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Achieving equitable space heating electrification: A case study of Los Angeles

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ABSTRACT

A major step towards residential building decarbonization is the electrification of natural gas space heating. Current inequities such as limited access to cooling technologies and high energy burden can be addressed in transition if we take steps now to understand the economic impacts of different electric technologies. This study presents a novel high-resolution techno-economic model, the Marginal Net Present Value Upgrade Analysis model, which improves upon existing literature that examines the economics of electrifying space heating through a more detailed cost calculation and the use of a variable discount rate. Results show that 1) electrifying with heat pumps is only recommended for owners who are replacing a natural gas furnace and central AC system, 2) renters are highly vulnerable in this transition in that electric resistance technologies are the least capital intensive technology for landlords to install, with renters bearing the increased operational cost, 3) rebates from the Inflation Reduction Act of 2022 allow most qualifying landlords and owners to install even the highest efficiency heat pumps at a net savings when compared to the baseline heating and cooling system, and 4) reducing capital costs are more critical than altering utility rates to achieve high heat pump penetration. The model developed herein can support decision-making related to electrification and energy efficiency policy and rule-making and will give insight into the impact residential building electrification can have on marginalized communities.

1. Introduction

Electrification is an important strategy for reducing CO_2 emissions [1,2]. A shift towards more widespread electrification is evident at both the federal and state levels; specifically emphasizing a shift towards electric heating in buildings [3].Then in 2018, California's governor signed Executive Order B-55–18, which mandated state-wide carbon neutrality by 2045 [4]. According to the California Air Resources Board, buildings are responsible for approximately a quarter of the state's greenhouse gas emissions [5]. According to the Energy Information Administration (EIA), space heating is the single-largest household end use in California and most of this space heating is fueled by natural gas [6]. Therefore, to meet these legislative goals and to mitigate the impacts of climate change, it is critical that California decarbonize space heating in residential buildings across the state.

While electrifying space heating in the residential building sector, it is key that we consider the equity implications of this transition. To do this we must understand how different resident characteristics are impacted differently in this transition. From a physical systems perspective, the primary proposed method to reduce building greenhouse gas emissions is through the combination of building electrification and increased penetration of renewable energy generation technologies [7–12]. However, the impacts of climate change are being felt disproportionately more by politically, economically, and culturally marginalized communities [13]. Yet, the policies set out to address climate change often neglect these same communities in the type of

Abbreviations: AEO, Annual Energy Outlook; AMI, Area Median Income; ASHP, Air-Source Heat Pump; AWS, Amazon Web Services; CARE, California Alternative Rates for Energy; CEC, California Energy Commission; CED, California Energy Demand; EIA, Energy Information Administration; HUD, U.S. Department of Housing and Urban Development; IRA, Inflation Reduction Act of 2022; LADWP, Los Angeles Department of Water and Power; LRD, Load Research Data; MSHP, Mini-Split Heat Pump; NPV, Net Present Value; NREL, National Renewable Energy Laboratory; UCLA, University of California – Los Angeles.

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support they provide or the types of households who can access the benefits of these policies [13]. Integrating equity implications into the energy transition requires that we consider additional factors in addition to the physical systems such as resident income level, their role as homeowner, landlord, or renter, along with the building type.

The City of Los Angeles, hereinafter referred to simply as Los Angeles, has many characteristics which make it an ideal case study. First, the electrification of residential space heating in Los Angeles will reduce close to 20 % of scope 1 emissions from this sector – a significant step towards decarbonization. Second, from a systems perspective, Los Angeles has a municipal utility, the Los Angeles Department of Water and Power (LADWP). Owning and operating its utilities gives the city much greater control over their energy system and its utility data [14]. Los Angeles is one of the largest metropolitan areas in the United States; more than 1 in every 100 U.S. resident lives in Los Angeles [15]. Thus, any change to this energy system will influence a significant portion of the California and U.S. populations. Third, from a societal viewpoint, Los Angeles offers not only a highly diverse population in terms of race, income, wealth, homeownership, and residential building type, but also a population with extreme disparities across these dimensions [16]. Therefore, the lessons learned from the implementation of electrified space heating in Los Angeles' residential building can be extrapolated nationally along these same demographic dimensions. Additionally, Los Angeles shares a similar climate with large populations centers including San Diego, Tijuana, Cape Town, Perth, and most of the Mediterranean. Thus, the technologies examined herein and their respective performance can be leveraged by a broad international audience. From a technological viewpoint, modern electric technologies, especially heat pump space heating and cooling systems have been found to be up to five times more efficient as compared to their natural gas equivalents, especially in mild, dry climates like those found in Los Angeles [17,18]. Finally, in the LA100 Equity Strategies study conducted by the National Renewable Energy Laboratory (NREL) and the University of California Los Angeles (UCLA), representatives from various community-based organizations were involved in a series of meetings regarding the city's efforts to decarbonize its energy, transportation, industrial, and building sectors. In those meetings the most common concern expressed by these representatives regarding residential buildings was the affordability of any proposed upgrades. Other major concerns included the health and safety of current residential buildings, the quality of current infrastructure in marginalized communities, and renter/landlord issues [19].

There is an existing body of work on modeling the consumer economics of space heating electrification retrofit upgrades in residential buildings. At the time of writing, we found 13 studies that examine the costs for retrofitting existing homes [20–32]. Table A 1 in the Supporting Information gives an overview of all these studies, their study design, and reporting metrics. The previous work on the economics of space heating electrification shows five critical areas where existing research is deficient if our aim is to truly understand the societal and equity impacts of a space heating electrification transition. First, all existing studies exclude some aspect of the costs associated with electrification upgrades. Only Mahone et al. [20], Billimoria et al. [24], Partridge [28], Kolwey and Petroy [31], and Nadel and Fadali [32] considered all installation costs and only one study by Asaee et al. [22] sized, and thus priced, both the baseline and upgrade space heating systems to the building being modeled. This shows that most of the existing studies weigh the relative impact of operating cost greater than the capital costs associated with these upgrades. Second, all previous studies used low and fixed discount rates, ranging from 1 % to 10 %, when valuing future savings of more efficient space heating technologies. In a review of large-scale, general equilibrium, economy-wide energy models, the discount rates for space heating retrofits technologies ranged between 5 % and 45 % [33–39]. Furthermore, the literature indicates that among a variety of other characteristics, households with lower incomes have a preference for higher discount rates [40–43]. Third, existing studies only considered a narrow range of baseline and upgrade space heating technology configurations. Only Asaee et al. [22], Deetjeen et al. [23], Kelly et al. [26], and Nadel and Fadali [32] considered all major baseline space heating technologies, and not a single study considered upgrading to electric resistance heating systems. Furthermore, only Deetjeen et al. [23], Billimoria et la. [24], Nadel [25], Hopkins et al. [27], and Nadel and Fadali [32] considered the situation where only the space heating system is upgraded. Fourth, several of these studies report their results in a way that obfuscated the real costs at the household level. They used metrics such as 'CO_2-abatement costs' [21], 'tolerable capital costs' [22], or the addition of health and climate cost [23], which do not represent the costs households will encounter when making these upgrades. Finally, the low reporting resolution of these studies impedes informed decision making. The highest geographic resolution of any of the studies were at the city level [20,23,24,27,28,30,31], only three studies ensured that both single- and multi-family households were modeled [20,27,32], only Nadel and Fadali [32] reported the impact of household income level on their results and not a single study disaggregated households by renter/owner status.

