Residential building shell modeling

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Prepared for:

EER Communications

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EVOLVED ENERGY RESEARCH

Agenda

- Background & motivation
- Data sources
- Methodology
- Results

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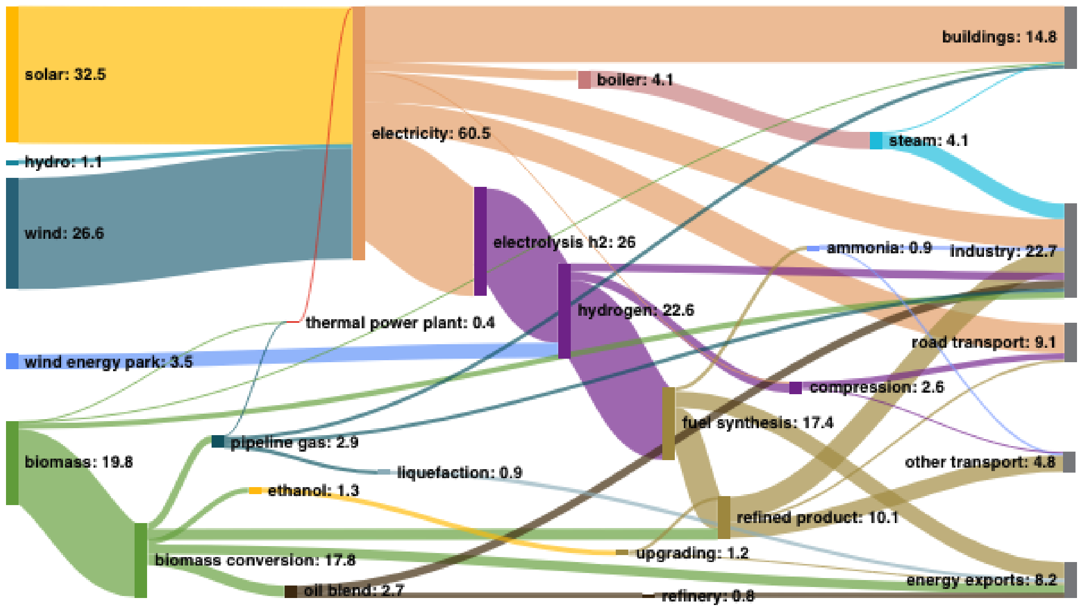
Background & Motivation

Building energy use

- Buildings use a lot of energy even in decarbonization scenarios and building efficiency measures may help meet demand for clean energy reliably and affordably but:
  - There is limited understanding in bottom-up energy modeling of the overall energy impact and cost of making homes more energy-efficient
  - Specifically, improvements to building shells is an uncertain factor in predicting future peak load from heating[1] and thus the cost-effectiveness of building strategies (full-electrification, hybridization, clean fuels, etc.) which features prominently in EER's state and regional analyses

FIGURE 19. Sankey diagram for 2050 100% Renewables scenario (Exajoules)



1 *Energy Pathways for Deep Decarbonization* (2021). Evolved Energy Research. https://www.mass.gov/doc/energy-pathways-for-deep-decarbonization-report
2 *Annual Decarbonization Perspective* (2023). Evolved Energy Research

Current state of residential building modeling

- EER's previous analysis of building shell energy efficiency potential has been relatively coarse and primarily focused on building equipment electrification
  - e.g. replacing gas furnaces and water heaters with electric heat pumps
- In previous modeling work, a 1% per year upgrade rate is assumed for the building stock[3]. This represents that one out of every hundred homes in the existing building stock is upgraded to 2010 energy efficiency standards every year.
- Service demand reductions were based on average savings values across census divisions and building types and the underlying source of these savings was somewhat unclear. This would mean that a house built in 1950 in Maine and a new construction in Massachusetts would see the same percentage impact (i.e. reduction in heating demand)
- The bespoke nature of retrofits means that a connection between cost data and energy savings has been difficult to analyze at the necessary granularity.

3 *Annual Decarbonization Perspective* (2023). Technical Documentation. Evolved Energy Research

Definitions

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- Building shell: the outer structure or envelope of a home, including walls, roof, windows, and doors
- Service demand: the amount of energy required to maintain a desired temperature (i.e. real time demand for heating / cooling)
- Efficiency measure: an upgrade or modification of a building element in order to improve its energy efficiency (e.g. installation of windows, insulation upgrade, air sealing)
- Package: a combination of efficiency measures applied to a home

Research questions

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- What impact do energy efficiency upgrades have on service demand? What benefits do they provide?
- What does it cost to make homes more energy efficient? Which packages are most cost effective?
- What types of buildings should be upgraded first?

Analysis tasks and deliverables

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- Identify data sources for building stock, service demand, and cost impact of retrofits
- Integrate databases into one table for analysis and demand-side model input
- Evaluate the impact on service demand of applying different combinations of upgrade packages to residential building shells
- Evaluate the role and relative importance of residential building shell efficiency measures in decarbonization pathways
- **Deliverables: data table & pipeline, blog post, final presentation**

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Data Sources

ResStock 2024.1 Database

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- Statistical representation of U.S. residential housing stock
- Contains 2.2 million dwelling unit models, each of which is representative of a small subset of the real housing stock (~60 homes)
  - Each model has its own value for each of over 100 building characteristics
- Provides annual estimates of energy consumption, carbon emissions, utility bills, and energy burden[4]
- Evaluates a baseline case and 260 energy efficiency packages
- Packages include combinations of upgrades to building envelope, appliances, pools and spas, lighting, water heating, and HVAC
- Results do not consider existing equipment lifetime, consumer adoption, or any factors that could limit adoption (i.e. equivalent to overnight technical potential)

