Upgrade California and the *Better Buildings Neighborhood Program*. Private companies are also streamlining home upgrade delivery with many of these same strategies, including *Sealed* and *BlocPower*, both of which have centralized sales, technology-driven recruitment, project design, financing and construction into a single workflow.

The *Zero Energy Now (ZEN)* pilot in Vermont is an example program that embodies all three of these highlighted trends—moderate envelope upgrades, programmatic use of carbon metrics, and "one-stop shop" project delivery services. ZEN has developed electrification-based work scopes to reduce carbon emissions, with average whole house savings of 64% in 24 pilot projects in the state of Vermont [23]. Pilot projects saved an average of USD 1878 per year in energy costs after the home upgrades. Funding has been made available for an additional 30 ZEN projects in the state of Vermont to be completed by the end of 2022. The ZEN program used decarbonization metrics, including minimum 50% reductions in fossil fuel use, delivered electricity and site energy use. The ZEN program offers a form of "one-stop shop" project delivery, which includes use of a vetted contractor network, energy savings guarantees, strong incentives, and integrated project design support by program staff, including building simulation modeling. Envelope upgrades in ZEN projects were generally limited to those used conventionally in existing homes by home performance and weatherization contractors, combined with cold climate heat pumps and roof top solar PV. An advantage of this approach is that envelope upgrades are a measure that the industry is already familiar with, there is an adequate work force and training, and the main materials and methods have not changed in decades. As noted above, this approach represents a shift away from heavy investments in building envelopes to reduce loads and towards decarbonization through end-use electrification and on-site PV. On average, about USD 12,000 was spent on building envelope upgrades, and total project costs (USD 54,500) were much lower than has been reported for traditional envelope-focused upgrades. Based on the demonstrated successes of this program, the *Building Performance Institute (BPI)* and the *Northeast Energy Efficiency Partnership (NEEP)* have recently announced the development of a new *Building Decarbonization Retrofit Specialist (BDRS)* certification for home decarbonization that is largely based on the strategies and outcomes of the ZEN program. These types of workforce development efforts are required to move home decarbonization from the pilot to market-ready phase.

2.2. Electrification Trends and Programs

Preliminary analyses have shown that the electrification of dwellings and energy end-uses has financial benefits in many contexts, with substantial variation based on local energy costs, fuel sources, dwelling types and climate zone [35]. For example, an analysis of the electrification of the California residential building stock assessed the short- and long-term economic impacts of home electrification [36]. In new home construction and in existing homes where high-efficiency heat pumps replace existing air conditioners, this study concluded that electrification can lead to upfront capital cost savings, utility bill savings and lifecycle savings. *Synapse Energy Economics* reached broadly similar conclusions in their analysis of heating electrification in California buildings [37]. The *Rocky Mountain Institute (RMI)* analyzed the economics of building electrification nationwide in both new and existing dwellings [38,39], and they reported that over the lifetime of the appliance, new home electrification is often a lower-cost solution. This holds true in some retrofit scenarios, including the replacement of high-cost fuels (e.g., propane or fuel oil), when replacing a gas furnace and air conditioning at the same time, and when bundling electrification with rooftop solar photovoltaics (PV). In an Australian pilot program, PV showed the potential to reduce hardship, debt and inequality in low-income communities [40]. A recent state-by-state analysis of space heating electrification in the US found that weighted average carbon savings of 35% (and a 1% energy cost increase) were possible nationally using currently available high-performance heat pumps compared with high-performance gas furnaces at 95% efficiency [41]. The carbon savings increase to 56% (and 31% energy cost savings) on average when modern heat pumps are compared with low-efficiency gas equipment common in existing homes. State-by-state performance varied widely, because the energy costs and carbon content of electricity differ by more than a factor of four across the US.

Based on these technical analyses, resources have been developed to help guide local government and utility coordination on these strategies [42] and as add-ons to building codes [43]. The *Sierra Club* has also offered a public policy action plan for building electrification [44]. The *Rewiring America* book [45] takes a broad approach to the issues around electrification and highlights the importance of having a clean energy infrastructure. Griffith also suggests that large-scale commitments to electrify our infrastructure will actually lower long-term energy costs, increasing affordability across the market. In addition to technical solutions and a low-carbon electrical grid, the success of widespread electrification programs requires myriad financing mechanisms (e.g., loans, incentives, subsidies).

Recently, several roadmaps have been published in order to provide guidance on home decarbonization and electrification in the US. For example, the Grid-interactive Efficient Buildings (GEB) roadmap published by the DOE Building Technology Office (BTO) [46] provides 14 recommendations for addressing the most important barriers to adoption and deployment. The proposed roadmap requires not only improving the efficiency and flexibility of dominant building loads that exist today, but also preparing to integrate valuable new, decarbonized sources of load and generation into building and grid operations. The document includes steps that are specifically oriented toward removing barriers to equity and inclusion in GEB, such as considerations including reducing up-front technology costs and increasing engagement with underrepresented consumer segments. The *New Buildings Institute (NBI)* wrote another roadmap for organizations developing, implementing and supporting electrification technology programs as a way to advance high-efficiency technologies, reduce greenhouse gas (GHG) emissions, and improve public health [47]. The *New York State Energy Research and Development Agency (NYSERDA)* has developed a draft roadmap for *Carbon Neutral Buildings*, which is to be updated every 2–3 years. The document is both a long-term planning document for New York's buildings sector to reach carbon neutrality by 2050 and an action plan in the short-term. It covers both new construction and existing building retrofits, with a strategic focus on four building types representing over 50% of the building sector's energy use: single-family residential, low- and mid-rise multifamily residential, low- and mid-rise commercial office buildings, and higher education. The roadmap addresses the state's entire building stock, focusing on key barriers, modeling solution sets, technology development and public policy recommendations. The state of California has published a similar road mapping effort by Kenney et al. [48], and other organizations have produced their own CA state roadmaps to decarbonize buildings [49]. Explicit goals identified in the *BDC* roadmap include the adoption of a *Zero Emissions Building Code*, building sector greenhouse gas emission reductions targets, and increasing the market share for HVAC domestic hot water heat pump technologies (50% of sales by 2025 and 100% of sales by 2030). Numerous local jurisdictions in the state have carried out more focused work, such as the City of Berkeley study that analyzed the city's building stock and developed building-by-building energy models [50].

A recent review of home heating electrification programs in the US was published by ACEEE [10]. This review noted that between 2020 and 2022, the number of programs promoting the electrification of homes increased from 22 to 42, with corresponding budget increases from USD 109 million to USD 166 million per year. The authors identified the following important trends:

- Rebates are significant. Rebates for electric heat pumps for space heating ranged from USD 165–USD 1600 per ton, and water heating and cooking incentives were commonly USD 91 to USD 800 per unit.
- More efforts are needed to help utilities align their programs with local carbon reduction goals and to track the actual outcomes.
- Energy efficiency and weatherization should be paired with space- and water-heating retrofits in order to reduce upfront cost and ongoing energy requirements for electric heating and cooling systems.