This study present presents a novel high-resolution techno-economic model, the Marginal net Present Value Upgrade Analysis model, which improves upon existing literature that examines the economics of electrifying space heating through a more detailed cost calculation of a wider range of baseline and upgrade technologies and the use of a variable discount rate. Methodologically, all major baseline space heating technologies were considered herein, and their electrification upgrades range from the lowest efficiency electric resistance systems to the highest efficiency heat pump systems currently available. Using a physics-based residential building stock energy model, all baseline and upgrade equipment are sized, and thus priced, to meet the heating load of each household. Furthermore, each simulated household was assigned a unique discount rate based on household income, and an individualized cashflow was calculated for every upgrade for each simulated household. This cashflow captures all associated upgrade costs – operating, equipment, installation, and fuel switching – a major improvement on existing studies. Marginal net present value was quantified alongside the change in capital costs and the change in operating costs of various space heating electrification upgrades in Los Angeles. Thus, this model quantifies how these costs uniquely impact owners, landlords, and renters along with reporting these costs for each space heating electrification upgrade by building type, income level, and renter/owner status. With this level of resolution, it is possible to give meaningful guidance to California policymakers to ensure an equitable transition to residential building electrification. Finally, using the provisions from the High Efficiency, Electric Home Rebates Program stipulated by the Inflation Reduction Act (IRA) of 2022, we quantify the impact of the point-of-sale rebates for high-efficiency heat pumps [44]. This unprecedented allocation of federal funding will have a significant impact for qualifying households and must be considered when understanding the economic implications of a transition to space heating electrification. The approach presented herein addresses the challenges and opportunities present in the electrification of space heating and enables decision-makers to ensure a fair and equitable energy transition.

2. Methodology

To quantify all costs associated with a transition to electrified space heating, we follow a four-step methodology. Section 2.1 demonstrates how the baseline energy consumption of 50,000 representative building samples was simulated using a custom version of NREL's ResStock^{TM} modeling framework, customized to better reflect the weather, income correlations, and technology stock distribution found in the Los Angeles and validated against Load Research Data from the city's municipal utility, LADWP. Section 2.2 outlines the creation of four different space heating electrification upgrade packages. We then simulate the energy consumption of each of these space heating upgrade packages for the representative building sample using the same methodology in Section 2.1. Section 2.3 details the quantification of the net present value (NPV), the change in capital costs, and the change in operating costs for each simulated building for each space heating electrification upgrade package, based on each building's unique cashflow and discount rate. In the calculation of these metrics the model considers households which qualify for utility bill assistance and IRA rebates along with federal rebates for qualifying technologies. Finally, Section 2.4 reviews the three sensitivity analyses we conducted – household discount rate, utility rate projections, and relative price of natural gas and electricity. Through this analysis, we can give custom recommendations for Los Angeles residents given their income level, renter/owner status, type of building, and existing technologies in their household.

2.1. Simulate Baseline Energy Consumption

ResStock is a physics-based, bottom-up, white box, residential building stock energy model developed by NREL [45]. ResStock defines the relative probability of 127 residential household characteristics through a set of conditional probability tables synthesized from 11 national data sources. These household characteristics include both the physical characteristics of the buildings themselves (e.g., wall insulation R-value, roof material type) and behavioral characteristics of the occupants (e.g., occupancy schedules, thermostat settings). For this study, the probability of some of these characteristics was customized to Los Angeles. ResStock model geographic resolution was improved from the U.S. Census Bureau's Public Use Microdata Areas to the Census Tract level by creating weighted crosswalk using the 2020 U.S. Census Bureau Redistricting data [46]. Appliance saturation levels were revised using the 2019 California Residential Appliance Saturation Study and correlated these saturations to both income and renter/owner status [47]. Finally, we adjusted the model to simulate the weather using a typical metrological year weather file for each of the four California Energy Commission (CEC) Climate Zones found in Los Angeles – CEC Climate Zones 6, 8, 9, and 16. One limitation of this study is that we use the same weather year for the duration of the projection period. Thus, we do not address the impacts of year-to-year climate variability or the long-term impacts of climate change.

With the aforementioned customizations to ResStock, we then created our baseline scenario. The hourly energy use of all major energy end uses for the residential buildings sector in Los Angeles was simulated. First, 50,000 dwelling units were sampled using a modified Latin hypercube approach to approximate the residential building stock of Los Angeles. After envelope characteristics were determined, space heating technologies were sized following the Air Conditioning Contractors of America's Manual J [48]. Next, the characteristics and weather files associated with each dwelling unit was fed into the building energy modeling platform OpenStudio® which employs the EnergyPlus™ modeling engine to generate the hourly energy consumption total for all major end uses using NREL's high-performance computing services [49]. Finally, the model results were then successfully validated against Load Research Data provided by the LADWP (See Appendix B in the Supporting Information).

2.2. Simulated Space Heating Electrification Upgrade Energy Consumption

A set of space heating electrification upgrade scenarios was developed at four different efficiency levels for comparison to the baseline scenario as described in Section 2.1. The upgrade scenarios are summarized in Table 1. All dwelling units with ducts were upgraded to an air-source heat pump (ASHP), and those without ducts were upgraded to a mini-split heat pump (MSHP).

Space heating system configurations are highly complex, with many different technology types, efficiency levels, and space cooling system pairings. The ResStock model simulates individual and shared heating

Table 1
Space Heating Electrification Upgrade Package Definitions.

Upgrade Technology and Scenario Name	***Baseline Technology*** *Natural Gas Furnace*	*Natural Gas Boiler*	*Natural Gas Wall/ Floor Furnace*
Electric Equivalent	Electric Furnace	Electric Boiler	Electric Wall Furnace
Low-Efficiency Heat Pump	For households with ducts: ASHP SEER 15, 8.5 HSPF[1] For households without ducts: MSHP SEER 17, 9.5 HSPF[2]		
Mid-Efficiency Heat Pump	For households with ducts: ASHP SEER 18, 9.3 HSPF[1] For households without ducts: MSHP SEER 25, 12.7 HSPF[2]		
High-Efficiency Heat Pump	For households with ducts: ASHP SEER 24, 10.8 HSPF[1] For households without ducts: MSHP SEER 33.1, 13.5 HSPF[2]		

[1] – Also replaces Central AC equipment when present in the baseline
[2] – Also replaces Room AC equipment when present in the baseline

configurations, central and room AC systems, households with and without cooling systems, households which fully and partially cool their floor area within the thermal envelope (based on % of floor area), and households which use and do not use their cooling systems. When upgrading to heat pump, we set the model to ensure that residents use their cooling systems whenever the temperature rise above the cooling setpoint and to cool 100 % of the floor area. One limitation of this study was that we did not address the shared space heating systems; shared heating systems are highly bespoke and thus difficult to accurately recommend effective upgrades, let alone determine accurate retrofitting costs.

Based on our previous work on developing high-quality scenario for energy models [50], we analyzed the scenario development process of this study using the Internal Consistency and Diversity Comparative Framework. In terms of internal consistency, there were two places in which this study could be improved. First, the stakeholder involvement could be improved. While we did consider comments and concerns from community-based organization representatives from Los Angeles, the authors were not part of the selecting of these individuals and organizations and therefore could not speak to the selection process. Second, given that access to this study is based on a subscription and only some of the information is publicly available, access is limited. In terms of diversity, the types of variables and scenarios featured in this study were deemed sufficiently diverse to answer the research questions presented in the Introduction. Full documentation of our scenario development analysis of this work can be found in Appendix B in the Supporting Information.

2.3. Upgrade Cost Quantification

Given the highly resolved data generated by the custom Los Angeles ResStock model, we created the Marginal Net Present Value (NPV) Upgrade Analysis Model as a techno-economic plug-in software tool to analyze the marginal cost to replace the baseline natural gas technologies with the various space heating electrification upgrades outlined in Table 1. In this section, we first discuss the theory behind calculating the marginal NPV of replacement for each space heating electrification upgrade. Then we outline how the Marginal NPV Upgrade Analysis Model processes the custom Los Angeles ResStock data to build a cashflow and then calculate the costs associated with the space heating electrification upgrades for each simulated dwelling unit.

