Priorities in building decarbonization:

Accounting for life-cycle carbon and the time value of carbon in cost-benefit analyses of residential retrofits.

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Abstract

Energy consumption in new construction is decreasing thanks to stricter building codes, but few codes limit emissions of existing buildings, particularly in existing homes. This study investigates the carbon- and cost-effectiveness of three decarbonization strategies in residential retrofits: electrifying buildings, upgrading envelopes, and adding renewable energy. Each strategy is further broken down into distinct retrofit interventions to guide homeowners and policymakers in prioritizing energy upgrades. Focusing on single-family homes built before 1980 in Houston, Los Angeles, and Chicago, the study analyzes homes in three cities with distinct climates and grid emission rates. Many studies on building performance upgrades have investigated the operational carbon reductions associated with different retrofit strategies, but embodied carbon, grid decarbonization, and the time value of carbon (TVC) are often omitted. And if those subjects are addressed, they are rarely analyzed all together. Using energy simulation and Life Cycle Assessment, we quantified the life-cycle carbon reduction and Life Cycle Cost associated with each retrofit, ranked the interventions accordingly, and calculated how the rankings would change if electricity grid emission rates decreased or if we accounted for the TVC. Assuming current grid emission rates, envelope retrofits tended to rank better than renewable energy and electrification upgrades in terms of carbon reduction per dollar spent. However, as anticipated emission rates decreased, electrification upgrades improved in rank, while renewable energy upgrades declined. Including the TVC generally caused retrofits with high initial carbon investments to drop in ranking. The results illustrate that considering life-cycle carbon and the TVC has important implications on decarbonization recommendations. Future work could explore policy tools to incentivize different retrofit approaches or propose an appropriate discount rate to more accurately assess the TVC.

Keywords

Decarbonization, energy simulation, Life Cycle Assessment, Life Cycle Cost, time value of carbon, retrofit

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1 Introduction

1.1 Context

Within the building industry, retrofits have been identified as a top priority to achieve a net-zero-carbon building stock by 2050. In fact, some research suggests that the number of deep energy retrofits in the U.S. needs to increase threefold in the next two decades if the U.S. wants to meet its decarbonization goals.[1] The U.S. has long relied on small-scale education campaigns and voluntary uptake to promote energy upgrades, but those strategies have not significantly increased the number of retrofit projects.[2]

Municipalities are beginning to mandate energy upgrades to existing commercial buildings, but there are still major barriers to implementing similar retrofit policies for single-family homes. For example, New York City's Local Law 97 establishes emission limits for all buildings over 25,000 square feet.[3] Owners of buildings that exceed the limit must pay a fine. Implementing legislation like Local Law 97 across the U.S. could provide building performance incentives for 18.1% of the existing building stock by floor area. Comparatively, targeting single-family homes, which represent 54.4% of the existing building stock by floor area, would have a huge impact.[4] However, without subsidies and guidelines on cost-effective retrofit measures, mandating an emission limit for single family homes would also present a significant financial burden to homeowners.[5]

For many reasons, regulating decarbonization of existing single-family homes has yet to gain traction.[6] Even though there are a handful of current or emerging mandatory performance standards for building retrofits, few mandate enforceable or quantifiable carbon reductions, particularly for single-family homes.[7] Considering the lack of guidance around residential decarbonization, this study presents a

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[1] Laski and Burrows, "From Thousands to Billions."
[2] Sebi et al., "Policy Strategies for Achieving Large Long-Term Savings from Retrofitting Existing Buildings."
[3] "Local Law 97 - Sustainable Buildings."
[4] "2015 RECS Survey Data"; "2018 CBECS Survey Data"; "2018 MECS Survey Data."
[5] Cluett and Amann, "Residential Deep Energy Retrofits."
[6] Sebi et al., "Policy Strategies for Achieving Large Long-Term Savings from Retrofitting Existing Buildings."
[7] Nadel and Hinge, "Mandatory Building Performance Standards."

methodology to compare monetary costs and environmental benefits among decarbonization strategies at various grid intensities and at different time values of carbon. The framework demonstrates that including embodied carbon, grid decarbonization, and the time value of carbon, all of which are commonly omitted from studies on building performance upgrades, had a significant impact on which retrofits saved the greatest carbon at the lowest price and therefore which decarbonization strategies homeowners and designers should prioritize.

Carbon drawdown strategies are numerous and varied, but at the building scale, three key strategies stand out: electrifying buildings, upgrading envelopes, and adding renewable energy. All three strategies have received substantial support in recent years. As the "electrify everything" movement has taken off, the proportion of all-electric homes has steadily increased across all regions of the U.S.[8] In the realm of envelope upgrades, many researchers have pointed out that achieving emission reduction targets will require extensive retrofits to existing buildings,[9] and the Biden Administration has recently pledged to invest over three billion dollars toward this effort.[10] Meanwhile, renewable energy has displaced fossil fuels as the least expensive power source, and solar energy has rapidly scaled up as a result.[11] With so many developments in building decarbonization, it can be difficult to know how to prioritize among them.

1.2 Literature Review

Our research explores different ways of evaluating the cost- and carbon-effectiveness of the decarbonization retrofit strategies presented above. Many previous studies that have optimized retrofit packages based on energy and cost reductions have measured buildings' energy performance in terms of source energy (expressed in kWh or kBtu) normalized by floor area.[12] In theory, the source energy metric should capture the effect of different electric grids' fuel mixes, but most energy modeling software, including EnergyPlus and Design Builder, use national averages to convert from site to source energy. As

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[8] Margolies, "'All-Electric' Movement Picks Up Speed, Catching Some Off Guard"; "2015 RECS: Overview."
[9] Laski and Burrows, "From Thousands to Billions"; Sebi et al., "Policy Strategies for Achieving Large Long-Term Savings from Retrofitting Existing Buildings"; Hoicka and Das, "Ambitious Deep Energy Retrofits of Buildings to Accelerate the 1.5°C Energy Transition in Canada"; Pombo, Rivela, and Neila, "Life Cycle Thinking toward Sustainable Development Policy-Making."
[10] "Biden Administration Announces Investments to Make Homes More Energy Efficient and Lower Costs for American Families."
[11] Rosner, "Why Did Renewables Become so Cheap so Fast?"
[12] Cluett and Amann, "Residential Deep Energy Retrofits"; Polly et al., "Method for Determining Optimal Residential Energy Efficiency Retrofit Packages"; Widder et al., "Pilot Residential Deep Energy Retrofits and the PNNL Lab Homes"; Less and Walker, "A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S."

a result, many source energy values are not fine-grained enough to capture variations in total energy consumption based on the specific fuel mix of a particular electric grid.

More recently, retrofit optimization studies have included greenhouse gas (GHG) emissions alongside or in place of the source energy results.[13] The GHG emission metrics are more holistic in that they capture grid impacts and associated carbon emissions, but they often do not include emissions associated with material manufacturing, maintenance, and disposal, often referred to as the project's embodied carbon. As a building's energy efficiency improves, the ratio of embodied carbon to operational carbon increases.[14] One study, for example, found that under current energy performance regulations, embodied emissions account for approximately 20% of life-cycle GHG emissions on average, 45% in high-efficiency buildings, and 90% in the most extreme cases, suggesting the growing importance of accounting for embodied carbon when considering environmental impacts of buildings.[15]

Many studies that do factor embodied carbon impacts measure the impacts in terms of a carbon payback period, or how many years it takes for the retrofit's operational carbon savings to make up for the retrofit's embodied carbon investment.[16] The carbon payback metric is important when weighing environmental impacts, but the absence of monetary information makes the metric less informative for homeowners and policymakers. Of the studies we found that consider both operational and embodied carbon in building retrofits, very few also consider the costs associated with the retrofits. One such study quantifies operational carbon, embodied carbon, and Life Cycle Cost to find the optimal retrofit package for a university laboratory building in Canada.[17] Though our study does not focus on optimization or parametric analysis, our work builds upon this study by taking the metrics of life-cycle carbon and Life

[13] Wu et al., "Multiobjective Optimisation of Energy Systems and Building Envelope Retrofit in a Residential Community"; Ali et al., "A Data-Driven Approach to Optimize Urban Scale Energy Retrofit Decisions for Residential Buildings"; Garriga, Dabbagh, and Krarti, "Optimal Carbon-Neutral Retrofit of Residential Communities in Barcelona, Spain"; Streicher et al., "Cost-Effectiveness of Large-Scale Deep Energy Retrofit Packages for Residential Buildings under Different Economic Assessment Approaches."
[14] Pombo, Rivela, and Neila, "Life Cycle Thinking toward Sustainable Development Policy-Making"; Akbarnezhad and Xiao, "Estimation and Minimization of Embodied Carbon of Buildings."
[15] Röck et al., "Embodied GHG Emissions of Buildings – The Hidden Challenge for Effective Climate Change Mitigation."
[16] Billimoria et al., "The Economics of Electrifying Buildings"; Abd Alla et al., "Life-Cycle Approach to the Estimation of Energy Efficiency Measures in the Buildings Sector"; Hossain and Marsik, "Conducting Life Cycle Assessments (LCAs) to Determine Carbon Payback"; Shirazi and Ashuri, "Embodied Life Cycle Assessment (LCA) Comparison of Residential Building Retrofit Measures in Atlanta."
[17] Sharif and Hammad, "Simulation-Based Multi-Objective Optimization of Institutional Building Renovation Considering Energy Consumption, Life-Cycle Cost and Life-Cycle Assessment."

Cycle Cost and applying them to single-family residences across the U.S.

Additionally, most of the studies that evaluate embodied carbon primarily focus on envelope upgrades that are further grouped into retrofit packages.[18] Few of these studies consider how the optimal retrofit package would change assuming a different grid intensity or include projections for future electricity emissions expected over the life of the building design decision. Though we found one study that considers the impacts of retrofit envelope upgrades under the current grid and two future grid mixes,[19] none of the papers that we reviewed track multiple distinct decarbonization strategies over time to understand how we might evaluate building decarbonization choices both now and into the future. By considering the life-cycle carbon impacts associated with each individual retrofit intervention and each larger decarbonization strategy, our research reveals overarching trends in building decarbonization methods over time.

Similarly, accounting for life-cycle carbon allowed us to capture the upfront impacts from high-carbon material choices and weigh our results to account for the time value of carbon (TVC). The idea that carbon reductions today are worth more than the same level of carbon reductions in the future, can be traced back prior to 2009.[20] The U.S. government uses a similar concept in the development of the Social Cost of Carbon (SCC), which is a dollar estimate of the economic damages that would result from emitting one additional ton of greenhouse gases into the atmosphere. The SCC uses a discount rate to determine how much weight is placed on impacts that occur in the future.[21] And although there has been extensive work to determine the SCC, to our knowledge, applying a similar discount rate to carbon emissions has not yet been explored in analysis of building efficiency upgrades.

In this study, we conduct a sensitivity analysis, using the same range of discount rates as proposed for the SCC, to understand how factoring for the TVC might impact decisions around carbon reductions in the built environment, as described further in Section 2.7. Understanding the TVC for building-related emissions is important if we want to compare design decisions that affect greenhouse gas (GHG) emissions at different times. For example, some design options may emit more GHGs in their

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18 Frey et al., "The Greenest Building: Quantifying the Environmental Value of Building Reuse"; Pedinotti-Castelle et al., "Is the Environmental Opportunity of Retrofitting the Residential Sector Worth the Life Cycle Cost?"
19 González-Prieto et al., "Environmental Life Cycle Assessment Based on the Retrofitting of a Twentieth-Century Heritage Building in Spain, with Electricity Decarbonization Scenarios."
20 "EPA Fact Sheet, Social Cost of Carbon."
21 Rennert and Kingdon, "Social Cost of Carbon 101."

construction but save more emissions in future years through building operations, and we need a way to compare among these options.

2 Methodology

2.1 Project scope

This study investigates the carbon- and cost-effectiveness of three decarbonization strategies in single-family home retrofits: building electrification, envelope upgrades, and adding on-site renewable energy and storage. In the study, building electrification entails installing new electric systems for cooking, water heating, and space heating in place of existing gas-fueled systems. Assumptions about the upgraded appliances' energy performance and embodied emissions can be found in Sections 2.3.3 and 2.4.3. Envelope upgrades include improvements to the home's wall insulation, ceiling insulation, air tightness, and windows per Sections 2.3.4, 2.3.5, and 2.4.4. Lastly, the addition of on-site renewable energy is limited to roof-mounted photovoltaic (PV) systems and battery storage as described in Sections 2.3.6 and 2.4.6. For the purposes of this study, all proposed retrofit interventions are introduced in 2020, and all carbon and cost expenditures incurred between 2020 and 2050 are included in the project scope.

To impact as many existing residential buildings as possible, the study focuses on detached, single-family homes built before the 1980's that have not undergone significant energy upgrades.[22] Federal legislation first required energy standards for new construction in 1978, and many states began regulating building performance shortly after.[23] As a result, homes built before 1980 are less likely to have specific air sealing and insulation materials and practices, contributing to higher levels of energy consumption than homes constructed more recently.[24]

To narrow our geographical scope, we prioritized urban areas in the South, Midwest, and West because those regions had the greatest quantities of housing.[25] We also limited our site selections to cities with high populations, distinct electric grid emission rates, and distinct climate conditions.[26] With the above constraints in place, we selected Houston, TX to represent a city with a mid-range grid emission rate in a hot-humid climate (climate zone 2A), Los Angeles, CA to represent a city with a low grid emission rate in

[22] "2015 RECS Survey Data."
[23] "The History of Energy Efficiency."
[24] "2015 RECS Survey Data."
[25] "2015 RECS Survey Data."
[26] "Urban Areas Facts, 2010."

a temperate, dry climate (climate zone 3B), and Chicago, IL to represent city with a high grid emission rate in a cold climate (climate zone 5A).

2.2 Prototype building assumptions

The U.S. Department of Energy (DOE) supports development of building energy codes and standards. As part of this process, the Pacific Northwest National Laboratory (PNNL) simulates energy savings associated with code changes using a series of residential and commercial prototype models developed in EnergyPlus (EP) v.9.5.[27] All residential prototype models assume the same building dimensions, window placements, occupancy, schedules, and equipment; some such assumptions are laid out in Figure 1. However, several parameters vary based on user selections, per Table 1. This study utilizes the single-family detached house prototype model with site and housing characteristics as indicated in Table 1.