- Electrification for low-income customers faces additional barriers, such as being unable to afford the upfront costs of conversion, a lack of access to financing, and an inability to control their built environment if they live in rental housing. Programs for low-income households encounter much higher costs per participant, due to upgrades often being provided at no cost, as well as the larger extent of improvements required for older dwellings.
- Integration of demand flexibility (through connected water heaters and thermostats) and renewable sources with electrification is an emerging area of interest.
- Only a small number of programs emphasized the role of contractors and provided them with incentives and education to sell heat pumps and other electrification equipment.

Due to difficulties in maintaining capacity at low outdoor temperatures for air source heat pump technologies, an emerging approach in the US is to partially electrify or decarbonize home heating by installing heat pumps to operate alongside existing combustion space heating appliances. These installations are termed "hybrid" systems. These systems require controls that preferentially operate each system at certain times based on ambient temperature or utility rates. This mitigates risk for the homeowners and contractors, because a heat pump has fossil fuel backup, and some argue that this eases the future transition to heat pump-only installations. Pantano et al. [51] explored the impacts of "hybrid" HVAC systems in the US through the drop-in replacement of current compressor-based cooling systems in US homes with heat pump units that provide both cooling and heating [51]. They estimate that a program with a subsidy of USD 400 to USD 500 (declining by USD 60–USD 75/year) paid directly to HVAC equipment manufacturers would be sufficient to convert all current cooling-only systems into heat pumps. A 4- to 7-year program period would result in an estimated 45 million new heat pump installations, at a program costs of USD 3 to USD 12 billion. They predict that a typical household would save USD 169 per year, with 10-year bill savings totaling USD 27 billion and an additional estimated USD 80 billion in societal benefits accrued from reduced ambient air pollution.

Building efficiency programs have historically been challenged to recruit participants, an issue that is all the more pressing as the industry faces the imperative of scaled electrification, where effectively all households in the country need to participate. Bardhan et al. [52] suggested that the core issues are informational, and that a lack of appropriate information on project economics ensures that the US financial system does not provide credit for upgrades. They contrast this with solar PV, where the energy production of a system is well known, and tax benefits have allowed the industry to reach an effective scale via third-party funding. Cluett and Amann [53] also identified trends and opportunities for scaling up participation and increasing realized energy savings for programs involved in whole-home energy upgrades. In some jurisdictions, decision makers are addressing the participation problem by creating public policy or offering incentives to upgrade homes to be all-electric. To date, this has mostly focused on new home construction. For example, over 50 cities in California have introduced ordinances to require new homes to be all-electric [54]. Similarly, the *Sacramento Municipal Utility District (SMUD)*, in California's Central Valley, does not require electrification, but it does offer electrification rebates of USD 5000 in new homes, and it offers substantial rebates up to USD 13,750 for electrification in existing homes. Local law 154 in New York City has mandated all-electric new construction, potentially to be expanded statewide by Senate Bill SB6843. Buildings regulations can be a successful way to encourage the decarbonization of homes. One example is the change in the building code in the State of Washington, which provided credits for electric home heating with heat pumps. This change increased the use of electricity for primary heat from about 20% to nearly 90% [55]. In California, the recently released *Title 24 Building Energy Code* will use an all-electric home as the reference for compliance, encouraging (but not requiring) all-electric strategies. At the state level, numerous states have enacted policy and planning documents aimed at the electrification of buildings as a key element to reducing carbon emissions, including California, Colorado, Maine, Massachusetts, Missouri, New Jersey, New York, Washington, and others. New York, for example, is planning a heat pump initiative aimed at increasing the market share from 2% to a target of 5% by 2025 [56]. Unfortunately, at least 19 other states in the US currently have policies restricting all-electric requirements in new construction [57]. Maine is planning to reduce natural gas use in buildings, by encouraging the installation of 100,000 heat pumps. New York State is embarking on a similar heat pump incentive program, targeting an increase from its current 2% market penetration to a target of 5% by 2025 [56].

Deason and Borgeson (2019) [35] identified the following key non-economic barriers to home electrification: a lack of familiarity and distrust of electric technologies amongst both consumers and contractors, long gas equipment lifetimes, building codes that do not encourage electrification, inadequate electric infrastructure, disadvantageous utility rate structures, and current building efficiency programs that are often not dual-fuel or explicitly are prohibited from supporting appliance fuel-switching. To this list, we add the following barriers based on our present review: increased upfront costs in some circumstances, electrical panel and branch circuit upgrade costs, the lack of a trained work force for heat pump and battery storage technologies, the lack of knowledge among local authorities governing construction permits and inspections, and supply chain challenges.

Several studies have identified a lack of project financing as a barrier to home upgrades [22,30,37]. However, these and other studies have shown that the majority of projects do not use financing [3,58,59]. One potential reason for this is that most households currently undertaking market-based energy upgrades have a higher income, with less need for external financing. To get to scale with home decarbonization, a much broader socio-economic spectrum of homeowners will need to be reached, requiring financing mechanisms that give easy access to funding for home decarbonization upgrades [60,61].

3. Energy Upgrades and Programs in Europe

While the focus of this literature review is on the US, it is instructive to examine efforts elsewhere to achieve home decarbonization, particularly in Europe, where their experience may help inform activities in the US. Significant home energy programs and legislation are underway in Europe, driven by a combination of high energy prices and a need to decarbonize the buildings sector. While there are some EU-wide initiatives, several of the activities outlined below are at a national level. Nevertheless, there is a strong push to have standardized coordinated activities and tracking of project performance for energy-upgrading European homes. For this reason, the EU has developed an Energy Efficiency Certificate (EEC) or Energy Performance Certificate (EPC) that covers most building loads (the most significant omission being plug loads). The building is given a rating between A (Very efficient) and G (Inefficient). This is similar to the European energy label for household appliances.