2.3.1. Cashflow calculations

The marginal NPV of replacement is determined by first creating the anticipated difference in cashflow of an upgrade scenario as compared to the baseline, discounting that cashflow across time. The marginal NPV of replacement is then calculated by summing the terms of this discounted cashflow (Equation 1).

Equation 1: General Net Present Value Equation

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1-r)^t}$$

where n is the number of time periods; C_t is the cashflow at time, t, r is the discount rate, and t is the time period.

The cashflow for any space heating upgrade project will be based on a combination of three costs across the projection period, the capital costs associated with purchasing a system (*Capex*), the operating costs associated with running that system (*Opex*), and the cost associated with renting a system when the average lifetime of that technology extends beyond the end projection period (*Rent*). For this analysis, the projection period is from January 2022 to December 2050, with each month representing a single time period in the projection period. A detailed overview of the creation of the cashflow can be found in Appendix B in the Supporting Information.

2.3.2. Net present value upgrade analysis model

To create the two cashflows used to calculate the marginal NPV of replacement for each space heating electrification upgrade, the Marginal NPV Upgrade Analysis Model must calculate each of these unique costs outlined in Section 2.3.1. This process is summarized in Fig. 1 which shows the software architecture diagram for the Marginal NPV Upgrade Analysis Model. Through this process, we determine the marginal NPV of replacement for each space heating electrification upgrade for each simulated dwelling as compared to the baseline.

To determine the difference in operating cost between the baseline and upgrade technologies, the Marginal NPV Upgrade Analysis Model considers two primary factors: the difference in energy consumption due to an upgrade and future utility rates. The change in energy consumption due to an upgrade is easily calculated using the Athena query

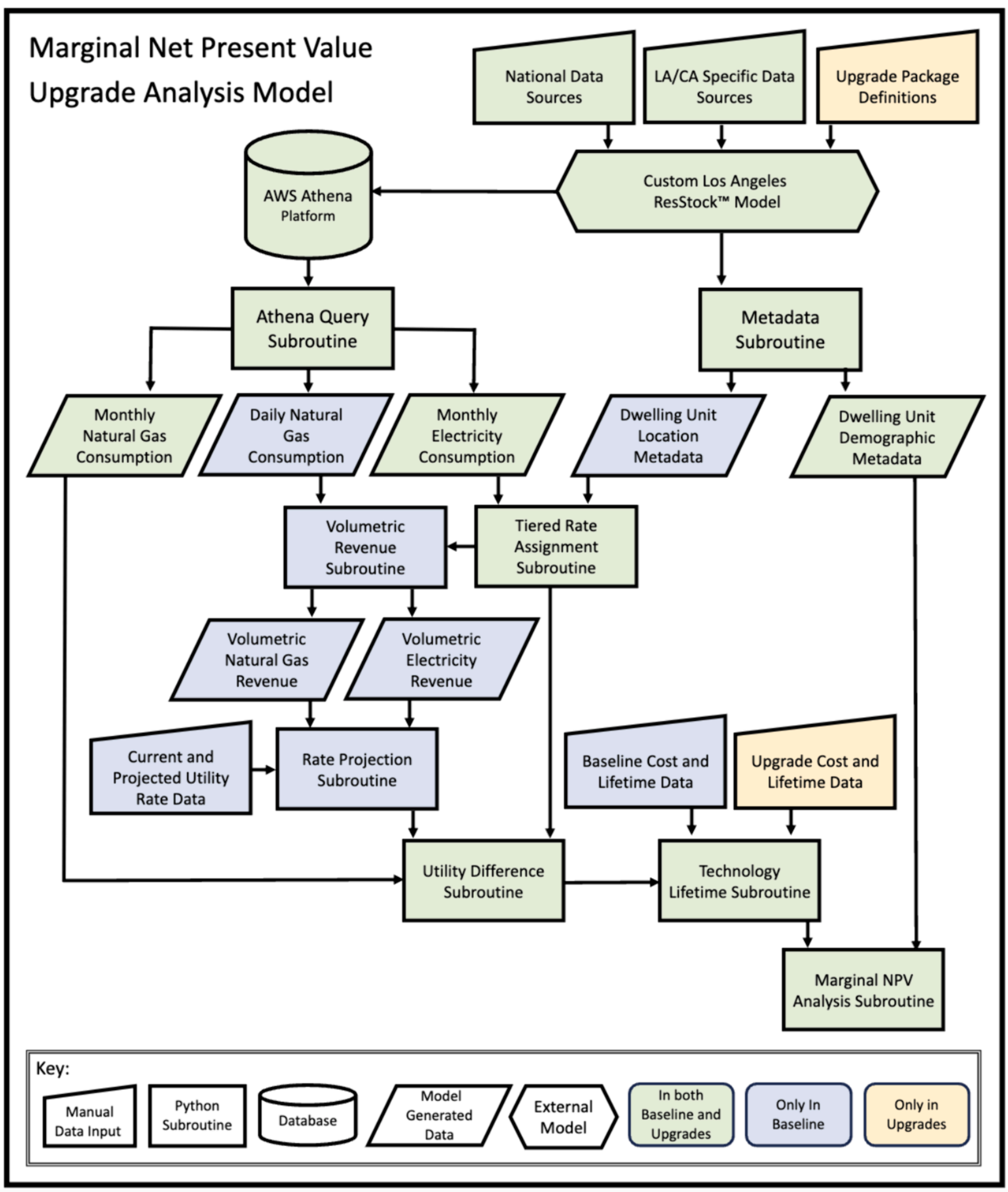

Fig. 1. Software architecture diagram for the Marginal Net Present Value Upgrade Analysis Model.

subroutine to access the natural gas and electricity consumption of both the baseline and upgrade scenarios and calculating the difference. The next step is to calculate future energy prices. First, the volumetric revenue subroutine calculates the simulated volumetric utility revenues for the base year (2022) using Los Angeles-specific utility rate along with the estimated volumetric utility revenues for the base year and the remainder of the projection period (2023–2050) using utility rates from EIA's 2023 Annual Energy Outlook (AEO) reference scenario [51]. Next, the rate projection subroutine, using the difference between the simulated and estimated volumetric utility revenues for the base year, computes the simulated volumetric utility revenues and by extension, the monthly Los Angeles-specific utility rates for the remainder of the projection period. Finally, the utility difference subroutine takes the changes in natural gas and electricity consumption and multiplies these by future utility rates to output the changes in monthly operating costs for each simulated dwelling unit for the entire projection period. This difference in monthly operating costs is then applied to the cashflow for each period in the projection horizon from $t = 1$ through $t = n$ (Equation 1). On top of these monthly operating costs, we applied a 30 % discount on monthly electricity costs and a 20 % discount on monthly natural gas costs for those households which qualify for the California Alternative Rates for Energy (CARE) program. Household qualify for CARE based on a combination of their household size and household income [52]. See Appendix B in the Supporting Information for a more detailed overview of these processes in the Marginal NPV Upgrade Analysis Model.

The Marginal NPV Upgrade Analysis Model uses the technology lifetime subroutine to determine the capital cost for the baseline ($Capex_B$) and upgrade ($Capex_U$) technologies. This subroutine considers all capital costs, including equipment, installation, labor, and fuel switching costs, of all baseline and upgrade technologies. The cost of fuel switching includes capping the existing natural gas line and running one or more dedicated electric circuits to the electric space heating system based on its type and size. These costs were collected in the summer and fall of 2022. Similar to the methodology used in Walker et al., using 2022 costs represents a real-time snapshot of the economic impacts of space heating electrification in Los Angeles [53]. All heat pump upgrades meet the EnergyStar rating to qualify for federal tax credits for energy efficiency home improvements [54]. These tax credits are added to the cashflow one year following their installation and are thus discounted to varying degrees given the household's income. Furthermore, these same upgrades will qualify for the IRA's High Efficiency, Electric Home Rebate Program. These rebates cover 100 % of all capital costs (both equipment and installation costs) for households below 80 % of Area Median Income (AMI) and 50 % of all installation cost for households between 80 %-150 % of AMI with a cap of $8,000 for heat pump systems [44]. These point-of-sale rebates are applied in time period in which these technologies are installed. The inputs of Marginal NPV Upgrade Analysis Model can be toggled such that IRA rebates can be included or not.

