BARRIERS AND STRATEGIES TO ACHIEVE AN EQUITABLE TRANSITION TO RESIDENTIAL LDING ELECTRIFICATION: A CASE STUDY OF LOS ANGELES

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Advanced Energy Systems).

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ABSTRACT

Widespread residential building electrification is a key component of achieving federal, state, and local decarbonization mandates. While there has been significant research into technologies needed to achieve residential building electrification, existing research has not investigated technology deployment, and more specifically, equitable deployment by 2050 to mitigate the worst impacts of climate change. In this dissertation, an energy justice-informed study design is used to explore viable pathways to achieve residential buildings electrification and outline the possible consequences of these pathways to ensure no household is over-burdened or left behind in this transition. First, a comparative framework is developed to analyze the scenario development process of energy models and is then applied to the development of high-quality electrification scenarios for the residential building sector. Second, a high-resolution techno-economic model is developed to calculate all costs associated with electrification upgrades. Setting a variable discount rate for each household based on income, this model compares the upgrades of varying efficiency levels for all the major electrification end uses – space heating, water heating, cooking, and clothes drying – and reports results based on income, building type, renter/owner status, and household cooling use. Lastly, two electrification supportive strategies – improved building envelope characteristics and universal access to cooling using heat pumps – are evaluated to determine if there are any synergistic benefits with the previously evaluated electrification upgrades. The work of this dissertation improves the scenario development and economic analysis of residential building electrification and provides a novel study design that incorporates the tenets of energy justice.

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LIST OF ABBREVIATIONS

Air Changes per Hour . . . . . ACH

Air Conditioning Contractors of America . . . . . ACCA

Air-Source Heat Pump . . . . . ASHP

Amazon Web Services . . . . . AWS

American Society of Heating, Refrigerating and Air-Conditioning Engineers . . . . . ASHRAE

Annual Energy Outlook . . . . . AEO

Area Median Income . . . . . AMI

Asia-Pacific Integrated Model . . . . . AIM

Buildings Technology Office . . . . . BTO

California Alternative Rates for Energy . . . . . CARE

California Energy Commission . . . . . CEC

California Energy Demand . . . . . CED

Combined Energy Factor . . . . . CEF

Department of Energy . . . . . DOE

Energy Information Administration . . . . . EIA

Inflation Reduction Act . . . . . IRA

Internal consistency and Diversity Scenario Development . . . . . IDSD

Load Research Data . . . . . LRD

Los Angeles Department of Water and Power . . . . . LADWP

Mini-Split Heat Pump . . . . . MSHP

National Energy Modeling System . . . . . NEMS

National Renewable Energy Laboratory . . . . . NREL

Net Present Value . . . . . NPV

Renewable Portfolio Standard . . . . . RPS

Shared Socio-economic Pathways . . . . . SSP

Standard Effective Temperature . . . . . SET

Strategic Long-Term Resource Plan . . . . . SLTRP

U.S. Department of Housing and Urban Development . . . . . HUD

Uniform Energy Factor . . . . . UEF

University of California - Los Angeles . . . . . UCLA

World Energy Model . . . . . WEM

World Energy Outlook . . . . . WEO

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For my wife, our dogs, and our time on trail together.

CHAPTER 1
INTRODUCTION

1.1 Motivation

In 2021, the U.S. Environmental Protection Agency estimated over 330 million metric tons of CO2 equivalent emissions could be attributed to fossil fuel combustion in the residential building sector [1]. Building electrification in conjunction with increased penetration of renewable energy generation could eliminate these emissions from the residential building sector - over 5 percent of all U.S. CO2 equivalent emissions [2–8]. Legislation at the federal, state, and local levels call for a wide range of strategies to reduce emissions created by residential building, including economy-wide emissions reductions goals, improved building performance standards, or full net-zero building requirements [9–11]. There has been significant research into technologies needed to achieve residential building electrification. Along with electric equivalent technologies, a wide range of high-efficiency heat pump technologies for space and water heating have been proven in across a wide range of climates [12–15]. However, existing research has not investigated technology deployment, and more specifically, how these technologies can be deployed equitably.

