ResStock Communities LEAP Pilot Residential Housing Analysis - Detailed Methodology

November 2023

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National Renewable Energy Laboratory

Produced for the U.S. Department of Energy by the National Renewable Energy Laboratory (NREL).

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Associated data and full results are available in the NREL Data Catalog: https://data.nrel.gov/submissions/224

List of Acronyms

ACH_{50}	Air Changes per Hour at 50 Pascals
AMI	Area Median Income
EUSS	End-Use Savings Shapes
HUD	Department of Housing and Urban Development
HVAC	Heating, Ventilation, and Air Conditioning
IECC	International Energy Conservation Code
NEC	National Electrical Code
PUMA	Public Use Microdata Areas

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This methodology document supports residential building analysis for some communities receiving technical assistance through the Department of Energy Communities LEAP (Local Energy Action Program). Communities LEAP supports community-wide economic and environmental benefits through technical assistance. This program was open to "…low-income, energy-burdened communities that are also experiencing either direct environmental justice impacts, or direct economic impacts from a shift away from historical reliance on fossil fuels." (U.S. Department of Energy, 2023) Below is a map showing the 24 communities who received assistance, and whether they were a fossil community, environmental justice community, both, or a tribe (U.S. Department of Energy, 2023). Those circled in red are the communities who received a residential building analysis using this methodology.