One limitation of this study is that we assumed that each household would have capacity in their electric panel to accommodate one if not many additional circuits. Therefore, while we are trying to quantify fuel switching costs, in many cases we are not capturing the possible expense of an electric panel upgrade which could cost residents hundreds if not thousands of dollars more. The provisions of IRA's High Efficiency, Electric Home Rebate Program also allow for up to $4,000 for electric panel/service upgrades [44]. Along with an overview of the cost data, Appendix B goes into detail about the development of this cost library including the search methodology and data sources.

The technology lifetime subroutine also considers the lifetime of each technology. This lifetime data was based on data used by the EIA in their own residential building modeling efforts [55]. At the end of the lifetime of either the baseline or upgrade technology, the model adds the replacement of this equipment to the next period in the cashflow. This process is then repeated whenever the technology needs replacement. If the technology's next lifetime extends beyond the projection period, the technology lifetime subroutine generates monthly cost for renting that technology, with a market interest rate of 5 %, through the end of the projection period. See Appendix B in the Supporting Information for a more detailed overview of these processes in the Marginal NPV Upgrade Analysis Model.

The marginal capital cost of replacement and marginal operating cost of replacement for each upgrade in input into the technology lifetime subroutine to generate a cashflow for each simulated household. This subroutine then takes each cashflow and calculates the marginal NPV of replacement for each upgrade using a unique discount rate for each household. In a review of various U.S. centric energy models and space heating electrification studies, the discount or hurdle rates for space heating technologies ranged significantly [20–39,45,56,57]. Additionally, research has shown that not all households value future savings to the same extent, among a variety of other household attributes, households with lower incomes have a preference for higher discount rates [40–43]. To account for this, we assigned each household a unique discount rate based on income. The household with the highest income was assigned a discount rate of 7 % and the household with the lowest income was assigned a discount rate of 45 %. The remaining households were assigned a discount rate on a linear scale between 7 % and 45 % based on their income relative to the households with the highest and lowest incomes. The upper bound of the discount rates, 45 %, was based on the highest rate we found in the literature for space heating technologies [36]. The lower bound of the discount rates, 7 %, is based on a median of the remaining discount rates found in the literature. The final element of the model is the marginal NPV analysis subroutine which appends all the dwelling unit demographic information (e.g., building type, renter/owner, income level, baseline technology, etc.) so that analysis of various cohorts can be performed.

2.4. Economic Parameter Sensitivity Analyses

To quantify the impact of various economic parameters on the marginal NPV calculations, we performed sensitivity analyses on three economic variables: discount rate, utility rate projections, and the relative price of electricity. The first sensitivity analysis, concerning discount rates, looked to understand the impact of assigning each dwelling unit a unique discount rate inversely proportional to their household income as compared to a fixed discount rate for all households. As discussed previously, the discount rates found in the literature were wide ranging, but all other studies which examine the economics of residential building electrification use a fixed discount rate in their analyses [20–32]. We did a sensitivity analysis using a low, fixed discount rate, 7 %, which is comparable to the range of discount rates used in the existing residential building electrification studies [20–32]. This low, fixed discount rate is an optimistic view of how households value future savings. In this way, we can compare the results of our model with the results of existing studies. Through this analysis will be able to determine impact of using a variable discount rate and how it might change recommendations for electrification upgrades.

The second sensitivity analysis examined the impact of different utility rate projections used to calculate the difference in operating cost through the projection period. For our model we used EIA's Reference electricity and natural gas rates from 2022 to 2050 from the AEO [51]. For this analysis we created a variety of utility rate projections that are more and less favorable for electrification. Favorable electrification rate projection scenarios are those in which the real electricity rate decreases over time relative to the real natural gas rate, and vise-versa for the non-favorable electrification rate projections scenarios. We conducted one favorable electrification and two non-favorable rate projection sensitivity analyses and compared these to the baseline (Table 2).

The EIA favorable and non-favorable electrification rate projection sensitivity analyses were created using the most extreme electricity and natural rate projections from the 2023 AEO side-cases [58]. The CEC creates periodic California Energy Demand (CED) Forecasts for each

Table 2
Electricity and Natural Gas Rates for Rate Projection Sensitivity Analysis.

	Utility Type	
Rate Projections	*Electricity*	*Natural Gas*
Baseline	EIA Reference	EIA Reference
EIA Favorable Electrification	EIA High Oil and Gas Supply	EIA Low Oil and Gas Supply
EIA Non-Favorable Electrification	EIA Low Oil and Gas Supply	EIA High Oil and Gas Supply
CED Non-Favorable Electrification	CED Mid-Demand Case	CED Mid-Demand Case

major California utility, including LADWP [59]. Based on their relative changes in electricity and natural gas rates, we used the Mid-Demand Case to create a second non-favorable electrification rate projection sensitivity analysis.

The final variable we performed sensitivity analyses on was the relative price of electricity compared to natural gas. Based on information from the U.S. Bureau of Labor Statistics, the Los Angeles metro area has some of the highest electricity costs relative to the cost of natural gas (Fig. 2) [60]. At approximately, $0.137 per kWh/$ per therm, the difference in cost between electricity and natural gas in Los Angeles used in our model is markedly higher as compared to the U.S. average ($0.099 per kWh/$ per therm) or any other U.S. regional average. Given the high cost of electricity compared to natural gas in Los Angeles, electrification could face barriers greater than those found in different areas across the nation. To test the impact of these relative costs, we reduced the price of electricity in the model to match the relative electricity and natural gas price of the U.S. average, and the lowest U.S. regional average, the South ($0.079 per kWh/$ per therm). Additionally, we observed that many of the population centers with similar climates to Los Angeles mentioned in the Introduction have relative prices of electricity that are generally less than the U.S. Average and are within a reasonable range compared to the other U.S. regional averages [61–64]. Performing this analysis, we can comment on how relative utility costs impact the ability to electrify space heating both across the U.S. and in populations centers with similar climates by analyzing the change this has on the marginal net present value of these different space heating electrification technologies.

3. Results and discussion

To understand the societal and equity impacts of a transition electrified space heating in the residential building sector, results for the upgrades outlined in Table 1 are disaggregated in this section by building type (e.g., single- vs. multi-family buildings), resident role (e.g., owner, landlord, renter), or income level by AMI ranges. All results display the marginal cost of replacement for upgrades. A positive marginal NPV indicates that an upgrade is more economical compared to the baseline and vice versa.

3.1. Upgrade results for homeowners who use cooling in the baseline

In Los Angeles, the most common HVAC configuration is a natural gas furnace paired with a central AC system. For owners who have this system type and actively use both heating and cooling, the electrification option with the highest marginal NPV is to replace both of these systems with a low-efficiency ASHP (Fig. 3). While the increased efficiency of this upgraded system will lower operating costs year over year, even with federal rebates, the median increase in capital cost for this upgrade compared to the baseline is approximately $830 and $3,490 for multi-family and single-family buildings, respectively (See Table C 1 in the Supporting Information). This finding is true regardless of building type or income level. For multi-family owners with these systems, both the low- and mid-efficiency heat pump upgrades provide a positive marginal NPV. However, upgrading to a mid-efficiency heat pump will increase capital costs by over $2,000, a sizeable increase potentially out of reach for many of these households.

While this HVAC configuration is the most common in Los Angeles, 18 % more high-income households have these systems compared to low- and moderate-income households and 7 % more single-family households have these systems compared to multi-family households. Thus, the positive marginal NPVs provided by these upgrades will be less available to more vulnerable households.