The European Energy Performance of Buildings Directive 2018/844 [62] addresses both new and existing buildings. In addition to addressing CO_2 reduction, it directs member states to also consider energy poverty, healthy indoor environments, the removal of existing harmful substances (e.g., asbestos, etc.), and the mobilization of the financial industry. According to the European Commission Recommendation (EU) 2019/786 on building renovation [63], each state member has the "obligation to establish a long-term comprehensive strategy to achieve a highly decarbonized building stock by 2050". In addition, each state member has to set cost-optimal minimum energy performance requirements for new buildings, for existing buildings undergoing major renovation, and for the replacement or retrofitting of building elements such as heating and cooling systems, roofs and walls. The health and well-being of building users is addressed, for instance through the consideration of indoor air quality (IAQ) and ventilation. Each country must draw up lists of national financial measures to improve the energy efficiency of buildings. The (EU) 2019/786 also includes the determination of cost-effective approaches to renovations appropriate to the building type and climate zone, considering potential trigger points in the building's life cycle, such as:

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

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

Currently, in the EU, there are several whole-dwelling energy upgrade programs, many of which include delivery models that align with the discussion above of "one-stop shop" program types in the US. Example European programs include:

- *EnerPHit*, the standard issued by the *Passivhaus* Institute that focuses on retrofit projects [64];
- Irish Guidelines for turning existing homes into passive homes [65];
- Two-year, 5 million Euros pilot program for deep home energy retrofits by the *Sustainable Energy Authority of Ireland (SEAI)*;
- In the UK, numerous government programs have been introduced, such as: *Carbon Emission Reduction Target (CERT), Community Energy Saving Programs (CESP), Housing Health and Safety Regulation, EPC and Standard Assessment Procedure (SAP)* rating to bring the households to a certain standard and alleviate fuel poverty [66]. One UK program that targeted substantial savings in existing homes was the *Retrofit for the Future (RfF)* program sponsored by the UK Government's *Technology Strategy Board (TSB)*, now *Innovate UK*, from 2009 to 2013 [67].;
- In Belgium, *The Meer met Minder* program is aiming to reduce energy consumption in 2.4 million homes by 2020 using subsidies and low-interest loans. It planned to use comprehensive packages of retrofits, with much of the coordination effort taken up by the program rather than individual building owners; and
- *The Climate Mission the Netherlands* is developing strategies for homes without natural gas, with optimal living comfort and a healthy indoor climate. This program has put together a method for getting to scale with retrofits. Their approach is to completely streamline the process for the owner/occupant. Their system takes care of financing, planning, packaged designs, installation, sourcing materials/equipment, etc.

Energiesprong is an innovative energy program that fundamentally changes the business model for residential retrofitting [34], aiming for the same cost of living for occupants. The *Energiesprong* approach uses laser scanning of the building to create 3D computer models used in an automated factory to assemble retrofit packages for the building envelope that combine insulated opaque surfaces, with windows and heating/cooling systems. The *Energiesprong* project delivery approach has been analyzed in detail [34], and the key features include property improvement, health, wellbeing and comfort; guaranteed net-zero-energy consumption; an integrated supply chain with rapid, industrialized and offsite manufactured solutions; a simple customer interface through a single point of contact; a financial model that ensures household affordability, based on realized energy and maintenance savings; reduced disruption to occupants; and integrated governance through a single solution provider. This approach began with a focus on a single market focused on buildings with homogeneous topology, limited issues with planning rules, and that present a secure investment. This commonly meant working with local social housing associations. Five thousand homes in the Netherlands and a couple of dozen in other EU countries have undergone an *Energiesprong* retrofit, and more than 20,000 additional projects are currently planned. The energy use of several hundred of these homes has been monitored, and the results show that these homes meet their program requirements' net zero specification [68].

4. Energy Upgrade Measure Cost

Our review of the research literature included the examination of cost data sources for numerous individual upgrade measures that are common in decarbonization and deep energy retrofit projects. High-level cost summaries are provided along with relevant data sources for the attic/roof, foundation, above grade walls, ductless heat pumps, heat pump water heaters, and electric panel/service upgrade measures in Table 2. Costs are normalized by square meter of treated surface area, per HVAC capacity or by other relevant metrics. We discuss each of these upgrade measures in additional detail below, and compare the costs from the literature with a recent database developed for energy upgrade costs in the US [3,11]. Our review did not identify existing literature documenting the costs of appliance electrification for clothes drying or cooking.

Table 2. Summary of energy upgrade measure costs. The table is reproduced from [4].

Energy Upgrade Measure	Measure Cost Summary	Sources
Attic/Roof	Attic Insulation Location: • Attic floor: USD 25.45–USD 171.79 per m^2 (USD 2.37–USD 16.00 per ft^2) • Below roof deck: USD 67.00–USD 197.45 per m^2 (USD 6.24–USD 18.39 per ft^2) • Above roof deck: USD 107.91–USD 238.57 per m^2 (USD 10.05–USD 22.22 per ft^2)	[7,13,69–72]
Foundation	Foundation Type and Insulation Location: • Sealed and insulated crawl: USD 38.76–USD 62.27 per m^2 (USD 3.61–USD 5.80 per ft^2); total: USD 5500 • Basement wall exterior: USD 3792–USD 7593 (up to USD 20,300) • Basement wall and slab interior: USD 21,500–USD 28,406 (wall-only: USD 7000) • Slab-on-grade perimeter: USD 53.66 per linear m	[7,15,69,73–75]
Above Grade Walls	Exterior Wall Insulation and Cladding Combinations: • Exterior insulation without finish: USD 53.04–USD 161.05 per m^2 (USD 4.94–USD 15 per ft^2) • Exterior insulation with finish: USD 140.65–USD 247.49 per m^2 (USD 13.10–USD 23.05 per ft^2) • Exterior finish: USD 65.50–USD 91.26 per m^2 (up to USD 155.26 per m^2) • USD 6.10–USD 8.50 per ft^2 (up to USD 14.46 per ft^2)	[7,13,14,16,70,76–79]
Ductless Heat Pumps	For 3.5 kW (1-ton), 1-zone ductless heat pump: • Standard: USD 3957–USD 5464 • Cold climate: USD 4058–USD 6705 Cost Premiums: • Cold climate: USD 100-USD 400 • Efficiency: USD 239–USD 689 • Variable speed compressor: USD 266–USD 759 • Additional interior zones: USD 1173–USD 2800 per zone • Gas-to-electric conversion: USD 267	[80–86]
Heat Pump Water Heaters	• Navigant cost curve: USD 2263–USD 2714 • Navigant contractor estimates: USD 2602–USD 4705 • SMUD +/− 1 standard deviation, 50 gallons: USD 3000–USD 5000, typically USD 3800 • Silicon Valley Clean Energy (SVCE): USD 4567 +/− USD 1397	[86–88]

Table 2. *Cont.*

Energy Upgrade Measure	Measure Cost Summary	Sources
Electric Panel and Service Upgrades	• SMUD low-income programs: USD 4725, up to USD 9000 for moving panel, underground service drop, vegetation management. • NV5 and Redwood Energy Report to PG&E and SDG&E: USD 2780 (from USD 2000–USD 4500), from USD 3000 to USD 10,000 for panel relocation, undergrounding. Substantial upstream costs for utilities of USD 10,000–USD 30,000 (not necessarily attributable to a single home). Three to eight months of project time. • Gordian RSmeans: USD 1950 • FIXR: USD 2500, from USD 800–more than USD 4000	[89–92]

Attic insulation includes three location options: framed attic floor and the sloped roof surface below or above the structural sheathing. Central estimates and typical cost ranges from the literature for these three locations are summarized in Table 2. The error bars span the range of estimates in the literature and do not represent a standard deviation. Above roof deck insulation is the most expensive (not including the replacement of the roof finish), followed by the below roof deck and attic floor locations. The estimates in the deep retrofit literature are generally much higher than those reported by [4] and other sources. The deep retrofit literature was focused on cold climate energy upgrade projects with ambitious design goals, and they almost certainly included substantial additional costs, including thicker insulation, the removal of existing insulation, the addition of attic ventilation, framing work and possibly abatement work for moisture, mold or asbestos, etc. The cost for attic floor insulation in the deep retrofit literature is USD 99 per m^2 (USD 9 per ft^2), compared with only USD 21 per m^2 (USD 1.91 per ft^2) for 495 upgrade projects in the US reported by Less et al. Less et al. also reported on 100 projects that placed insulation below the sloped roof surface at a median cost of USD 53 per m^2 (USD 4.9 per ft^2), compared with USD 133 per m^2 (USD 12.32 per ft^2) in the deep retrofit literature, Figure 1.