Energy justice is based on the philosophy of the environmental justice movement, which was a response to the unequal distribution of environmental burdens especially on marginalized communities [16]. The overarching goal of energy justice is to provide all households with modern, sustainable, and affordable energy services by addressing current energy inequities and ensuring that the benefits of future energy systems are justly shared with marginalized communities [16–19]. In a transition to residential building electrification, it will be important to ensure that disadvantaged and vulnerable communities share in the benefits of residential building electrification and are not unduly burdened by the repercussions of this transition.

Therefore, the goal of this research is to 1) explore viable pathways to achieve residential building electrification and, 2) outline the possible consequences of these pathways, while 3) ensuring no household is over-burdened or left behind in this transition. I address this research goal by answering three research question (Figure 1.1). Each of these questions will be answered through the lens of energy justice to ensure a just transition to residential building electrification.

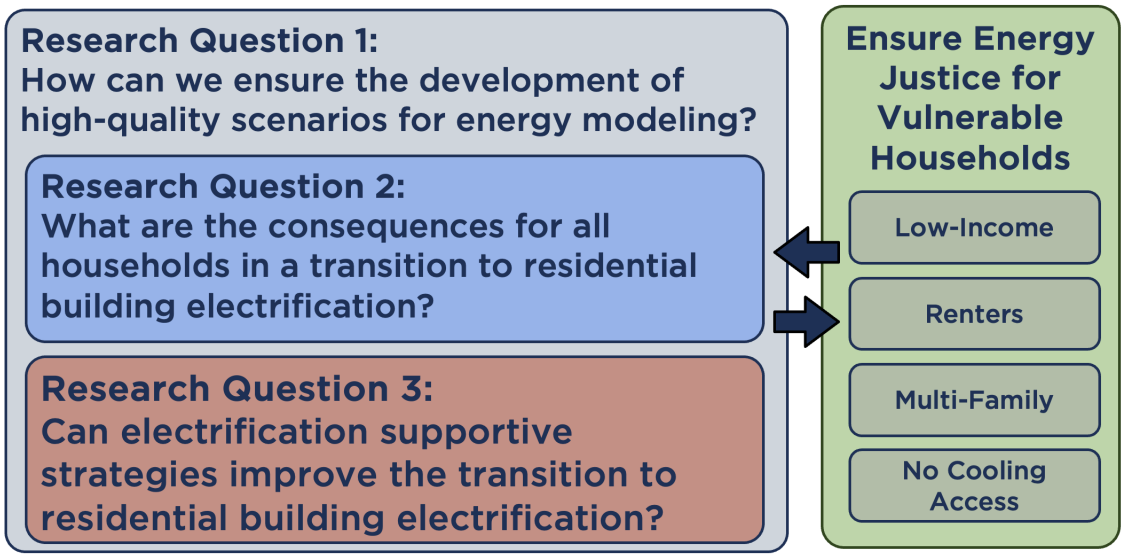

Figure 1.1 Research questions and their relationship with the energy justice

1.1.1 Research Questions

To answer Research Question 1, I develop a framework to create high-quality scenarios. To create viable electrification pathways, scenarios must be plausible, coherent, focused descriptions of a possible future [20–23]. To create these high-quality scenarios, it is critical to understand both the theory behind scenario development and their practical application. As shown in Figure 1.1, Research Question 1 encompasses Research Questions 2 and 3 because the methodology for developing high-quality scenarios is applied within the latter research questions. Energy justice is addressed in Research Question 1 through project scoping – when stakeholders are identified that have been negatively impacted by the energy system or who have been left out of energy policy and decision making. In developing just scenarios, it is critical to involve marginalized communities in the decision making process by understanding their needs and learning what questions and concerns they may have [17, 24–26]. As the activist, Regan Byrd, lays out in her Anti-Oppression Framework, marginalized communities are experts in their own oppression [27].

Research Question 2 examines the positive and negative consequences of basic residential building electrification. This includes understanding the impacts of upgrading natural gas space heating, water heating, cooking, and clothes drying appliances with a variety of electric alternatives at different efficiency levels. The consequences of these upgrades focus on the outcomes for households such as the difference in installation costs, the change in energy burden, and impact of certain rebates and tax credits. In addition, I examine the impact on the electric utility, the associated costs to manage this transition, and how these costs will be passed on to the ratepayers. These costs are calculated by leveraging data from highly

resolved energy modeling coupled with techno-economic modeling.

