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The Costs of Decarbonizing Multifamily Buildings in DACs and Rural Areas

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ABSTRACT

Decarbonization technologies are becoming easier to implement and more cost-effective in new multifamily housing, but retrofitting costs remain a significant challenge. Energy retrofits are crucial for prioritizing low- and moderate-income communities already burdened by energy, environment, and health issues. Cost and split incentives are the main barrier hindering the scalability of home decarbonization in affordable multifamily housing, creating unique challenges and opportunities for homeowners and renters. Therefore, understanding and addressing cost barriers is important for a fair energy transition. We lack essential data on the costs of affordable multifamily electrification solutions and technologies. Such data is essential for effective planning/policy activities, implementation of home decarbonization efforts, and guiding R&D aimed at reducing retrofit costs. To address these issues, we compiled information from 3,208 multifamily energy upgrade projects covering 14 US states, encompassing a total of 7,126 individual retrofit measures. Our findings summarize electrification technologies and associated decarbonization measures in current practice. We also examined cost data to identify key factors influencing both project measures and overall project costs. Some key results are that in high-rise buildings, the impact of the cost per unit is more significant when retrofitting the building envelope compared to low-rise buildings, however; the cost per unit for HVAC installation remains relatively consistent across all multifamily building types. Also, rural areas have higher retrofit costs, even when considering factors like DACs status.

Introduction

Buildings contribute significantly to global energy consumption and emissions, with the U.S. residential sector accounting for 21% of building-sector energy use in 2022 (EIA 2023). Meeting global climate goals requires aggressive decarbonization strategies (Camarasa et al. 2022), yet challenges such as construction costs, lack of skilled workforce, technology limitations, and behaviors hinder progress. The U.S. government has emission reduction targets and given the substantial environmental impact of the residential building stock, policies promoting green residential construction are vital to reduce the U.S.'s residential carbon emissions. Another key issue is ensuring that decarbonization at a social level is fair and equitable. Buildings located in disadvantaged communities (DACs) or rural areas also play a significant role in energy consumption and carbon emissions. These buildings may face unique barriers such as limited access to technology, financial constraints, and different behavioral patterns. These barriers may require specific policies and initiatives to promote green building practices and reduce the carbon emissions of residential energy use in these communities.

Energy policy is increasingly recognizing the ability of residential decarbonization to address the environmental and health burdens on disadvantaged communities. In this context decarbonization includes both electrification of end-uses as well as reductions in emissions through reduction in energy consumption. In the U.S., many programs and policies aim to address energy burden with a focus on low-income households, ranging from utility bill assistance to regulation and rate reform (Brown et al. 2020). Most recently, the Justice40 initiative established in 2020 sought to ensure that at least 40% of the overall benefits from federal climate and clean energy investments flow to DACs. The Department of Energy's policy priorities for the implementation of Justice40 included decreasing energy burden in DACs (The

White House 2021; Office of Energy Justice and Equity 2022). Some states, such as New York, New Jersey and Virginia, have established councils or task forces, or passed legislation to incorporate energy justice into energy efficiency policy and programs (National Conference of State Legislatures 2022). A number of geographic information systems-based tools, such as the Climate and Economic Justice Screening Tool (CEJST), have also been developed to identify communities that have been historically subject to environmental and other burdens. The CEJST classifies a census tract as disadvantaged if it meets both of the following criteria (1) the census is at or above the threshold for one or more of the eight environmental, climate, or health burdens; and (2) the census tract is above the threshold for an associated socioeconomic burden, either income or higher education enrollment rate (World Resources Institute 2022). In addition, the CEJST considers federally recognized tribes as DACs. Based on the CEJST classification, approximately 93.5 million people (29% of the U.S. population) are identified as disadvantaged. Disadvantaged communities face greater health hardships and financial challenges, where the average median household income in a non-DAC ($93,800) is almost double that in a DAC ($47,300). In addition, rural areas are more likely to be classified as disadvantaged, with 38% of rural census tracts classified as disadvantaged compared to 30% of urban census tracts (World Resources Institute 2022). In this paper, we use the CEJST's definition of disadvantaged communities to examine the current state of decarbonization retrofit impacts on these communities facing a variety of burdens, which is crucial for ensuring our climate goals are achieved equitably.

In previous LBNL studies (Less and Walker 2014; Less, Walker, and Casquero-Modrego 2021; Less et al. 2021), we assessed the construction cost and barriers associated with energy retrofits in single-family buildings across the US. The lowest cost approaches to achieving significant greenhouse gas emission reductions were about $50,000 per home (Walker et al. 2022). This is clearly unaffordable for DACs (and most middle-income households) without rebates or other policies addressing these high costs. Pathways to reducing these costs for single family dwellings have been outlined (Walker, Less, and Casquero-Modrego 2022; Walker, Casquero-Modrego, and Less 2023), and a similar analysis is needed for multifamily buildings. Studies have indicated that deep energy retrofit costs in cold climates, may incur higher costs (Holladay 2012; Cluett and Amann 2014). However, existing cost data may not accurately reflect recent changes such as inflation and shifts in energy rates, and often focus on single-family housing (NREL 2018). It is well-documented that costs often act as significant barriers to the widespread adoption of energy retrofits (McIlvaine et al. 2013; EMI Consulting 2016; Casquero-Modrego et al. 2022). Recognizing that retrofits with decarbonization strategies can mitigate energy burdens in vulnerable populations, some cost studies have explored the potential savings for low- and moderate-income households. Additionally, retrofit decisions are influenced by various household and community factors, including geography and socioeconomic characteristics, utility rates, return on investment and climate zone, yet these aspects have received relatively less attention in the literature (Drehobl and Castro-Alvarez 2017; Hancevic and Sandoval 2022; Willand 2022). Although the reported deep retrofit costs are high, they are in-line with other home remodeling projects, e.g., Remodeling magazine 2023 cost vs. value report (Remodeling by JLC 2024) indicates that a mid-range kitchen remodel is about $78,000.