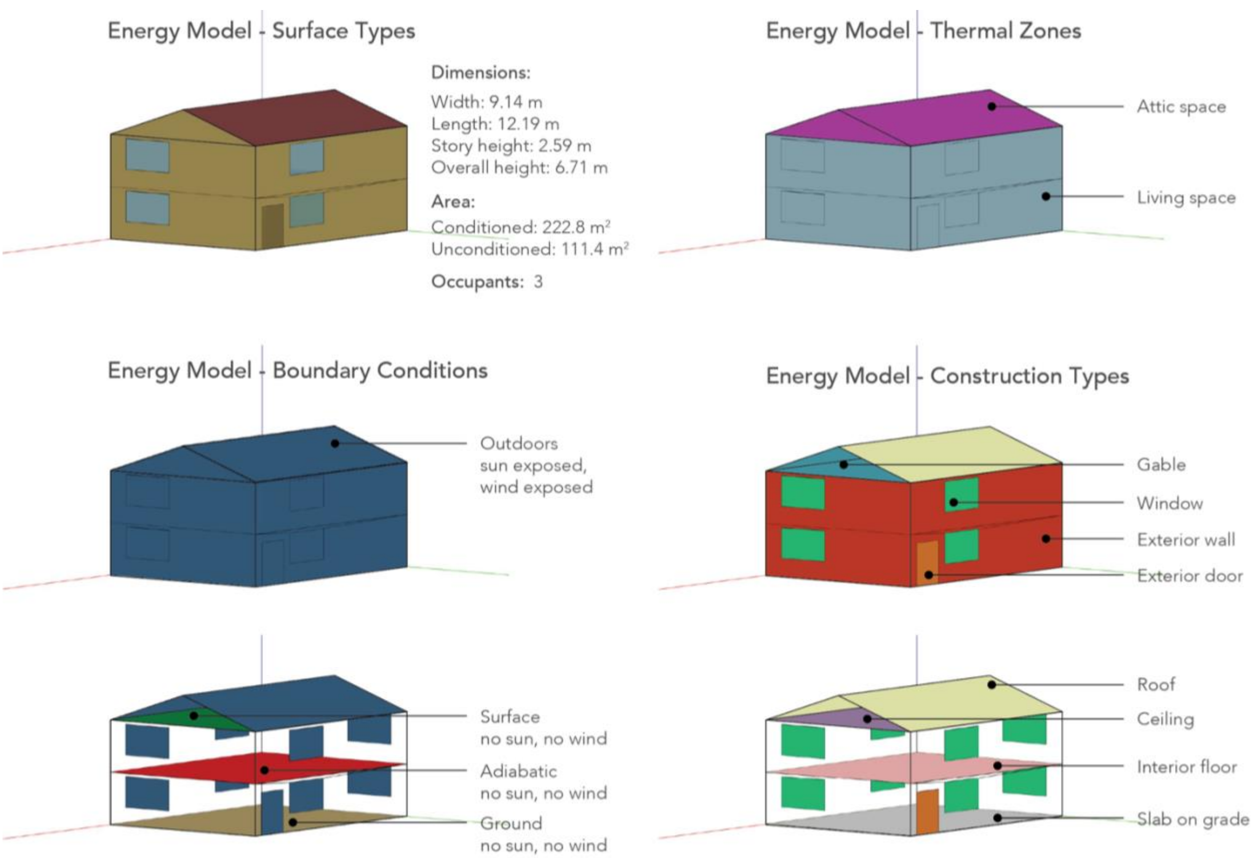

Figure 1. Residential prototype model characteristics. *The above characteristics are default to all residential EP prototype models; all above characteristics were duplicated in the Design Builder energy models as described in Section 2.3.1.*

[27] "Prototype Building Models."

PROTOTYPE PARAMETERS

PROTOTYPE	CLIMATE ZONE	MOISTURE	HEATING	FOUNDATION	IECC YEAR
Multi-family (MF)	1	**A - moist**	**Electric resistance**	**Slab**	**2006**
Single-family (SF)	**2**	**B - dry**	**Gas furnace**	Crawlspace	2009
	3	C - marine	Oil furnace	Heated basement	2012
	4		Heat pump	Unheated basement	2015
	5				2018
	6				2021
	7				
	8				

PROTOTYPE SELECTIONS

Houston, TX: SF	2A	Gas furnace	Slab	2006
Los Angeles, CA: SF	3B	Gas furnace	Slab	2006
Chicago, IL: SF	5A	Gas furnace	Slab	2006

Table 1. Residential prototype model parameters and prototype selections. *The prototype models can be used to analyze buildings with different climates, heating systems, foundation systems, and construction dates. The parameters selected for this study are bolded under "Prototype Parameters," and summarized by region under "Prototype Selections". Decisions regarding the prototype heating and foundation type were chosen based on the most common system by census division across all three selected cities.*[28]

Whereas the prototype models are designed to establish a minimum level of building performance for building code development, this study aims to estimate the energy performance of typical existing homes. To ensure the prototype models' assumptions were consistent with our research goals, we performed a benchmarking exercise that compared the energy consumption of the 2006 prototype energy models to that of comparable homes in the Residential Energy Consumption Survey (RECS) dataset. Developed by collecting housing surveys from across the U.S., the RECS dataset provides estimates on energy consumption of residential buildings based on climate, housing type, construction year, floor area, heating fuel, and number of occupants.[29]

Based on 2015 RECS data, the average single-family, detached household consumed 28,407 kWh/yr. Annually, our 2006 prototype models consumed 32,959 kWh, 26,826 kWh, and 60,952 kWh in Houston, Los Angeles, and Chicago, respectively. The energy consumption reported in RECS was close to that of the prototype models in Houston and Los Angeles. And given that the average RECS energy consumption is approximately 83% higher for very cold regions than for temperate regions, the energy consumption of the Chicago prototype model is feasible, especially considering the RECS energy consumption for single-family, detached housing is averaged over all climates, household sizes, and construction years.[30] We

[28] Taylor, Mendon, and Fernandez, "Methodology for Evaluating Cost-Effectiveness of Residential Energy Code Changes."
[29] "2015 RECS Survey Data."
[30] "2015 RECS Survey Data."

concluded that the energy consumption from our DOE prototype models was reasonably aligned with the energy consumption reported in RECS. The 2006 prototype model was later translated to a model of a pre-1980's home for use in our base case analyses per Section 2.3.2.

2.3 Operational energy

We used Design Builder, a user interface to EP, to quantify the operational energy savings associated with each retrofit intervention in terms of source energy.[31] Site energy was converted to source energy based on standard EP site to source conversion factors, as outlined in the Appendix B. Table 2 summarizes the assumptions for each retrofit intervention in Houston and clarifies which measures fall under which decarbonization strategy.

HOUSTON, TEXAS	BASE	ELECTRIFICATION	SHALLOW ENV	DEEP ENV	PV
ELECTRIFICATION					
Cooking	Gas range (2.5 W/m^2)	Electric range (1.1 W/m^2)	See base case	See base case	See base case
Water heating	Gas boiler (80% efficiency)	Heat pump WH (COP: 3.0)	See base case	See base case	See base case
Space conditioning	Gas furnace (80% efficiency)	ASHP (COP: 4.1 cooling, 2.9 heating)	See base case	See base case	See base case
ENVELOPE UPGRADES					
Windows (W/m^{2}K) *SHGC, VT*	U-6.412	See base case	U-2.270 0.25, 0.66	U-1.05 0.25, 0.66	See base case
Ceiling insulation (W/m^{2}K)	U-0.285	See base case	U-0.251	U-0.100	See base case
Wall insulation (W/m^{2}K)	U-2.555	See base case	U-0.458	U-0.221	See base case
Wall infiltration	0.38 ACH(nat)	See base case	5 ACH50	0.6 ACH50 ERV ventilation	See base case
RENEWABLE ENERGY					
PV	n/a	See base case	See base case	See base case	7.15 kW DC PV
PV and battery storage	n/a	See base case	See base case	See base case	7.15 kW DC PV 5 kW/12 kWh

Table 2. Houston energy model retrofit interventions and performance targets.

We applied each retrofit intervention one at a time to the base case energy model. After running both the base case and retrofit energy models, we took the difference in source energy consumption between the two to quantify the source energy savings associated with that specific intervention. The base case model represents a typical pre-1980's home and was developed by adjusting the 2006 prototype energy models in Table 1 using the process described in Section 2.3.1. Each city had its own set of base case and retrofit models, with slight variations in base case assumptions and target performance values to account for climate differences. We ran the simulations using EP weather files that corresponded to the cities of

[31] *DesignBuilder*.

interest. For simplicity, this paper focuses on the studies associated with the prototype home in Houston, but assumptions and results from the Los Angeles and Chicago studies are further detailed in the Appendix.

2.3.1 Energy model calibration

The first step in developing the base case model was to translate the 2006 prototype model developed in EP to a comparable 2006 energy model in Design Builder. The prototype model's geometry had already been built out in Design Builder and was readily available for our use. For most parameters, we looked up the assumed values in the EP IDF file and input the same value directly into the Design Builder model settings. These directly transferrable parameters included thermal zone assignments, occupant density, occupancy schedules, metabolic rates, clothing levels, domestic hot water (DHW) consumption, heating and cooling setpoints, interior lighting loads and schedules, exterior lighting loads and schedules, construction assemblies, infiltration rates, and glazing assemblies. Some settings including window shades and lighting controls were not included in the EP prototype, so were also omitted from our Design Builder models. Other settings, however, did not directly translate from EP to Design Builder. These settings were more challenging to accurately incorporate into the Design Builder models and included equipment loads and ground modeling.

In EP, equipment loads are highly customizable. Each appliance can be assigned a unique power density, fuel source, fraction of lost energy, fraction of latent energy, fraction of radiant energy, and custom operation schedule. However, in the chosen modeling method in Design Builder, there are only three spots to input different equipment load profiles. To put this into perspective, the EP prototype residential models come with nine distinct equipment load profiles. To address this discrepancy, we grouped EP equipment by fuel type (electric or gas) to fill the first two sets of inputs in Design Builder. All electric equipment utilized the same fuel source, and we averaged the other parameters: power density, fraction of lost energy, fraction of latent energy, fraction of radiant energy, and operation schedules. We followed the same process for the gas equipment. For the third set of inputs, we singled out equipment that would impact energy consumption in a proposed retrofit case. Therefore, we singled out the stove, and values for the stove did not need to be averaged because there was only one piece of equipment in the category.

Ground modeling in Design Builder requires a series of inputs that do not align exactly with the inputs required in EP. In Design Builder, we used the “Ground domain” method to model heat transfer between the ground and the building, assuming the building foundation is slab on grade.[32] From the header of the relevant city's EP hourly weather file, we used ground temperatures at 0.5 m deep to specify "Shallow Monthly Temperatures" and ground temperatures at 2 m deep to specify "Deep Monthly Temperatures". However, per EP documentation, "Monthly Temperatures" should not be based on temperatures provided in the header of .epw files because those temperatures represent undisturbed ground temperatures. For "Monthly Temperatures," a reasonable default value of 2°C less than the average monthly indoor building temperature is appropriate for commercial buildings. For smaller buildings, the ground temperature will be somewhere between that value and undisturbed ground temperatures.[33] To simplify our approach, we followed the methodology for commercial buildings; the implications of this decision are further discussed in Section 4.2. Given that Houston is a cooling-dominated climate, we used the cooling setpoint temperature (23.9°C) from the EP prototype model as the average monthly indoor building temperature.

Once we translated the 2006 EP prototype parameters to comparable inputs in the Design Builder models (assuming the same 2006 construction date), we compared the energy consumption by end use for each model. The comparison results are presented in Table 3. Within each end use category, the difference in energy consumption between the EP prototype model and Design Builder energy model was never greater than 12%. More broadly, the differences in overall energy consumption between the two models never exceeded 3%. With these relatively narrow differences between the two sets of results, we proceeded to develop the pre-1980's base case model in Design Builder.

	HOUSTON			LOS ANGELES			CHICAGO		
	EP	DB	DIFF	EP	DB	DIFF	EP	DB	DIFF
Heating (kWh)	9121	8588	-5.84 %	6957	7396	6.30 %	39007	37815	-3.06 %
Cooling (kWh)	5496	5036	-8.38 %	1832	1618	-11.71 %	1837	1689	-8.10 %
Interior lighting (kWh)	1663	1686	1.40 %	1663	1686	1.40 %	1663	1686	1.40 %
Exterior lighting (kWh)	345	345	-0.07 %	345	345	-0.07 %	345	345	-0.07 %
Interior elec eqpt (kWh)	7052	7024	-0.40 %	7052	7024	-0.40 %	7052	7024	-0.40 %
Interior gas eqpt (kWh)	3228	3215	-0.39 %	3228	3215	-0.39 %	3228	3215	-0.39%
Fans (kWh)	1925	1935	0.56 %	1055	1014	-3.83 %	1800	1788	-0.63%
Water systems (kWh)	4129	4204	1.83 %	4694	4641	-1.13 %	6019	5733	-4.77%
Total (kWh)	**32958**	**32034**	**-2.80 %**	**26826**	**26939**	**0.42 %**	**4.85**	**3.06**	**-2.72%**

Table 3. Energy simulation results by end use after model calibration. *Results from the EP model are compared with those from the Design Builder (DB) model, with the percentage difference between the two as shown (DIFF).*

[32] "Ground Modelling - Standard Method."
[33] "Input Output Reference - EnergyPlus 9.5."

2.3.2 Base case

The base case model represents a typical home built before the 1980's. However, the calibrated Design Builder energy model was based off a home constructed in 2006. We modified the calibrated Design Builder model by updating the simulation parameters to align with the base case characteristics described in Table 2. We also removed elements that likely would not be found in a home built before the 1980's. Specifically, our base case models do not include mechanical ventilation, under-slab insulation, or vertical insulation at the slab perimeter. With regards to the base case envelope, we assumed that the existing walls have no wall insulation and that the homeowners have added some attic insulation since the home was first built. Further assumptions about the assumed insulative properties of the base case envelope are outlined in Table 2.

To estimate infiltration, we referenced a study that reviewed air exchange rates in existing residential buildings.[34] One study in particular compiled air exchange rates in existing homes in Detroit, MI, Elizabeth, NJ, Houston, TX, and Los Angeles, CA. The study provides air exchange rates for the 10th, 50th, and 90th percentile of homes, distinguishing between different infiltration rates in cold and warm weather and for homes with and without central air-conditioning.[35] We used the infiltration values directly from Houston and Los Angeles for the corresponding cities. To estimate air exchange rates in Chicago homes, we used infiltration values from Detroit since it falls within the same climate zone as Chicago. For all cities, we used the 50th percentile air exchange rates. For heating-dominated cities, we used the infiltration rates associated with cold weather in older homes. For cooling-dominated cities, we used the infiltration rates associated with warm weather in homes with central AC. The selected air infiltration rates for Houston can be found in Table 2.

For all residences, we assumed operable windows with 50% operable area at the bottom of the window. Natural ventilation settings allowed for occupant control of windows when beneficial. All homes in the base case models are equipped with gas appliances for cooking, water heating (gas tank water heater), and space heating (gas furnace).

2.3.3 Electrification

The electrification decarbonization scenario encompasses three distinct retrofit interventions: swapping out the base case gas-fueled stove, water heater, and space heating systems for higher-performing electric

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[34] Reichman et al., "US Residential Building Air Exchange Rates."
[35] Isaacs et al., "Identifying Housing and Meteorological Conditions Influencing Residential Air Exchange Rates in the DEARS and RIOPA Studies."

systems. We evaluated each swap individually to understand the energy reduction associated with each system change. We also simulated a retrofit intervention that combines all three swaps, referred to as "electrification all." The original prototype files we used to set up our base case utilized all gas equipment, but there are similar prototype files that simulate a home furnished with all electric equipment. In our electrification energy simulations, we used the specifications for the electric stove and air source heat pump from the electrified prototype model. Similarly, we assumed a new heat pump water heater with a COP of 3.0 to match the water heater specifications in the electrified prototype model.

Our electrified space heating system uses an air source heat pump (ASHP) to warm the house. We utilized Design Builder's Simple HVAC functionality to simulate the performance of the mechanical system. However, there are important differences between how HVAC performance is simulated in EP versus how it is simulated using Design Builder's Simple HVAC functionality. One key difference is that EP uses the manufacturer's stated Coefficient of Performance (COP) as the input to simulate mechanical systems' energy performance. The COP is then varied according to a series of performance curves that relate the COP to other factors such as outdoor air temperature.[36] This means that the COP value found in EP files cannot be used directly with Design Builder's Simple HVAC tool when the system's efficiency varies with environmental conditions. Instead, Design Builder requires a seasonal average COP that accounts for the decreasing efficiency of ASHPs with cooler outside air temperatures.

We calculated the seasonal ASHP COPs specific to Houston, Los Angeles, and Chicago by finding the average outdoor air temperature (T_{amb}) under three conditions: the cooling season, the heating season when temperatures are above 0°C, and the heating season when temperatures are less than or equal to 0°C. To determine the average design condition COP values, we plugged the average outdoor air temperatures for each condition into Equations 1.1 – 1.3 developed by Ruhnau et al, below: [37]

$$COP_{mfr} = 6.08 - 0.09 * \Delta T + 0.0005 * \Delta T^2 \quad (1.1)$$

Where, COP_{mfr} – ASHP COP as reported in manufacturer documentation;

ΔT – Difference in temperature between the heat sink and heat source per Equation 1.2 ($°C$).