4 *ResStock Dataset 2024.1 Documentation* (2024). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy24osti/88109.pdf

ResStock Building Shell Efficiency Measures

Name	Description
ENERGY STAR Windows	Replace any less-efficient existing windows with windows that meet ENERGY STAR (v7) criteria.
Thin Triple Windows	Replace any less efficient existing windows with thin triple-pane windows.
Attic Floor Insulation	Increase attic floor insulation to IECC-Residential 2021 levels for dwelling units with vented attics and any lower level of insulation
General Air Sealing	30% reduction in infiltration (ACH50) for dwelling units with greater than 10 ACH50 in the baseline
Duct Sealing	Duct sealing to 10% leakage and R-8 duct insulation for any leakier or less-insulated ducts
Drill-and-fill Wall Insulation	Drill-and-fill wall insulation (R-13) for dwelling units with no wall insulation and wood stud walls
Foundation Wall and Rim Joist Insulation	Add R-10 interior insulation to foundation walls and rim joists in conditioned basements and crawlspaces; seal crawlspace vents
Exterior Continuous Wall Insulation	1” exterior insulation to foundation walls and rim joists in conditioned basements and crawlspaces; seal crawlspace vents
IECC 2021 Air Sealing	Improve dwelling unit infiltration to IECC 2021 air sealing requirements
Roof Insulation	R-30 insulation for less-insulated finished attics and cathedral ceilings
Improved Ventilation	Energy recovery or exhaust-only ventilation added to dwelling units depending on climate zone and ACH50 values.

Building Shell Only Efficiency Packages

Package	Included Measures
2.01 Windows, Thin Triple	• Thin triple windows
2.02 Windows, ENERGY STAR	• ENERGY STAR windows
2.03 Envelope, Light Touch	• Attic floor insulation • General air sealing
2.04 Envelope, Intermediate	• Attic floor insulation • General air sealing • Duct sealing • Drill and fill wall insulation • Foundation wall and rim joist insulation with sealing of crawlspace vents
2.05 Envelope, Advanced	• Attic floor insulation • Duct sealing • Drill and fill wall insulation • Foundation wall and rim joist insulation with sealing of crawlspace vents • ENERGY STAR windows • Exterior continuous wall insulation • IECC 2021 air sealing • Improved ventilation

National Residential Efficiency Measures Database (REMDB)

- Contains residential building retrofit measures and associated costs
- Includes cost estimates for upgrading or modification of appliances, water heating, HVAC, envelope, lighting, and other miscellaneous retrofits
- Provides a range of costs and an average value
- Cost data represents the total cost to implement the retrofit measure including installation costs[5]

Before Component	Properties	Performance Standards	Lifetime
8 ACH50	• Living Space ACH50: 8.0 1/hr		999 Years

After Components	Properties	Performance Standards	Lifetime	Cost [$/ft^2 Finished Floor]
1 ACH50	• Living Space ACH50: 1.0 1/hr	• exceeds IECC 2009 (1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 6C, 7, 8) • exceeds IECC 2012 (1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 6C, 7, 8)	999 Years	1.6
2 ACH50	• Living Space ACH50: 2.0 1/hr	• exceeds IECC 2012 (1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 6C, 7, 8) • exceeds IECC 2009 (1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 6C, 7, 8)	999 Years	1.4
3 ACH50	• Living Space ACH50: 3.0 1/hr	• exceeds IECC 2012 (1A, 1B, 1C, 2A, 2B, 2C) • exceeds IECC 2009 (1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 6C, 7, 8) • meets IECC 2012 (3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 6C, 7, 8)	999 Years	1.2
4 ACH50	• Living Space ACH50: 4.0 1/hr	• exceeds IECC 2012 (1A, 1B, 1C, 2A, 2B, 2C) • exceeds IECC 2009 (1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 6C, 7, 8)	999 Years	0.94
5 ACH50	• Living Space ACH50: 5.0 1/hr	• meets IECC 2012 (1A, 1B, 1C, 2A, 2B, 2C) • exceeds IECC 2009 (1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 6C, 7, 8)	999 Years	0.73
6 ACH50	• Living Space ACH50: 6.0 1/hr	• exceeds IECC 2009 (1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 6C, 7, 8)	999 Years	0.52
7 ACH50	• Living Space ACH50: 7.0 1/hr		999 Years	0.31

Example costs for air sealing.

5 *National Residential Efficiency Measures Database v3.1.0* (2018). National Renewable Energy Laboratory. https://remdb.nrel.gov/

Methodology

Data architecture

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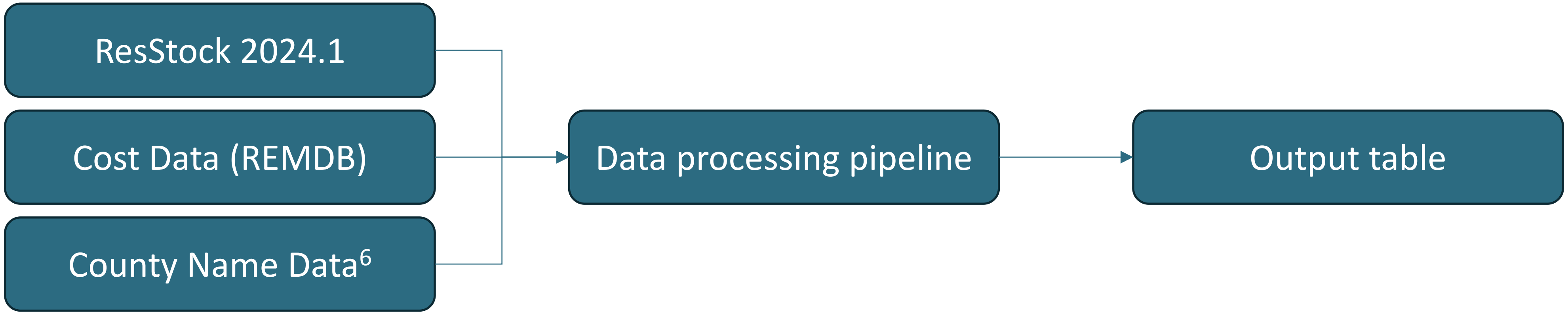