For those in non-ducted households the improved efficiency of MSHPs does not outweigh their high capital costs. The next three most common HVAC configurations are homes with wall and floor furnaces, boilers, and furnaces that have room AC systems. For these homes, the best option is to upgrade to the electric equivalent of their current fuel-fired equipment type, and in every case the marginal NPV is much lower compared to households with ducts (Table 3).

The primary reason is that, even when considering the cost of fuel switching, the capital costs of these electric technologies are similar to those of the baseline natural gas technologies they replace. However, these electric equivalent systems almost always increase annual utility bills; for some households this increase is hundreds of dollars (See Table C 2 in the Supporting Information). Given the high discount rate assigned to many households, these future costs may not be as highly valued by some households, but these upgrades will increase both their utility bills and strain on the electric grid for the entirety of that technology's lifetime.

In Los Angeles, 50 % more low-income households (0–80 %) have non-ducted HVAC systems as compared to low-income households that have ducted systems. Furthermore, 30 % more multi-family households have non-ducted systems, compared to multi-family households that have ducted systems. Thus, for these vulnerable households the upgrade

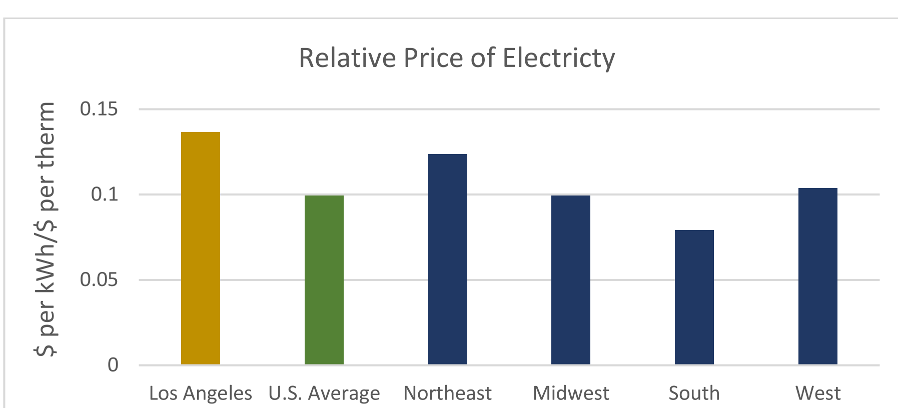

Fig. 2. Relative Electricity and Natural Gas Utility Prices.

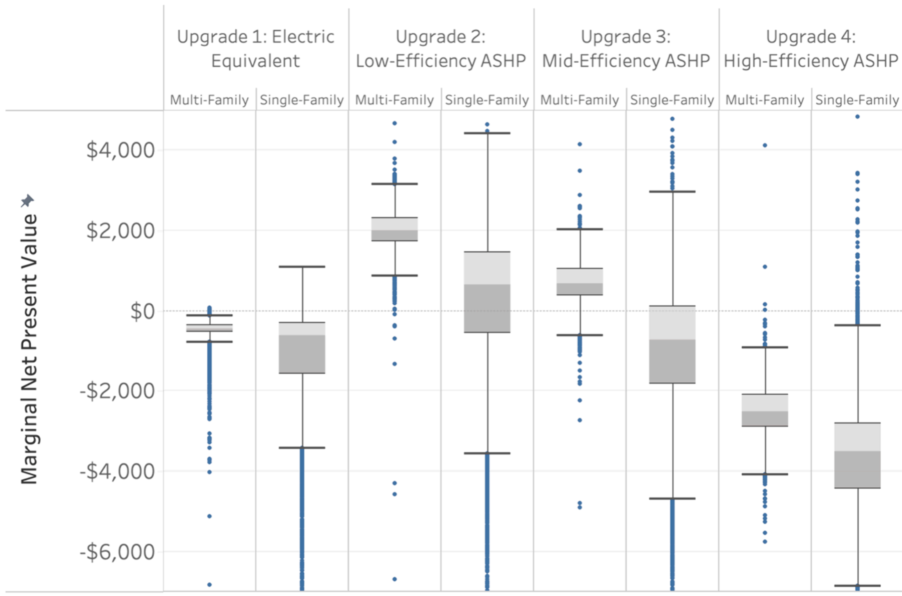

Fig. 3. Distribution of marginal net present value of replacement for space heating electrification upgrades for buildings with natural gas furnaces with central ACs in the baseline.

Table 3
Interquartile range of the highest marginal NPVs for electrification upgrades in the most common non-ducted household types.

HVAC system		*Electrification upgrade with the highest marginal NPV*	*Marginal net present value*		
			75 % Percentile	*50 % Percentile*	*25 % Percentile*
Natural Gas Furnace	*Room AC*	Electric Equivalent	−$307	−$494	−$808
Natural Gas Boiler	*Room AC*	Electric Equivalent	$278	$47	−$686
Natural Gas Wall/ Floor Furnace	*Room AC*	Electric Equivalent	$225	$81	−$564

which has the best marginal NPV is lower and more negative compared the best upgrade for ducted households. Also, these systems do not provide cooling; increase the equity gap in terms of technology saturation and access to cooling.

3.2. Upgrade results for homeowners who do not use cooling in the baseline

For owners who do not use cooling, space heating electrification increases costs (Fig. 4). For these households, the most economic option is to upgrade to the electric equivalent space heating technologies. Upgrading to a heat pump is only a viable option when replacing both the space heating and cooling systems and reaping the benefits of increased efficiency when providing both heating and cooling. If owners are not replacing a cooling system or not using cooling in their homes, the capital costs associated with heat pumps provides cooling capability that will go unused and thus provides no benefit. For these households without access to or use of cooling, upgrading to the electric equivalent systems will result in a negative marginal NPV for most. While the capital cost of these electric equivalent systems is roughly the same, the increase in annual operating costs of these systems is more than $100 for many households (See Table C 3 in the Supporting Information).

In Los Angeles, 43 % more low-income households (0–80 % AMI) do not have or use a cooling system compared to low-income households that use cooling. Therefore, the recommended electrification upgrade for more low-income households will be the electrical equivalent systems that have a negative marginal NPV for most households and which do not provide cooling for their residents.

3.3. Renter vulnerability

Renters are highly vulnerable in a transition to residential building electrification. Regardless of baseline space heating technology, the least expensive upgrade option is the electric equivalent technology (Table 4). In some cases, it is even cheaper to install the electric equivalent technology than replace the baseline natural gas system. Regardless, the difference in capital costs between installing electric equivalent systems and the low-efficiency heat pump upgrades is thousands of dollars. In this situation, with no incentive to upgrade to heat pump technologies, it can be assumed that few landlords would opt into the higher efficiency upgrades.

Any decision a landlord will make has serious implications for renters. If landlords take the cheapest option and electrify the space heating systems in their units with the electric equivalent technology, the tenants will face the consequences of the increase in utility bills that come with these less efficient technologies (Table 5).

For those who qualify for utility bill assistance, the change could be minimal, with most households seeing less than a $1 increase in monthly utility bills. However, for those who do not qualify or who are not enrolled the increase could be more significant. Over 25 % of those who do not qualify will see a nearly $100 increase in annual utility bills. While this may not seem significant over the course of the year, to an already energy burdened household this could mean missing rent, a utility disconnection, or sacrifices with food, clothes, or medication, all of which could negatively impact mental, physical, and emotional health [65,66].