[36] "Performance Curves: Engineering Reference — EnergyPlus 8.0."
[37] Ruhnau, Hirth, and Praktiknjo, "Time Series of Heat Demand and Heat Pump Efficiency for Energy System Modeling."

$$\Delta T_{sink,source} = T_{sink} - T_{source} \tag{1.2}$$

Where, T_{sink} – Heat sink temperature, assuming radiator heating per Equation 1.3 ($°C$);

T_{source} – Heat source temperature; for ASHP, the ambient air temperature is directly used ($°C$).

$$T_{sink} = 40°C - 1.0 * T_{amb} \tag{1.3}$$

Where, T_{amb} – Ambient air temperature ($°C$).

We then multiplied the design condition COP values by 63% based on findings that design condition heat pump performance can differ substantially from installed heat pump performance.[38] When temperatures were less than or equal to 0°C, we assumed the heat pump no longer provided a sufficient heat supply, and the system switched to electric resistance heating with a COP of 1. We then found the weighted average among the two heating season conditions to arrive at the seasonal COP for the total heating season using Equation 2. For the cooling season COP, the installed COP was the same as the seasonal COP because we assumed the efficiency of the heat pump was not changing substantially with the warmer outside air temperatures. The COP values for each season and site are summarized in Table 4, below.

	SEASON	# HOURS	AVG TEMP	MFR COP	INSTALLED COP	SEASONAL COP
HOUSTON						
Cooling season	Mar. – Nov.	6600	22.868 °C	6.58	4.14	4.14
Heating season (>0℃)	Dec. – Feb.	1992	12.567 °C	4.85	3.06	-
Heating season (≤0℃)	Dec. – Feb.	168	-2.023 °C	1	1	-
Heating season	Dec. – Feb.	2160	11.432 °C	-	-	2.90
LOS ANGELES						
Cooling season	Apr. – Nov.	5856	18.028 °C	5.73	3.61	3.61
Heating season (>0℃)	Dec. – Mar.	2904	13.915 °C	5.06	3.19	-
Heating season (≤0℃)	Dec. – Mar.	-	-	-	-	-
Heating season	Dec. – Mar.	2904	13.915 °C	-	-	3.19
CHICAGO						
Cooling season	May – Sept.	3672	19.959 °C	6.07	3.82	3.82
Heating season (>0℃)	Oct. – Apr.	3063	7.442 °C	4.14	2.61	-
Heating season (≤0℃)	Oct. – Apr.	2025	-5.262 °C	1	1	-
Heating season	Oct. – Apr.	5088	2.386 °C	-	-	1.97

Table 4. Air source heat pump heating COP values. *Seasonal COP values are calculated by weighting temperature-specific COP values based on hours ambient air temperature is above- and sub-zero.*

[38] Schoenbauer et al., "Field Assessment of Cold Climate Air Source Heat Pumps."

$$COP_{avg\_htg} = \frac{hrs_{gt0}(COP_{gt0}) + hrs_{lt0}(COP_{lt0})}{hrs_{gt0} + hrs_{lt0}} \tag{2}$$

Where, COP_{avg_htg} – Total weighted average for the seasonal, manufacturer-given COP in the heating season;

COP_{gt0} – Average design condition COP when outside air temperature is greater than 0°C;

COP_{lt0} – Average design condition COP when outside air temperature is less than 0°C;

hrs_{gt0} – Number of hours outside air temperature is greater than 0°C (hrs);

hrs_{lt0} – Number of hours outside air temperature is less than 0°C (hrs).

2.3.4 Shallow envelope retrofits

Like the electrification decarbonization scenario, the envelope upgrade scenario includes many different retrofit interventions – improved ceiling insulation, wall insulation, windows, and infiltration – all of which we applied to the base case on an individual basis. There is also a retrofit intervention that includes all interventions, referred to as "shallow all," and one that includes all interventions except the window upgrades, referred to as "shallow envelope." All design targets that fall under shallow envelope retrofits are intended to be minimally invasive and do not require removing or replacing existing roofing, cladding, or finishes. The target values for all retrofit interventions are outlined in Table 2, but we explain the assumptions behind the values in more detail below.

Proposed parameters for the envelope upgrades are borrowed from a variety of regulations, standards, and guidelines. For example, the 2021 International Residential Code (IRC) determines the infiltration rate and window specifications for the shallow retrofits. The infiltration target of 5ACH50 can be achieved fairly easily using standard air sealing techniques, and the IRC had the least restrictive window specifications of the standards we reviewed.[39] EnerPHit, the Passive House certificate for retrofits, has stringent requirements for infiltration and window performance, but acknowledges the difficulty of adding insulation to existing structures.[40] For this reason, EnerPHit proposes easily achievable ceiling U-values, which we used for our shallow ceiling insulation design targets. We determined the target U-value for wall insulation based on the U-value from filling the wall cavity (assuming true 2x4 framing) with spray-in cellulose. Any additional wall insulation would have required removing wall cladding or

[39] Fitzgerald-Redd, "Getting 3 ACH50 Without Breaking the Bank"; *2021 International Residential Code (IRC)*.
[40] "Criteria for the Passive House, EnerPHit, and PHI Low Energy Building Standard."

damaging interior finishes and would not have qualified as a shallow envelope upgrade.
For the energy simulations, we varied the wall and ceiling U-values as necessary to meet the target values per Table 2. For the window glazing specifications, the IRC specifies a maximum Solar Heat Gain Coefficient (SHGC) for Houston and Los Angeles but does not specify a Visible Transmittance (VT) that would realistically work with the specified SHGC. Because low SHGC values often require darker tinted glass, we used LBNL Window 7.7 to find a realistic maximum VT value that would work within our constraints on SHGC.[41] This was important because lower VT values can decrease the level of daylight that reaches the interior spaces and consequently increase the artificial lighting loads.

2.3.5 Deep envelope retrofits

The deep envelope retrofit interventions include the same measures as the shallow envelope upgrade scenario but have different target values associated with each intervention. Whereas the shallow envelope retrofits are intended to be as minimally invasive as possible, the deep envelope retrofits are meant to maximize energy reductions without considering how impractical the upgrade may be to the homeowner. For this reason, we used the Passive House guidelines for new construction to set the target values for each intervention. Since Passive House did not specify prescriptive requirements for the building envelope at the time the research was conducted, we used the Prescriptive Snapshot map to find residential projects in the region of interest and used the specifications from projects in the region as our target values as shown in Table 2.[42]

Many of the methods described in Section 2.3.4 for shallow envelope retrofits, including assigning insulation U-values for energy simulation and assigning VT values for window glazing, also apply to the deep envelope retrofits. Unlike the IRC, Passive House does not specify maximum SHGCs for any of the cities in our study. However in many cities, homeowners must comply with the IRC to the extent possible to secure building permits for renovation work. As such, we also included the maximum SHGC values in our deep retrofit window interventions. Passive House does include a minimum SHGC value for Chicago to encourage passive heat gain. We included the minimum SHGC value in our target window specifications, but it did not have an impact on the proposed VT values.

The deep envelope retrofits differ from the shallow envelope retrofits in the realm of infiltration. Because of the higher air exchange rate and lower insulation levels in shallow envelope retrofits, we did not

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41 *WINDOW*.
42 "PHIUS 2021: Emissions Down, Scale Up."

observe unwanted heat gain in the shallow retrofit cases. However, the very low infiltration rate and high insulation levels in the deep envelope scenario result in a very tight envelope. As such, the deep envelope retrofits need to be paired with additional mechanical ventilation to avoid unwanted heat gain and maintain healthy air quality. Any time the infiltration rate of 0.6 ACH50 was used, we assumed the household would need to add an ERV system for adequate mechanical ventilation. We matched the ERV specifications from the 2006 electrified prototype model whenever mechanical ventilation was needed. Additionally, achieving an infiltration rate of 0.6ACH50 is extremely difficult and would only be feasible if the existing cladding was removed and replaced. Therefore, the deep infiltration intervention never stands on its own; it is always paired with upgrading the wall insulation to Passive House levels per Table 2. The deep infiltration intervention is encompassed in the "deep envelope" and "deep all" retrofit cases.

2.3.6 Renewable energy

There are two retrofit interventions associated with the renewable energy decarbonization scenario: addition of a photovoltaic (PV) system, and addition of a PV system with battery storage. To model the electricity generation from added PVs, we applied a DC PV system with an assumed efficiency of 19.7% to the base case Design Builder energy models.[43] Each energy model assumes a 7.15 kW PV system with 23 photovoltaic (PV) panels, measuring approximately 1.65 m long by 1 m wide. The PV array covers 37.6 m^2 of the energy model's 58.8 m^2 roof, and there is a total of 117.6 m^2 of roof area available. The modeled extents of the PV array are illustrated in Figure 2.

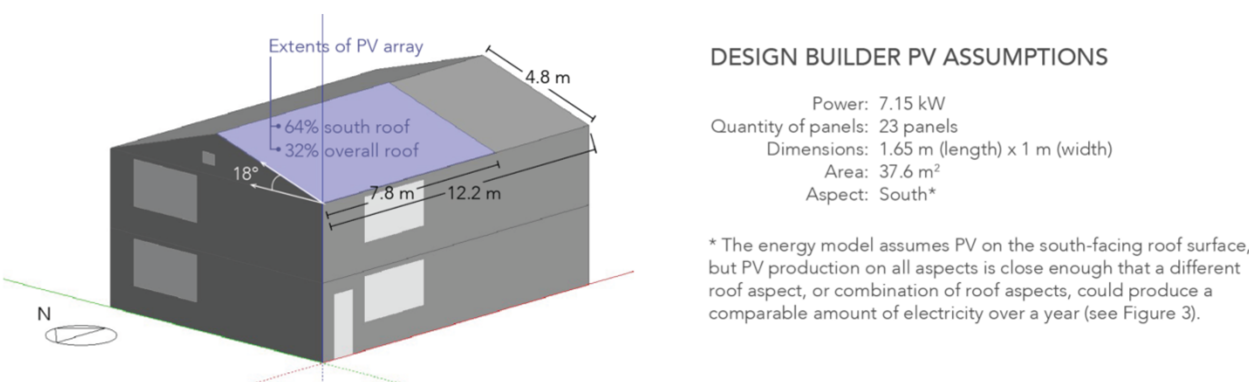

Figure 2. Extents and placement of PV array in Design Builder energy model.

Though the energy model assumes PV on the south-facing roof surface, the solar radiation on all roof aspects is close enough to that of the south-facing aspect that a different roof aspect, or combination of different roof aspects, could generate a comparable amount of electricity over a year to the modeled PV

[43] Ramasamy et al., "U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks."

array. Monetary costs and embodied emissions associated with the PV array were all based on the PV being installed on the south-facing roof as shown in Figure 2. The range in solar radiation by roof aspect is illustrated in Figure 3. The potential electricity generated is proportional to the amount of solar radiation that each roof aspect receives.

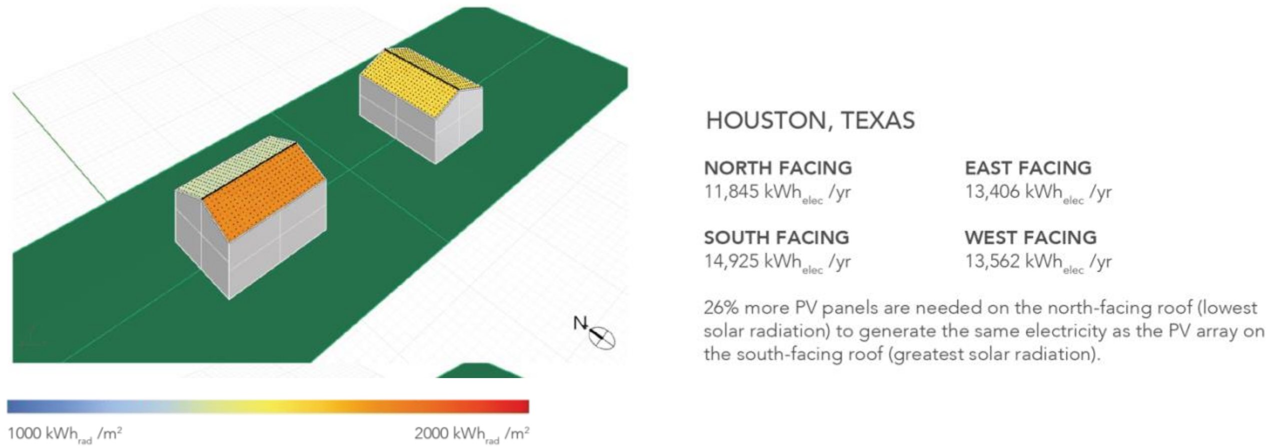

Figure 3. Solar radiation and estimated PV electricity generation by roof aspect. *The electricity generated by the PV system assumes a PV efficiency of 19.7% and 75% roof coverage.*

We used the energy models' hourly energy consumption and PV generation outputs to estimate how much electricity the PV system and PV system with battery storage would offset. For the retrofit intervention with only PV, if the home's electricity consumption was greater than or equal to the PV-generated electricity, we assumed that all electricity generation went toward fulfilling the building's energy demands. If the home's electricity consumption was less than the PV-generated electricity, we assumed the homeowners sold the excess energy back to the grid and received a credit on their electrical bill up to their total amount owed for the year. The retrofit intervention with PV and battery storage was handled in largely the same way. However, if the home's electricity consumption was less than the PV-generated electricity, we assumed that the excess energy would be stored and the homeowner would directly use all the PV-generated electricity eventually. For excess PV-generated energy that wasn't immediately used, we assumed that using the lithium-ion battery to store and discharge energy had an efficiency of 95%.[44]

2.4 Life-Cycle Carbon

This portion of the study uses Life Cycle Assessment (LCA) to quantify the embodied carbon from the

[44] Penev, Hunter, and Eichman, "Energy Storage: Days of Service Sensitivity Analysis."

retrofit upgrades and the operational carbon from the homes' energy consumption. Summing the embodied and operational carbon yields the life-cycle carbon. The LCA methodology is consistent with LCA standards ISO 14040,[45] ISO 14044,[46] and EN 15978:2011.[47] Figure 4 illustrates the system boundary for the LCA of the retrofit and base cases. The functional unit is the retrofit installation along with the operation and maintenance of the detached, single-family home (based on the EP prototype models) in Houston, Los Angeles, or Chicago from 2020 to 2050.