- Output table has one row per dwelling unit + package combination
  - 6 packages x 2.2 million dwelling unit
- Includes building characteristics such as location, vintage, occupants, building geometry, input and upgraded measure attributes (insulation levels, windows, air sealing levels)
- Costs calculated for each individual measure and at the overall package level

6 *Federal Information Processing System (FIPS) Codes for States and Counties.* Federal Communications Commission. https://transition.fcc.gov/oet/info/maps/census/fips/fips.txt

Building attributes

- *Geometry:* square footage, height, attic and foundation types
- *Location:* city, county, climate zone, census division
- *Building type:* number of units, height, ACS and RECs classification, vintage
- *Shell characteristics:* insulation, ventilation, materials
  - Both initial and upgraded characteristics

in.sqft	in.county_name	in.geometry_building_type_recs	in.infiltration	upgrade.infiltration
2179.0	Washoe County	Single-Family Detached	15 ACH50	3 ACH50
2179.0	Tarrant County	Single-Family Detached	15 ACH50	3 ACH50
854.0	Guilford County	Multi-Family with 5+ Units	6 ACH50	3 ACH50
1138.0	Genesee County	Multi-Family with 2 - 4 Units	50 ACH50	3 ACH50
2678.0	Mecklenburg County	Single-Family Detached	6 ACH50	3 ACH50
5587.0	Jackson County	Single-Family Detached	6 ACH50	3 ACH50
623.0	Hennepin County	Multi-Family with 5+ Units	10 ACH50	3 ACH50
881.0	Coffee County	Single-Family Detached	15 ACH50	3 ACH50
1138.0	Essex County	Multi-Family with 5+ Units	20 ACH50	3 ACH50
1228.0	East Baton Rouge Parish	Single-Family Detached	30 ACH50	5 ACH50
634.0	Los Angeles County	Single-Family Detached	25 ACH50	3 ACH50

Efficiency measure specifications[7]

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7 *ResStock Dataset 2024.1 Documentation* (2024). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy24osti/88109.pdf

Window cost assumptions

- *EnergyStar window costs:* chose least costly window in REMDB that met or exceeded EnergyStar Standards
- *Thin tripe windows:* chose least costly window in REMDB with triple panes and U-value and solar gain heating coefficients closest to the specifications

Climate Zone	EnergyStar Window ($/sqft window)	Thin Triple Window ($/sqft window)
Northern	45 (Air, H-Gain, Low-E, Non-metal, Triple)	57 (Low-E, Triple, Insulated, Arg, H-Gain)
North Central	45 (Air, H-Gain, Low-E, Non-metal, Triple)	57 (Low-E, Triple, Insulated, Arg, H-Gain)
South Central	46 (Air, L-Gain, Low-E, Non-metal, Triple)	57 (Low-E, Triple, Insulated, Arg, L-Gain)
Southern	39 (Arg, Double, L-Gain, Low-E, Non-metal)	57 (Low-E, Triple, Insulated, Arg, L-Gain)

** The windows chosen for the Southern / South-central climate zones do not meet the specifications set out in the ResStock documentation, but are the closest available option in the cost database.*

National Residential Efficiency Measures Database. Retrofit Measures for Windows. National Renewable Energy Laboratory. https://remdb.nrel.gov/measures?group_id=16&component_type_id=190

Air sealing cost assumptions

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- Two types of air sealing modifications included in the retrofit packages
  - General air sealing (percent reduction in infiltration) and IECC standards (compliance to a certain ACH level)
- Estimated the cost by calculating the difference in ACH levels between baseline and upgraded levels and then mapping to cost using the delta
  - Cost data in table on this page
  - Costs are extrapolated above a delta of 24 ACH as REMDB only includes a difference in air sealing levels up to that number

Delta ACH	Cost ($/sqft)	Delta ACH	Cost ($/sqft)
1	0.31	**17**	3.7
2	0.52	**20**	4.3
3	0.73	**22**	4.7
4	0.94	**25**	5.3
5	1.2	**27**	5.7
7	1.6	**35**	7.3
10	2.2	**37**	7.7
12	2.6	**45**	9.3
15	3.3	**47**	9.7

National Residential Efficiency Measures Database. Retrofit Measures for Air Leakage. National Renewable Energy Laboratory.
https://remdb.nrel.gov/measures?group_id=10&component_type_id=376

Additional cost assumptions

Measure	Assumptions
Attic Floor Insulation	Fiberglass loose fill insulation
Duct Sealing	Baseline is uninsulated
Drill-and-fill Wall Insulation	Baseline is uninsulated, upgraded to R-13 fiberglass 2 $/sqft exterior wall
Foundation Wall and Rim Joist Insulation	Baseline is uninsulated, upgraded to R-10 XPS rigid foam board 3.1 $/sqft of foundation wall + 1.8 $/sqft of rim joist area
Exterior Continuous Wall Insulation	Baseline is uninsulated, upgraded to R-5 XPS rigid foam board 1.3 $/sqft of exterior wall
Roof Insulation	Baseline is uninsulated, upgraded to R-30 fiberglass 4.3 $/sqft roof
Improved Ventilation	$360 for Exhaust, $1300 for ERV, 72%

* *When multiple options in REMDB complied with the measure specifications, the least costly upgrade was selected*