The current study builds on our previous single-family cost analyses to examine costs in multifamily energy and decarbonization retrofits. Multifamily buildings have a wide range of ownership structures and access to capital to pay for retrofits is property dependent. In addition, even if occupants want to reduce energy use or decarbonize their home, renters in multifamily buildings are not the owners and are severely restricted in their ability to upgrade their homes. While cost benchmarks are essential for guiding strategies and cost reduction efforts, research using actual retrofit data is relatively scarce, basically due to lack of publicly available project cost information.

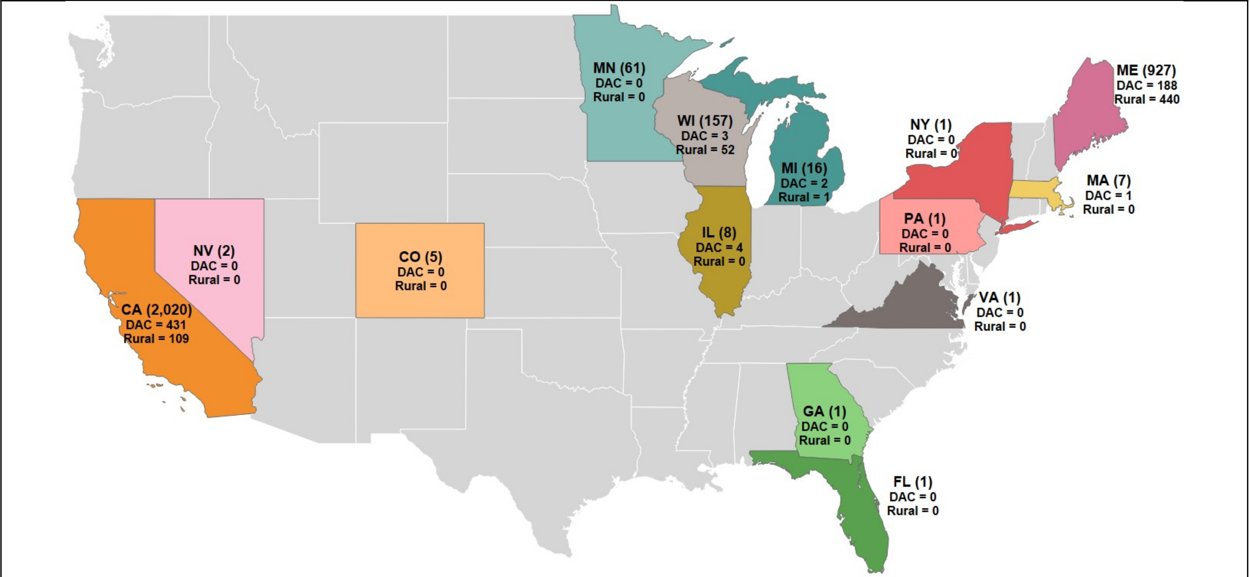
In this study, we aimed to deepen our understanding of energy retrofits in multifamily buildings by creating a database of multifamily electrification and decarbonization costs. This database includes building metadata such as location and vintage, among others, as well as project and measure costs and energy data. With this database, we can compare construction and energy data between DACs and non-DACs, including rural areas. In this research project, we collected data from various sources such as contractors, developers, and energy programs. If the shared information confirmed that the building was affordable housing, we categorized it as such, however we did not have additional information such as if the affordable housing was subsidized/ deed restricted or naturally occurring. The database has been developed as a basis for future residential energy upgrade data gathering activities by the US Department of Energy (DOE) and other agencies. The goal of this study is to assess how community type characteristics (i.e., DAC, rural and income), influence project costs and carbon emissions per unit. The findings will shed light on retrofits scalability, and policy development, aiming towards a more equitable distribution of retrofit costs and benefits to *priority communities*.

Database Summary

To gain insights into addressing cost barriers and scaling retrofits for decarbonization of DACs and rural areas in the US, between 2022 to 2024 we conducted an analysis of current retrofit costs for decarbonization in multifamily buildings across the country. This database establishes the foundation for future research by the U.S. Department of Energy on multifamily retrofit costs, building upon the groundwork laid by the previous single-family housing study (Walker, Less, and Casquero-Modrego 2022; Walker et al. 2022).

This study aims to assess how community type characteristics (i.e., DAC, rural, and income) impact project costs ($) and carbon emissions *per unit*. Therefore, we have developed a comprehensive retrofit cost database to enhance our understanding of energy retrofits for decarbonization in multifamily buildings. This includes building metadata for comparison between DACs and non-DACs including rural areas. 20% of the projects are situated within DACs in CA, IL, MA, ME, MI and IL, 19% are in rural areas of CA, ME, MI, and WI) For the database we compiled detailed data from a total of 3,208 projects, including building characteristics, project costs, implemented measures, and energy data. The cost analysis includes total project costs plus estimates of costs for individual measures. Figure 1 presents the total number of projects within the database across each state, accompanied by a high-level breakdown separating DACs and rural projects. While substantial efforts were undertaken to obtain as broad data set as possible, the non-uniformity between states and regions shown in

Figure 1 illustrates the wide variance in where projects are undertaken, the detail recorded for projects and data availability. There are many more projects in the country that did not record the information we require for our data set, such as measure breakdowns or dwelling size. There are also projects and programs that do not have mechanisms in place to share their individual building data. Furthermore, our sample was limited by selecting projects that specifically focused on decarbonization/electrification, rather than all energy retrofits. To widen the sample size in the future we recommend that we establish national guidelines for data sharing including ensuring that data is secure and anonymized and reduce the burden on potential data providers by requiring less information of construction specifics and focusing on having fewer questions more focused on basic information about costs and building size. The total number of projects, measures, floor area (m^2) and cost ($) represent the cumulative values of all projects in the database in those categories.



Total Projects = 14 states 3,208 projects 6,949 measures $395,750,685 (project cost)
Projects in DACs = 6 states 629 projects 1,195 measures $66,222,608 (project cost)
Projects in Rural area = 4 states 602 projects 1,166 measures $34,109,949 (project cost)

Figure 1. Map of project locations, including projects in DACs and rural area, and overall summary statistics.