If landlords are provided support to install higher efficiency systems, both renters and landlords could benefit. Most renters will see a decrease in operating costs, even for those without cooling in the baseline, with an upgrade to a low-efficiency heat pump (See Table C 4 in the Supporting Information). While IRA benefits can cover entire heat pump systems up to $8000, more modest support (from $1000-$3000) will

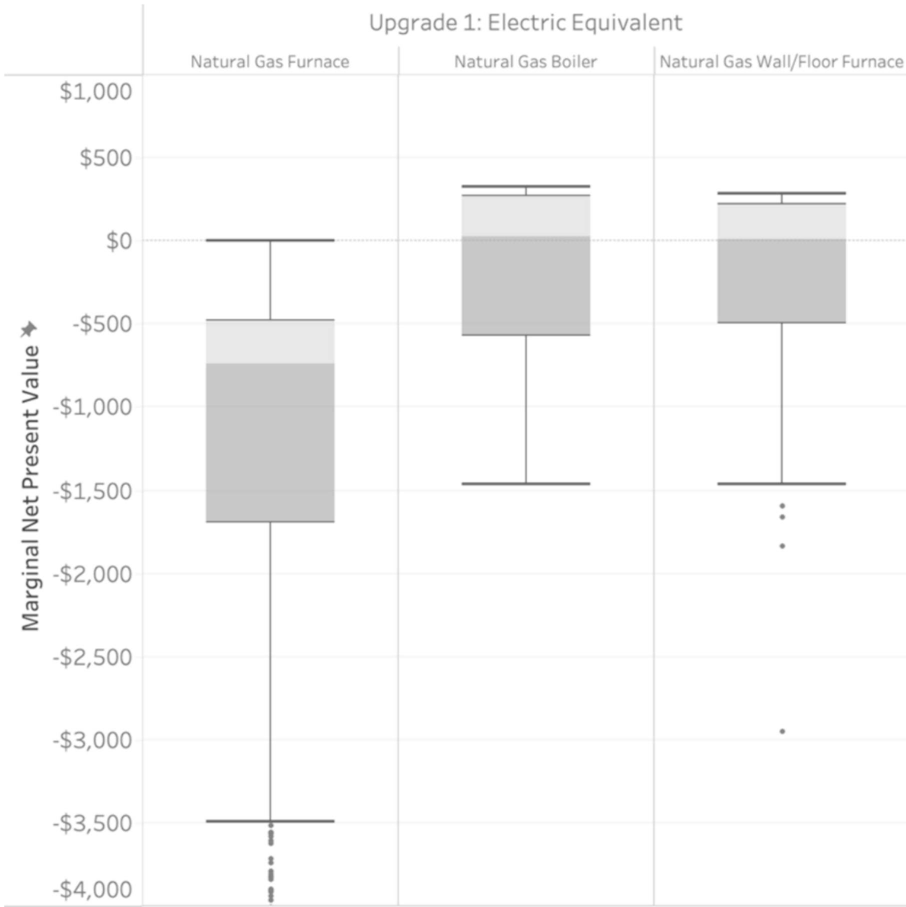

Fig. 4. Distribution of marginal net present values for electric equivalent space heating electrification upgrades for households that do not have or do not use cooling.

Table 4
Median capital cost savings for landlords (Note: Negative values indicate an increase in capital costs compared to baseline natural gas systems).

Baseline Space Heating Technology	*Upgrade 1: Electric Equivalent*	*Upgrade 2: Low-efficiency Heat Pump*	*Upgrade 3: Mid-efficiency Heat Pump*	*Upgrade 4: High-efficiency Heat Pump*
Natural Gas Furnace	−$480	−$1028	−$2487	−$5984
Natural Gas Boiler	$305	−$911	−$1576	−$3649
Natural Gas Wall/Floor Furnace	$223	−$2728	−$3345	−$5243

Table 5
Median annual operating cost savings for renters (Note: Negative values indicate an increase in operating costs compared to the baseline natural gas systems).

Utility Bill Assistance Eligibility	*Baseline Space Heating Technology*	*Upgrade 1: Electric Equivalent*		
		25th Percentile	*50th Percentile*	*75th Percentile*
Eligible	*Natural Gas Furnace*	−$40	$0	$7
	Natural Gas Boiler	−$61	−$5	$0
	Natural Gas Wall/ Floor Furnace	−$62	−$7	$0
Ineligible	*Natural Gas Furnace*	−$94	−$1	$9
	Natural Gas Boiler	−$160	−$35	$0
	Natural Gas Wall/ Floor Furnace	−$145	−$31	−$1

cover the additional capital costs to install these systems compared to the baseline space heating system for most landlords. Installation of these systems will benefit landlords by adding cooling to their units, making them more desirable. Along with this studies have shown that when advertised, units with higher home efficiency scores are valued more by renters and prospective buyers [67–69].

3.4. Impact of discount rates on economic viability of air-source heat pump technologies

Findings show that low, fixed discount rates overestimate economic viability of air-source heat pump technologies. Low, fixed discount rates lead to a significant increase in marginal NPVs for high efficiency electrification upgrades, and thus in the apparent viability of those upgrades. In the case of natural gas boilers paired with room AC systems, compared to a variable discount rate, using a discount rate of 7 % led to a much more negative marginal NPV for the upgrade to an electric equivalent system, whereas it increased the NPVs of the upgrades to heat pumps (Fig. 5). In this situation, increased operational costs of the electric equivalent systems is valued more driving the marginal NPV of these upgrades lower, while at the same time pushing the marginal NPV of the heat pumps higher given their superior efficiency.

Given the results of fixed, low discount rate, the electrification upgrade that appears most favorable would be the highest efficiency heat pumps as compared to the results from Section 0 which indicate that low-efficiency heat pumps and electric equivalent technologies are the best option (Table 6). Rather than advocating for an electric equivalent system given the high capital costs of the heat pump systems, the results

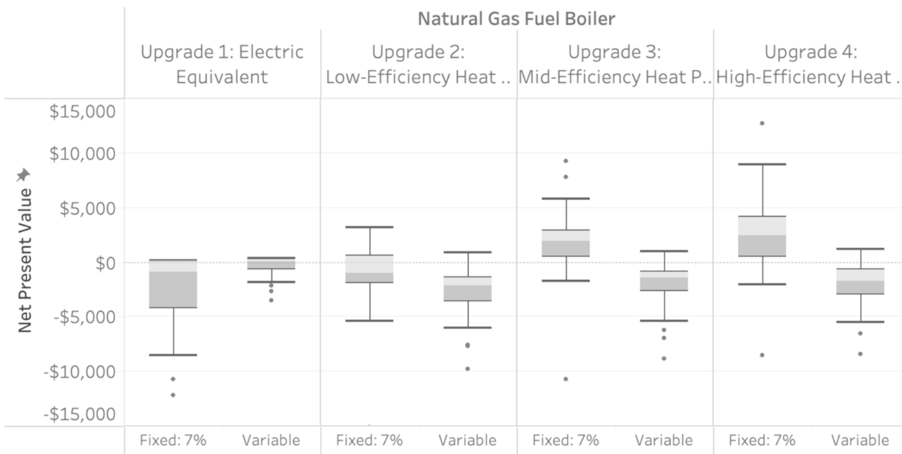

Fig. 5. Distribution of marginal net present value for space heating electrification upgrades for buildings with natural gas boilers with room ACs in the baseline using fixed and variable discount rates. Note:

Table 6
Recommended electrification upgrade differences between the variable discount rate and the fixed, low discount rate along with their associated increase in capital costs.

HVAC system		***Electrification upgrade with the highest marginal NPV***		***Median increase in capital cost***
		Variable Discount Rate	*Fixed (7 %) Discount Rate*	
Natural Gas Furnace	Central AC	Low-Efficiency Heat Pump	Mid-Efficiency Heat Pump	$2100
	Room AC	Electric Equivalent	Electric Equivalent	N/A
Natural Gas Boiler	Central AC	Low-Efficiency Heat Pump	Mid-Efficiency Heat Pump	$1900
	Room AC	Electric Equivalent	High-Efficiency Heat Pump	$4460
Natural Gas Wall/ Floor Furnace	Central AC	Electric Equivalent	Low-Efficiency Heat Pump	$4800
	Room AC	Electric Equivalent	High-Efficiency Heat Pump	$6240

from this sensitivity analysis suggest that the best upgrade would be the high-efficiency heat pump which has a median capital cost of more than $1,300, and $4,500 compared to the electric equivalent systems for multi-family and single-family households respectively (See Table C 5 in the Supporting Information).