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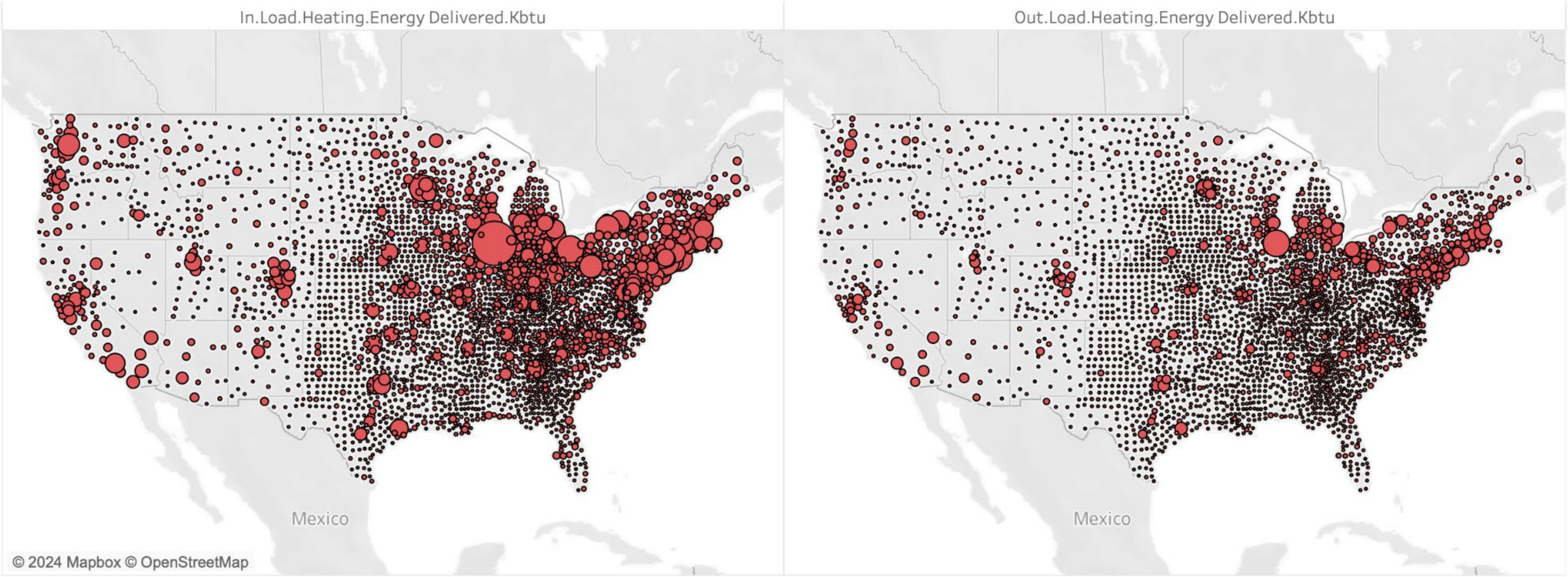
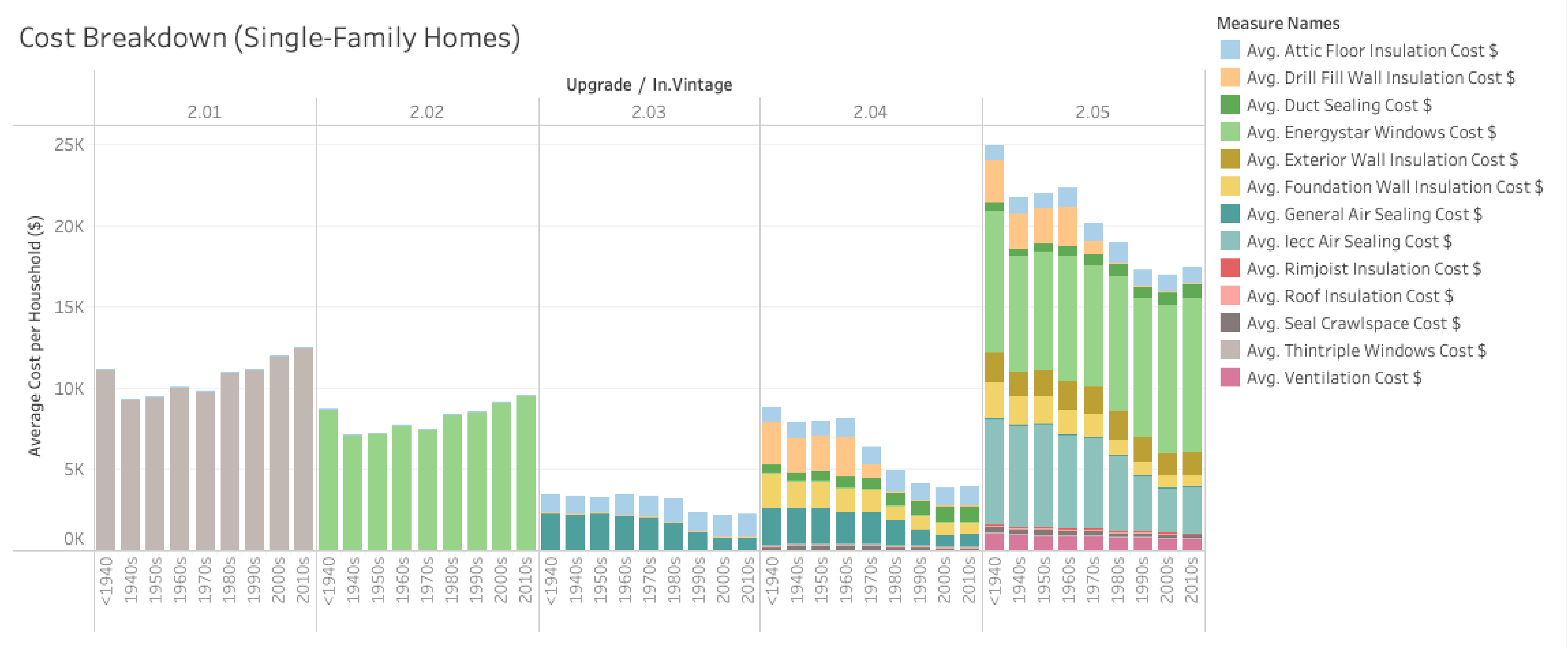
Results