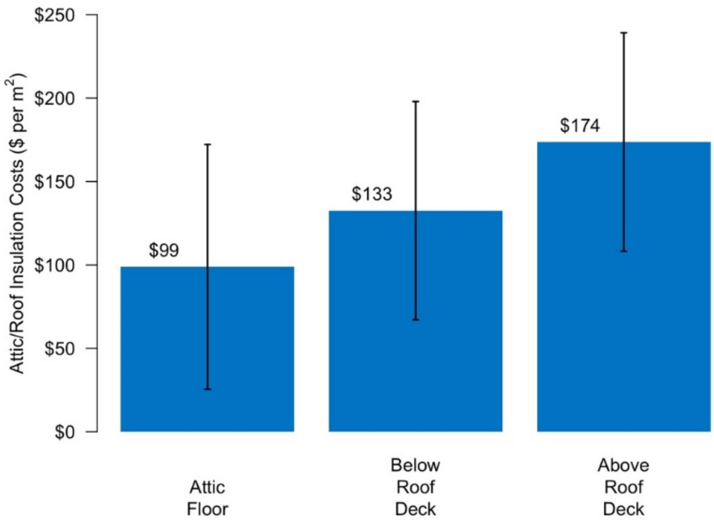

Figure 1. Comparison of attic and roof insulation cost. The figure is reproduced from [3].

Foundation upgrade costs depend greatly on the foundation type, the insulation location and available access to the working areas (e.g., if excavation required). Notably, exterior basement wall upgrades were reported as having a lower cost than interior basement upgrades in the literature. This is surprising, due to the need to excavate the entire perimeter of the foundation to place insulation at the exterior basement wall surface. Often, interior basement insulation upgrades included substantial additional costs, including the demolition and removal of existing basement floor concrete slabs, the installation of interior perimeter drainage, the pouring of a new concrete slab, and wall insulation. These more extensive projects total in the range of USD 21,500 to USD 28,406, while exterior basement wall, slab perimeter and sealed crawlspace projects had costs well below USD 10,000.

Above grade wall insulation upgrades, which include insulation placed on the exterior of the structural sheathing (and sometimes within framing cavities, as well), have received substantial attention in the research literature. *Pacific Northwest National Laboratory (PNNL)* has produced an extensive review of wall insulation upgrade costs, material and methods for residential buildings in the US [79]. The typical costs and cost ranges from our review of this literature are shown in Table 2. Error bars represent the range in the literature, not standard deviations. Typical costs for wall insulation outside the structural sheathing were USD 107 per m^2 (USD 10 per ft^2) of the treated surface area, while the exterior cladding represents another USD 79 per m^2 (USD 7 per ft^2) on average, Figure 2. Across the literature, the combined costs of both insulation and cladding replacement were typically around USD 195 per m^2 (USD 18 per ft^2). For comparison, [4] reported cost data for 229 projects in the US that insulated the wall cavities of homes, with median insulation costs of USD 24 per m^2 (USD 2.2 per ft^2). Substantial R&D in the past decade has been directed towards reducing costs when placing wall insulation outside of the structural sheathing [14,16,17], but reductions have been hard to come by and significant adoption in the market has not occurred. These efforts at cost reduction and market stimulus are ongoing in the US, with a particular focus on the potential for panelized construction and factory prefabrication technologies [18,93]. While prices remain extremely high for wall insulation exterior to the structural sheathing in existing homes, upgrades occurring at the time of cladding replacement remain a more cost-effective option. *Earth Advantage Institute* [78] has documented incremental costs of only USD 47 per m^2 (USD 4.35 per ft^2) for this application with 1″ of exterior foam insulation, though costs remain fairly high and the construction workforce is not familiar with the methods and materials.

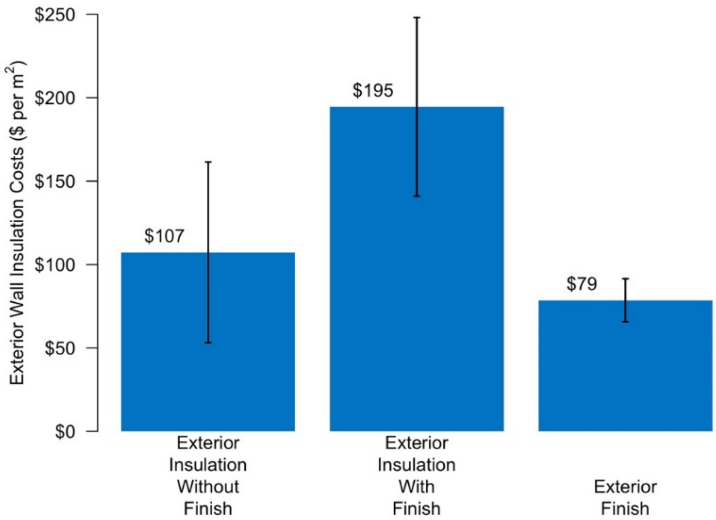

Figure 2. Above grade wall insulation upgrade costs. The figure is reproduced from [3].

Electric heat pump technologies are a high priority in home decarbonization, and we found a small number of sources in the research literature documenting installation costs for ductless heat pumps. Along with central estimates for installed costs normalized by system heat output, we also identified features of projects that can increase costs. These features are shown along with a central cost estimate in Figure 3. Important drivers of cost increases include additional interior zones, variable speed compressors, improved efficiency ratings, converting existing gas appliance to an electric heat pump, and cold climate heat pump technology. Additional elements of projects that can affect heat pump price include the size and condition of existing distribution ducts (if any), equipment location options for indoor and outdoor units (e.g., ground mounted, wall mounted, roof mounted), and the existing electric wiring infrastructure in the home (e.g., main service panel amperage, legacy wiring). The pricing details found in the literature agree closely with data collected by [4] from US home energy upgrades, where they found median installed ductless heat pump prices to be USD 4421 per ton across 180 projects. Less et al. reported USD 192 in additional cost for cold climate heat pump units, which agrees well with estimates from the literature (USD 250). They also found effectively no consistent impact of ductless heat pump efficiency on installed price, suggesting that other factors were more important in determining prices, including regional market differences, labor prices, installation practices, business overhead, etc.