Table 6 provides an overview of the upgrade with the highest marginal NPV for the variable and fixed, low discount rates. Some of the largest increases in capital costs are found in households which upgrade from natural gas boilers and wall/floor furnaces paired with room AC systems. As outlined in Section 0, more low-income (0–80 % AMI) and multi-family households have HVAC systems; households that may not be able to cover these much higher capital costs. Realistically representing discount rates is crucial to meaningful conclusions about the viability of heat pumps, particularly for lower income households.

3.5. Effect of electricity and natural gas rates

Alternative relative electricity and natural gas rates and future rate projections do not impact overall recommendations for electrification upgrades. First, while we found that while the relative price of electricity compared to natural gas did not impact the recommended electrification upgrades, this sensitivity analysis did lead to a surprising finding. Compared to the relatively high cost of electricity in Los Angeles as compared to the US average or the South regional average, the marginal NPV of upgrading to the electrical equivalent improves as electricity decreases in price relative to natural gas (Fig. 6). These more favorable rate ratios make the switch from natural gas to electric appliance better. However, when looking at upgrading to heat pump systems, these more favorable rate ratios decrease the marginal NPV of these upgrades. We see this rebound effect due to the increase in efficiency of these systems. In Los Angeles, where electricity is so costly, the impact of upgrading to the higher efficiency space heating systems plays a role in making these systems more economically feasible. However, as the cost of electricity decreases relative to natural gas these improved efficiencies account for a smaller operational savings. Therefore, as the relative cost of electricity decreases compared to the cost of natural gas, the impact of capital costs only increases. The relatively high price of electricity in Los Angeles make electrification via heat pumps more economically feasible, whereas the lower relative price of electricity may make these heat pump upgrades more difficult in many other areas across the U.S. or in the population centers with similar climates to Los Angeles which generally have lower relative prices of electricity.

Second, the sensitivity analysis of future rate projection showed no meaningful impact on the marginal NPV results. The different sensitivities increase and decrease utility rates by over 20 % with almost undetectable changes in marginal NPVs (See Figure C 1 in the Supporting Information). This shows two things. First, massive changes in the utility rates would need to occur for these to markedly impact marginal NPV results. Changes of this magnitude would be procedurally difficult to execute given the pushback from ratepayers and public utility commissions. Second, this shows again the dominance of initial capital costs in these marginal NPV calculations. Even the large changes in utility rates do not push households towards or against any one upgrade option. However, the CEC's own forecasts for LADWP have electricity prices increasing significantly over the next 10 years. This only further solidifies that heat pump systems are the best option for space heating system electrification upgrades given their lower energy consumption.

3.6. IRA Implications

Given the previous results, the most significant variable impacting the marginal NPV of an upgrade and a household's ability to consider any upgrade is the capital costs associated with these electric space heating technologies. Given their current, high capital costs, heat pump systems, while offering substantial increases in efficiency for both heating and cooling, require thousands of dollars more in upfront costs for owners and landlords.

However, in the provisions of the Inflation Reduction Act (IRA) of

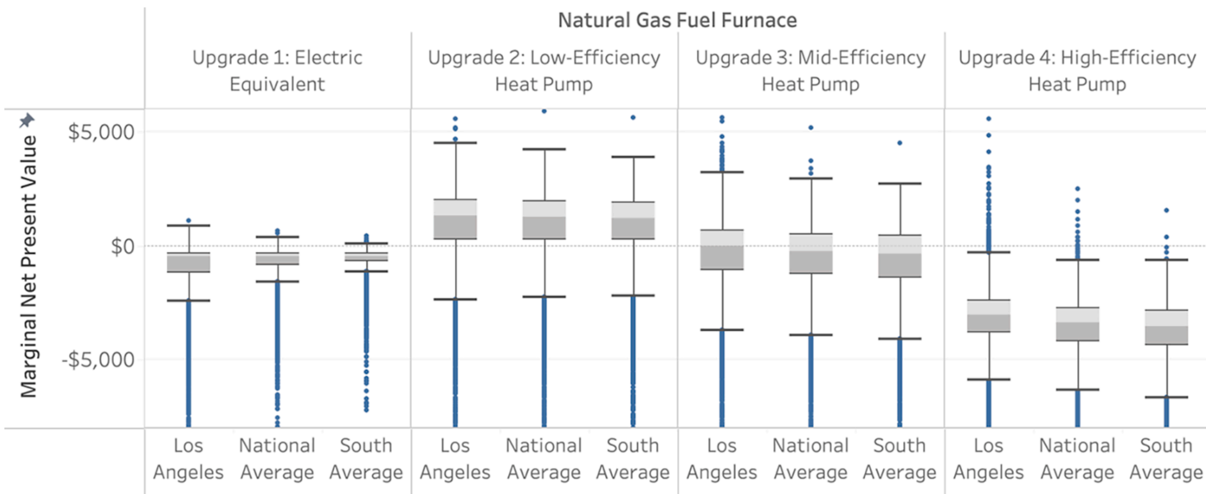

Fig. 6. Distribution of marginal net present value for space heating electrification upgrades for buildings with natural gas furnaces with central ACs in the baseline at different relative electricity and natural gas prices.

2022, owners and landlords can qualify for financial assistance to install heat pump space heating and cooling systems for households who are classified within the 0–80 % AMI or the 80–150 % AMI tiers [70]. The highest income bin used by the ResStock model is + 120 % AMI, therefore we were only able to give the second tier of IRA incentives to households from 80 %-120 % AMI and not the entire 80 %-150 % AMI cohort. If a homeowner or landlord qualifies at either of these tiers, we see a significant change in outcomes as compared to these costs without IRA incentives (Table 7). These results include all households regardless of building type, cooling access or use.

The results from Table 7 show that for all households, regardless of existing space heating technology, who are within the 0–80 % AMI range, installing low- or mid-efficiency systems will save them thousands of dollars in capital costs as compared to re-installing the existing system. For households in the 80–120 % range, while the savings are not as significant, most households with natural gas boilers or furnaces will see savings if they install the low-efficiency heat pump. In addition to providing significant capital cost savings, heat pump technologies can provide access to cooling for those who currently do not have or use their cooling systems. Through their superior efficiency, even with the added cooling service, these systems largely reduce annual utility bills (See Table C 6 in the Supporting Information), combined with the capital cost savings (See Table C 7 in the Supporting Information), for low-income households (0–80 % AMI) who did not have or use cooling the baseline, many of these upgrades lead to highly positive NPV values (Fig. 7).

3.7. Importance of Capital Costs

Results show that capital costs, including equipment, installation, and fuel switching costs have the greatest impact on determining the feasibility of an upgrade. By more accurately representing the actual upgrade costs and by including all installation costs and sizing each unit to meet the heating load of the household, the capital costs of heat pumps are higher and thus net present value are much lower compared to similar studies that quantify the costs of electrifying space heating in southern California [20,24,27] (See Table C 8 in the Supporting Information). Beyond a more detailed model of capital costs, another contributing factor to this difference is the use of a variable discount rate. This variable, and thus much higher, discount rate for many of the households we modeled places much more weight on the immediate change in capital costs as compared to the future changes in operating costs.

Beyond the results from the model, we must consider a consumer's perspective when trying to understand this transition to electrified space heating. When contemplating an upgrade to their space heating system, a consumer will be able to determine the difference in capital costs of these different options. Whereas the difference in operational savings can only be estimated and therefore may not necessarily be relied upon or used in decision-making [71]. Furthermore, While heat pumps have the ability to reduce utility bills throughout the entire year for all household types (Table C 2, Table C 3, and Table C 4 in the Supporting Information), households may be limited to certain upgrade options based on their immediate financial situation regardless of how greatly these households value future savings. This is especially true for landlords who have even less incentive to install a heat pump unless they qualify for and receive financial assistance through the IRA (Table C 7). Therefore, for policymakers and utilities looking to ease the transition to space heating electrification, a focus on reducing capital costs through point-of-sales rebates, like the IRA, should be prioritized over changes in utility rate structures or utility bill assistance programs.