Figure 1 Map of 24 Communities LEAP communities

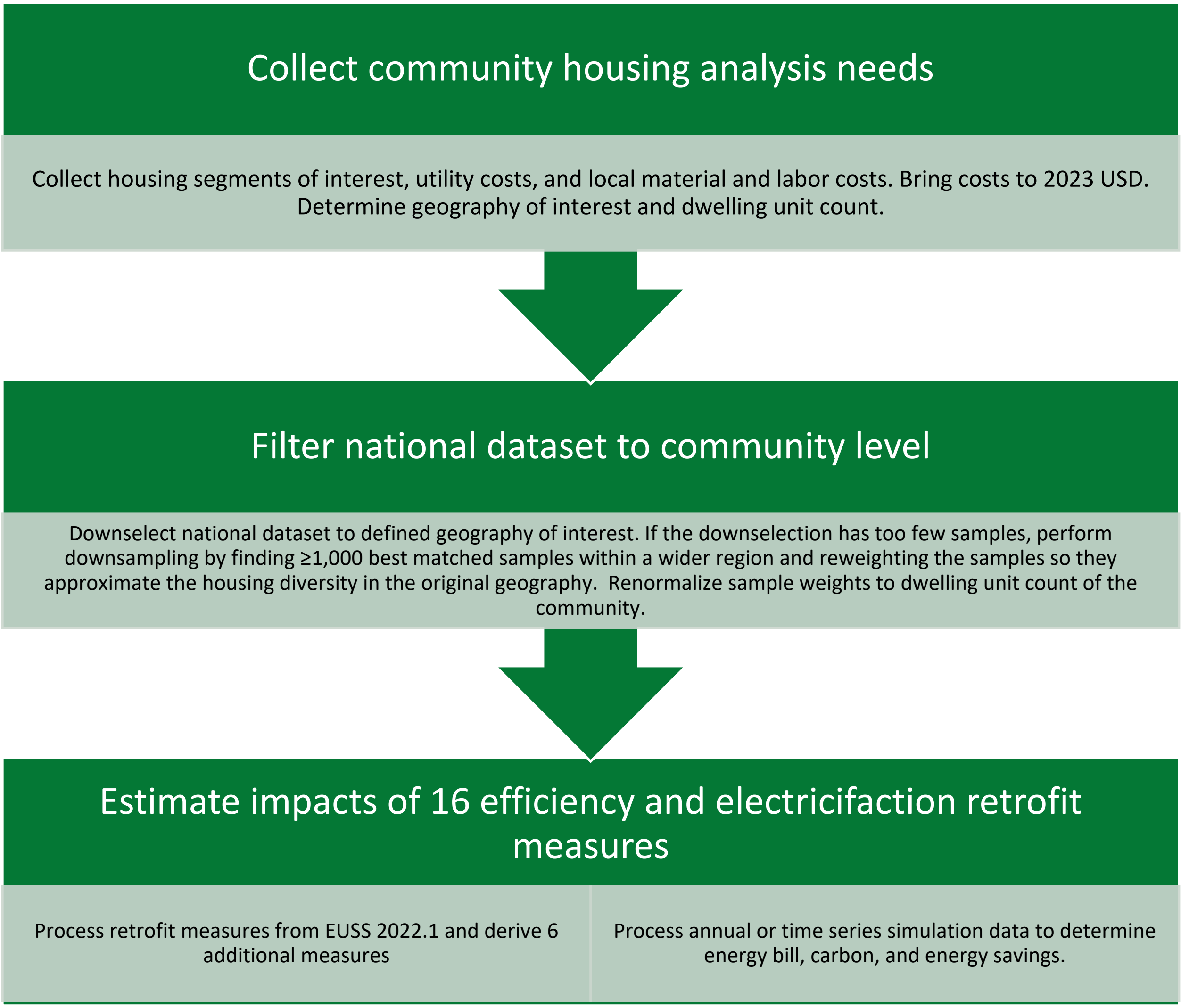

Figure 2 Workflow of the analysis

1 Tools and Datasets

The building analyses provided through the Communities LEAP pilot technical assistance program leveraged the ResStock EUSS 2022.1 dataset, tools, and resources to estimate the potential impacts of the energy efficiency and electrification retrofit packages on communities' housing stock. Table 1 summarizes how each tool was used.

Table 1. Tools and datasets used in the analysis.

Tool / Data Source	General Use	Analytical Output
ResStock EUSS 2022.1	Characterization of housing typology and residential technologies; load and emission profiles pre- and post-retrofit	Prevalence of housing characteristics, energy, and carbon emission savings from retrofit measures
Buildstock-Query (NREL, 2023)	Calculate energy bills	Time of use electricity bill savings and tiered electricity and natural gas bill savings
Panel upgrade calculation (National Fire Protection Association, 2023)	Estimate existing panel sizes in baseline stock.	Estimate percentage of housing that likely requires a higher service panel as part of the retrofit measures
Downsampling algorithm (NREL, n.d.)	Filter national dataset and ensure there are at least representative samples for the geography of interest	≥ 1,000 building samples for the community
2010 Census Tract to 2010 PUMA Relationship File Record Layout (United States Census Bureau, 2021)	Convert 2010 census tracts to 2010 PUMAs	Geographic resolution suitable for analysis
Census Reporter (Census Reporter, n.d.)	Housing unit counts	Number of housing units by county, PUMA, or census tract.
IECC R402.1.3 Insulation Minimum R-values and Fenestration Requirements by Component (International Code Council, 2021)	Housing envelope requirements for new constructions per 2023 IECC	Code compliant metrics for envelope figure
California Building Code Insulation Requirements (RMax, 2022)	Housing envelope requirements for California housing	Code compliant metrics for envelope figure
EPA Greenhouse Gases Equivalencies Calculator (EPA, 2023)	Convert emission savings into a more relatable metrics	Equivalent number of cars taken off road from emission savings
2020 RSMeans Location Factors – Residential (Lane)	Multiplication factor to localize national costs by adjusting for cost-of-living or purchasing power	Cost of living adjustment of retrofit measure costs by nearby city
National Association of Home Builders Cost of Constructing a Home Reports (Ford, 2020) (Lynch, 2023)	Multiplication proxy to convert 2020 upgrade costs to 2023 level based on average change in cost of new construction	Adjustment of retrofit measure costs to 2023 level

Tool / Data Source	General Use	Analytical Output
U.S. Energy Information Administration Weekly Heating Oil and Propane Prices (U.S. Energy Information Administration, 2023)	Residential heating oil and propane costs	Price per gallon of propane and price per therm of natural gas in March 2023

The tools listed in Table 1 were used to combine components of the analysis. San Jose, for instance, wanted to know when electrical panel upgrades would be needed because of electrification. Two service load estimates were performed based on sections of the 2023 National Electrical Code (NEC) to predict whether existing panel capacity is sufficient to serve new electrical loads from the electrification packages. An additional analysis characterized the distribution of changes in electrical peak due to the electrification packages. All three calculations were provided to inform the range of potential electrical panel upgrade needs for San Jose.