Heating vs. cooling loads

Heating Loads Pre and Post Upgrade (2.05)



Package cost composition



Cost and savings distributions

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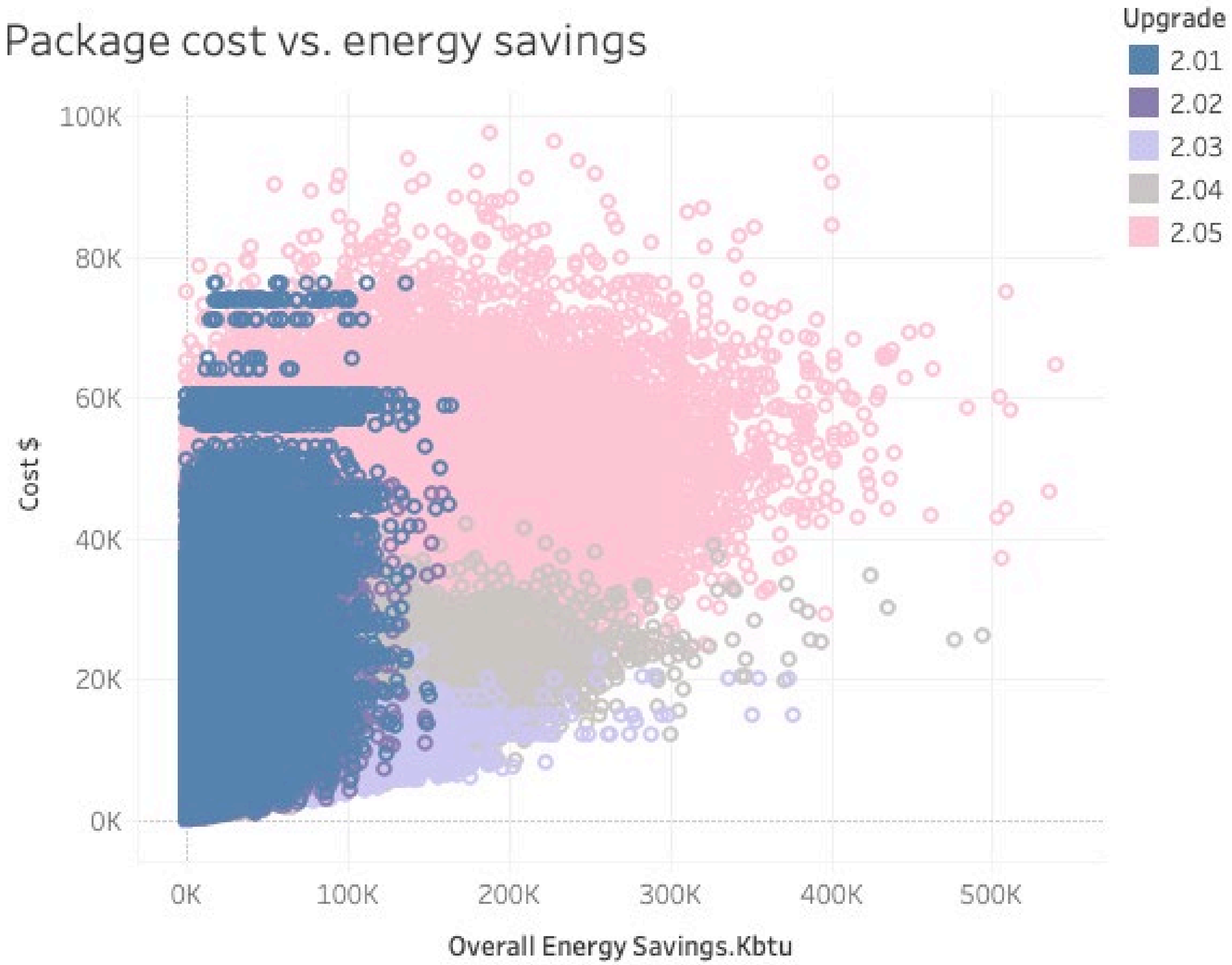
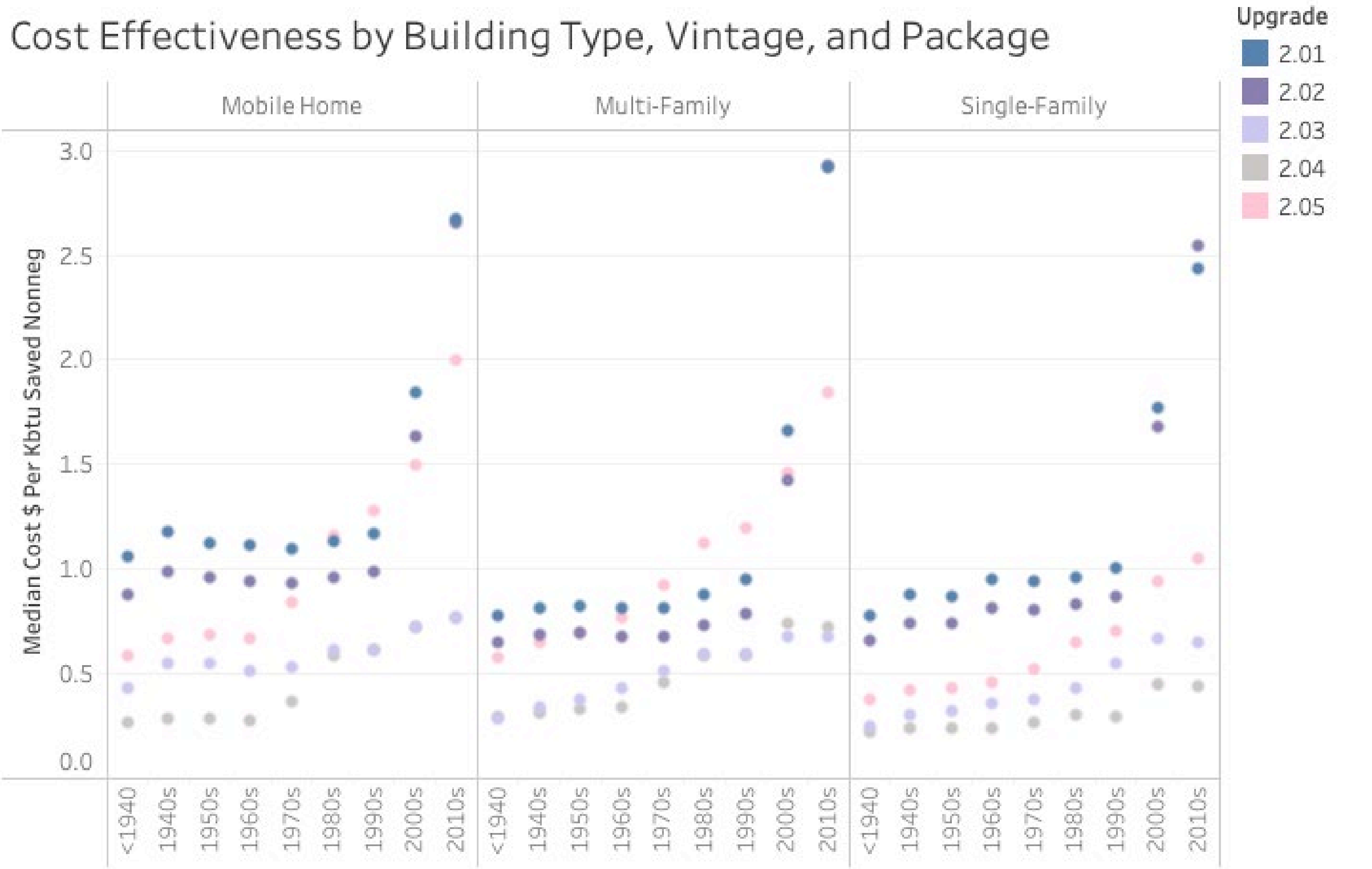
- Savings from window-only packages rarely yield savings above 0.1 MMBtu
- The variability of overall energy savings is large within each package
- Cost distribution can vary widely within packages containing window replacements. The light-touch and intermediate packages are more condensed in cost.