The database includes a range of upgrade projects, including heating/cooling (HVAC) and domestic hot water (DHW), lighting or appliance replacements, as well as building envelope energy upgrades like wall and attic insulation or window replacements. All the projects included costs ($), and 66% of the projects in the database included CO_2e reduction data. For the energy estimate, the results are a combination of what was provided for each project, that could be real, modeled, and estimated energy data (for both electricity and fossil fuels). 91% of the projects received rebates or incentives from energy programs at the local, state, or federal levels. However, the costs presented here exclude any form of rebate or incentive. We used non-rebated costs because rebates may come and go and not represent future costs and because decisions about rebate programs should be made on the full non-rebated costs.

Table 1. Summary of project characteristics reported in the database.

	TOTAL Database				Disadvantage Community (DAC)			Rural Community		
	Project Characteristics	**Reported Buildings**	**Low-rise**	**Mid- & High-rise**	**Reported Buildings**	**Low-rise**	**Mid- & High-rise**	**Reported Buildings**	**Low-rise**	**Mid- & High-rise**
Home Vintage	Pre 1900	3%	4%	---	4%	4%	---	---	---	---
	1900 - 1959	32%	33%	27%	13%	13%	---	---	---	---
	1960 - 1979	27%	31%	15%	35%	35%	---	---	---	---
	1980 - 1999	16%	16%	13%	19%	17%	---	40%	---	---
	2000 - 2020	22%	16%	46%	29%	21%	8%	60%	---	---
Project Year	2010-2018	22%	13%	60%	21%	17%	4%	6%	---	---
	2019	8%	6%	22%	6%	6%	---	2%	---	---
	2020	4%	3%	4%	2%	1%	---	1%	---	---
	2021	43%	50%	6%	45%	43%	---	60%	56%	---
	2022	23%	27%	6%	24%	23%	---	31%	29%	---
	2023	---	---	1%	1%	1%	---	---	---	---
	2024	---	---	---	---	---	---	---	---	---
Project Duration	≤1 month	31%	47%	---	34%	33%	---	50%	50%	---
	2 months	20%	19%	2%	26%	10%	---	26%	16%	---
	3 months	14%	8%	2%	6%	6%	---	6%	6%	---
	4 months	8%	4%	10%	2%	2%	---	2%	2%	---
	5 months	5%	3%	6%	2%	2%	---	1%	1%	---
	6 months	2%	3%	4%	3%	3%	---	1%	1%	---
	≤1 year	17%	10%	55%	22%	6%	1%	14%	3%	---
	≤2 years	3%	5%	14%	5%	5%	---	---	---	---
	>2 years	1%	1%	6%	---	---	---	---	---	---

Number of Stories	*Low-rise*	91%
	Mid-rise	7%
	High-rise	2%

Table 1 presents a summary of the key characteristics of multifamily buildings recorded in the database. This study relies on a convenience sample, meaning that any trends observed in these values only reflect the contributed data. Therefore, these data may not necessarily represent the national characteristics. The database is divided in two main sections as follows: Building and project characteristics.

Building Characteristics

The building characteristics in the database covered several broad categories:

- General: (1) housing type (e.g., affordable housing, market rate, luxury); (2) building typology (e.g., detached, attached, semi-attached); (3) unit ownership status (e.g., rental, owner, mix, housing authority, non-profit, community property); (4) vintage; (5) historical designation (yes or no); (6) original use of the building (e.g., residential, commercial, educational, etc.).
- Construction-related: (7) number of stories above grade (e.g., low-, mid- or high-rise; (8) number of stories below grade; (9) total number of units per building; (10) building construction type (e.g., wooden frame, brick masonry, steel, concrete, mix, other); (11) façade type (e.g., traditional, rainscreen cladding, lightweight, prefabricated, prefabricated, other); (12) roof pitch (e.g., flat, high-slope, low-slope); (13) foundation type (e.g., slab-on-grade, basement, crawlspace, split level, mixed, other).
- Energy-related: (14) heating configuration (e.g., central, in-unit); (15) cooling configuration (e.g., central, in-unit); (16) domestic hot water configuration (e.g., central, in-unit); (17) electric metering (e.g., individual, master); and (18) gas metering (e.g., individual, master);

(19) retrofitted area pre and post-energy retrofit; (20) presence of elevator pre- and post-energy retrofit (yes or no).

As we observe in Figure 1, it is evident that the total 3,208 projects were unevenly distributed across 14 states nationwide. This allocation spans various economic regions and climates. Notably, DAC projects are predominantly situated within climate regions 3B, 6A, 3C, 5A, 7C, and 4B, particularly in rural areas (6A, 3B, 7C, 4B, and 3C). The DACs projects recorded are primarily located in dry regions (42%, followed by moist (31%) and marine regions (27%). However, projects within rural areas are mainly situated in moist environments (82%, followed by dry ones (18%). This provides us with the opportunity to compare the disparities between cold and warm climates.

The present study encountered limitations in gathering enough information to assess the building typology of the recorded projects (e.g., detached, attached, or semi-attached). The median conditioned floor area was 2,353 m² or 25,326 ft², with a mean of 5,489 m² or 59,083 ft². It most of the cases, it was often unclear whether the area referred to individual apartment units, entire buildings, or building floor plans. Moreover, the database did not document any changes in floor area during the renovation work, suggesting that such type of projects is uncommon for multifamily retrofits in the buildings of the study.

The data indicates a diverse range of building ages (construction dates from 1800 to 2020), with a significant proportion of older buildings undergoing energy retrofits, with the majority of reported projects being over 50 years old, primarily constructed between 1900 and 1979 (62%), consisting mainly of low-rise buildings (67%). Interestingly, a notable number of energy retrofits were identified in buildings constructed between 2000 and 2020 (22%), of which 46% were mid- and high-rise buildings, indicating recent energy updates despite their relatively recent construction years. This observation leads us to anticipate a prevalence of energy retrofit projects focusing on individual measures to address the existing climate requirements or motivated by energy programs economic incentives rather than intrinsic inefficiency issues such as lack of envelope insulation. Concerning the projects in DACs, approximately 50% of the recorded buildings were constructed prior to 1979, while the remaining 50% were built between 1980 and 2020. Specifically, 69% of all projects in DACs are low-rise buildings. Regarding rural areas, the buildings in the database were constructed between 1980 and 2020, and all of them have been identified as low-rise buildings.