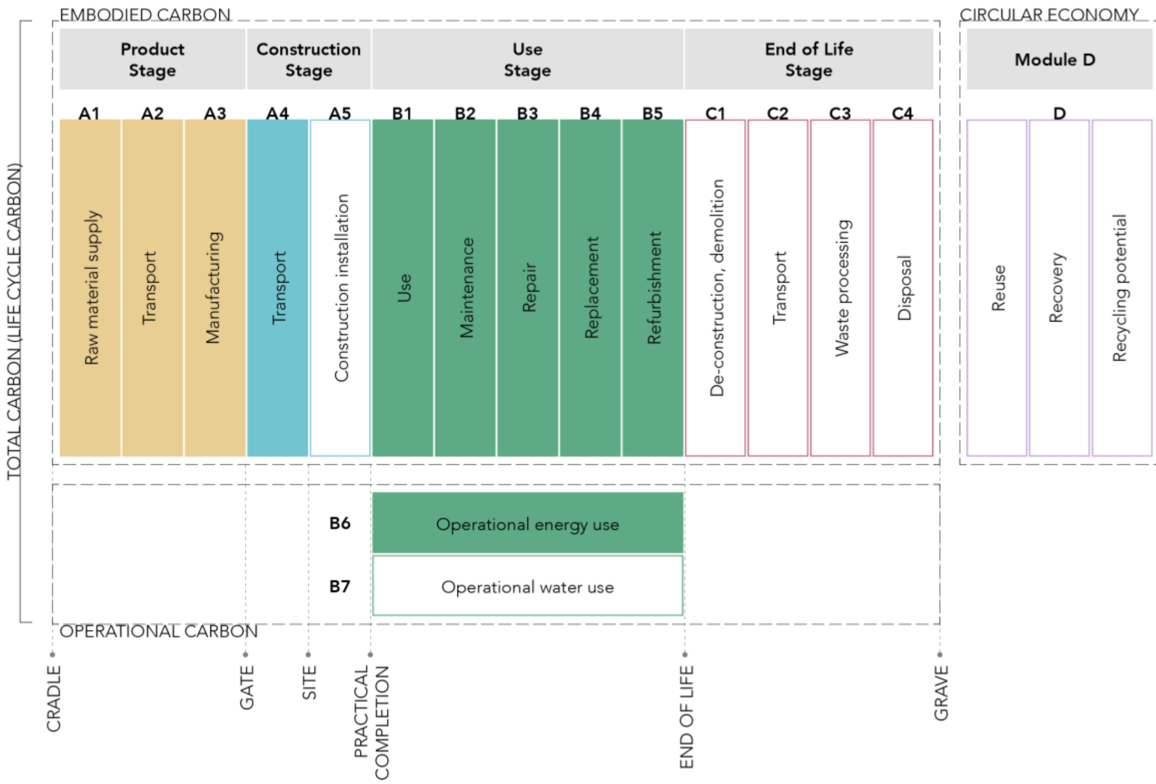

Figure 4. System boundary for LCA of retrofit interventions. *The shaded processes are included in the LCA scope. The outlined processes are excluded.*

The retrofit interventions listed in Table 2 remain unchanged for the life-cycle carbon portion of this study. Table 5 outlines the material assumptions and specifications required to reach the target performance values. Table 5 is important for calculating the embodied carbon associated with each retrofit intervention, as described further in Section 2.4.3 – 2.4.6.

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45 "ISO 14040."
46 "ISO 14044."
47 "BS EN 15978."

HOUSTON, TEXAS	BASE	ELECTRIFICATION	SHALLOW ENV	DEEP ENV	PV
ELECTRIFICATION					
Cooking	Gas range (68L)	Electric range (64L)	See base case	See base case	See base case
Water heating (WH)	Gas tank WH (40 gal)	Heat pump WH (40 gal)	See base case	See base case	See base case
Space conditioning	Gas furnace (75k Btu)	Air-Source Heat Pump (ASHP) (5-ton)	See base case	See base case	See base case
ENVELOPE UPGRADES					
Windows	1x pane	See base case	2x pane, fiberglass	3x pane, fiberglass	See base case
Ceiling insulation (W/m^2K)	Existing loose fill	See base case	1.5" cellulose[1]	1.5" cellulose[1] 8" polyiso	See base case
Wall insulation (W/m^2K)	n/a	See base case	4" cellulose	4" cellulose 3" polyiso .5" sheathing Stucco finish	See base case
Wall infiltration	0.38 ACH(nat)	See base case	1x blower door[2] 1x labor[2]	2x blower door[2] 2x labor[2] ERV ventilation	See base case
RENEWABLE ENERGY					
PV	n/a	See base case	See base case	See base case	23 mono panels
PV and battery storage	n/a	See base case	See base case	See base case	23 mono panels Lithium-ion battery

Table 5. Houston energy model retrofit interventions and material assumptions.
1. Insulation depth was chosen to meet target U-values, assuming existing ceiling insulation remains (see Table 2).
2. These multipliers are used in pricing. Embodied carbon assumptions for infiltration are outlined in Section 2.4.4.

2.4.1 Overview of methodology for calculating life-cycle carbon reductions

The base case represents an existing home. Therefore for most base case calculations, there is no associated embodied carbon expenditure, and we only need to calculate operational carbon. To do so, we used eGRID2020 to find emission rates and grid gross loss factors associated with the ERCT (Houston), CAMX (Los Angeles), and RFCW (Chicago) grids.[48] We then used Equation 3, published by the U.S. EPA, to estimate the emission rates from combined generation and line losses.[49] Assuming current grid intensities remain constant between 2020 – 2050, we multiplied the emission rate (ER_c) by our base case site energy consumption (kWh) from the energy simulations in Section 2.3; the product yields the base case's operational carbon over the 30-year analysis period.

[48] "EGRID 2020 Summary Data."
[49] Diem and Quiroz, "How to Use EGRID for Carbon Footprinting Electricity Purchases in Greenhouse Gas Emission Inventories."

$$ER_c = \frac{ER_g}{(1-GGL)} \tag{3}$$

Where, ER_c – Emission rate to estimate emissions from combined generation and line losses (kgCO2e/kWh);

ER_g – eGRID generation-based output emission rate (kgCO2e/kWh);

GGL – eGRID grid gross loss factor (decimal).

Next, we calculated each retrofit intervention's operational carbon (EN 15978 B6) using the same process as described for the base case. We also quantified the carbon emissions associated with the retrofit's product manufacturing (EN 15978 A1-A3), transportation (EN 15978 A4), maintenance (EN 15978 B2-B3), and replacement (EN 15978 B4-B5).[50] We added manufacturing, maintenance, and replacement emissions to building operational emissions, then subtracted the sum from the base case operational emissions per Equation 4.1. The difference represents the retrofit's reduced Global Warming Potential (GWP) over the thirty-year study period.

$$GWP_{retr}^{red} = OC_{base} - \left(EC_{retr}^{mfr} + EC_{retr}^{maint} + OC_{retr}\right) \tag{4.1}$$

Where, GWP_{retr}^{red} – Retrofit's reduction in GWP from the base case (kgCO2e);

OC_{base} – Base case operational carbon (kgCO2e);

EC_{retr}^{mfr} – Retrofit's embodied carbon associated with product manufacturing (kgCO2e);

EC_{retr}^{maint} – Retrofit's embodied carbon associated with product maintenance and replacement (kgCO2e);

OC_{retr} – Retrofit's operational carbon (kgCO2e).

Using Equation 4.1 to calculate a retrofit's life-cycle carbon reduction works well for the envelope upgrade and renewable energy scenarios because both involve adding assemblies absent from the base case. For example, if calculating the carbon reduction from adding PV, the embodied carbon from the PV array's manufacturing and maintenance stages needs to be added to the operational carbon of the retrofit case, but because there were no PV panels in the base case, only the operational carbon of the base case is considered. The electrification interventions, however, require a slightly different method. Calculating GWP reductions for the electrification retrofits requires adding the manufacturing and maintenance

[50] "BS EN 15978."

emissions from the base case gas appliances, per Equation 4.2.

$$GWP_{retr}^{red} = \left(EC_{base}^{mfr} + EC_{base}^{maint} + OC_{base}\right) - \left(EC_{retr}^{mfr} + EC_{retr}^{maint} + OC_{retr}\right) \quad (4.2)$$

Where, EC_{base}^{mfr} – Base case embodied carbon associated with product manufacturing (kgCO2e);

EC_{base}^{maint} – Base case embodied carbon associated with product maintenance and replacement (kgCO2e).

For example, if calculating the GWP reduction from replacing a gas stove (base case) with an electric stove (retrofit intervention), the embodied carbon from the gas stove's manufacturing and maintenance processes needs to be added to the base building's operational carbon emissions because the electric equipment is replacing other equipment that would have otherwise remained operational had the retrofit not occurred. Equation 4.2 accounts for product lifespan as outlined in Table 6 and Table 7.

2.4.2 Base case

For each gas-fueled system in the base case, GWP values, broken down by product, transport, and use stages, were collected from literature. The sum of the GWP values from all considered life cycle stages is noted in Table 6. The referenced values were taken from LCA studies on residential equipment, and all values were converted to the same functional unit per Section 2.4. Manufacturing GWP values were assumed to be applicable to the U.S. context.

EMBODIED CARBON	LIFESPAN (yrs)	GWP[1] (kgCO2e/product)	TOTAL QUANTITY (# products over 30 yrs)	TOTAL GWP[2] (kgCO2e over 30 yrs)
COOKING				
Gas stove	19	209.0 [51]	2	418.0
WATER HEATING				
Gas boiler water heater	12	1694.5 [52]	3	5083.6
HEATING				
Gas furnace	20	1500.0 [53]	2	3000.0

Table 6. Gas equipment assumptions used to conduct the LCA for the base case.
1. "GWP" values represent the sum of embodied carbon from the manufacturing and maintenance product stages for a single system or piece of equipment.
2. The "Total GWP" is the product of the GWP and number of products over 30 years ("Total

[51] Landi et al., "Comparative Life Cycle Assessment of Electric and Gas Ovens in the Italian Context."
[52] Piroozfar, Pomponi, and Farr, "Life Cycle Assessment of Domestic Hot Water Systems."
[53] Li, "Life Cycle Assessment of Residential Heating and Cooling Systems in Minnesota."

Quantity"). The values in this column represent the sum of the embodied carbon from the manufacturing and maintenance stages over the study period (EC_{base}^{mfr} and EC_{base}^{maint}, respectively, per Equation 4.2).

All use-stage values were derived by running climate-specific energy simulations as described in Section 2.3 and multiplying the resulting site energy consumption by the grid emission factor per Section 2.4.1. The GWP for the gas furnace was taken from a LCA study that groups a gas furnace and air conditioning system.[54] We could not separate the GWP values for the two systems so conservatively assumed that all the emissions could be attributed to the gas furnace. However, because the electric heating system described in Section 2.4.3 has a much higher GWP than the gas system, the inflated GWP for the gas furnace does not have a sizeable impact on the results.

2.4.3 Electrification

Per Section 2.3.3, the electrification decarbonization scenario encompasses three distinct retrofit interventions that involve replacing existing gas equipment with a new electric induction stove, electric heat pump water heater (HPWH), and/or ASHP. For each, GWP values, broken down by product, transport, and use stages, were collected from literature. The sum of the GWP values from all considered life cycle stages is noted in Table 7. The referenced values were taken from LCA studies on residential equipment, and all values were converted to the same functional unit described in Section 2.4. Manufacturing GWP values were assumed to be applicable to the U.S. context.

EMBODIED CARBON	LIFESPAN (yrs)	GWP[1] (kgCO2e/product)	TOTAL QUANTITY (# products over 30 yrs)	TOTAL GWP[2] (kgCO2e over 30 yrs)
COOKING				
Electric stove	17	199.0 [55]	2	398.0
WATER HEATING				
Heat pump water heater	14	2835.6 [56]	3	8506.7
HEATING				
Air source heat pump	20	6252.6 [57]	2	12504.8

Table 7. Electric equipment assumptions used to conduct the LCA for the electrification scenarios.
1. "GWP" values represent the sum of embodied carbon from the manufacturing and maintenance product stages for a single system or piece of equipment.
2. The "Total GWP" is the product of the GWP and number of products over 30 years ("Total Quantity"). The values in this column represent the sum of the embodied carbon from the manufacturing

[54] Li.
[55] Landi et al., "Comparative Life Cycle Assessment of Electric and Gas Ovens in the Italian Context."
[56] Piroozfar, Pomponi, and Farr, "Life Cycle Assessment of Domestic Hot Water Systems."
[57] Bachmann, Carnicelli, and Preiss, "Life Cycle Assessment of Domestic Fuel Cell Micro Combined Heat and Power Generation."

and maintenance product stages over the 30 year study period (EC_{retr}^{mfr} and EC_{retr}^{maint}, respectively, per Equation 4.2).

All use-stage values were derived by running climate-specific energy simulations as described in Section 2.3 and multiplying by the resulting energy consumption by the grid emission factor per Section 2.4.1. Then, we followed the same process outlined Section 2.4.1, using Equation 4.2 to find the GWP reduction associated with each, individual electrification retrofit described in Table 5.

2.4.4 Envelope retrofits

Envelope material specifications are outlined in Table 5, but a series of LCA studies helped inform those decisions. Because material choice can have a huge impact on the life-cycle carbon emissions and payback period associated with retrofits, we standardized our approach to material specification as much as possible.[58] We prioritized materials with low GWPs, low costs, and high durability. For window retrofits, we specified fiberglass window frames. For insulation in the ceiling and wall cavities, loose fill or spray-in insulation was acceptable (cellulose), but we specified a rigid insulation (polyisocyanurate) outside of the wall cavities for ease of installation.

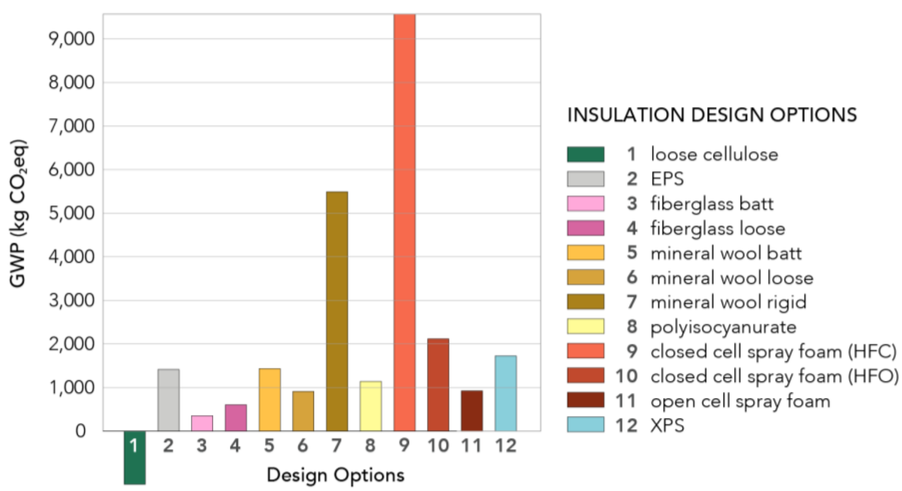

Figure 5. Global Warming Potential associated with various insulation options. *To compare insulation, we assumed a functional unit of U-0.284 W/m^2K. Section 4.2 describes limitations of this analysis.*

[58] Röck et al., "Embodied GHG Emissions of Buildings – The Hidden Challenge for Effective Climate Change Mitigation"; Pomponi and Moncaster, "Embodied Carbon Mitigation and Reduction in the Built Environment - What Does the Evidence Say?"; Thormark, "The Effect of Material Choice on the Total Energy Need and Recycling Potential of a Building."

Once the material specifications were set, we modeled the prototype home in Revit.[59] We modeled one design option for the base case, one for the shallow envelope retrofit scenario, and another for the deep envelope retrofit scenario as seen in Figure 6. We maintained the window-to-wall ratio (WWR) native to the prototype models but further divided the window area to reflect more-typical dimensions (24 windows, 0.9 m wide x 1.5 m high each).