Communities were asked to provide local pricing of retrofit measures where possible. If local costs were not provided, default values were taken from the ResStock EUSS 2022.1 dataset, which contains national average pricing as of 2020 costs. These 2020 data sets were updated to 2023 costs. Estimated construction costs from the National Association of Home Builders and RSMeans Location Factors help bring the national costs closer to community level costs. The intent is to provide data at a local level. Federal, state, and local rebates may help lower upfront costs of energy efficiency upgrades. Communities were asked to provide their own utility costs. Electricity rates could either be volumetric, tiered, or time of use. The price of fuel oil and propane, if not supplied by the community, were taken from the U.S. Energy Information Administration database from March 2023 (U.S. Energy Information Administration, 2023).

2 Definitions

2.1 Measure Definitions

A total of 16 energy efficiency and retrofit packages were analyzed for each community's building analysis. Ten of the measures were taken directly from EUSS 2022.1. Six were derived as subpackages from four of the original packages.

The 10 EUSS packages are listed below and described in documentation available online (NREL, 2022) [1]:

1. Basic enclosure
2. Enhanced enclosure
3. Minimum efficiency heat pump with electric heat back up
4. High efficiency heat pump with electric heat back up
5. Minimum efficiency heat pump with existing heat back up
6. Heat pump water heater
7. Minimum efficiency whole home electrification
8. High efficiency whole home electrification
9. Basic enclosure and high efficiency whole home electrification

[1] *End-Use Load Profiles for U.S. Building Stock: Technical Documentation.* Retrieved from OEDI Data Lake: https://oedi-data-lake.s3.amazonaws.com/nrel-pds-building-stock/end-use-load-profiles-for-us-building-stock/2022/EUSS_ResRound1_Technical_Documentation.pdf

10. Enhanced enclosure and high efficiency whole home electrification.

The other six packages are derived from four of the previous ten and include:

11. Electric dryer (clothes dryer from Package 7)
12. Heat pump clothes dryer (clothes dryer from Package 8)
13. Electric cooking (range from Package 7)
14. Induction cooking (range from Package 8)
15. Basic enclosure with heat pump water heater and high efficiency heat pump with electric heat backup (Package 9 without range and clothes dryer)
16. Enhanced enclosure with heat pump water heater and high efficiency heat pump with electric heat backup (Package 10 without range and clothes dryer)

The new packages were derived with the assumption that the interaction is negligible between the end uses being extracted and the end uses that remain. In reality, individual technologies could influence each other through physical interactions. For example, heat pump dryers work by extracting heat from ambient air, which is conditioned by the HVAC system. Therefore, it could reduce cooling load in the summer and increase heating in the winter. However, this interaction is small given that dryer energy consumption represents only a small fraction of a home's total energy use. This is just one example of a system's interaction that could impact the derived packages.

2.2 Area Median Income

Area median income (AMI) was not available in EUSS 2022.1, the ResStock dataset used for this work. A workflow to take publicly available income data from the American Community Housing Survey and convert it to HUD defined AMI bins for each dwelling unit sample was created.

AMI is defined as the midpoint of a specific area's income distribution and is calculated on an annual basis by the Department of Housing and Urban Development (HUD) (Hamann, 2023). To add this metric into the EUSS 2022.1 dataset, the income bins of the dwelling unit samples for each community were converted to representative income values (2019 USD) using a lookup table derived from the 2019 5-year American Community Survey data, the same underlying data that defines the income distribution in ResStock.