Project Characteristics

The project characteristics covered in the database are as follows: (1) project status as of June 2023 (e.g., design, construction, complete, audit); (2) project start year; (3) project finish year; (4) project length in months; (5) whether the building was occupied during retrofit works (yes or no); (6) whether the building had an audit (yes or no); (7) type of retrofit (e.g., retrofit, renovation, gut rehabilitation, addition); (8) project retrofit focus (e.g., HVAC, DHW, individual measures, appliances, lighting, electrification, etc.,); (9) energy rating program; and (10) energy program.

It is important to note that many of the multifamily projects in the database did not provide complete information for all the requested building characteristics. This may result in instances where the recorded values do not sum up to the total number of projects. However, for this study, we emphasized using only the data from projects that were able to provide, at a *minimum*, the following values: (1) gross cost (\$); (2) breakdown of the gross cost (\$) into different measures; (3) zip code; (4) total number of units per building; (5) total number of stories per building; and (6) project completion year.

To obtain recent cost and energy data from multifamily retrofits for decarbonization, the study limited the data analysis to energy retrofit projects starting from 2010. This approach allows for a future comparison of results from this study with a previous one conducted on single-family energy retrofits in the US (Less et al. 2021; Less, Casquero-Modrego, and Walker 2022).

Table 1 reveals that the majority of projects occurred in 2021, 2022, and 2018 (43%, 23%, and 22% respectively), with the most recent ones being completed in 2023. A significant portion of the retrofits carried out in 2021 and 2022 were focused on low-rise buildings, whereas those in 2018 were primarily for mid- and high-rise buildings. Similarly, for projects located in DACs, the distribution aligns closely with the overall trend, with the majority occurring in 2021, 2022, and 2018 (43%, 23%, and 17% respectively), primarily for low-rise buildings. In rural areas, the projects mainly took place in 2021 and 2022, with all projects being for low-rise buildings in this case. On the other hand, we observe that 31% of the recorded projects in the database took less than one month to complete the retrofit work, followed by 20% taking two months, and then 17% of the projects completed the retrofit in less than one year. We can observe this trend for the DACs (34%, 10%, and 6%) and rural areas projects (50%, 26%, and 14%). Recorded projects with a duration of more than one year are typically for mid- and high-rise buildings. Due to the variation in retrofit work years (2010 to 2024) and the variety of locations of the projects across the US, the reported costs (\$), including project and measures, were adjusted to year 2023 using inflation and location adjustment factors sourced from RSmeans (RSMeans 2022). The energy data was converted to kWh units, and then translated into energy costs and CO_2e emissions using average retail energy prices from the US EIA and carbon intensity data from US EPA eGRID. We used the latest data in eGRID from 2021 in our analysis.

In this study, we characterized the energy upgrade projects based on the retrofit types they received, primarily dependent on the energy objectives outlined in the incentive energy programs from which the data was gathered. Consequently, the results do not reveal any discernible pattern or trend in energy upgrades across the US. Each project in this study was classified into up to five retrofit types. The most common energy retrofit types observed in the database were HVAC-focused (30%), DHW (29%), lighting (11%), single-measure projects (9%), and attic insulation (7%). In the case of projects located in DACs, the retrofit types varied as follows: HVAC-focused (46%), DHW (20%), individual measures (9%), lighting (8%) and appliances (4%). Retrofit types for projects situated in rural areas varied as follows: HVAC-focused (22%), DHW (18%), attic insulation (14%), lighting (13%), and individual measures (12%).

Project Total Costs

In our previous single-family energy retrofit cost study, we utilized *cost per floor area* as a reference metric. However, due to the variety of parameters present in this multifamily cost assessment, we have opted to use *cost per unit* as metric. This approach not only facilitates the comparison of our multifamily results but also allows for more a direct comparison with the findings from our previous single-family project.

Table 2. Results of database project cost gross and, including DAC and rural communities.

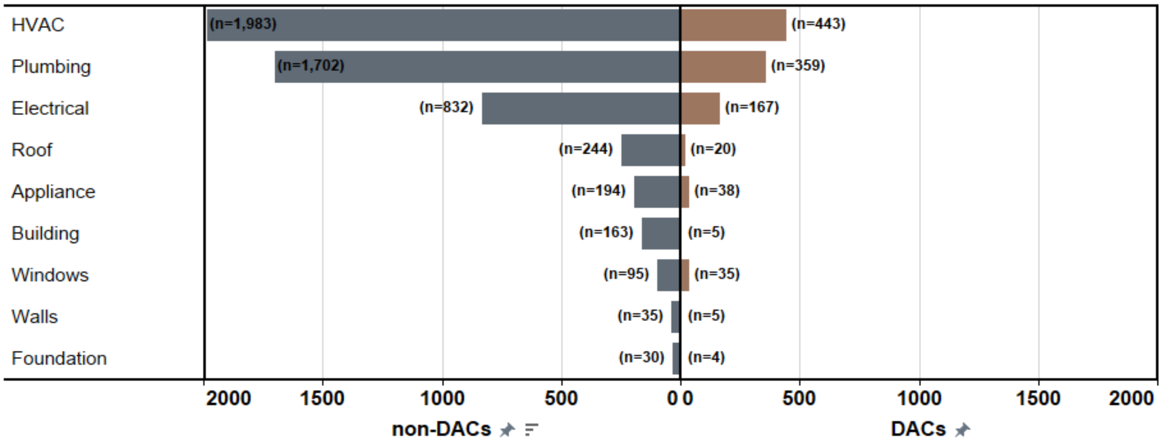
Project Cost	**TOTAL Database**		**Disadvantage Community (DAC)**		**Rural Community**	
	Median	Mean	Median	Mean	Median	Mean
Cost gross ($)	$6,511 (n=3,208)	$124,060 (n=3,208)	$7,257 (n=629)	$105,787 (n=629)	$7,257 (n=602)	$13,306 (n=602)
Cost per unit ($)	$3,319 (n=2,282)	$5,747 (n=2,282)	$2,279 (n=441)	$7,724 (n=441)	$6,171 (n=164)	$6,061 (n=164)
Incentives per project ($)	$1,563 (n=2,924)	$12,268 (n=2,924)	$1,739 (n=590)	$15,715 (n=590)	$1,010 (n=545)	$1,526 (n=545)
Incentive per unit ($)	$760 (n=2,000)	$1,339 (n=2,000)	$1,239 (n=403)	$1,386 (n=403)	$1,681 (n=107)	$1,531 (n=107)
Incentive fraction of project cost gross (%)	24% (n=2,924)	9% (n=2,982)	24% (n=590)	14% (n=590)	14% (n=545)	12% (n=545)
Incentive fraction of project cost per unit (%)	23% (n=2,000)	23% (n=2,000)	54% (n=403)	18% (n=403)	27% (n=107)	25% (n=107)