We used Tally, a Revit plug-in that estimates a design's embodied carbon, to assign materials and emission factors from Tally's database to our design options.[60] From the outputs, we calculated GWPs for all insulation and window retrofits over the 30-year study period. All materials analyzed in Tally had lifespans over 30 years, so we did not need to factor in carbon emissions associated with product replacement. Tally's LCA modeling is conducted in GaBi 8.5 using GaBi 2018 databases; its impact category outputs are reported according to the TRACI 2.1 characterization scheme and include biogenic carbon. We omitted emissions associated with end-of-life (EN 15978 C2-C4) and Module D (EN 15978 D) life cycle stages to align with our study's system boundary per Figure 4.[61]

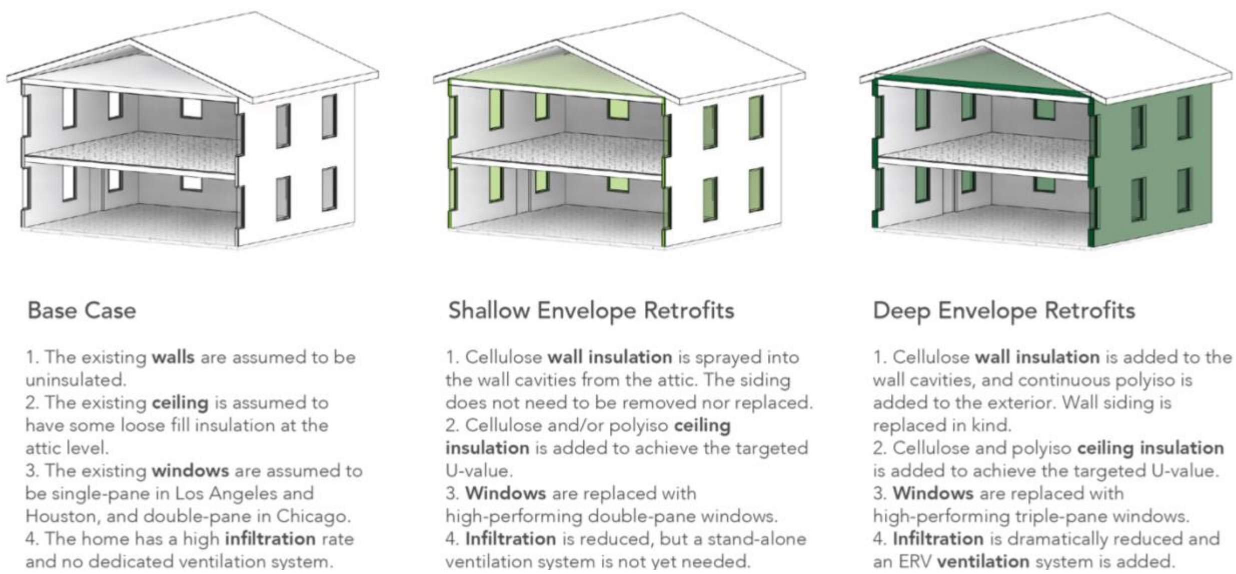

Figure 6. Life Cycle Assessment scope for the envelope upgrade scenarios.

Quantifying the GWP of the infiltration retrofits in Tally was not possible, so we turned to other methods. For the shallow envelope infiltration case, we did not have data for the GWP of air sealing products and

[59] *Revit*.
[60] *Tally*.
[61] "BS EN 15978."

assumed that embodied emissions from air sealing to 5ACH50 would be negligible. Similarly, for the deep envelope infiltration case we assumed that the ventilation system addition would be the main source of embodied carbon. We used SimaPro (EcoInvent 3 library, allocation at point of substitution, and TRACI 2.1 characterization scheme)[62] to estimate the GWP of the ERV unit, motor, and filters based on the Life Cycle Inventory (LCI) from Nyman et al's assessment of residential ventilation units per Table 8.[63] Given that the lifespan of an ERV system is typically at least 20 years, we assumed one replacement to the ERV unit itself.[64] The LCI accounted for both motor and filter replacement but was based on a 50-year study period.[65] To ensure the LCI aligned with our 30-year study period, we multiplied the LCI values for filter and motor replacement by a factor of 0.6.

MATERIAL	SIMAPRO ENTRY	MASS (kg)	QTY	GWP (kgCO2e)
ERV UNIT		36.00	1	417
Steel and sheet metal	Steel, chromium steel 18/8 {GLO}| market for | APOS, S	26.90	1	
Polyurethane	Polyurethane, flexible foam {GLO}| market for | APOS, S	0.02	1	
Polyethene and polyester	Polyethylene, high density, granulate {GLO}| market for | APOS, S	0.45	1	
PVC	Polyvinylchloride, bulk polymerized {GLO}| market for| APOS, S	0.59	1	
Copper	Copper {GLO}| market for | APOS, S	1.29	1	
Aluminum	Aluminum alloy, AlLi {GLO}| market for | APOS, S	4.92	1	
Natural rubber	Seal, natural rubber based {GLO}| market for | APOS, S	0.23	1	
Cardboard	Corrugated board box {CA-QC}| market for | APOS, S	1.98	1	
Paper	Tissue paper {GLO}| market for | APOS, S	0.10	1	
FILTERS		6.20	0.6	11
Polyurethane	Polyurethane, flexible foam {GLO}| market for | APOS, S	1.20	0.6	
Paper	Tissue paper {GLO}| market for | APOS, S	5.00	0.6	
MOTORS		10.15	0.6	29.3
Steel	Steel, chromium steel 18/8 {GLO}| market for | APOS, S	6.50	0.6	
Copper	Copper {GLO}| market for | APOS, S	2.40	0.6	
Aluminum	Aluminum alloy, AlLi {GLO}| market for | APOS, S	0.90	0.6	
Polyethylene	Polyethylene, high density, granulate {GLO}| market for | APOS, S	0.35	0.6	

Table 8. Life Cycle Inventory of ERV units and replacement filters and motors. *Values are based on average material masses from two ERV units in the referenced paper.[66] The GWP associated with material manufacturing and maintenance was quantified in SimaPro; use phase energy from the paper was not included, and instead was calculated through energy simulations in Design Builder.*

2.4.6 Renewable energy

We conducted LCA for the two renewable energy retrofit interventions – PV and PV with battery storage

[62] *SimaPro*.
[63] Nyman and Simonson, "Life Cycle Assessment of Residential Ventilation Units in a Cold Climate."
[64] "HRV/ERV Information."
[65] Nyman and Simonson, "Life Cycle Assessment of Residential Ventilation Units in a Cold Climate."
[66] Nyman and Simonson.

– using SimaPro. The analysis included the PV panels, a lithium-ion battery (for relevant retrofit cases), and inverter per Table 9 below. The energy meter and wiring were not considered and the carbon benefits from excess electricity sold back to the grid were not credited to the residence. The PV panels have a 30-year lifespan, so we did not include PV replacement in our analysis.[67] The inverter and battery, however, have a lifespan closer to ten years, so we accounted for replacing both twice.[68]

MATERIAL	SIMAPRO ENTRY	UNIT	QTY	GWP (kgCO2e)
PV SYSTEM ONLY				10,700
PV panel	Photovoltaic panel, single-Si wafer {GLO}| market for | APOS, S	1.635 m^2	23	
Inverter	Inverter, 2.5kW {GLO}| market for | APOS, S	1 piece	3	
PV SYSTEM + BATTERY				15,800
PV panel	Photovoltaic panel, single-Si wafer {GLO}| market for | APOS, S	1.635 m^2	23	
Battery	Battery, Li-ion, rechargeable, prismatic {GLO}| market for | APOS, S	253 kg	3	
Inverter	Inverter, 2.5kW {GLO}| market for | APOS, S	1 piece	3	

Table 9. Life Cycle Inventory of proposed photovoltaic systems, with and without battery storage. *Values are based on a DC 7.15 kW system with 23 PV panels, measuring approximately 1.65 m long by 1 m wide as described in the U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021.*[69]

2.5 Life Cycle Cost

Life Cycle Cost (LCC) is the primary financial metric we used to evaluate the carbon- and cost-effectiveness of each retrofit intervention. Any intervention with a negative LCC was deemed cost effective and reduced carbon while saving the homeowner money. Along with the EP prototype residential models, the DOE also publishes their methodology for calculating LCC.[70] We followed the DOE methodology to calculate the LCC values for each retrofit intervention in this study.

The DOE methodology assumes that homeowners finance the retrofits' initial investment primarily through increased mortgage costs, but it also accounts for the retrofits' tax impacts, energy savings, replacement costs, and residual values. DOE publishes the equations they use to quantify these cash flows, and these equations are referenced in Appendix E. Equations 5.1 and 5.2 sum costs and savings over multiple years by adjusting all cash flows from different years to the present value using a discount

[67] Curtis et al., "A Circular Economy for Solar Photovoltaic System Materials."
[68] Kennedy, "How Long Do Residential Solar Inverters Last?"; Svarc, "Detailed Home Battery Cost Guide."
[69] Ramasamy et al., "U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks."
[70] Taylor, Mendon, and Fernandez, "Methodology for Evaluating Cost-Effectiveness of Residential Energy Code Changes."

rate; multiple present values representing different cash flows are added together to arrive at the LCC.[71] Table 10 summarizes the assumptions that factor into each cash flow calculation.

PARAMETER	SYMBOL	CURRENT ESTIMATE
Mortgage interest rate	R_{MI}	5%
Loan term	T	30 years
Down payment rate	R_{DP}	10% of home price[1]
Points and loan fees	R_{MF}	0.6% (non-deductible)
Discount rate	d	5% (equal to mortgage interest rate)
Period of analysis	N	30 years
Property tax rate	R_P	1.1% of home price[1]
Income tax rate	R_I	15% federal, 0.0% state (Houston)[72] 9.3% state (California)[73] 5.0% state (Illinois)[74]
Home price escalation rate	E_H	Equal to inflation rate
Inflation rate	R_{INF}	1.6% annual
Fuel prices and escalation rate		Latest national average prices based on current Energy Information Administration data and projections;[75] price escalation rates taken from latest Annual Energy Outlook.

Table 10. Summary of current economic parameter estimates based on DOE's cost methodology.
1. For the scope of this study, "home price" referred to the first cost of the retrofit intervention.[76]

$$LCC = PV_{costs} - PV_{benefits} \quad (5.1)$$

Where, LCC – Life Cycle Cost ($);

PV – Present value ($).

$$PV = \sum_{y=0}^{N} \left[\frac{CF_y}{(1+d)^y}\right] \quad (5.2)$$

Where, CF_y – Annual cash flows at a specified year, y ($).

The positive cash flows (benefits) in the DOE methodology include annual tax deductions, annual energy savings, and residual value of the retrofit intervention at the end of the analysis period. The negative cash flows (costs) include the one-time down payment cost, one-time mortgage fee, annual property tax, annual mortgage payments, and replacement costs which vary in frequency depending on the product

[71] Taylor, Mendon, and Fernandez.
[72] "Texas Tax Rate."
[73] "California State Tax."
[74] Smith, "Illinois State Taxes."
[75] "Annual Energy Outlook 2022."
[76] Taylor, Mendon, and Fernandez, "Methodology for Evaluating Cost-Effectiveness of Residential Energy Code Changes."

lifespan. Equations E1 – E8, published by DOE and referenced in Appendix E, describe how to calculate each cashflow considered in the methodology, but before we could run the cashflow calculations, we had to determine the first cost of each retrofit intervention.

The first cost includes costs associated with demolition or equipment removal (as needed), materials, and labor. We used a combination of construction cost estimating software to estimate these costs. RSMeans offered an extensive database for pricing construction materials (as opposed to building systems), and we used its database for pricing most envelope retrofits with only a few exceptions.[77] We did not find cost data on triple-pane windows, ERV units, and blower door tests in RSMeans, and for those we relied on outside sources.[78] Retrofits involving infiltration upgrades were especially difficult to price. Although the RSMeans database contained pricing for air barrier materials, installation, and installation equipment, it was not clear how the assumed cost of labor related to the target infiltration rate. For that reason, we assumed the shallow infiltration retrofit required the default material and labor cost in RSMeans associated with a fluid-applied air barrier. For the deep infiltration retrofit we assumed the same material costs as the shallow infiltration retrofit. However, we also assumed that after the first round of labor, a blower door test would be needed to identify areas with air leaks, which would be followed by another round of labor and a second blower door test to confirm the target air exchange rate.[79]

We used another cost estimating software, Clear Estimates, to calculate pricing for appliances, building systems, and equipment.[80] Clear Estimates provided detailed costs for equipment removal and replacement, which was critical for pricing the electrification retrofit scenarios. All costs in RSMeans and in Clear Estimates reflect regional differences in pricing. To price the retrofits that added photovoltaics and/or battery systems, we assumed $2.65/W for the PV array and $4.49/W for the PV array with battery storage.[81] The pricing for PV assumes a 7.15 kW rooftop system with 5 kW/12.5 kWh of storage for applicable retrofit cases.

Although many local, state, and even federal programs offer incentives for certain retrofit interventions, current incentive programs that might impact the cost of the proposed measures were not included in this analysis. Because one of the goals of this research is to help evaluate and inform policy, the research does

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[77] *2022 RSMeans*.
[78] "Triple Pane Windows"; "2022 Energy Recovery Ventilator Costs"; "Energy Auditing / Blower Door Testing."
[79] Fitzgerald-Redd, "Getting 3 ACH50 Without Breaking the Bank."
[80] *Clear Estimates*.
[81] Ramasamy et al., "U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks."

not consider current incentive programs in pricing. In doing so, the results reveal where we should incentivize investments for the greatest environmental benefits rather than how retrofits with current financial incentives stack up against those without incentives.

2.6 Decarbonization of the electric grid

To estimate the impact of the cities' grids becoming less carbon-intensive over time, we considered four scenarios, the grid as-is and then three additional decarbonization scenarios, all of which are analyzed over the same study period from 2020 – 2050:

1. Each representative city's grid remains at its current grid intensity.
2. Each representative city's grid becomes as carbon-intensive as California's current grid.
3. Each representative city's grid becomes as carbon-intensive as New York's current grid.
4. Each representative city's grid achieves net-zero emissions.

For each scenario, we multiplied the site energy consumption for the base case and retrofit interventions by the target emissions rate to calculate the life-cycle carbon associated with each case. As in Section 2.4.1, we then found the life-cycle carbon reduction resulting from each retrofit intervention using Equation 4.1 or 4.2.

In Figure 7, we show the emission rates for the relevant grids, represented by the black dots with corresponding eGRID acronym labels. We also illustrate the hypothetical projected grid intensity for each city, assuming linear decarbonization and assuming each city can achieve a zero-carbon-grid by 2050. Referencing these projection paths, one can estimate about how long it would take for each city's grid to reach another city's emission rate. Although it is not realistic that any one of the grids in the study would be able to jump so rapidly to a much lower grid intensity and operate at that intensity between 2020 and 2050, the decarbonization scenarios serve to illustrate the range of outcomes for each retrofit intervention under different levels of decarbonization.

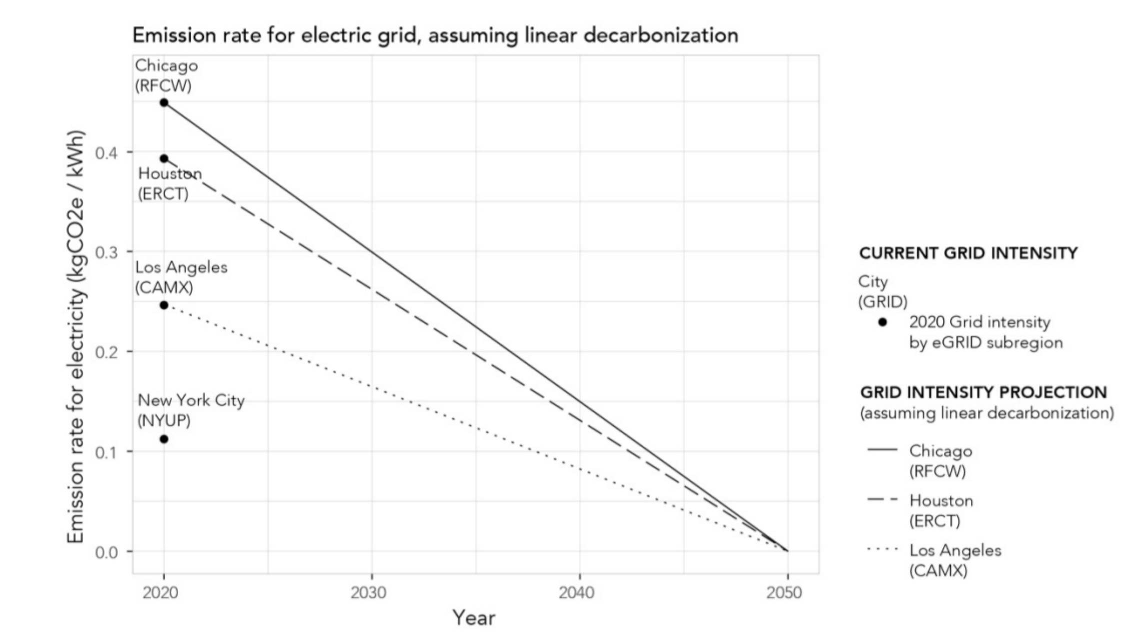

Figure 7. Hypothetical projected emission rates for electric grids, assuming linear decarbonization. *The grid intensity for each city begins at its current grid emission rate in 2020 and reaches a zero-carbon grid in 2050.*

2.7 The time value of carbon

The time value of carbon (TVC) is the concept that reductions in carbon emissions today are more valuable than the same reductions in the future because of the urgent need to draw down GHG emissions. This concept has also been explored in efforts to establish a Social Cost of Carbon (SCC). The SCC is a dollar estimate of the monetary costs resulting from emitting one additional ton of GHGs into the atmosphere. The discount rate used in SCC calculations determines how much weight is placed on future emissions, with a high discount rate signaling future emissions are considered less significant than present emissions.[82] Though there is not yet consensus on one appropriate discount rate (or even one discounting method) and the recommended value changes depending on study scope, federal regulatory analysis for carbon pricing has used discount rates of 3% and 7%.[83] We applied both discount rates to the carbon emissions from each base case and retrofit case as a sensitivity analysis to understand how the range of discount rates might impact our study results.