Then, the income samples were mapped to the 2019 HUD Income Limits to define the AMI bin (0-80%, 80-150%, 150%+) of the dwelling unit sample. The income samples were matched to the HUD Income Limit data using household size and county. The 2019 HUD Income Limits data is available online (HUD, 2019). If an income limit was not specified in the 2019 HUD Income Limits data, the very low-income values were used to calculate the other income limits, as stated in the methodology document for section 8 income limits by HUD (HUD, 2019). The HUD section 8 income limit methodology document also covers scenarios for when there are more than 8 members in a household.

Here is an example for Richland County, South Carolina. This is the location of a coalition in Columbia, South Carolina. For example, after these calculations, the income for a two-person dwelling unit was calculated as $27,800. After downloading and looking at the 2019 HUD Income Limits for Richland County, South Carolina for a two-person dwelling unit, the 80% AMI level is $44,100. The example income level, $27,800, is below the 80% AMI level for Richland County, therefore the final income bin for this dwelling unit sample would be 0-80% AMI. This mapping is done for each ResStock sample.

2.3 Envelope Definitions

To describe the overall quality of a building envelope, the performance of three building envelope components—infiltration, ceiling or roof insulation, and wall insulation—were blended to create the "combined envelope" metric. Three categories were defined to bucket the envelope component performance levels: Good (modern code performance levels), Fair (comfort issues possible), and Poor (comfort issues likely). Good or modern code performance level was defined by 2023 IECC R402.1.3 or Title 24 based on the climate zone of the communities. Fair and poor were defined by finding the mean rating value of each climate zone's respective baseline housing samples, which is at or below the 2023 code performance levels. The mean values for R-value and infiltration amounts were each determined. Fair values were defined as those above the average value for that climate zone, but below the modern code performance level. Poor values were defined as those below the average value for that climate zone. Individual metric values were calculated for the R-value, the insulation rating, or the infiltration amount (ACH_{50}). The combined envelope metric was determined by the worst performing of the three individual metrics. For example, if a building had good infiltration, fair ceiling insulation, and poor wall insulation, the building was labeled as poor for the combined envelope. This process was done separately for stud walls and masonry walls because they have different code requirements.

Tables 2 through 9 show the definitions of good, fair, and poor for each community. If a community only has two masonry wall values, that means the average value was equal to the code requirement, so there are only two values: modern code performance and below average.

Table 2. Columbia, South Carolina Envelope Definitions

Envelope Metric (unit)	Good	Fair	Poor
Frame wall insulation (R-value)	$x \geq 20$	$8 \leq x < 20$	$x < 8$
Masonry wall insulation (R-value)	$x \geq 8$		$x < 8$
Ceiling or roof insulation (R-value)	$x \geq 49$	$12 \leq x < 49$	$x < 12$
Infiltration (ACH_{50})	$x \leq 3$	$3 < x \leq 17$	$x > 17$

Table 3. Duluth, Minnesota Envelope Definitions

Envelope Metric (unit)	Good	Fair	Poor
Frame wall insulation (R-value)	$x \geq 30$	$14 \leq x < 30$	$x < 14$
Masonry wall insulation (R-value)	$x \geq 19$	$8 \leq x < 19$	$x < 8$
Ceiling or roof insulation (R-value)	$x \geq 60$	$17 \leq x < 60$	$x < 17$
Infiltration (ACH_{50})	$x \leq 3$	$3 < x \leq 14$	$x > 14$

Table 4. Hill District, Pennsylvania Envelope Definitions

Envelope Metric (unit)	Good	Fair	Poor
Frame wall insulation (R-value)	$x \geq 30$	$7 \leq x < 30$	$x < 7$

Envelope Metric (unit)	Good	Fair	Poor
Masonry wall insulation (R-value)	x ≥ 8	5 ≤ x < 8	x < 5
Ceiling or roof insulation (R-value)	x ≥ 60	14 ≤ x < 60	x < 14
Infiltration (ACH_{50})	≤ 3	3 < x ≤ 20	x > 20