Table 2 provides a summary of the gross project costs and costs per unit for all projects in the database, as well as results obtained for DACs and rural areas. These numbers provide insights into the cost variations across different types of multifamily projects, offering a comparison between DACs, rural areas, and the overall dataset. The lower median project cost compared to the mean suggests high-cost outliers, likely driven by a few major renovation projects with exceptionally high costs, such as expensive envelope upgrades. While the median costs for projects in DACs and rural areas are the same, the mean cost is notably higher for DACs, suggesting a prevalence of high-cost projects in DACs compared to rural areas. Additionally, the cost per unit is significantly lower in DACs than in rural areas, implying that while overall project costs may be higher in DACs (as reflected in the mean), projects are more affordable per unit in DACs.

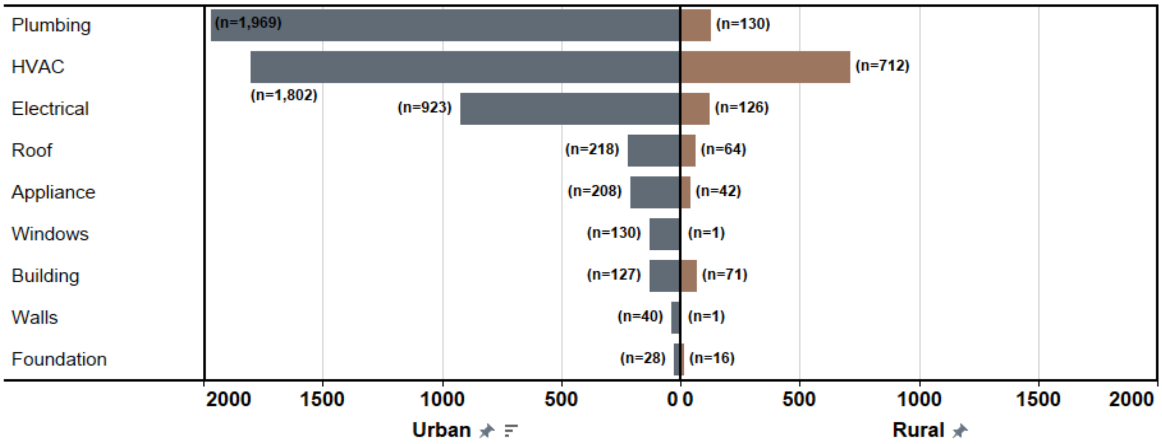
There are a significant number of projects with a single measure: the median number of measures in a project is 1, with a mean of 2.4. This trend remains consistent for the DACs, with a median of 1 measure per project and a mean of 2.3, and similarly for rural areas with a median of 1 measure and a mean of 1.9 per project. This is because the majority of our projects come from energy programs that incentivize single-measure upgrades, particularly focusing on HVAC and DHW work. In addition, it is noteworthy that, as shown in Table 1, most multifamily buildings in the database located in DAC or rural areas were constructed within the last 20 years. This suggests that these projects are potentially driven by the attractive economic incentives provided through energy programs rather than the aging of the buildings themselves. In addition, these newer buildings were built under improved building codes, so they do not require aggressive energy upgrades requiring multiple measures, particularly measures such as envelope insulation.

This study highlights the importance of incentives in the multifamily sector, with a majority of projects benefitting from them. In this study, 91% of the multifamily projects reported receiving incentives to help with the total construction costs. This represents a 28% increase compared to the previous study on single-family buildings. For this study, the median incentive per project accounts for 9% of the average gross project cost. This number is 57% lower compared to the single-family cost study. In DACs, the median incentive represents 4% of the average gross project cost, whereas in rural areas, it is 12%. The lower median incentive compared to single-family buildings suggests potential areas for improvement or further investigation into the effectiveness of incentive programs. Moreover, incentives per project and per unit are higher in DACs, indicating potentially greater support or incentives for DAC projects compared to rural areas. This likely contributes to the lower cost per unit in DACs despite the higher mean project cost. The higher fraction of project costs covered by incentives in DACs emphasizes the role of incentives in cost reduction, particularly in DACs where a larger portion of costs is covered. The higher percentage of the average gross project cost covered by incentives in DACs and rural areas indicates targeted support for these communities, which could be crucial for their development.