For each retrofit intervention, we listed the building’s carbon emissions for each year from 2020 – 2050,

[82] Rennert and Kingdon, “Social Cost of Carbon 101.”
[83] “EPA Fact Sheet, Social Cost of Carbon”; Rennert et al., “The Social Cost of Carbon: Advances in Long-Term Probabilistic Projections of Population, GDP, Emissions, and Discount Rates.”

assuming the city's current grid emission rate. Annual carbon emissions always included the home's operational carbon for that year. In addition, year 2020 always included the additional embodied emissions from the systems or materials installed during the retrofit. The same embodied carbon calculations used in Section 2.4 were also used for this exercise. Depending on the lifespan of the retrofit materials, additional embodied emissions were added when product lifespan elapsed, representing the embodied carbon from product replacement. Some retrofit interventions also had regular embodied emissions associated with product maintenance. Once we had the life-cycle carbon emitted in each year of the analysis period, we applied the discount rate as shown in Equation 6 to convert future damages (carbon emissions) into present-day values and summed the emissions over the 30-year analysis period.

$$TCPV = \sum_{y=0}^{N} \left[\frac{TC_y}{(1+d)^y} \right] \tag{6}$$

Where, $TCPV$ – Life-cycle carbon present value associated with retrofit intervention over the analysis period (kgCO2e);

N – Number of years in the analysis period (yr);

TC_y – Life-cycle carbon associated with retrofit intervention at a specified year, y (kgCO2e);

d – Discount rate of 3% or 7%.

2.8 Ranking

Comparing each retrofit intervention back to the base case, we ranked each retrofit based on one of two metrics: (1) reduced source energy (kWh) per dollar saved/spent or (2) reduced life-cycle carbon (kgCO2e) per dollar saved/spent. Both metrics consider the retrofit's energy performance and LCC over the 30-year analysis period. For simplicity, we refer to the second metric for the remainder of Section 2.8. Reduced life-cycle carbon was calculated per Equation 4.1 or 4.2, and the associated cost per Section 2.5. Using the second metric, each ratio had four possible outcomes. To rank among them, we created a hierarchy where retrofit interventions that fall under outcome 1 have the highest (best) rankings, and interventions under outcome 4 have the worst rankings: (1) the retrofit decreased carbon at a cost savings, (2) the retrofit decreased carbon at a cost expenditure, (3) the retrofit increased carbon at a cost saving, and (4) the retrofit increased carbon at a cost expenditure. Within each outcome, retrofit interventions with the greatest carbon reductions (or lowest carbon expenditure) per dollar saved/spent were ranked highest.

We conducted the ranking exercise for each retrofit intervention under the current grid, California's grid (CAMX), New York's grid (NYUP), and a zero-carbon grid (see Section 2.6). Under the current grid, we also ranked each retrofit intervention assuming no carbon discount rate, a 3% carbon discount rate, and a 7% carbon discount rate (see Section 2.7). Results for the prototypical home in Houston illustrating the change in carbon emissions as the grid decarbonizes are described in Section 3.3. Section 3.4 describes the change in carbon emissions for Houston retrofits when accounting for different carbon discount rates.

One challenge with the metric proposed for the study's ranking system is that the metric's ratio format made it difficult to understand the scale of each retrofit intervention and the scale of the associated cost. This could make it difficult for homeowners or policymakers to narrow down their options if they are limited in budget. To address this issue, we also provided our results in terms of life-cycle carbon expenditure per LCC, and life-cycle carbon expenditure over time as the grid decarbonizes. These results are graphed and explained further in Section 3.1 and 3.2, respectively.

3 Results

3.1 Carbon emissions and associated costs

As mentioned in Section 2.8, the metric used to rank retrofits based on carbon reduction per LCC did not make it easy to compare the relative scale of retrofit emission reductions or costs. Figure 8 was designed to reintroduce some of that missing information. Assuming current grid intensities, we plotted the life-cycle carbon reductions on the y-axis against LCC on the x-axis. Quadrant II houses retrofit interventions that reduce carbon and save the homeowner money over the 30-year study period. Quadrant I, where the bulk of the retrofits fall, contains retrofits that reduce carbon at an overall cost to the homeowner. The few retrofits in Quadrant IV increase carbon emissions at a cost to the homeowner, and none of the analyzed retrofit interventions increase carbon and save the homeowner money under current grid emission rates (Quadrant III).

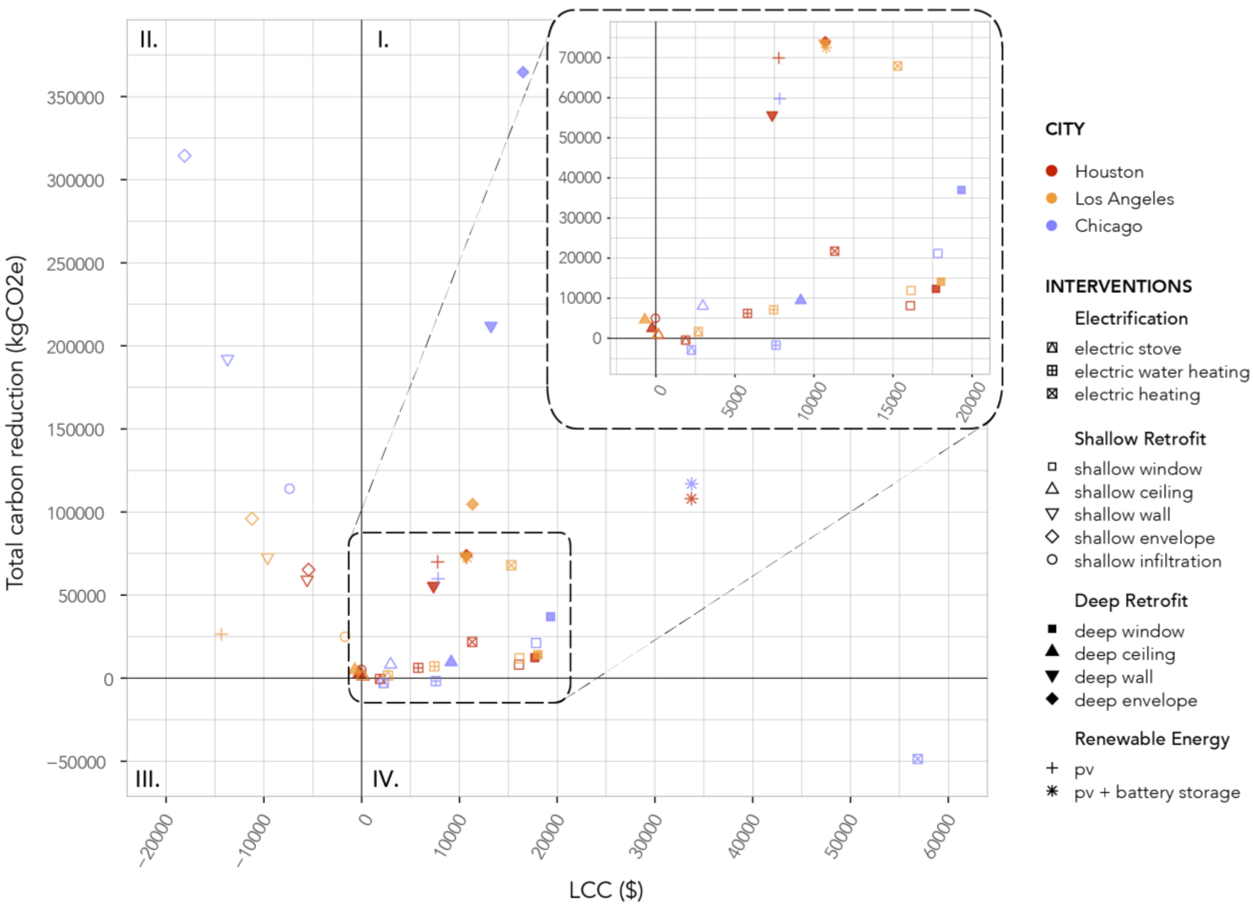

Figure 8. Life-cycle carbon reduction versus LCC of retrofit interventions by city.

From Figure 8, a few trends become apparent. Of the twelve retrofit interventions that fall in Quadrant II, nine of them belong to the shallow retrofit scenario, and the only shallow retrofit interventions that do not provide cost savings over the course of the analysis period are the window upgrades and the addition of ceiling insulation. This suggests that existing homes without proper insulation and air sealing can see significant carbon reductions and save money while doing so, and it makes sense to target these retrofits first.

We also observe that homes with the highest energy consumption to begin with, often homes in cold climates like Chicago, stand the most to gain from energy retrofits. The life-cycle carbon reductions we saw for most retrofits in the Chicago home, namely the envelope upgrades, far surpass those from the homes in Los Angeles or Houston. However, homes in Chicago also saw the greatest increases in carbon emissions from the proposed energy retrofits. In fact, the electric stove, electric water heater, and electric heating retrofit interventions resulted in the greatest carbon increase of all the interventions analyzed. Therefore, if targeting geographical regions to prioritize carbon reductions, it makes sense to start with the most extreme, cold climates, but it is also imperative that we encourage retrofits strategically. For instance, in Chicago it makes more sense to tackle shallow retrofits, and even some deep retrofits, over electrification – at least until Chicago's grid becomes less carbon intensive.

In Los Angeles, PV upgrades make a lot of sense from a financial perspective, but do not reduce as much carbon as many of the other retrofit interventions. Because California's grid already has a relatively high percentage of renewables (and lower carbon-intensity), the electrification retrofits in Los Angeles, particularly the switch from gas furnaces to ASHPs, make more sense from a carbon-standpoint than they would for the other two cities we analyzed. However, switching to electric heating in Los Angeles has one of the highest LCCs of the retrofits analyzed in that city, with only shallow and deep window upgrades coming in at a higher LCC. While the PV with battery storage retrofits tend to save a lot of carbon, especially in Los Angeles and Houston, the high cost paired with short battery lifespans make the intervention less appealing from a financial standpoint. However, as renewable energy becomes more abundant, batteries are likely to play an increasingly important role in decarbonization and energy management, and their role in the energy transition warrant further study.

3.2 Carbon emissions over time

While Section 3.1 describes the cost and carbon impacts of retrofit measures under each city's current grid, Section 3.2 removes cost from consideration and describes the retrofits' life-cycle carbon emissions as the grid decarbonizes. As such, the results from this section can help guide policies targeting the greatest possible carbon reductions regardless of cost and determine where it is most logical to subsidize retrofit measures. Figure 9 plots life-cycle carbon emissions against time for the Houston retrofits. The emission rate used for 2020 reflects Houston's current grid mix. Moving beyond 2020, the city's grid intensity decreases, assuming linear decarbonization, until it reaches zero-emissions in target year 2050. Houston's grid reaches California's current grid intensity (CAMX) in 2031 and New York's current grid intensity (NYUP) in 2041 as indicated in Figure 9 and detailed further in Section 2.6.

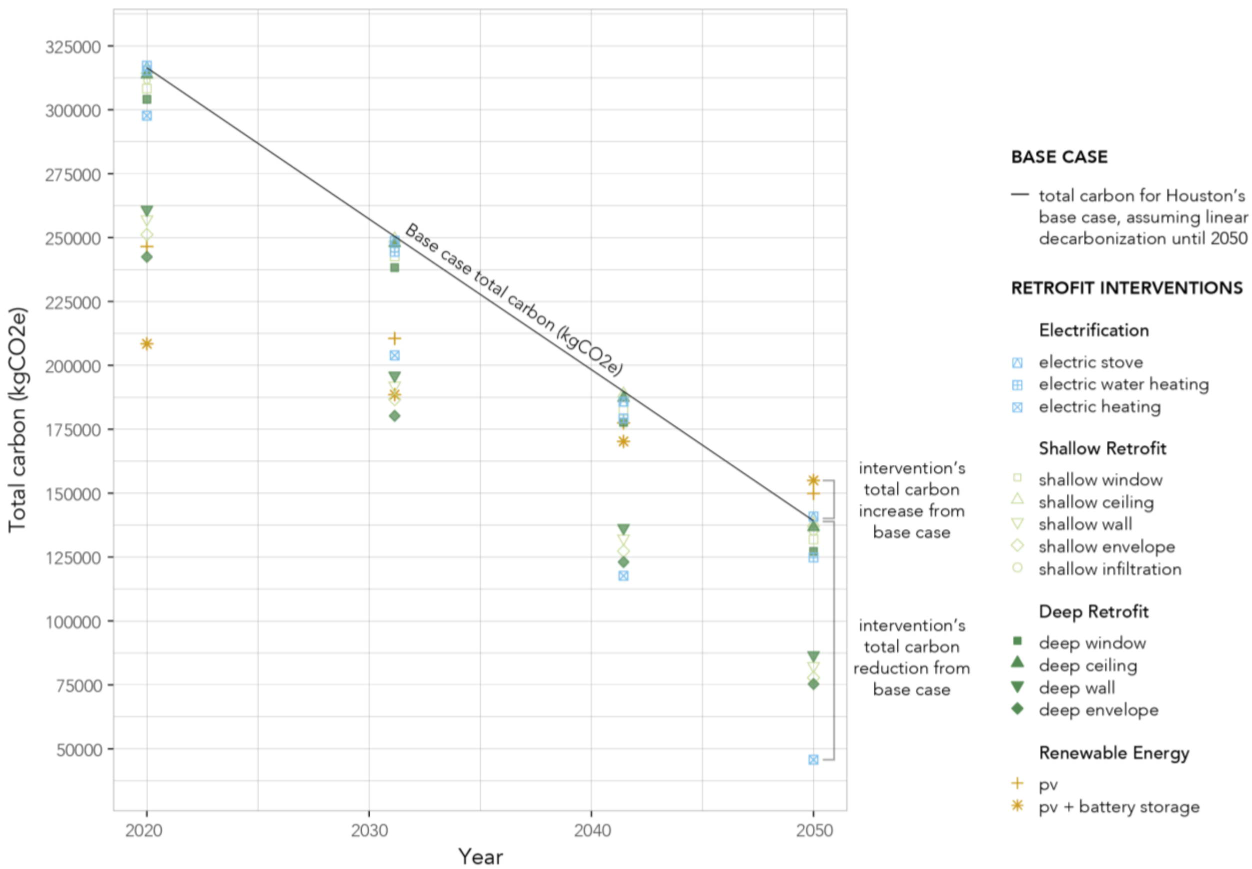

Figure 9. Life-cycle carbon associated with Houston retrofit interventions, assuming linear decarbonization.