Table 5. Jackson County, Illinois Envelope Definitions

Envelope Metric (unit)	Good	Fair	Poor
Frame wall insulation (R-value)	x ≥ 30	7 ≤ x < 30	x < 7
Masonry wall insulation (R-value)	x ≥ 8	5 ≤ x < 8	x < 5
Ceiling or roof insulation (R-value)	x ≥ 60	14 ≤ x < 60	x < 14
Infiltration (ACH_{50})	≤ 3	3 < x ≤ 20	x > 20

Table 6. Lawrence, Massachusetts Envelope Definitions

Envelope Metric (unit)	Good	Fair	Poor
Frame wall insulation (R-value)	x ≥ 30	7 ≤ x < 30	x < 7
Masonry wall insulation (R-value)	x ≥ 13	5 ≤ x < 13	x < 5
Ceiling or roof insulation (R-value)	x ≥ 60	14 ≤ x < 60	x < 14
Infiltration (ACH_{50})	≤ 3	3 < x ≤ 17	x > 17

Table 7. Louisville, Kentucky Envelope Definitions

Envelope Metric (unit)	Good	Fair	Poor
Frame wall insulation (R-value)	x ≥ 30	7 ≤ x < 30	x < 7
Masonry wall insulation (R-value)	x ≥ 8	5 ≤ x < 8	x < 5
Ceiling or roof insulation (R-value)	x ≥ 60	14 ≤ x < 60	x < 14
Infiltration (ACH_{50})	≤ 3	3 < x ≤ 20	x > 20

Table 8. North Birmingham, Alabama Envelope Definitions

Envelope Metric (unit)	Good	Fair	Poor
Frame wall insulation (R-value)	$x \geq 20$	$8 \leq x < 20$	$x < 8$
Masonry wall insulation (R-value)	$x \geq 8$		$x < 8$
Ceiling or roof insulation (R-value)	$x \geq 60$	$14 \leq x < 60$	$x < 14$
Infiltration (ACH_{50})	≤ 3	$3 < x \leq 20$	$x > 20$

Table 9. San Jose, California Envelope Definitions

Envelope Metric (unit)	Good	Fair	Poor
Frame wall insulation (R-value)	$x \geq 9$	$6 \leq x < 9$	$x < 6$
Masonry wall insulation (R-value)	$x \geq 8$	$3 \leq x < 8$	$x < 3$
Ceiling or roof insulation (R-value)	$x \geq 23$	$12 \leq x < 23$	$x < 12$
Infiltration (ACH_{50})	≤ 2	$2 < x \leq 16$	$x > 16$

3 Data Collection

3.1 Energy Costs

Communities provided their local utility energy rates to estimate energy bill savings. Communities could input different electric rate structures of volumetric, time of use, or tiered pricing, along with the average monthly meter charge. Communities were also asked to provide energy prices for natural gas (volumetric or tiered rate + meter charge), propane (volumetric rate only), and fuel oil (volumetric rate only). If propane or fuel oil costs were not provided, state average costs were taken from the U.S. Energy Information Administration from the week of March 27th, 2023 (U.S. Energy Information Administration, 2023).

3.2 Geography of Interest

Each community defined the area of interest for the analysis, ranging from a few census tracts to an entire county. The areas of interest were used to look up the total unit count for the community and converted to PUMAs to down-select from the national dataset. PUMA or Public Use Microdata Areas are nonoverlapping statistical Census areas containing at least 100,000 people (United States Census Bureau, 2022). ResStock can filter to this geographic resolution.

3.3 Housing Segments of Interest

Each community was asked to define a few housing segments of interest for the analysis. Housing segments could be any combination of the following: building type, vintage, wall construction, fuel type, occupancy status, or AMI. For example, one housing segment is single family detached homes built before 1940 with 0-80% AMI occupants. These housing segments, along with the defined geography, were used to "customize" the analysis by filtering out other housing segments. Results aggregated by housing segment are also helpful for comparing the differences in pre-retrofit energy use baseline and subsequent retrofit package scenarios between different groups. For example, comparing the results for low-income housing against stock average or high-income housing results could help reveal electrification opportunities unique to the community. Communities could also choose if vacant housing was included in the analysis. Vacant housing has significantly lower energy use profiles than occupied units, and could skew the results to show lower savings. Columbia, Duluth, Jackson County, Louisville, North Birmingham, San Jose excluded vacant units from their analysis. On the other hand, some communities are keeping vacant units in the analysis as they represent a nontrivial proportion of the stock due to historical disinvestment in the area. These communities include Hill District and Lawrence.