Finally, Research Question 3 builds on Research Question 2 by investigating strategies which run in parallel to basic electrification to determine if it is possible to improve the outcomes of this transition, especially for the vulnerable households. These strategies, which come from community input (see Appendix A), include upgrades that improve building envelope characteristics and universal access to cooling technologies. The purpose of this research question is to determine if these upgrades will work synergistically with the various electrification upgrades from Research Question 2 to improve the economic or welfare outcomes for households as they navigate the transition to residential building electrification. Research Questions 2 and 3 address energy justice by focusing on the analysis on four cohorts of vulnerable communities: low-income households, renters, households living in multi-family buildings, and households who do not use cooling.

1.1.2 Energy Justice-Informed Study Design

To ensure that no household is over-burdened or left behind as we transition to residential building electrification, I have applied an energy justice framework to this research based on the tenets of energy justice as initially proposed by McCauley et al. [16], and subsequently refined and expanded by others [17, 18, 26, 28–30]. Figure 1.2 shows the four tenets of energy justice used in this research along with questions that apply to each tenet. In this research, I will use distributional, recognition, and procedural justice to guide the research with the goal to provide data-based strategies to promote restorative justice in this transition to residential building electrification.

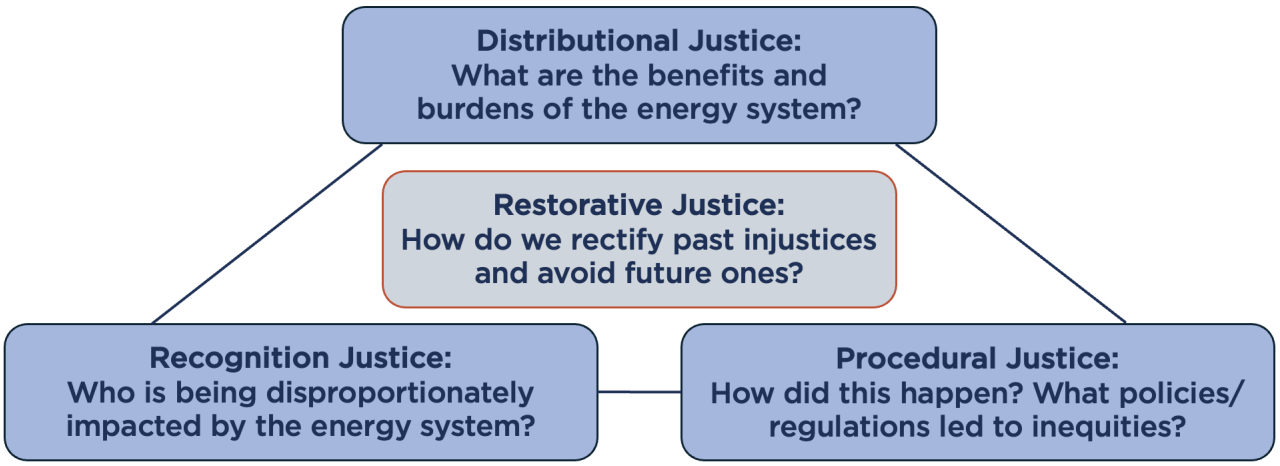

Figure 1.2 The tenets of the energy justice framework used in this research

In this research, I applied these tenets of energy justice in two ways. First, I conducted a literature review of energy justice issues in the residential building sector. In this process, I combined distributional, recognition, and procedural justice to analyze the various burdens created by the energy system, determined the process through which these burdens were created, and identified specific cohorts of vulnerable households that bear a disproportionate amount of these burdens. In this process, I identified four types of vulnerable households – households of color, low-income households, renters, and households living in multi-family buildings.

Second, I leveraged the work done the LA100 Equity Strategies conducted by the National Renewable Energy Laboratory and the University of California Los Angeles on behalf of the Los Angeles Department of Water and Power (LADWP) [**?**]. In this project, LADWP seeking to decarbonize its energy, transportation, and building sectors sought the input from the community through the a series of steering committee meetings made up of representatives from community-based organizations [31]. By seeking out these groups and involving them in the decision-making process, this project achieved elements of recognition and procedural justice, respectively. To address distributional justice, I conducted a coding analysis of the notes from these steering committee meetings (see Appendix A). In this process, I identified four primary community concerns pertaining to a transition to residential building electrification. These concerns are the affordability of upgrades, the conditions of existing building and infrastructure, access to cooling, and renter/landlord issues.