In Figure 9, retrofit interventions above the base case line represent an increase in carbon, and interventions further below the baseline represent the greatest carbon reductions. Some retrofit interventions drastically change position relative to other retrofits as the grid decarbonizes. For instance, the electric heating retrofit initially provides low- to mid-range carbon reductions relative to the other retrofit interventions. But as the grid decarbonizes, the switch from gas to electric heating quickly becomes the retrofit measure with the greatest carbon reduction. This is because the heating provided by the ASHP is extremely efficient and it replaces much of the furnace's "would-be" gas consumption with clean electricity.

On the other hand, the installation of PV and PV with battery storage start out offering relatively large carbon reductions compared to the other retrofits. However, the addition of renewable energy without increased energy efficiency does not reduce carbon on a decarbonized grid and the system's high embodied carbon leads to an overall increase in emissions for PV retrofits by 2050. Takeaways from this finding are discussed further in Section 4.1.

In contrast to the electrification and PV retrofits, the envelope retrofits' emissions remain consistent over time because the improved energy efficiency from envelope upgrades impact each energy fuel source proportionally. As seen in Figure 9, the imaginary slope for each shallow and deep retrofit comes very close to matching the slope for the base case life-cycle carbon emissions. Among both deep and shallow envelope retrofits in Houston, the wall insulation and infiltration upgrades should consistently be a high priority whereas the window and ceiling insulation upgrades can consistently be a lower priority when cost is not a factor.

3.3 Cost-effectiveness of carbon reductions as the electric grid decarbonizes

Figure 10 uses the reduced life-cycle carbon per dollar spent/saved metric as outlined in Section 2.8 to rank the retrofit interventions as the grid decarbonizes. As per Section 3.2, the results described in Section 3.3 are specific to the Houston prototypical home. Results for the analysis conducted in Los Angeles and Chicago can be found in Appendix A. Observing the trajectory of the retrofits from column B to column E, many of the patterns observed in Section 3.2 are also evident with the carbon per cost metric. Retrofits that fall under the electrification decarbonization scenario, except for electric cooking, tend to increase in ranking as the grid decarbonizes. Meanwhile, retrofits in the renewable energy decarbonization scenario begin at the middle and top of the rankings and move all the way down to the bottom of the rankings by 2050, along with electric cooking. Shallow and deep retrofits do not change position very drastically, and when they do, it seems to be because other retrofit interventions are trending up or down in rank.

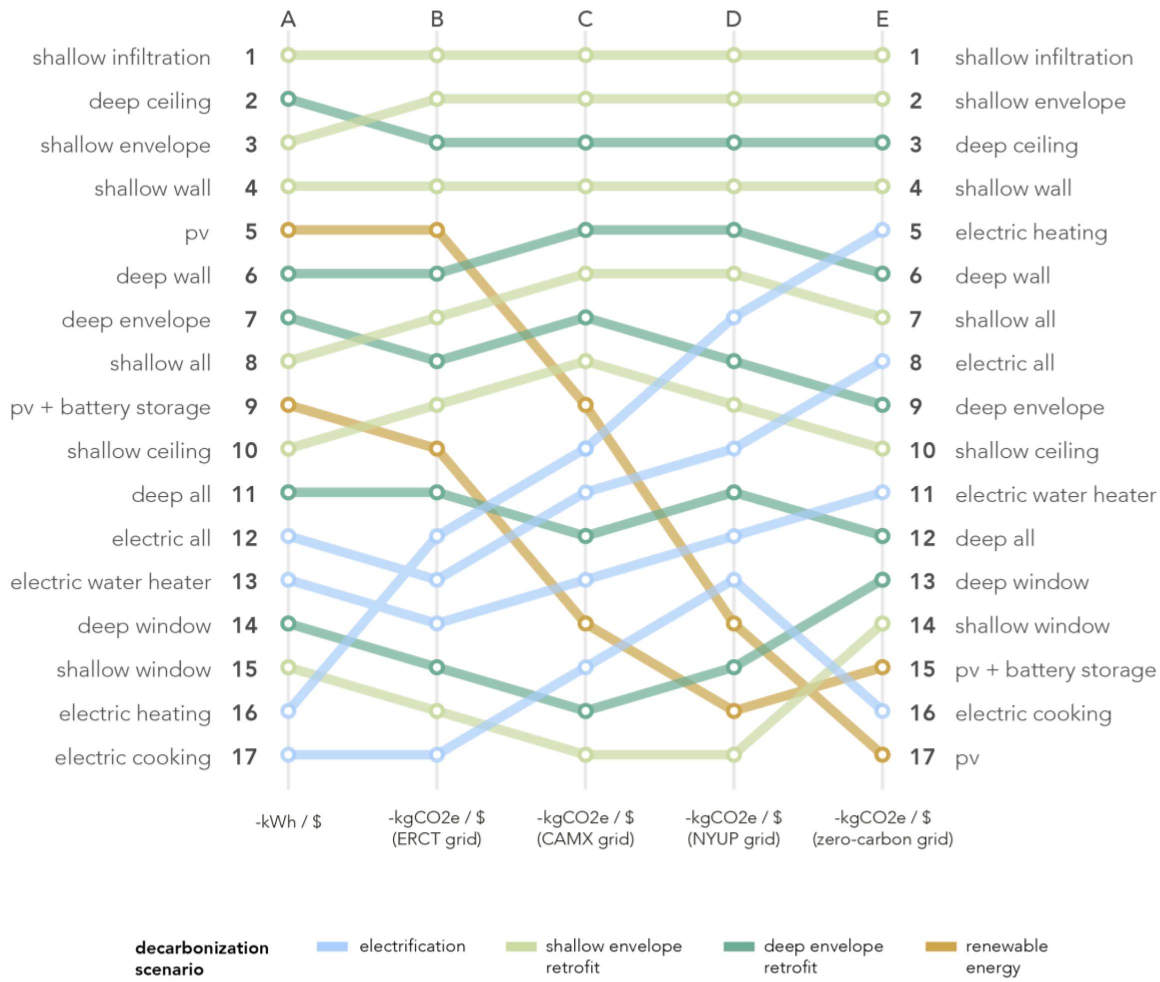

Figure 10. Ranking of retrofit interventions from best (1) to worst (17) as Houston's electric grid decarbonizes.

Figure 10 also displays results using the more typical metric of reduced source energy per dollar spent/saved. When comparing between the energy metric (-kWh/$) in column A and the life-cycle carbon metric (-kgCO2e/$) in column B for Houston's current grid intensity, the difference in rankings is noticeable, but not so noticeable that one metric would be an obvious choice over the other. However, as the grid decarbonizes, the retrofit rankings based on the energy metric remain the same; regardless of the grid emission rate and regardless of the retrofits' embodied carbon, each retrofit's energy consumption stays constant. Using the life-cycle carbon metric, however, yields entirely different results over time, especially when comparing between columns A and C, columns A and D, or columns A and E. Key takeaways from these results are discussed further in Section 4.1.

3.4 Cost-effectiveness of carbon reductions considering the time value of carbon

Carbon reductions for each retrofit intervention were calculated to account for the TVC as described in Section 2.7 then ranked using the reduced life-cycle carbon per dollar saved/spent metric outlined in Section 2.8. The results from ranking the Houston retrofit interventions, considering different carbon discount rates and assuming Houston's current grid over the 30-year analysis period, are shown in Figure 11.

The change in rankings among the different carbon discount rates can be attributed to small differences in a product's initial embodied carbon expenditure, how often the products and materials need to be replaced, and when embodied emissions are "spent" over the product's lifespan. As a result, the discount rate's impact on life-cycle carbon reductions and retrofit rankings are subtle. Still, we can observe patterns as the assumed carbon discount rate increases, signaling greater emphasis on present-day carbon emissions over future carbon emissions.

As the discount rate goes up, shallow retrofits either maintain their ranking or move up in rank. The shallow retrofits that move up in rank (shallow wall and shallow ceiling insulation) utilize extremely low-carbon materials like cellulose insulation. As a result, when the carbon discount rate is applied, the low initial carbon expenditure associated with the cellulose results in proportionally greater carbon reductions when compared to the other retrofits that employ higher-carbon materials. Meanwhile, many of the deep retrofits (deep ceiling insulation retrofits, deep wall insulation retrofits, and deep envelope retrofits) decline in rank. These deep retrofits have higher upfront carbon expenditures because they rely on higher-carbon insulation, polyisocyanurate, and require wall cladding replacement. As a result, when the carbon discount rate is applied, the high initial carbon expenditure brings down the rankings for many deep envelope retrofits. The same is true for the PV with battery storage retrofit, which has relatively high embodied emissions and frequent equipment replacement. Electric heating follows the same pattern as well, with very high initial embodied carbon from the system's refrigerants.

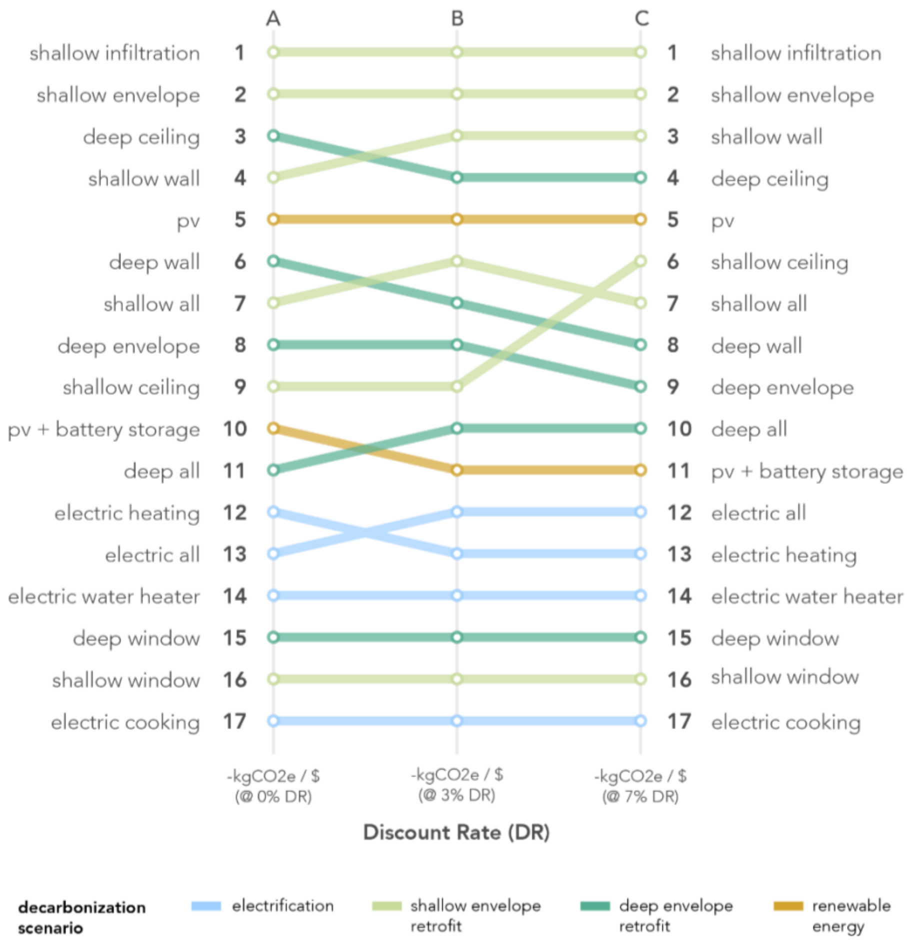

Figure 11. Ranking of Houston retrofit interventions from best (1) to worst (17) considering the time value of carbon.

4 Discussion

4.1 Contributions

This study presents a proof of concept for a methodology to compare monetary costs and environmental benefits among decarbonization strategies at various grid intensities and at different time values of carbon. The study is unique in that its metrics consider both embodied and operational carbon emissions over time, As described in Section 3.3, The widening discrepancy over time between the more typical metric of reduced energy per dollar spent (-kWh/$) and the proposed metric of reduced carbon per dollar spent (-kgCO2e/$) suggests that the life-cycle carbon metric will become even more important as time goes on.

The rankings of distinct retrofit interventions vary from city to city, but the general trends in how our three decarbonization strategies (upgrading the building envelope, switching from gas to electric equipment, and adding renewable energy) perform over time are relatively consistent across all cities we studied. Assuming current grid emission rates, envelope retrofits tended to rank higher (better) than renewable energy and electrification upgrades in terms of kgCO2e per dollar spent. However, as emission rates decreased, electrification upgrades rose in rank, while renewable energy upgrades fell.

While the results suggest that adding PV will make less sense as the grid decarbonizes, this finding poses a paradoxical challenge. Saving energy with a cleaner grid requires a significant upfront carbon investment in renewable energy systems, and it would be worth comparing embodied emissions of different renewable energy sources to understand the trade-offs between solar energy and renewable energy systems that were not explored in this study. Further, we should not invest resources in overproducing clean energy, because once all the electricity needed is provided from clean sources, there would be no need to build more until demand increases.

Including the TVC generally caused retrofits with high initial carbon investments to drop in ranking. The results illustrate that considering life-cycle carbon and the TVC has important implications on decarbonization recommendations for homeowners, policymakers, and researchers. In evaluating different building performance upgrades, the TVC is rarely considered or quantified. As a result, studies that do consider life-cycle carbon emissions from buildings are assuming a carbon discount rate of 0% by default.

Although there isn't yet consensus on what the correct discount rate should be, the results from this study reinforce that it is probably not 0%, and assuming there is no discount rate can change our recommended retrofit interventions.

In all, the change in results from considering the TVC are somewhat subtle, particularly at low discount rates, but our TVC sensitivity analysis indicates that accounting for the TVC can provide important insights when making decisions regarding building decarbonization and timing of different decarbonization approaches. Shifts in rankings as the carbon discount rate increases do not follow the same patterns observed as the grid decarbonizes (see Section 3.3). Ideally, future research would consider both life-cycle carbon and the TVC but putting a number to the TVC is still a recent development that could benefit from further advancements in methodology per Section 4.3.

By comparing homeowners' project locations and grid emission rates to those analyzed in the study (the study's three sites [Houston, Los Angeles, and Chicago] and four grid emission rates [assuming the current grid, CAMX grid, NYUP grid, and a zero-carbon grid] make for a total of 11 distinct combinations), homeowners can use the reduced carbon per dollar spent rankings to approximate the best retrofit investments for their specific home and budget. Given the lack of regulation around residential retrofits, understanding the projected emissions associated with various decarbonization strategies can help a lot of homeowners make informed decisions about home upgrades until mandated carbon limits can be further developed and implemented.

The results can also help homeowners decide when it makes the most sense to replace gas equipment with electric equipment. For instance, in our electrification scenarios, we assume the switch to electric equipment happens in 2020. However, in locations with more carbon-intensive grids, homeowners would ideally keep their gas-fueled equipment up until the emission rate is low enough for electric equipment to have lower environmental impacts. We could refer to this emission rate as the "carbon break-even point." Additionally, replacing existing gas-fueled equipment (having an assumed efficiency of 80%) with more efficient gas-fueled equipment (efficiencies ranging from 90% - 98.5%)[84] would push that "carbon break-even point" further into the future, so it is worth thinking through which building systems are currently viable options for consumers, and at what point it really makes sense for homeowners to consider an electric replacement.
Policymakers and researchers have a particularly pressing role. Historically, uptake of residential retrofits

[84] "Furnaces and Boilers."

has been low.[85] With the U.S. government expressing renewed interest in investing in home energy upgrades, policymakers and researchers are well-poised to develop incentives, standards, and educational materials that expand the percentage of homeowners pursuing retrofit projects.[86] The findings from this study, namely the importance of considering both life-cycle carbon and the time value of carbon, can serve as a foundation to build a deeper understanding of residential carbon emissions and how emission projections vary based on the metrics considered.