Measure Costs



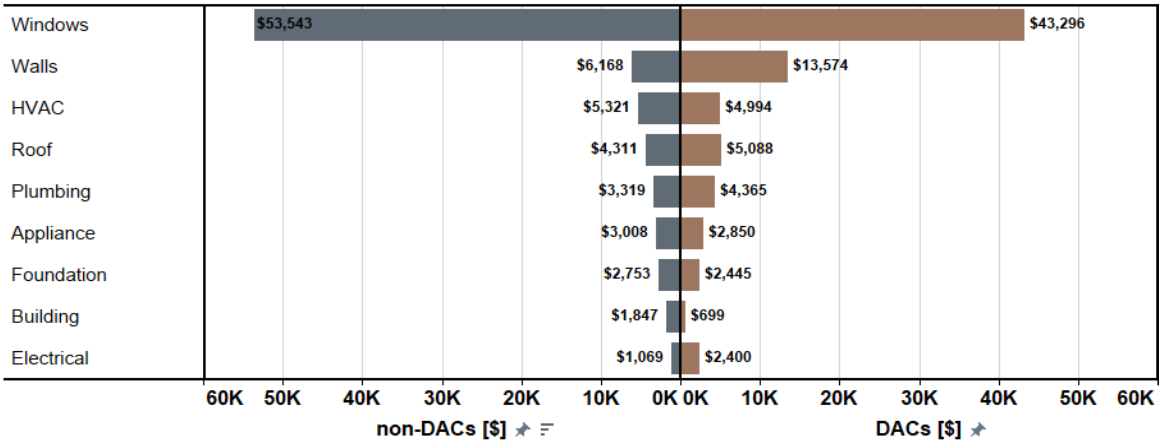
a) The count of recorded measures by section of Non-DACs and DACs



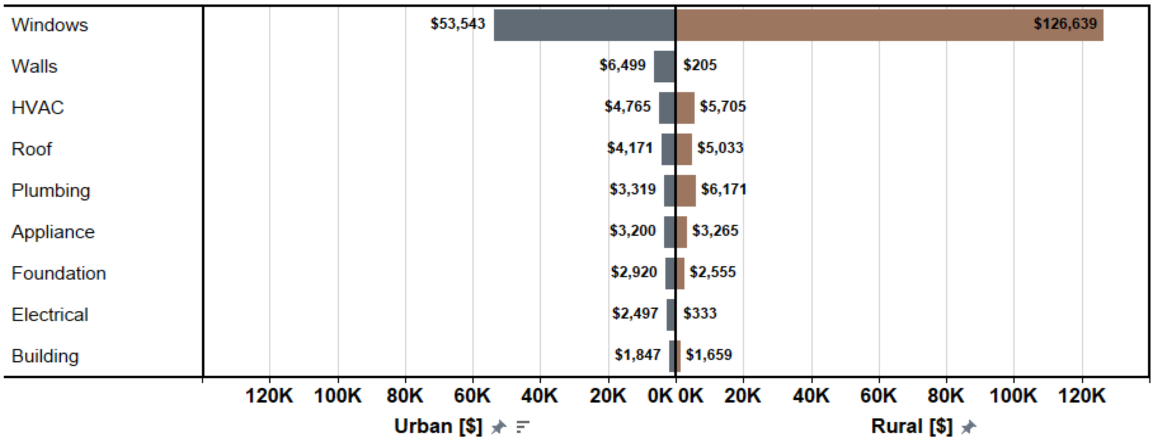
b) The count of recorded measures by section of urban and rural areas.

Figure 2. The count of recorded measures by section: a) Non-DACs and DACs; b) Urban and rural areas.

In this multifamily energy retrofit cost analysis, a total of 6,949 retrofit measures with associated cost data were categorized into sections, as see in Figure 2a (for Non-DACs and DACs) and Figure 2b (for urban and rural areas). The analysis reveals that the most prevalent measures are found within the HVAC and plumbing sections, followed by electrical upgrades, roof improvements, appliance replacements, and upgrades to the building envelope (such as window replacements and wall insulation, among others.). The distribution of measures from DACs follows the same pattern. However, in rural environments, the distribution varies. The majority of measures in this case are allocated to HVAC upgrades (61% of recorded rural measures), followed by plumbing (11%), and electrical upgrades (10%).



a) The median of total recorded costs by section of Non-DACs and DACs.



b) The median of total recorded costs by section of urban and rural areas.

Figure 3. The median of total recoded costs by section: a) Non-DACs and DACs; b) Urban and rural areas.

The majority of the measures of the database pertains to total costs, with limited information available in some cases regarding labor and material costs. The largest expenditures, totaling $148.6 million, were observed in the HVAC, electrical, and plumbing sections, followed by building envelope upgrades focusing on wall, window, roof, and basement improvements, amounting to $51.7 million. The electrical section primarily comprises lighting upgrades, wiring, and PV installation. When all sections related to the building envelope are combined, they amount to 697 measures, compared to 2,518 measures for HVAC, 2,106 measures for plumbing, and 1,053 measures for lighting. These numbers underscore the prevalence of HVAC, plumbing, and electrical work in these retrofit projects, potentially influenced by the incentives provided through energy programs.

For the DACs (Figure 3a), we observe a similar trend as for the non-DACs explained earlier, with a total of $22.9 million spent on HVAC, plumbing, and electrical work, and $6.8 million for sections related to the building envelope. However, there is notable variation in the numbers for the rural areas (Figure 3b). A clear trend emerges in HVAC installation work (n=712) compared to plumbing and electrical work (n=256), which is reflected in the total costs. HVAC work totaled $6.1 million, while electrical and plumbing work totaled $3.7 million. In this case, the building envelope section has a smaller representation. It is important to note that all buildings classified in rural environments of our database are low-rise buildings.

When examining the median of total recorded costs by section for non-DACs and DACs (Figure 3a), we notice a roughly 19% lower median cost in DAC projects. As noted previously, measures related to window replacement tend to be the most expensive. On the other hand, rural areas present a mixed median cost picture compared to projects in urban areas, with some similarities (e.g., appliances) but several deviations (e.g., windows, walls, or electrical). Projects in rural areas show about a 10% lower median cost compared to urban areas (Figure 3b).

Equity Implications of Project Costs and Carbon Savings

To determine the extent to which DAC, rural and other community level characteristics may play a role in project costs and carbon savings, we used *hierarchical multiple regression* and added these variables to the regression model one at a time while controlling for other variables that influence project costs and savings.