The study design for this research combined the technical aspects required in answering the research questions with the energy justice framework (Figure 1.3). Community concerns that were identified in the coding analysis of the LA100 Equity Strategy steering meeting were layered with the energy justice issues identified in the literature review on the technical workflow to achieve an energy-justice informed study design. The elements of this study design are outlined in the following paragraphs.

The scenario development element of the workflow was informed by three aspects of the energy justice framework. First, the most common resident concern was the affordability of any proposed electrification upgrades. Therefore, when designing electrification scenarios it was critical to evaluate a variety of different efficiency levels of these electric technologies. In this way, it is possible to analyze the tradeoffs between the capital and operating costs of these different technologies. Second, residents expressed concerns with the current conditions of the residential buildings in Los Angeles along with a need to provide cooling access to all. Therefore, beyond pure electrification, a set of electrification supportive scenarios were developed. These scenarios include upgrade packages that improve building envelope characteristics, another set where cooling technologies would be installed in households, and a set which included both.

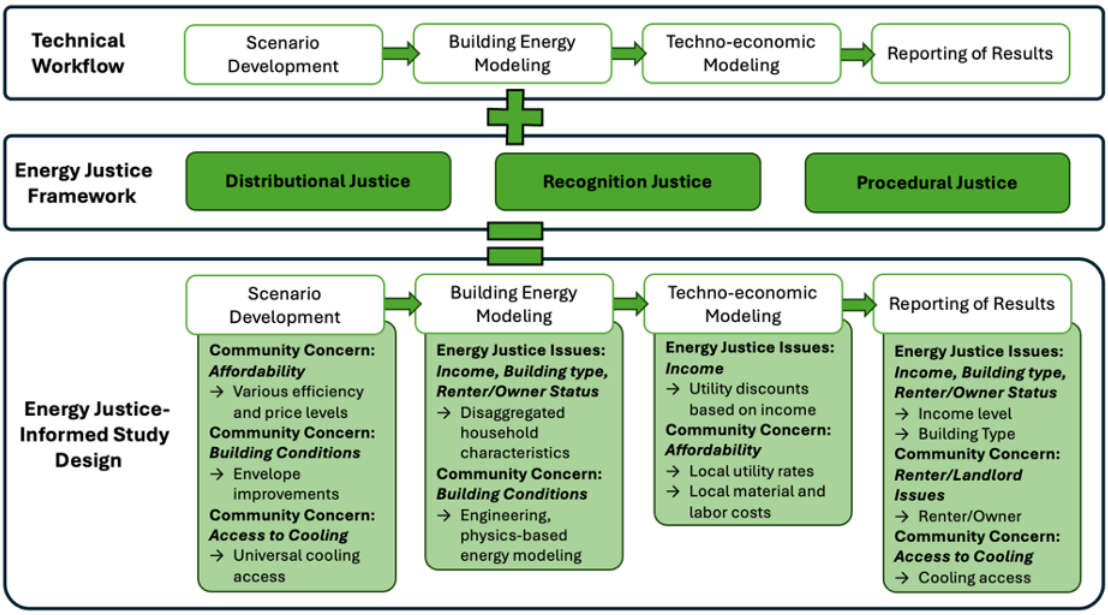

Figure 1.3 Energy justice-informed designed developed through characteristics identified through the application of the energy justice framework

The building energy modeling element of the workflow was informed by two aspects of the energy justice framework. First, when simulating each scenario, it was key to represent the wide range of household characteristics in Los Angeles which could be disaggregated by income, building type, and homeownership. Second, residents expressed concerns about the current conditions of residential building stock in Los Angeles. Thus, these buildings' physical characteristics (e.g., insulation level) and existing equipment (e.g., space heating type and efficiency) would need to be considered to appropriately model and understand the impacts of any proposed upgrades. Therefore, this research used an engineering, physics-based building stock energy model, ResStock^{TM}, to perform these simulations. In this way, it is possible to attribute the change in energy consumption in each simulated household to the specific upgrades applied to that household. One limitation of ResStock is that it does not include a resident's race in the household characteristics, therefore the final list of vulnerable households examined in this research is as follows: low-income households, renters, households in multi-family buildings, and households who do not use cooling.