An in-depth analysis of the housing segments of interest are available to each community. Should a community want to know about other housing segments, information is available at the state level through other ResStock tools.

3.4 Estimated Cost of Upgrade Packages

Initial upgrade costs were based on the National Residential Efficiency Measures Database version 3.1.0 (NREL, n.d.) and a 2021 cost characterization study (Less, Walker, Casquero-Modrego, & Rainer, 2021). They represent estimates of national average pricing as of the beginning of 2020. An itemized spreadsheet of these costs was sent to NREL community leads to update as needed. If local costs were not provided, the RSMeans Location Factor and the National Association of Home Builders cost adjustment factors were applied to the default values from EUSS to better estimate the 2023 regional costs.

Even after cost adjustment and review, the estimates do not capture all the nuanced differences and considerations for home electrification upgrade projects. Upgrade costs do not consider other home upgrades that might need to be performed such as lead and mold abatement, structural repair, adding mechanical ventilation, wiring or electric panel upgrades, and more. Some of these upgrades, and their associated costs, may impact LMI and historically disadvantaged communities at higher rates, especially when costs are considered as a fraction of total income (Mayes & Martin, 2022).The costs used in this analysis only represent an estimate of the material cost of the technology in the package and the labor required to install it. The cost estimates also do not include any potential financial incentives or rebates that may be available. Federal, state, and local rebates may help lower upfront costs of energy efficiency upgrades.

4 Model Down-Selection

4.1 Number of Dwelling Unit Samples

A minimum of 1,000 dwelling unit samples were used to describe the community's housing baseline to ensure statistically sound results. The 2020 End Use Load Profiles project suggests that aggregates at that sample size are comparable within a 15% or less discrepancy to those of higher sample sizes (NREL, 2023). In other words, 1,000 samples were sufficient to show the diversity of the stock while maintaining the average trends in the stock.

4.2 Down Selection from National Scope to Geography of Interest

To curate data for each community, the EUSS 2022.1 national dataset was down-selected to the defined geographic boundary of analysis chosen by each community or the "truth" geography. If there were not enough dwelling unit samples after this step, a new down sampling method was employed to search within a wider geographic boundary for samples that best match the characteristics of the geography of analysis (NREL, n.d.). For example, the search could be widened to the county, state, or even climate zone containing the geography of interest. The matching process works to align as many characteristics as possible in this prioritization order: income, climate zone, state, building type, heating fuel, cooling type, tenure, water heater fuel, vintage, floor area, heating type, federal poverty level, and vacancy status.

Once enough samples are found, they are reweighted such that the new sample group has the same or similar distributions of housing characteristics as the original geography of analysis. The samples are reweighted to approximate the diversity of housing characteristics of the "truth" geography. Finally, the sample weights are normalized to the total dwelling unit count of the community.

To further customize the building stock analysis, communities could adjust the "truth" distributions of housing characteristics before they were used to reweight individual building samples. For example, if there is a larger share of multi-family than single family dwelling units observed for the community than what is shown in the down-selected "truth" data, the latter can be adjusted to reflect the desired proportionality of building types.

5 Results and Limitations

Results for each community can be found in their respectively named CSV files. There are two types of results: results aggregated for the whole community (i.e., from all dwelling units within the geography of analysis) and results for each housing segment of interest. Each file contains results for 0-80% AMI as well as for all households regardless of income. Estimates of energy bills, energy consumption, energy burden, emissions, package costs, and a few financial metrics are the types of results presented in the data. Unless otherwise specified, the values represent average values per dwelling unit. Results for a multifamily building are for each unit within the multifamily building. Some of the results are specified in percentiles to show range. P10, P25, P75, and P90 represent the 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentile of the results, respectively.