Implementing life-cycle carbon metrics into research, planning, and design allows researchers, policymakers, and designers to be far more strategic with their building decarbonization targets and recommendations. Embodied carbon, grid decarbonization, and the time value of carbon are often omitted from studies that focus on building performance, but these parameters matter. Consideration of these factors not only changed the predicted carbon emissions, but they also changed which design interventions performed best in terms of kgCO2e per dollar spent. This finding suggests that analysts, especially those supporting building policy or incentive programs, should update their methods to include these considerations.

4.2 Limitations

Although the overarching trends in retrofits' carbon emissions over time were consistent across the three cities we studied, the emissions associated with individual retrofit measures were more sensitive to the assumptions behind each energy simulation, LCA, and LCC assessment. For example, we expected the shallow and deep ceiling retrofits to rank higher than they did, particularly in Chicago where the homes in the very cold climate could benefit from high levels of insulation. Yet, the ceiling insulation upgrades often ranked lower than wall insulation upgrades, except for in Houston. We suspect that because we assumed U-0.285 W/m^2K existing attic insulation (compared to our assumption of no existing wall insulation), the most cost-effective carbon savings had already been realized by the existing attic insulation. It is also likely that the ceiling insulation simply does not pay off as quickly in locations where the sun spends fewer hours directly overhead (compared to Houston). Though our results suggest adding additional ceiling insulation is not the highest priority in any of the studied cities, it may in fact be a worthwhile investment for homes with no existing ceiling or roof insulation.
Air infiltration was another envelope upgrade that could have yielded a much higher or lower ranking

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[85] Laski and Burrows, "From Thousands to Billions"; Sebi et al., "Policy Strategies for Achieving Large Long-Term Savings from Retrofitting Existing Buildings."
[86] "Biden Administration Announces Investments to Make Homes More Energy Efficient and Lower Costs for American Families."

depending on our base assumptions. For air sealing renovations, most of the cost is related to labor, and because of the wide range of conditions in existing homes, these air sealing costs (and reasonably achievable air exchange rates) are highly variable. In general, the infiltration renovations ranked very high in terms of reduced kgCO2e per dollar spent, but if our assumptions about the labor involved for each air exchange rate (outlined in Section 2.5) were too low, then the infiltration retrofits would fall in ranking accordingly.

In Section 2.3.1, we describe the ground modeling methodology we adopted when we translated the EP prototype models to Design Builder. We set the "Monthly Temperature" for the ground adjacent to the slab to 2°C less than the average indoor temperature (23.9°C or 22.2°C, depending on whether the city is in a cooling- or heating-dominated climate, respectively). Per EP documentation, this method would be most appropriate for commercial buildings. For residential buildings, the ground adjacent to the slab would fall somewhere between 21.9°C (or 20.2°C) and the undisturbed ground temperature, which in Houston averages to 19.9°C. Though the range in potential "Monthly Temperatures" is not very large in Houston, the average ground undisturbed ground temperature is 16.6°C in Los Angeles and 9.5°C in Chicago. In cooler climates especially, an assumed "Monthly Temperature" of 2°C less than the average building temperature could result in lower heating energy consumption than would be realistic, and a more precise ground modeling method would improve the accuracy of our results.

The assumptions behind our building systems could have impacted our results as well. For instance, we did not account for structural reinforcement of the roof that would be required for roof-mounted PV. Compared to the GWP of the PV and battery system (where applicable), the wood framing for structural reinforcements would have likely had a relatively small impact on the retrofits' total GWP. Similarly, when calculating the embodied emissions associated with mechanical systems, we did not quantify the ductwork infrastructure that would be necessary to transfer heat from the heating equipment to the point of distribution. The materials associated with such infrastructure varies widely depending on building layout, but the ductwork needed for the gas-fueled system would be similar to the ductwork needed for the electric system. Therefore, omitting the carbon associated with the ductwork would not have had a substantial impact on the carbon reduced through the mechanical system retrofit.

Changing the assumptions behind our decarbonization scenarios, described in Section 2.6, could have made the changes we observed between decarbonization scenarios more subtle. The assumption of one grid emission rate from 2020 – 2050 served as an easy-to-assess comparison rather than an indicator of reality. Had we varied the grid emission rate over time rather than maintaining one grid mix over the entire analysis period, the differences between each grid decarbonization scenarios would be less pronounced, as all the decarbonization scenarios would approach the same zero-carbon target, reaching an emission rate of zero by 2050.

Finally, the lack of directly comparable data, particularly for the LCC and LCA scope, increased the uncertainty of some of our calculations. To estimate the first cost of each retrofit intervention, we utilized two different cost estimating programs per Section 2.5. Relying on two databases introduced discrepancies between similar materials depending on the database. To minimize such discrepancies, we used RSMeans for all envelope retrofits, and Clear Estimates for all equipment retrofits. For a select few retrofits, we could not find cost data in either database and had to consult other sources. Even if we had been able to consult just one cost database, the range of existing homes is huge, and our study makes a lot of assumptions about the existing conditions of the homes and existing assemblies. In reality, the cost of many of these retrofit options, particularly the deep retrofits, could cost far more or far less than we budgeted for within the scope of our study. Though the results presented in this paper are meant to serve as a rough guideline and illustrate general trends, the results may vary widely on a case-by-case basis.

We ran into similar challenges when conducting LCA for the retrofit interventions. For most envelope upgrades, we calculated embodied emissions using Tally. For all gas-fueled and electric equipment, we borrowed embodied emissions data from existing literature (most of which used SimaPro for their LCA). And for PV systems and mechanical ventilation, we quantified the embodied emissions using SimaPro. Tally and SimaPro rely on different LCA databases for material carbon emission factors, so there are bound to be discrepancies between the two. Further, there are numerous ways of accounting for embodied emissions within SimaPro, and it is not always clear in the literature which methods were used. By normalizing the reported emissions from literature to the functional unit described in Section 2.4, we were able to minimize discrepancies among the retrofit cases. With greater resources, the materials associated with all retrofit interventions could be evaluated in SimaPro using one database and the same set of underlying assumptions, increasing the accuracy of our results.

Due to the lack of available LCA data, we did not include our retrofit materials' End of Life (EOL) or Module D emissions. Though we could have included this data for most of the envelope upgrades, we did not find comparable data in literature for the gas-fueled and electric equipment. To ensure we could compare among all retrofit interventions and among all decarbonization scenarios, we omitted those life cycle stages. Figure 12 references the emissions included as well as the emissions omitted for the envelope upgrade scenarios. The figure illustrates how considering EOL and/or Module D would have impacted the

GWP values used in the analysis.

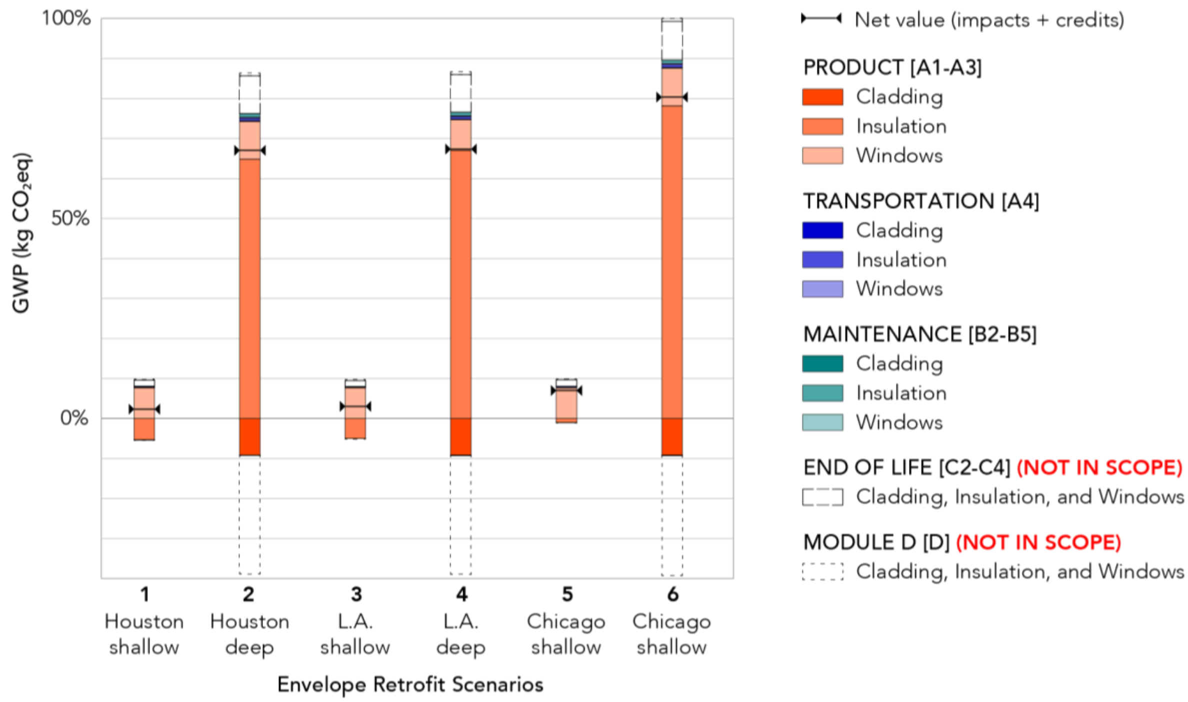

***Figure 12. Global Warming Potential of envelope upgrade scenarios by life cycle stage.** Considering EOL and Module D emissions would increase the net GWP value associated with shallow envelope retrofits and decrease the net GWP value associated with deep envelope retrofits. Though the overall GWP from deep envelope retrofits would still far outweigh those from shallow envelope retrofits, the difference between the two would decrease.*

Further, as seen in Figure 5, some of the embodied carbon estimates using Tally yield net negative GWPs. When an analysis includes biogenic carbon, the Tally software assumes bio-based materials like cellulose and wood sequester carbon in the product stage, resulting in net negative emissions. Per ISO 21930-2017, products that act as carbon sinks with negative emissions in A1-A2 should release the positive emissions back to the environment in life cycle stages A1, A5, and C3-C4.[87] This means that bio-based materials should have zero or near-zero emissions because the carbon that the product sequesters will be released back to the atmosphere at the product's end of life. Based on our results, Tally does not account for sequestered carbon being released back to the atmosphere at the end of life per ISO 21930-2017. Therefore, the GWP of bio-based materials tend to be lower using Tally than they would be if following the ISO 21930-2017 standard, which could cause the performance of retrofits with biogenic carbon to be overstated.

[87] "ISO 21930."

4.3 Future Work

As noted in Section 4.2, the method that our software of choice, Tally, uses to estimate embodied emissions for bio-based materials does not follow ISO 21930-2017. Future work should use this standard to account for a net neutral biogenic carbon balance. Additionally, including emissions associated with the retrofits' EOL, and Module D life cycle stages would provide a more complete picture of life cycle carbon trade-offs among material choices and among retrofit interventions. Homeowners and developers are beginning to embrace the need to shift to low-carbon materials. Further research and data development for EOL and Module D emissions could help quantify the benefits of such materials and build a stronger case for working toward closed loop systems and manufacturing processes.

Future work should also consider the life-cycle carbon impact of the additional electric infrastructure that will be needed to support a large-scale shift to electrification. Given the results in Section 3.3 that indicate the growing importance of building electrification as grid emission rates continue to decline, it will be important to understand the GWP associated with expanded electrification infrastructure in individual homes and at the larger grid scale. This study assumes that switching from gas-fueled to electric equipment does not entail an upgrade in electric service. However, serious electrification upgrades may require new service panels in existing homes and upgraded transformers, energy storage systems, metering infrastructure, and transmission lines at the grid scale. These upgrades can be material-intensive, and often involve extraction of Rare Earth Elements, which can have disproportionately large environmental impacts compared to more widely-available materials.[88]

This research did not account for the changing value of renewable energy based on time. We assume that all PV-generated electricity can be used in the building and that all PV-generated electricity has the same monetary value and environmental impact. Ideally, future research would account for the timing of battery use, its impacts on peak load emissions, and its impacts on electricity costs to the consumer. Time of use pricing is beginning to address some such impacts, but time of use rates are still not widely implemented, with only about 1.7% of all residential customers opting in to pilot programs that utilize the variable rates.[89] Because this research did not consider time of use pricing, the results understate the value of battery storage. Yet battery storage will be critical to the energy transition and being able to account for and quantify its benefits warrants further research.

Capturing the full value of battery storage would benefit homeowners as well as utilities. For example, if

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[88] Navarro and Zhao, "Life-Cycle Assessment of the Production of Rare-Earth Elements for Energy Applications."

[89] "An Emerging Push for Time-of-Use Rates Sparks New Debates about Customer and Grid Impacts."

buildings reduce peak period demand, then utilities can delay infrastructure investment. Similarly, if homeowners and utilities can better-align energy supply and demand, we can reduce the number of batteries and their associated embodied emissions. To help in that effort, future studies should research which strategies are most effective in deploying battery storage.

In Section 4.2, we discussed the limitations of maintaining one grid emission rate from 2020 – 2050 for each grid decarbonization scenario rather than varying the grid emission rate over time. In addition to varying the grid emission rate over time, future work could consider the life of the design decision. For example, if the analysis period remained at thirty years, insulation might be assumed to last the full thirty years whereas a heat pump might be assumed to last for about 14 years. Therefore, only the grid emissions over the next 14 years would be included in the heat pump analysis, which would make heat pumps less attractive in grids expected to maintain a relatively high carbon intensity over the next 14 years.

Lastly, we conducted a sensitivity analysis to illustrate how accounting for the TVC can impact how we prioritize different decarbonization strategies. In Houston, our TVC results changed enough among the different discount rates we considered, that we were able to observe clear trends as described in Section 3.4; with higher discount rates, higher initial carbon expenditures brought down the rankings for many deep envelope retrofits and renewable energy retrofits. However, the results for Los Angeles and Chicago do not show as significant, nor as intuitive of shifts in retrofit ranks as the discount rate changes. We could speculate as to why this might be, but ultimately a wider range of discount rates in more cities with different electric grid emission rates would be helpful to inform the results we found in our work. Additionally, assigning an appropriate discount rate to calculate the TVC requires additional research and would benefit from further advancements in methodology. Work in this realm should consider the discount rate's consequences on future generations.

4.4 Conclusion

This research analyzed the carbon- and cost-effectiveness of three decarbonization strategies in residential retrofits of pre-1980's homes in Houston, Los Angeles, and Chicago. The decarbonization strategies – electrifying buildings, upgrading envelopes, and adding renewable energy – were further divided into distinct retrofit interventions to help homeowners and policymakers prioritize energy upgrades for different climates and electricity grids. Using energy simulation and LCA, we quantified the life-cycle carbon reduction and LCC associated with each retrofit, ranked the interventions accordingly, and calculated how the rankings would change if electricity grid emission rates decreased or if we accounted for the TVC. Assuming current grid emission rates, envelope retrofits tended to rank higher than renewable energy and electrification upgrades with a few exceptions. However, as anticipated emission rates decreased, electrification upgrades rose in rank, while renewable energy upgrades fell. Including the TVC generally caused retrofits with high initial carbon investments to drop in ranking. The results illustrate that considering life-cycle carbon and the TVC has important implications on decarbonization recommendations.

This work and work that stems from it can be used to explore policy tools that will incentivize appropriate decarbonization strategies in residential retrofits or to propose a discount rate that helps researchers and policymakers assess the TVC more accurately. Such policy measures are urgently needed to increase the percentage of existing homes that pursue retrofits, but until additional mandates can be enacted, the trends and methods provided in this research can guide homeowners and researchers to make more informed decisions about building decarbonization within the existing residential building stock.

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