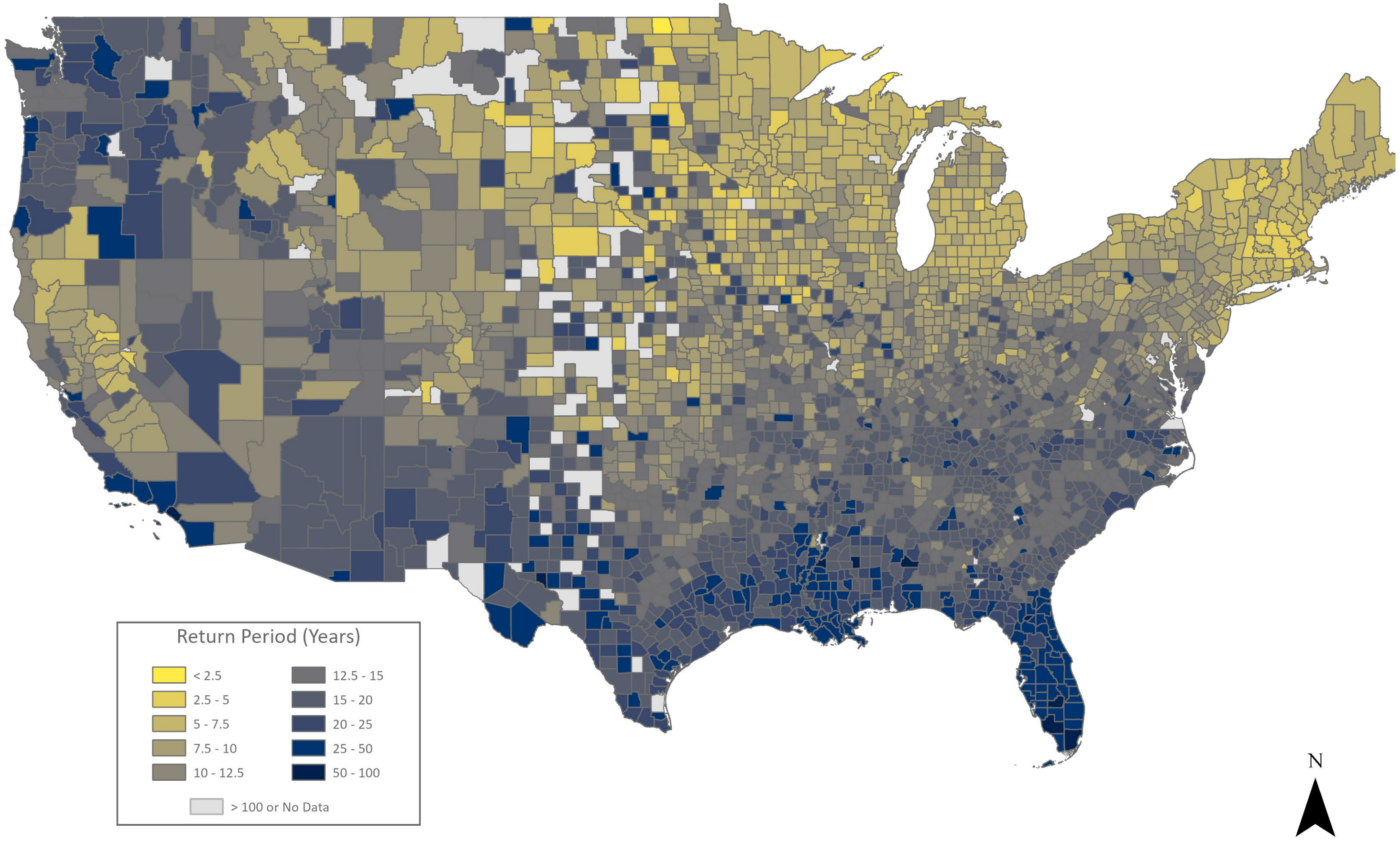
Significance of building type and vintage