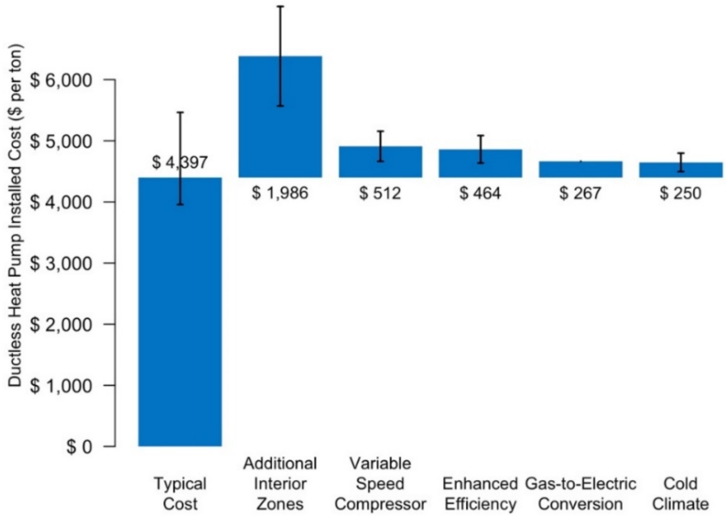

Figure 3. Ductless heat pumps installed costs per ton and incremental costs for features of equipment and project. The figure is reproduced from [3].

We identified three detailed cost breakdowns for ductless heat pump installations in the literature, and these are shown together in Figure 4, representing efficiency program survey data from Massachusetts [80] and the Pacific Northwest [94], along with a practitioner summary from California [32]. The categories used by different parties in summarizing costs makes comparison difficult between these estimates. For example, Navigant and Hanna Lee et al.'s estimates do not separately identify overhead costs or electric upgrade costs. These are presumably rolled into the much larger equipment and labor cost estimates. Together, equipment and labor make up the strong majority of installed costs, with relatively low costs associated with permits and other materials.

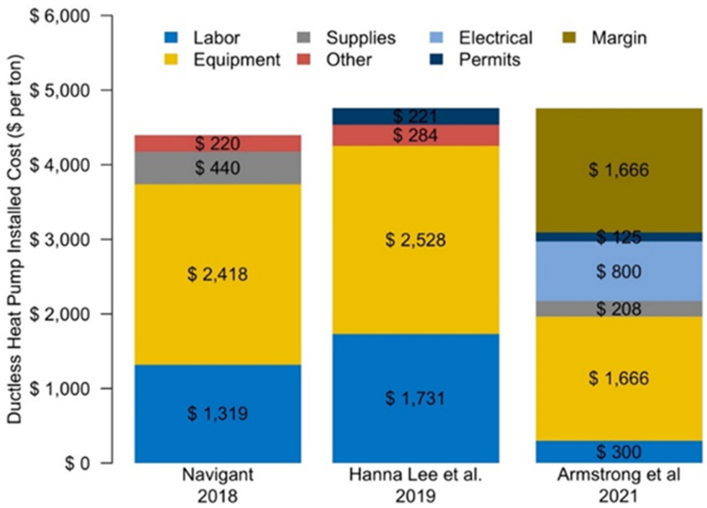

Figure 4. Ductless heat pump installation cost breakdowns. The figure is reproduced from [3].

The other critical electric heat pump technology currently deployed in US decarbonization upgrades is the unitary heat pump water heater (HPWH). Once again, available data sources for HPWH are limited in the existing literature, but we identified a few sources of reliable data, which are plotted in Figure 5. The central estimates range from roughly USD 2500 to USD 4500. Less et al. also reported on heat pump water heater costs in 79 US energy upgrades, which varied strongly by storage tank volume. Fifty-gallon tanks had median costs of USD 2242, while 80-gallon tanks had median costs of USD 3828. In contrast, heat pump water heater installation data from *Silicon Valley Clean Energy (SVCE)* suggest little variability in installed cost based on tank volume. Overall, the values from the database of US upgrade projects align closely with the literature estimates. Cost breakdown estimates provided in the literature suggest that the equipment itself is the largest cost in most HPWH installations (61%), followed by labor costs (26%) [87]. Once again, there are important factors that affect HPWH costs that are not discussed in the literature, namely the condition of existing electrical service, HPWH supply chain availability, space constraints, and the availability/ease of providing venting for the heat pump unit. Several US manufacturers have recently developed plug-in HPWHs that use (potentially pre-existing) standard 120 V receptacles, as opposed to most existing HPWHs, which require dedicated 240 V circuits, due to large resistance electric heat capacity. The performance of these new plug-in HPWHs are currently being assessed in research by the *New Buildings Institute (NBI)* [95].

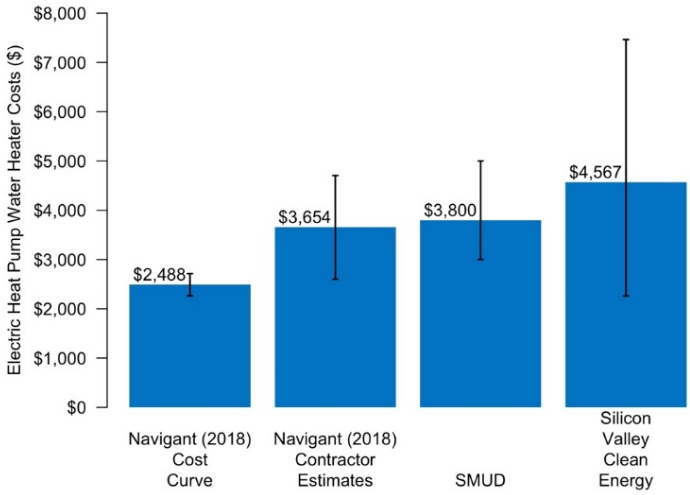

Figure 5. Electric heat pump water heater costs. The figure is reproduced from [3].

Electrical upgrades can be a significant component of home upgrade costs, and there is increasing recognition that converting appliances with high energy use (e.g., electric vehicle charging, space and water heating) from fossil fuel to electricity will substantially increase the overall power requirements in existing homes [96]. Pecan Street reported that 59% of homes in their sample had electric panels sized under 200 amps (about 50 kW), and they argued that these all would potentially need panel/service upgrades in a fully electrified future. Notably, they found no relationship between house age/vintage and existing panel ampacity. Another analysis by BayREN based on visual inspections in 4605 California Bay Area homes suggested that approximately 35% of the local housing stock had 200 amp panels sufficient for full electrification, leaving roughly 65% of regional homes potentially requiring panel/service upgrades [97]. Based on these results, many homes currently lack the electrical capacity to add these new electric loads, and they will potentially require panel and service upgrades. This can add substantial costs to home electrification, as documented in Table 2, with typical customer costs reported in the range of USD 2000 to USD 4000. These can increase substantially in situations where electric panels need to be re-located, where service drops are moved underground, or where substantial vegetation management is required for access. There is a need to better document and understand these costs outside of California, and to improve our understanding of how many homes require electrical upgrades, along with the development of pathways to electrify existing homes without upgrading panels and service. There are nascent efforts to reduce the need for these panel and service upgrades [85], and to provide guidance for utilities on how to reduce these costs [91], but home electrical capacity and infrastructure remain a serious barrier to home electrification in the US. These issues can be even worse in multi-family dwellings, which have lower power available per unit (typically 50–70 amps) and are even more restrictive on a whole building basis, due to assumptions about load diversity used in the *US National Electric Code*.