The carbon saving results were taken from one of the four available emission metrics in EUSS 2022.1 – the Low Renewable Energy Cost scenario where the emissions are levelized at a 3% discount rate for 25 years from 2025. The energy savings were calculated directly from the dataset and the energy bill savings were calculated based on the pricing structure supplied by the community, as described in Section 3.1 Energy costs. Energy burden, a measure of how much gross household income is spent on energy costs, is calculated as a fraction of energy bill to the representative income assigned to each dwelling unit using method described in Section 2.2 Area Median Income.

Energy savings are communicated in a few ways, and one of them is the annual average energy use for the equivalent number of homes. This was done to communicate the energy savings in a more easily understood metric. The annual average home energy consumption was calculated for each community based on the average for all of the down selection samples, and this value was used to convert MMBtu savings into the average number of homes energy use. Below are the annual average energy use values for each community for all income types across all housing types.

Table 10. Annual average energy use per home

Community	Energy Use [MMBtu]	Energy Use [kWh]
Columbia, South Carolina	61.77	18,103
Duluth, Minnesota	147.79	43,312
Hill District, Pennsylvania	69.97	20,418
Jackson County, Illinois	94.67	27,745
Lawrence, Massachusetts	117.40	34,406
Louisville, Kentucky	99.05	29,028
North Birmingham, Alabama	75.39	22,094
San Jose, California	45.29	13,273

This analysis tries to emulate local housing representation and results where possible, however there are some limitations to this work.

- ResStock represents the building stock as it was in 2018.
- Analysis is based on ResStock modeled energy consumption, and all models have uncertainties. For example, discrepancies in assumptions of HVAC setpoints and occupant behaviors could introduce gaps between modeled and realized energy savings for a home upgrade project.
- ResStock models do not account for energy-conserving behaviors (e.g., not using an appliance due to bill concerns), broken equipment, or other housing conditions requiring remediation (e.g., mold and moisture, broken windows), which may be prevalent in some housing.
- Except for one community, the study did not account for other upgrades that may be needed to perform home upgrades, namely, electrical service upgrades.
- Description of the building stock is based on national surveys and datasets, which may hide local unique characteristics that are limited in scale.
- Although this analysis provides comparison of energy differences by AMI, it did not provide the spatial distribution of these impacts by neighborhood due to a lack of smaller geographic resolutions (e.g., census tract or block).
- States/local jurisdictions have local housing codes, which may differ from IECC 2023, which was used for the envelope metric.
- Any assumptions made during EUSS 2022.1 are carried over into this analysis. For example, all heat pumps are modeled with electric resistance backup (except in packages that use existing heating as backup). Centrally ducted heat pumps are sized for cooling, which can produce conservative system sizes in heating-dominant climates.
- Households without existing cooling systems were assumed to use cooling after a heat pump upgrade, which adds a new service and improved thermal comfort, but can also substantially affect the cost-effectiveness of packages due to increased energy usage.
- Costs that were not modified by communities were based on national average information adjusted by a simple proxy to account for cost-of-living differences. In reality, local costs could have more variations from national data and the cost differential could be different between technology options.

- Costs do not include rebates, incentives, or any other financing mechanisms.
- Cost effectiveness calculations were based on full cost of purchasing and installing a technology, rather than the marginal (or incremental) cost of replacement at the failure of existing equipment, that is, the additional cost of a replacement option compared to the incumbent choice of replacing like with like. For example, if a home had an existing electric resistance water heater, the full cost of a heat pump water heater was considered rather than its marginal cost of replacement, which is the full cost of replacing with a heat pump water heater *minus* the cost of replacing with a new electric resistance water heater. The full cost assumption generally leads to more conservative cost-effectiveness estimates; homes with equipment at or near end of life may have more cost-effective opportunities if marginal costs are considered.
- Six of the packages were not modeled directly but derived from larger packages, which may have larger result uncertainties.

The data and associated files are located in the NREL Data Catalog[2].

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