- Cost effectiveness is calculated as the cost per kbtu of energy saved compared to the baseline use (both heating and cooling)
- Building vintage is an important factor in determining cost-effectiveness – older structures have more room to improve from a given efficiency upgrade



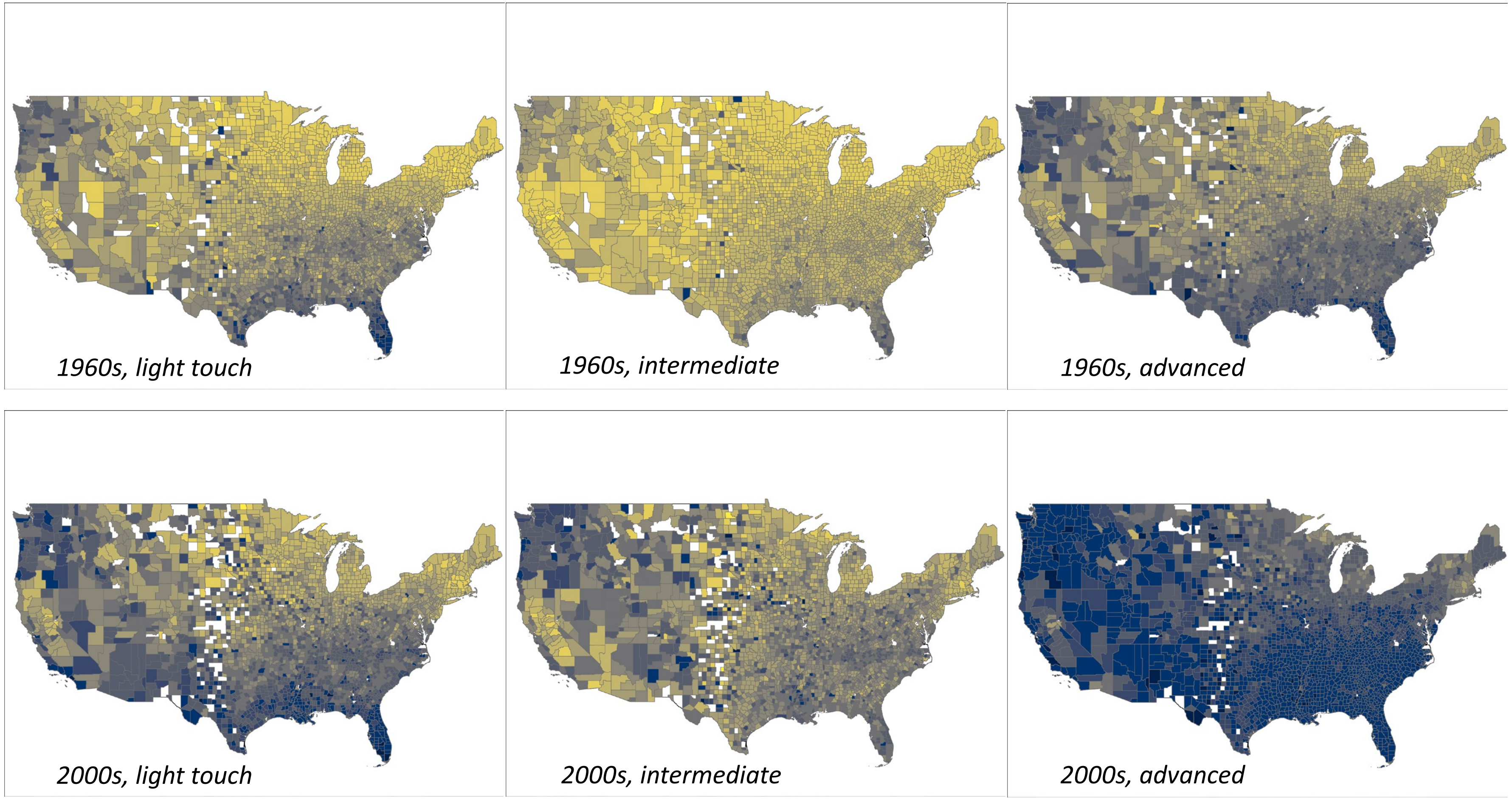
Utility savings payback period

- Payback period is calculated as the time needed for savings on electricity bills to equal the cost of the retrofit
  - Using local utility rates by zipcode[8]
- Significant variation across counties and vintages
- Figure shows the payback periods for light-touch retrofits of residential homes (vintage 2000s)