5. Business Models, Gross Margins and Soft Costs in Energy Upgrades

Home decarbonization will only happen at-scale if owner/occupant needs and goals are met, businesses can thrive, and business models exist to deliver the required services, along with the required supply chains that facilitate growth throughout the market. Broadly speaking, the literature acknowledges that current contractor businesses and business models are not conducive to large-scale decarbonization/electrification [18,34].

5.1. Business Models

The US DOE's *Better Building Neighborhood Program (BBNP)* documented business models for the contractor, remodeling contractor, HVAC contractor, home performance contractor, and retailer in the early 2010s [98]. For each of these business types, the report outlines the governance, financial model/structure, assets and infrastructure, service offerings, and customer acquisition/marketing. It posits that the unique mix of these business model elements determines how actors in the energy upgrade market will respond to incentives, regulations and fluctuations in the market. It shows their capability to either grow their existing home energy upgrade services, or expand into the energy efficiency upgrade market, if they do not currently offer those services. Despite the development of these clearly defined business models, energy upgrades have not scaled in the US in the past decade. The industry remains dominated by ad hoc local efficiency programs and small business contracting models.

Newly emerging business models for the delivery of home upgrades at scale aggregate savings over multiple customers using *pay-as-you-save (PAYS)* approaches. In some cases, these electrification and energy upgrade business models include the use of Internet technologies, machine learning and *one-stop shop* services to target, communicate with and conveniently serve customers. A one-stop shop combines planning, financing, and the physical home upgrades in a single solution provider, in order to simplify and remove risk from the decision making and construction processes for homeowners/occupants. One example is the *EnergieSprong* program. Another example, from the US, is a company named *Sealed*. Sealed pays upfront for the majority of home energy upgrade costs, and they then create a bill for each customer that combines the utility fees with an additional fee to pay for the upgrades. Customers effectively see little or no upfront cost and only small changes in monthly expenses. Sealed has shown an overall 99% prediction accuracy for electricity savings in a population of 338 homes in New York state [33]. This is critical to Sealed's business model, as their past work in selling efficiency to customers has shown that consumers typically discount predicted energy savings down to USD 0.25 for each USD 1.00 of predicted savings. Similar business models exist for decarbonizing small-to-medium multi-family dwellings (e.g., *BlocPower*).

5.2. Gross Margins, Overhead and Profit in Residential Construction

In order to understand potential changes to project delivery models, we must characterize current practices and costs. The "gross margin" of a business is defined as the fraction of total sales revenue made up of business operations/overhead costs and profit. The remaining costs of goods sold include equipment, materials and labor costs. High gross margins increase the cost of energy upgrade projects, because much of the revenue from each executed project is required to support new customer acquisition, industry training, specialized equipment, and traditional business expenses (e.g., marketing, office space). For smaller companies with fewer projects, these business costs can become particularly high relative to the labor and materials involved in the actual construction works. Some have suggested that gross margins in home energy upgrade work are too high, substantially exceeding those of standard residential remodeling, due to the particular nature of home performance jobs (Andy Frank, personal communication, 28 May 2020). To assess these claims, we have examined the available literature describing typical gross margins in residential remodeling and construction, and we compare these in Figure 6 against values reported from industry stakeholders in the *LBNL Deep Energy Retrofit market survey* [1]. Overall, the gross margins reported by home performance professionals in the DER survey are substantially higher (median of 47%) than those for typical remodeling and construction. General contracting (commercial), construction services and renewable energy have the lowest margins (from roughly 10–25%) [99,100], while standard residential remodeling gross margins are typically around 30–35% [100–102]. The survey data suggest that the primary difference between residential remodeling and home performance companies are that profit margins are higher in energy upgrade work, while business overheads are reported as only slightly higher.

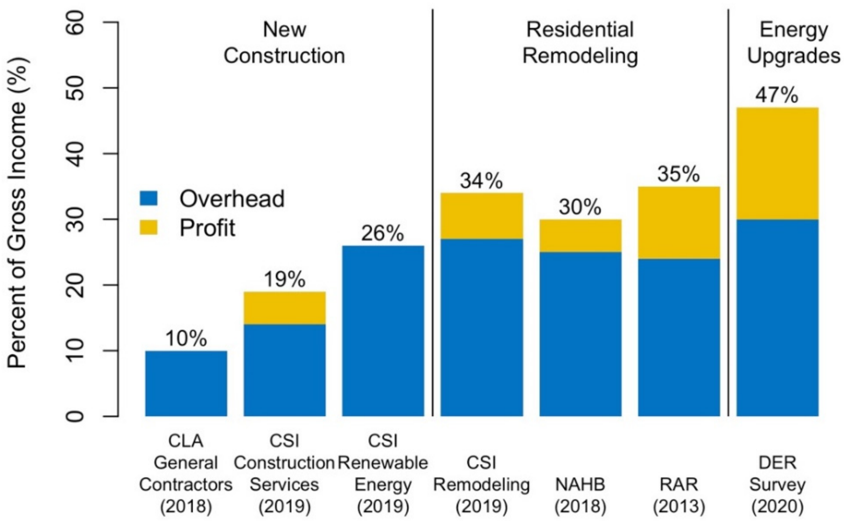

Figure 6. Comparison of gross margins in residential energy upgrades with other construction sectors. The figure is reproduced from [12].

It is clear that within the larger construction industry, different business types have substantially different financial situations. In line with the reported values for home improvement above, others have suggested that gross margins vary from 34 to 42% for remodeling, from 26 to 34% for specialty work, and from 21 to 25% for new home construction [103]. In general, remodeling work entails higher gross margins than new construction. Some high-end remodeling companies actually design their business processes around maintaining much higher gross margins in the range of 40–60% [104]. These same companies also targeted higher than average net-profits.

A key point of comparison for home energy upgrade business overheads and soft costs is the solar PV industry. Ref. [105] showed that the installed cost of residential PV systems is dominated by gross margins and supply chains that make up more than half of the installed cost. This exceeds the estimates provided above for residential remodeling and for energy upgrade businesses. Extending this further, Farnsworth categorized a full 68% of PV costs as "soft". However, this total includes in the "soft cost" category the installation labor and structural components of the system, which were not considered soft costs in the other analyses referenced here.