Variables Used in the Regression

We developed a model, incorporating various predictor variables that might affect project *costs per unit*. These control variables included the main project retrofit focus (i.e., HVAC, plumbing, lighting, attic insulation, among others), the count of retrofit measures (up to five measures per project), simplified climate classifications (grouped into three categories: cold and mixed humid; marine; hot and mixed-dry), and carbon savings (expressed in Kg of CO_2e saving per unit). Values for the first three variables were extracted or computed from the database. We used the location of the project to determine the Department of Energy climate zone, which was subsequently condensed into three categories for a more streamlined approach. Although building characteristics such as number of stories, vintage and size of building (number of units) may also influence retrofit costs and carbon savings, they were excluded from the regression analysis due to limited data availability.

We integrated the following community type variables into the model to assess their influence: DAC (a binary value of 0 or 1, with 1 denoting location in a DAC according to the White House Climate and Economic Justice Screening Tool), rural area (a binary value of 0 or 1, with 1 indicating location in a rural area according to the U.S. Department of Agriculture's Rural-Urban Commuting Area Codes), and income (a ratio of the census tract's median family income to the median family income of the metropolitan area, if urban, or the state, if rural, utilizing definitions from the U.S. Department of Housing and Urban Development). Some projects had overlap between these factors; for example, almost all projects located in rural areas were also in areas considered as DAC and with a low median income relative to the state median income.

Data Summary, Results and Discussion

This section presents the results of the multiple linear regression, examining the impact of community type characteristics (i.e., DAC, rural and income), on project costs and carbon per unit. These findings offer insights for both project implementation and policy development, aiming towards a more equitable distribution of retrofit costs and benefits to *priority communities*.

Table 3. Results from multiple regression analysis of project costs per unit with control and community type variables

Predictor Variables			**Community Type Variables Incorporated in Model**			
			Model 1 No Community Type Variables	**Model 2** 1 Variable (DAC)	**Model 3** 2 Variables (DAC + Rural)	**Model 4** 3 Variables (DAC + Rural + Income)
Control Variables	Number of measures		576.0**	574.8**	549.3**	554.9**
	Climate type	Cold / Mixed Humid	7050***	7043***	6363***	6325***
		Marine	694.1	689.0	713.9	690.1
	Emissions Savings		0.2573**	0.2575**	0.2532**	0.2531**
Community Type Variables	Disadvantaged Community (DAC)			-16.31	-804.7*	-465.5
	Rural Community				3314***	3213***
	Income					493.6
Model Intercept			242800***	242800***	242900***	242300***
Model R^2			0.7645	0.7645	0.7690	0.7691
Model Adjusted R^2			0.7623	0.7621	0.7665	0.7665

*** indicates statistical significance to the 0.001 level
** indicates statistical significance to the 0.01 level
* indicates statistical significance to the 0.05 level

Table 4. Results from multiple regression of carbon savings per unit on control and community type variables.

Predictor Variables			**Community Type Variables Incorporated in Model**			
			Model 1 No Community Type Variables	**Model 2** 1 Variable (DAC)	**Model 3** 2 Variables (DAC + Rural)	**Model 4** 3 Variables (DAC + Rural + Income)
Control Variables	Number of measures		85.21	99.74	99.78	99.71
	Climate type	Cold / Mixed Humid	2108***	2193***	2195***	2195***
		Marine	452.1***	509.4***	509.3***	509.5***
	Project Cost Per Unit		0.02331**	0.02327**	0.02333**	0.02334**
Community Type Variables	Disadvantaged Community (DAC)			186.7	189.2	18.54
	Rural Community				-10.26	-9.172
	Income					-5.453
Model Intercept			-5543**	-5614**	-5629**	-5624**
Model R^2			0.1521	0.1540	0.1540	0.1540

Model Adjusted R²	0.1442	0.1455	0.1450	0.1445

*** indicates statistical significance to the 0.001 level
** indicates statistical significance to the 0.01 level
* indicates statistical significance to the 0.05 level

The regression analysis was conducted using a subset of the original database due to missing data in the predictor variables for some projects. Within this subset, the most common project focuses were DHW, HVAC, and lighting, with a majority of projects incorporating only one cost measure. On average, these retrofits resulted in 670 kg (1,477 lbs) of CO_2e savings per unit annually. This is lower than the 2,290 kg/year per single family home from our previous study (Less et al. 2021), but this is as expected due to the much smaller size of multifamily dwellings and their reduced envelope loads. On a per project basis, the multifamily retrofits delivered an average of 8,966 kg/year of carbon savings, highlighting the ability to address a larger quantity of units or equipment in a single energy retrofit. Some of the multifamily projects resulted in a net increase in carbon emissions. These projects had some natural gas savings but the increase in electricity consumption outweighed these savings. Regarding geographical and community type, the majority of projects were located in hot/mixed dry, urban areas, and non-DACs. The median income of the census tract where the retrofit took place was similar to the region's median income, and the lowest-income communities had a median income that was 35% of the regional median income.

To evaluate multicollinearity, we generated a correlation matrix. None of the predictor variables showed a high correlation (greater than 0.9) with each other, although it is worth noting that DACs and income have a relatively strong correlation of 0.74. Consequently, when the models with two and three variables showed comparable adjusted r-squared values (indicative of similar strength of correlation), we chose to proceed with the two-variable model for further interpretation due to the high correlation between DAC and income.

Table 3 shows results from adding the community type variables of interest to the model one at a time, as well as the model selected for further interpretation. This selection was based on the highest adjusted r-squared value and multicollinearity considerations as explained above.