8 *U.S. Electric Utility Companies and Rates: Look-up by Zipcode* (2021). National Renewable Energy Laboratory. https://data.openei.org/submissions/5806

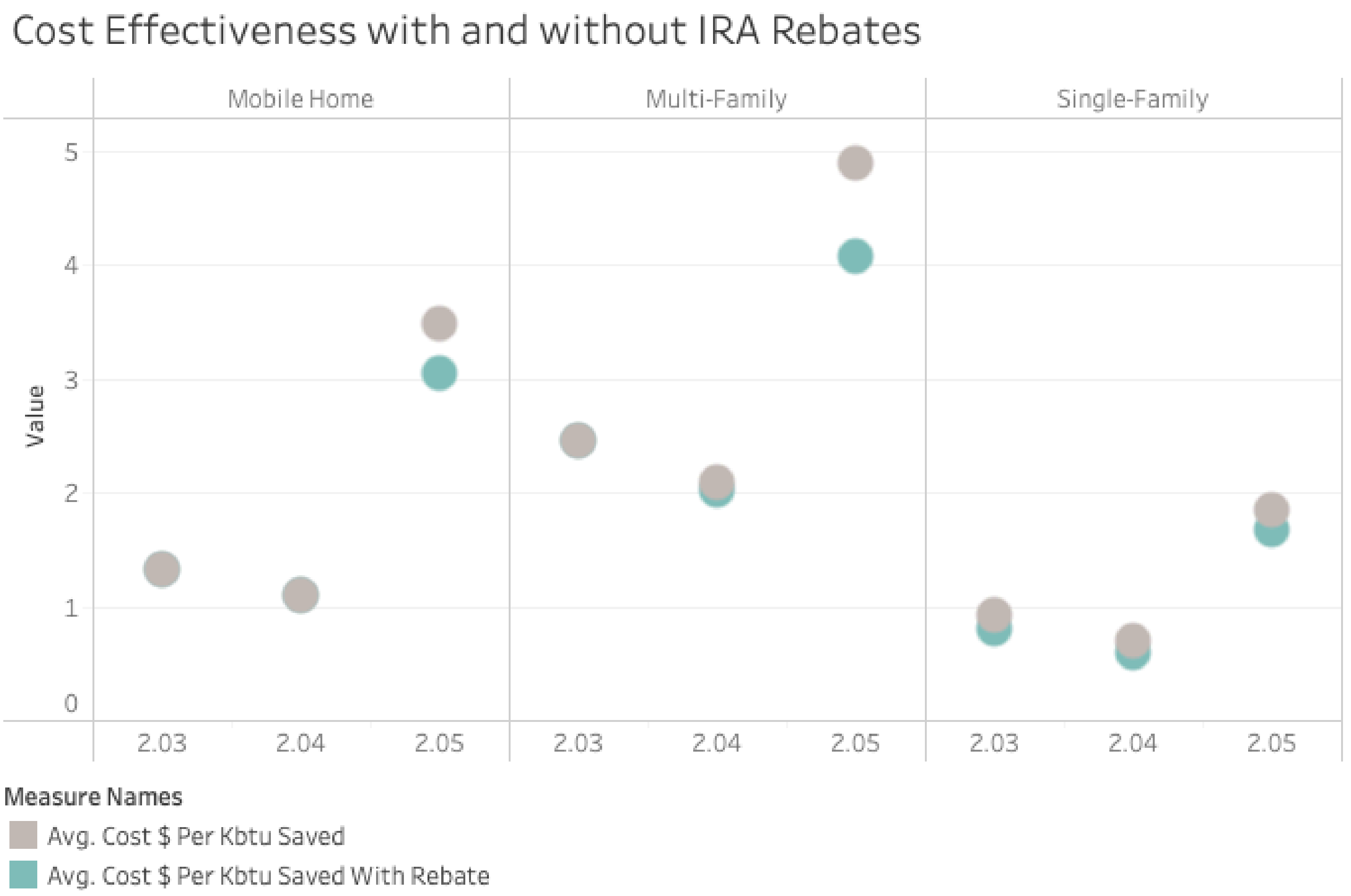
Utility savings payback period



- Intermediate package is most likely to have the smallest payback period, but depends on the county
- There are some places where any retrofit will take more than 10 years to pay back in utility bill costs
- Highlights importance of location

Impact of IRA rebates

- The Inflation Reduction Act (2022) authorized tax credits for 30% of qualified expenses related to home energy efficiency, up to $1200 total[9]
- Rebates have largest impact on the advanced package
  - Includes up to $600 off window costs
- Inclusion of rebates switches the most cost-effective package for only 0.5% of modeled homes



9 *Energy Efficient Home Improvement Credit.* IRS. https://www.irs.gov/credits-deductions/energy-efficient-home-improvement-credit

Takeaways

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- **Window costs matter – a lot**. The installation of more energy-efficient windows is the largest single component of retrofit package cost.
- **Heating vs. cooling.** The energy savings from upgrades can vary depending on whether you're trying to keep your home warm or cool. More savings are realized from homes with larger need for heating
- **Location, location, location.** While the average cost of different retrofit packages ($/sqft) are similar across the U.S., the impacts on energy demand vary widely as a function of building location due to climate and building codes.
- **Age matters too.** Building vintage is a significant indicator of cost-effectiveness: simply put, older structures have more room to improve from a given efficiency upgrade.
- **The intermediate package wins.** Regardless on the amount of savings realized, the intermediate envelope package is likely to give the most bang for your buck spent on retrofitting ($/kbtu saved).
- **Payback periods help give a sense of economics of retrofits.** Depending on location, age, and package, it could take less than 2.5 years to save in utility bills the investment in energy efficiency.

THANK YOU

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Appendix

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- All datasets and code here.