5.3. Soft Cost in Energy Upgrades

As shown above, the gross margins for home energy upgrade work are typically 15–20% greater than those reported for standard residential remodeling (see Figure 6). The differences may be attributable to unique expenses incurred during home upgrade work that are not part of general remodeling, including testing and diagnostics, building energy simulation, program administration and compliance, etc. An industry survey of deep retrofits in the US [1] collected responses on the assortment of soft costs in energy upgrade projects, and the typical reported soft costs are shown in Figure 7 along with the count of responses for each category. Professional design services were the most expensive soft costs, but they are not required in most single-family upgrade projects in the US. Project management (9% of total cost), jobsite travel (7%), customer management (4%) and home inspections were all reported as being both common and costly. Many elements that are unique to energy upgrade projects were relatively low-cost measures, such as infrared camera inspection or the measurement of fan airflows and duct leakage. Substantial business overhead costs not attributed to individual projects might include ongoing training, certifications, and efficiency program participation and documentation. Survey respondents reported spending the most non-construction time on customer acquisition and on work scope development (i.e., selecting and specifying upgrade measures), followed by initial home inspection/energy audit and program/rebate administration. Soft cost reductions may be achievable by targeting the range of costs incurred during upgrade projects and either incrementally reducing them (e.g., automating part of the customer acquisition process) or eliminating the costs entirely (e.g., no combustion safety testing in all-electric homes). Compression of these numerous soft costs is one potential benefit of the "One-Stop Shop" program type described above.

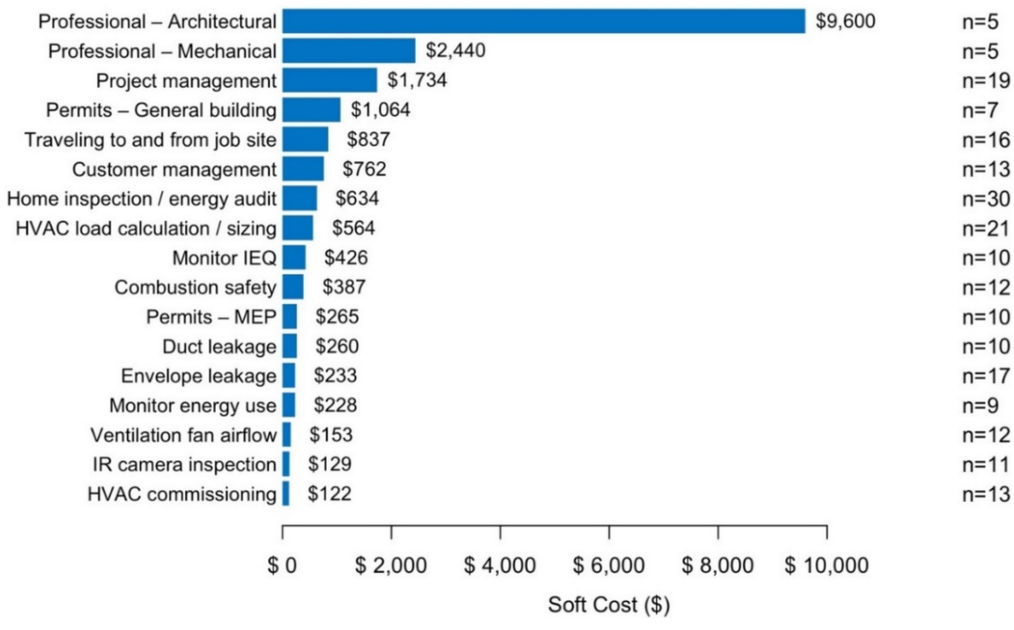

Figure 7. Average soft costs reported for deep retrofit projects [1].

6. Health Benefits of Energy Upgrades and Electrification

The health benefits of energy upgrades and decarbonization/electrification are often cited as a factor when households are making decisions about home improvements [1]. In addition, any health benefits may result in significant savings for public health programs, and they need to be included in public policy assessments [106]. Numerous reviews of the scientific evidence have concluded that housing interventions that support home warmth, reductions in fuel poverty and energy upgrades have the potential to improve health, particularly for sensitive populations [106,107]. Maidment et al. [108] performed a meta-analysis that pooled together the results from 36 past studies of the health effects of energy efficiency in homes, for a total sample of over 33,736 participants. On average, interventions had a small, but significant, positive impact on residents' health. This result was largely in agreement with prior reviews that reported modest health improvements [109], as well as more mixed, though mainly positive outcomes in past systematic reviews [110–112].

The IEA outlines the multiple benefits of energy efficiency, with a chapter dedicated to the health benefits of energy efficiency [113]. Their key findings were: (1) improving energy efficiency in buildings creates conditions that support improved health and well-being for occupants; (2) positive health outcomes are consistently strongest among vulnerable groups, including children, the elderly and those with pre-existing illnesses; (3) health improvements at the individual level generate indirect social impacts and relieve pressure on public health budgets (an estimated savings to the European public health budget of USD 99 billion per year in 2020); and (4) health benefits represent up to 75% of overall energy efficiency program benefits. These health impacts are greater in low-income communities due to: (1) disparities in health outcomes; (2) higher location-based exposure; (3) higher in-home exposure; and (4) increased vulnerability (often referred to as the "heat or eat" dilemma [114].

In 2016, the US DOE published a report [115] that reviewed the available evidence on the relationship between health and home performance. This review was conducted primarily by representatives from the *National Center for Healthy Housing (NCHH)*, along with other individual contributors. Forty studies were reviewed and are summarized in a white paper. The reviewed works were categorized by the type of intervention (e.g., basic weatherization, green renovation, ventilation intervention, etc.). They reported that interventions at all levels improved occupant health and had positive impacts. A more recent review analyzed the impacts of residential energy efficiency retrofits on indoor environmental quality conditions and self-reported thermal comfort and health [116]. A total of 36 studies were reviewed, with most studies focused on low-income homes in Europe or the United States. Overall, indoor radon and formaldehyde concentrations tended to increase after retrofits that did not add whole-house mechanical ventilation; however, other contaminants, such as nitrogen dioxide (NO_2) and volatile organic compounds other than formaldehyde, increased and decreased with approximately equal frequency. Average indoor temperatures during winter typically increased after retrofits, usually by less than 1.5 °C. Dampness and mold, usually based on occupant's reports, almost always decreased after retrofits. Subjectively reported thermal comfort, thermal discomfort, non-asthma respiratory symptoms, general health, and mental health nearly always improved after retrofits.