4. Conclusion

In this study, we developed a novel high-resolution techno-economic model, the Marginal NPV Upgrade Analysis Model. Not only will the results from this model provide owners, landlords, and renters guidance on electrification upgrades, but it will also support policymakers and utility decision making related to electrification and energy efficiency policy and rulemaking, especially in regard to subsidies for specific households and specific technologies. Additionally, the results from this model give insight into the impact a mandatory transition to residential building electrification can have on marginalized communities. This model enables evaluation of strategies to ensure that disadvantaged communities are supported in the energy transition. The conclusions from this research are outlined as follows:

a) For owners who already have and use home cooling systems, replacing ducted space heating and cooling systems with ASHPs is the best electrification option. This situation applies to more single-family and high-income (+120 % AMI) households. For those in non-ducted households the improved efficiency of MSHPs does not outweigh their high capital costs. Conversely, more multi-family and low-income (0–80 %) households are non-ducted.
b) For owners who do not already have or use cooling, space heating electrification increases costs. For these households, the electric

Table.7
Median Capital Cost Savings for owner and landlords who qualify for IRA rebates Note: Negative values indicate an increase in capital costs compared to baseline natural gas systems.

IRA Rebates	*Baseline Space Heating Technology*	Upgrade 2: Low-Efficiency Heat Pump				Upgrade 3: Mid-Efficiency Heat Pump				Upgrade 4: High-Efficiency Heat Pump			
		0–80 % AMI		80–120 % AMI		0–80 % AMI		80–120 % AMI		0–80 % AMI		80–120 % AMI	
		Landlord	Owner	Landlord	Owner	Landlord	Owner	Landlord	Owner	Landlord	Owner	Landlord	Owner
Included	*Natural Gas Furnace*	$2,774	$3,568	$833	$373	$3,212	$2,862	$329	−$671	$2,092	−$530	−$1,257	−$2,177
	Natural Gas Boiler	$3,812	$3,223	$1,113	$150	$3,873	$3,334	$1,077	$140	$3,670	$2,297	$763	−$669
	Natural Gas Wall/Floor Furnace	$1,939	$1,228	−$791	−$1,684	$2,024	$1,372	−$834	−$1,747	$1,839	$378	−$1,346	−$2,532
Not Included	*Natural Gas Furnace*	−$993	−$2,998	−$1,194	−$3,173	−$2,441	−$5,044	−$2,643	−$5,273	−$5,908	−$8,530	−$6,186	−$8,679
	Natural Gas Boiler	−$1,559	−$4,416	−$2,044	−$4,868	−$1,699	−$4,527	−$2,157	−$4,791	−$2,125	−$5,703	−$2,875	−$6,001
	Natural Gas Wall/Floor Furnace	−$3,370	−$6,192	−$3,967	−$6,461	−$3,518	−$6,362	−$4,172	−$6,565	−$4,012	−$7,622	−$5,098	−$7,843

equivalent technologies provide the best marginal NPV. However, for most households this marginal NPV is negative due to the increased operating costs of these systems. More low-income (0–80 % AMI) do not have or use their cooling systems.

c) Renters are highly vulnerable in a transition to residential building electrification. For landlords, regardless of baseline technology, the upgrade with the lowest capital costs are the electrical equivalent systems. These systems increase operating costs for most renters.

d) For those who qualify for IRA funding, the previous conclusions alter dramatically. For owners and landlords who qualify, installing low-, mid-, and in even in some cases and high-efficiency heat pump generates a net savings when compared to the cost of the baseline system. These savings paired with the operation savings make an upgrade to a heat pump preferable for almost all households regardless of building type or renter/owner status.

e) Similar studies examining the economics of space heating electrification in California overestimate economic viability of air-source heat pump technologies. First, these studies, along with all the existing literature in this area, used low, fixed discount rates which overvalue future savings. Research into discount rates have found that they are not uniform across a population, nor should they be so low.

f) Alternative relative electricity and natural gas rates and future rate projections do not impact findings as compared to changes in capital costs. If looking to ease the transition to electrified space heating, policymakers and utilities should look towards point-of-sales incentives similar to those found in the IRA. These incentives can get higher efficiency heat pumps into all households, at the same time lowering utility bills and providing access to cooling for those who did not have it initially.

g) The impacts of climate change, while not directly addressed in this work, are important to consider. The increase in cooling load that could occur as a result of a warming climate could increase the danger of unsafe home temperatures for those households which do not use cooling. For these households, heat pump systems can both electrify space heating and provide access to cooling. Additionally, increased temperatures could improve the marginal net present value of heat pump systems relative to the electric equivalent systems. However, the high capital costs of these systems still pose a veritable barrier for many vulnerable households.

h) The implications of residential building electrification go far beyond household economics. This transition will shift the emissions associated with residential building space heating from scope 1 to scope 2 emissions [72]. In the near future, this larger demand on traditional electricity generators will exacerbate existing inequities through the increased combustion, and resultant pollution, of fossil fuels. While in the long run, these scope 2 emissions can be reduced through the implementation of renewable energy generation, there is still the question of where and how these technologies are manufactured. The CalEnviroScreen tool evaluates the relative environmental burden on communities across California [73]. The latest version of this tool showed that many Los Angeles neighborhoods already experience some of the highest PM 2.5, toxic chemical release, and aggregate pollution burden in the state. Therefore, based on where this additional electricity is generated and where the renewable energy technologies are manufactured, this pollution burden on vulnerable communities could increase. Wherever we are considering a transition to widespread electrification these negative externalities must be evaluated and weighed against their possible advantages. Cost-benefit analyses, like the one conducted by Koley, need to be administered to ensure that we are reducing the equity gap rather than replacing one burden with another [74]. This is only possible if we consider the many dimensions of our energy use and the impact they have on society.

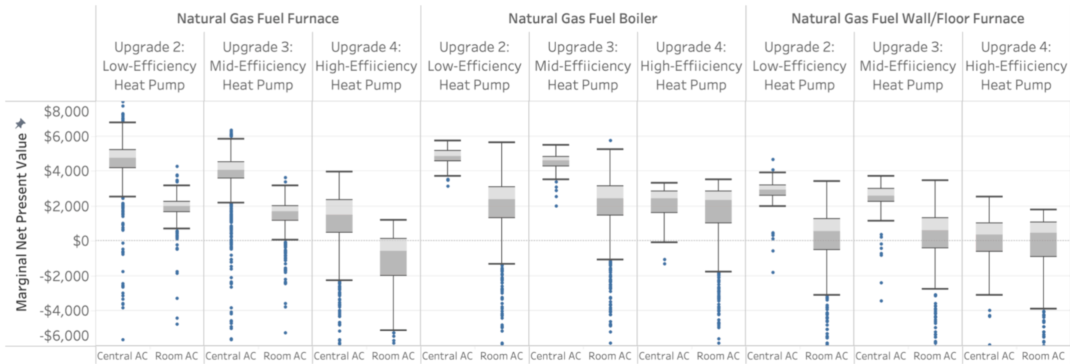

Fig. 7. Distribution of marginal net present values, including IRA rebates, for space heating electrification Upgrades for low-income households (0–80% AMI) which did not have or did not use cooling in the baseline.

CRediT authorship contribution statement

Noah Sandoval: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Chioke Harris:** Writing – review & editing, Resources, Methodology, Conceptualization. **Janet L. Reyna:** . **Anthony D. Fontanini:** Validation, Software. **Lixi Liu:** Validation, Software. **Katelyn Stenger:** Software. **Philip R. White:** Software. **Amy E. Landis:** .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Data availability.

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2024.114422.

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