The techno-economic modeling element of the workflow was informed by two aspects of the energy justice framework. First, with the scenarios developed and modeled, the affordability of each upgrade would then be able to be calculated. Considering income, one of the primary household characteristics which predict energy injustices, the modeled developed herein applied utility discounts and other incentives

which could ease a transition to electrification for qualifying households. Second, the disaggregated household characteristics from the energy model would allowed for the application of local utility rates (based on location) and local capital costs (based on current household equipment) to provide highly resolved cost information for each household simulated.

Finally, the reporting of results element of the workflow was informed by three aspects of the energy justice framework. First, in reporting results, the model would need report out on income, building type, and homeownership. The second aspect was residents' concerns about renter and landlord dynamics, which has already been addressed. Third, when providing cooling access to all, results would need to disaggregate by those who currently do and do not have access to cooling services.

By addressing each technical research question through the lens of an energy justice framework design, it was possible to achieve the goal of this research to ensure an equitable transition to residential building electrification. This will be done by evaluating the implications of this transition and outlining potentially strategies to assist vulnerable households. In this way, we can work towards restorative justice by attempting to provide all households with modern, affordable, and sustainable energy services and ensuring the benefits of the future energy systems are justly shared with previously marginalized communities [16–19].

1.1.3 Organization of Thesis

This thesis is organized around a set of peer-reviewed journal articles that are either published, under review, or are in preparation to be submitted to journals. Each subsequent chapter begins with a preface which introduces the article and explains how it fits into the greater research narrative and in some cases are followed by a postface to connect the major findings of the chapter to this greater research narrative. Each chapter features its own abstract and a stand-alone article presented as published or as submitted for review. The articles and their corresponding research questions are summarized in Table 1.1. Chapter 6 discusses the conclusions from the entire research, major findings, and recommendations for future work.

Table 1.1 Overview of publications and the associated research questions they answer

Publication	Motivation	RQ 1	RQ2	RQ3	Addresses Energy Justice?	Status	Journal
Internal consistency and diversity scenario development: A comparative framework to evaluate energy model scenarios	Understand why major energy modeling scenario development did not align with scenario development theory.	X				Published	Renewable and Sustainable Energy Reviews
Achieving Equitable Space Heating Electrification: A case study of Los Angeles	Quantify the installation and operating costs for households as they upgrade to electric space heating.		X		X	Under Review	Energy and Buildings
Achieving equitable widespread residential building electrification – examining barriers, strategies, and opportunities using Los Angeles as a case study	Quantify the installation and operating costs for households as they upgrade to electric water heating, cooking, and clothes drying. Quantify the impacts of widespread residential building electrification on the electric utility.		X		X	In Preparation	Energy and Buildings
Cooling – not weatherization – provides an effective electrification supportive strategy for residential buildings in Los Angeles	Quantify the installation costs of building envelope upgrades in conjunction with electric heat pump upgrades.			X	X	Under Review	ACEEE Buildings Summer Study Conference Proceeding
A comparative analysis of US state-level policies and programs to advance energy justice	No existing analysis of state-level energy justice policies and programs.				X	Published	Progress in Energy

1.1.4 Intellectual Merit

Given the importance of accurately determining the consequences associated with residential building electrification, there is a well-established body of research on the economics of this transition (Table 1.2). While each of these studies provide important insights, each is missing at least one key aspect of accurately portraying the costs households will face when electrifying. This research presents a novel high-resolution techno-economic model, the Marginal Net Present Value Upgrade Analysis model, which improves upon the existing literature that examines the economics of electrifying the residential building sector by combining four key elements. These elements are the:

- Analysis of all electrification end uses including electrification via electric equivalent technologies,
- Calculation of all costs associated with electrification upgrades,
- Development a new methodology that assigns households discount rate by income, and
- Reporting of results based on income level, building type, and renter/owner status.

First, this research examines all the major end uses that use natural gas: space heating, water heating, cooking, and clothes drying. Of the existing literature, only Mahone et al. [32] and Hopkins et al. [33] look at all four of these technologies. Given current mandates that require future electrification to achieve residential building decarbonization, understanding the costs of electrifying only a select set of combustion-based equipment masks the total costs associated with this transition that households will need consider. Furthermore, none of the existing studies considers the economics of upgrading to electric equivalent systems (e.g. natural gas furnace to electric furnace). All recent studies focus on the economics of heat pump technologies which have far higher capital costs and are thus that much more difficult for low-income owners and landlords to consider.