Others have developed frameworks for valuing the health impacts of energy upgrade projects. *E4TheFuture* published a report in 2016 [117] that summarized potential health benefits of energy efficiency programs and developed a roadmap for future efforts. This document also provided an estimate of the monetary value of health improvements and noted that states are increasingly recognizing such co-benefits in cost-effectiveness practices [118]. Monetary estimates of household health benefits ranged from USD 3 to over USD 900 per household unit per year for residential energy retrofits. Other studies have estimated that health improvements represent as much as 75% of the total return on the investment for these interventions [119]. Recent studies have calculated the monetary value of health and safety-related impacts of home energy upgrades. A study of several hundred low-income households in multifamily buildings estimated an annual total of USD 1537 for these non-energy benefits [120]. Home energy use also has important impacts on ambient air quality and health. For example, [121] estimated that outdoor $PM_{2.5}$ from burning fossil fuels in US homes leads to 3646–5170 annual premature deaths, with a corresponding annual health burden of USD 40–USD 58 billion.

The key limitations in the existing literature addressing home upgrades and health include the use of short study periods, small sample sizes, the use of self-reported health outcomes, an almost exclusive focus on low-income households, and an inability to correlate changes in health with changes in indoor air contaminant concentrations. Recent research in Europe and Australia has pushed the boundaries with improved methodologies that include long-term study periods (years as opposed to months), the use of objective health data (e.g., hospitalization or healthcare system cost data), and sufficiently large sample sizes to support robust statistical analysis. Some of these studies found remarkable positive health outcomes from upgrading existing social housing to new standards in the UK [122,123]. Home ceiling and floor insulation upgrades in thousands of Australian homes were similarly shown to reduce hospitalizations by 11% [124]. Unfortunately, other similarly large studies on the impacts of energy efficiency have found increased radon concentrations in more efficient homes [125] and increased hospitalization rates for respiratory and cardiovascular illness in UK dwellings with higher energy ratings [126], indicating that attention must be paid to ventilation and indoor air quality issues when upgrading home performance.

The health literature described above is for standard home upgrades, often targeting home warmth through basic envelope weatherization and the replacement of low-efficiency equipment with similar but higher efficiency options. However, no research has been carried out to date that specifically addresses home decarbonization upgrades, particularly those focused on electrification. Yet, home electrification and decarbonization likely present some additional, new potential health impacts that are not incorporated in the summary above. We expect the health and IAQ impacts of electrification to be distinct from those associated with traditional efficiency upgrades for several reasons. First, electrification projects make substantial changes to the home's electrical infrastructure (i.e., service panel, breakers, branch circuit wiring), potentially impacting fire, burn and shock risks. Second, unlike traditional efficiency upgrades, the replacement of gas cooking appliances with electric options can eliminate the most substantial non-smoking source of combustion pollutants in most dwellings, with potentially important impacts on cardiovascular and respiratory health. Cooking with gas is a major source of contaminants of concern for health: primarily nitrogen dioxide (NO_2) and fine particles ($PM_{2.5}$). For particles, the cooking process itself generates some particles, but there are additional particles resulting from the combustion process for fossil fuel appliances. NO_2 exposure related to cooking has been shown to have strong health impacts, particularly for asthmatic children [127–132]. Although there is a less established connection between ultrafine particles (UFP) and specific health outcomes, testing has shown that cooking with fossil fuels produces increased levels of UFP [133]. Electrification also leads to less NO_2 and fewer particles being emitted into the outdoor environment, where they contribute to public health hazards, with total benefits estimated at USD 108 billion per year in 2050 for California [134]. Finally, many electrification upgrades will introduce mechanical cooling in previously uncooled dwellings, which can have substantial benefits in reducing heat stress, particularly in the elderly and other vulnerable populations (e.g., those with pre-existing conditions). Other impacts of electrification compared with standard home upgrades are expected to be more minor, such as reduced household ventilation rates, due to the elimination of combustion ventilation openings and the elimination of atmospheric combustion appliances in the conditioned space.

7. Discussion

This review included home energy, decarbonization and electrification upgrade programs in the United States and in Europe, with a focus on innovative approaches to financing, performance metrics, project design and delivery. This review also included summaries of upgrade/measure costs, business model financials (e.g., gross margins, soft costs), and health and safety impacts. The work of much of the second decade of the 2000s has sought to bring energy upgrade design and construction principles to a broader market, generally as part of utility- and market-based programs. However, much has changed since the first meta-analysis of DERs [2], with substantial impacts on how energy upgrades can (or should) be designed, implemented and marketed. This new economic and technological landscape requires that we reassess what kinds of interventions are recommended in homes.

Key changes identified in home upgrade programs included: (1) a shift from superinsulation to more traditional envelope upgrades combined with end-use electrification and on-site renewables, (2) the use of carbon metrics in program and project design, and (3) the proliferation of "one-stop shop" project delivery models, including financing. Traditional project delivery business models are hampered by gross margins (i.e., overhead and profit) and soft costs that are substantially higher than in standard residential remodeling. These high costs limit the widespread market adoption of home upgrades. It may be possible to reduce upgrade gross margins and soft costs by simplifying processes related to customer acquisition, work scope development and permits, as is being pioneered in *one-stop shop* programs. The health and comfort benefits of home energy upgrades have been well documented in the literature, but no efforts have specifically characterized the health and comfort benefits of decarbonization or electrification upgrades in homes, such as electrical safety upgrades, the removal of gas cooking appliances and the addition of mechanical cooling. These represent potentially important additional benefits attributable to decarbonizing the residential buildings sector. Additional research addressing these and other non-energy impacts (e.g., increased home value, resilience, durability) is necessary, as they may play a critical role in home upgrade deployment in the coming decades.

Numerous barriers to widespread home decarbonization remain, including high upfront and operating costs, the lack of a suitable workforce, limited consumer demand, unreliable supply chains, the use of outdated home performance metrics, and many others. Surveys have suggested that there is increasing homeowner desire to make homes sustainable and that incentives are helpful, but a better understanding of potential solutions is needed. For example, how might carbon taxes or time-of-sale upgrade mandates change people's perspectives? Substantial new research is required to characterize and address these barriers.

While there are tangential references to added home value and data for specific decarbonization measures (such as adding PV systems), we could not find publicly available studies evaluating the added value from both homeowner and real-estate industry perspectives. There are published values for many home upgrades (e.g., kitchen remodeling), but they do not include improved energy performance. The literature does point out that a lack of consumer demand is a limiting factor; however, there is little information on how to address this.

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

A limitation of this review is that it focused predominantly on single-family homes, and there is a need to review work in multifamily buildings, manufacturing homes, and heritage retrofitting. There is a need to also study decarbonization for other building types (commercial, industrial, institutional, etc.) where decarbonization efforts are less advanced compared to residential efforts [135].

Several topics were not addressed directly in this review due to a lack of established literature. For example, there is an increasing awareness about the importance of when homes use energy, and what type of energy they use and from what source. Emerging technologies for electricity and thermal storage integrated into grid-integrated smart home energy systems with the ability to manage, reduce and communicate about energy use need further study. Energy production and storage are now becoming cost-competitive with traditional load reduction measures, and the efficiency industry must adapt its approaches accordingly. Another key issue not addressed in the literature is upgrading energy software/modeling/optimization tools (used in both program and building design) to optimize for carbon reductions rather than energy savings.

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