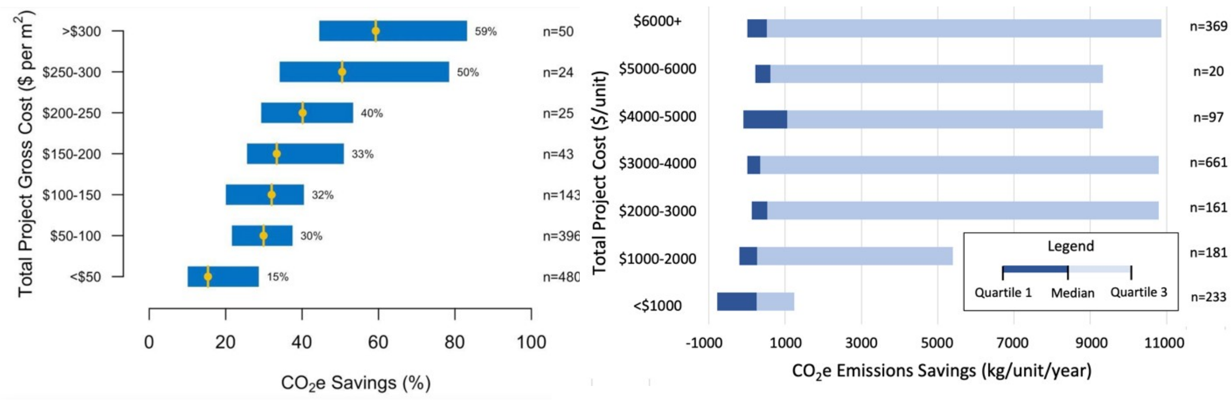


Figure 4. Comparison of carbon savings dependence on energy retrofit project cost for single-family (left) and multifamily (right) databases. (n=number of homes in each cost category)

Regarding predictor variables based on community characteristics, DAC showed a moderate significance level of 0.05. The analysis revealed a negative relationship with project cost, indicating that costs in DACs are generally lower than in non-DACs. On the other hand, the rural or urban classification had a more significant impact on project costs per unit, showing high significance at the 0.001 level. Model 3 shows that even when considering DACs status and other variables, rural status is positively associated with retrofit costs. This aligns with prior findings by (MacDonald, Winner, and Smith 2020), which suggests that rural areas encounter increased barriers to retrofits, including cost-related barriers such as a lack of awareness about financing mechanisms and high cost of transportation and services.

Multiple regression analysis was employed to assess the impact of DAC status and rural status on project carbon emissions savings, measured in Kg of CO_2e. The results of the regression analysis, which controlled for variables including project type, number of measures, climate, and cost, are presented in Table 4.

The presence of community type variables in the model shows no significant relationship with project carbon savings per unit. The analysis found instead that other geographical factors, namely climate type, significantly affect the project carbon savings to the 0.001 level. Project costs were also somewhat significant at the 0.01 level.

In slight contrast to previous single-family building studies, where project cost and number of measures had the greatest influence on carbon savings (Walker, Less, and Casquero-Modrego 2022; Walker et al. 2022), this analysis on multifamily buildings found that while project cost per unit does have a somewhat significant influence on carbon savings, other factors appear to be more important such as the climate type and whether the project is located in a rural community. Figure 4 demonstrates that there is only a weak trend in the carbon savings with increased project costs, and that there is a large range of carbon savings for any given cost per unit. The trend is less apparent for multifamily retrofits than for the previous single family retrofit analysis.

This may be because the cost per home is much higher than the cost per unit. The lowest category for the single-family homes (<\$50/m^2) represents a project cost higher than the highest per unit cost for multifamily, indicating that the single-family homes had much more work done to reduce energy use and emissions. Each binned range of cost for the single-family data is a big enough step to include a major change in household energy use, such as installing a heat pump or air sealing and insulating the home. This is not the case for the small cost increments per unit for multifamily. This could be because multifamily projects can achieve greater cost effectiveness through bulk purchasing technologies that serve multiple units at once.

The multifamily data indicates that higher carbon savings are more attainable with higher project costs, as projects exceeding \$2,000 per unit showed greater carbon savings. However, projects with costs surpassing \$3,000 per unit do not show a consistent increase in carbon savings. This highlights the necessity for careful consideration at the project level to select measures and design features that lead to a reduction in carbon emissions, especially for higher-cost projects.

Overall, the regression results for carbon emissions savings (Table 4) indicate that other factors such as project costs and climate type have a more significant relationship with project carbon savings than community type variables such as disadvantaged community status, and rural areas status. This suggests that retrofit benefits, in the form of carbon savings, may not be as inequitably distributed between priority communities as retrofit project costs.

Conclusions

The costs of multifamily building decarbonization projects, while lower on a per dwelling unit basis are highly variable depending on project scope and selection of measures. This multifamily database comprises a wide range of projects, from one measure up to more than ten measures per project, ranging from installing a new heat pump to retrofitting the entire buildings. The median CO_2e reductions were 670 Kg/unit/year. However, unlike for single family homes, the project cost was not an indicator of CO_{2e} reductions. This implies that there is considerable scope for optimizing multifamily projects to better focus on CO_{2e} savings. This result is primarily because the available data were mostly sourced from energy programs that were focused on single measures. The measures focused on heating/cooling and hot water rather than envelopes. Window and wall measures were very rare due to a combination of high costs and lack of program support based on the programs that supplied data to this study. Of the total 3,208 multifamily projects recorded in the database, the median project cost per unit is $3,319 (mean $5,747/unit). These costs are much lower in terms of costs per dwelling than single-family homes, even when normalized by floor area. Mostly this is because they have less envelope area and lower heating and cooling loads.

DAC status, rural status and income have little impact on project carbon savings, but rural status and DAC status were found to significantly affect project costs. Projects in DACs have lower median cost per unit of $2,279, but a higher mean ($7,724/unit). In rural areas, the median project cost per unit is $6,171 with a mean of $6,061/unit. Given the wide range in costs and high project to project variability it is challenging to conclusively state if costs are higher or lower for DACs, however the results do indicate that projects in rural areas tend to have higher costs. Our analysis suggests more efforts should focus on reducing costs in rural areas, going beyond the DAC definitions currently used by several state and federal programs. HUD's Green and Resilient Retrofit Program (GRRP) represents a good example as it provides funding set-asides for non-metro areas.

In the future this database can be used to guide the development of home decarbonization policies and in technoeconomic analyses. We will also break down the cost and carbon savings estimates by individual measures to determine if there are optimum measures (and/or combinations of measures) for reducing carbon emissions for multifamily dwelling units. If additional data collection is possible, other building-specific factors such as building age that may affect costs and carbon emissions should also be included in the regression. In terms of the distributional equity implications of these retrofits, this analysis provides a starting point for further research considering other socioeconomic and geographic indicators.

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