Second, this thesis research improves the existing methodology by calculating detailed costs for the households that are modeled. One aspect of this is the consideration of all costs associated with an electrification upgrade: material, installation/labor, and fuel switching costs. Of the existing literature, only five of these studies include all these costs [32, 34–37]. The second consideration is calculating the material cost of both the baseline and upgrade space heating (and cooling) systems. Using a physics-based building stock energy model, this research appropriately sizes and can therefore appropriately price both. Of the existing literature, only Asaee et al. uses this same sizing methodology [38]. None of the existing literature takes into account both of these considerations in their calculation of the costs associated with residential building electrification. The result is that low-income households could struggle the most to meet electrification mandates given their limited financial resources, inaccurately calculating the costs

associated with these upgrades could lead to many detrimental outcomes. This could include 1) a household being able to purchase the equipment, but not being able to use it, 2) requiring a household to get a high-interest rate loan which could be difficult to repay, 3) a household simply not being able to purchase this electric equipment and falling behind in this transition.

Third, this research improves the methodology to determine the net present value or life cycle costs of upgrades by using a variable discount rate. According to several studies, households value future costs and saving very differently [39–42]. However, all existing studies on the economics of residential building electrification use fixed and low (1-10%) discount rates for all households. These fixed and low discount rates vastly overestimated a household's value of future savings, especially for low-income households. In this research, when discounting the change in cashflow for any upgrade, each household is assigned a unique discount rate ranging from 7% - 45% which is inversely proportional to the household's income. The columns in the Study Design section of Table 1.2 give an overview of the gaps associated with accurately calculating the costs of all type of electrification upgrades.

Fourth, this thesis research also contributes new knowledge and tools to understand the equity implications of residential building electrification. Energy justice issues in the residential building sector primarily coalesce around four household characteristics: race, income, homeownership, and building type. These characteristics and the findings in this research underscore the difficulty that low-income residents might face when purchasing and using electric technologies. Furthermore, Los Angeles residents stressed the difficulty of split incentives between renters and landlords when trying to incentivize any proposed upgrade. The results from this research allow detailed reporting on three of these household characteristics: income, homeownership, and building type. Using this reporting, the model developed herein can apply utility discounts, federal rebates, and rebates from the 2022 Inflation Reduction Act (IRA) for qualifying households based on income level. Additionally, this reporting is leveraged to aggregate the data to for specific vulnerable cohorts of households (e.g., low-income, renters in multi-family units with natural gas furnaces) to give more targeted recommendations for electrification upgrades. The columns in the Reporting section of Table 1.2 give an overview of the lack of appropriate reporting to ensure equitable outcomes from residential building electrification upgrades. No other study which examines the economics of residential building electrification allows for this level of reporting.

Table 1.2 Summary of existing studies on the economics of residential building electrification

		Study Design					***Reporting***		
Model type	***Study***	*Electrification technologies*	*Considers electric equivalent technologies*	*Includes all installation costs*	*HVAC sizing and pricing*	*Discount Rate*	*Building Type*	*Income Level*	*Renter/ Owner*
White-box, phyiscs-based models	Patteeuw et al. (2015)	SH, WH	No	No	Mixed	Fixed (7%, 3.5%)	Single-family	No	No
	Asaee et al. (2017)	SH	No	No	Variable	Fixed (1%, 3%, 6%, 9%)	Single-family	No	No
	Mahone et al. (2019)	SH, WH, CD, CR	No	Yes	Fixed	Fixed (3.35%)	Single-family Multi-family	No	No
	Deetjen et al. (2021)	SH	No	No	Mixed	Fixed (7%)	Single-family	No	No
	Billimoria et al. (2021)	SH	No	Yes	Fixed	Not specified	Single-family	No	No
Black-box, economic models	Nadel (2016)	SH	No	No	Fixed	Fixed (5%)	Did not specify	No	No
	Raghavan et al. (2017)	WH	No	No	N/A	Fixed (3%)	Did not distinguish	No	No
	Kelly et al. (2018)	SH	No	No	Fixed	Fixed (5%)	Single-family	No	No
	Hopkins et al. (2018)	SH, WH, CD, CR	No	No	Fixed	Fixed (5%)	Single-family Multi-family	No	No
	Partridge (2018)	SH, WH	No	Yes	Fixed	Fixed (5%)	Did not specify	No	No
	Nadel (2018)	SH, WH	No	No	Fixed	Fixed (5%)	Did not specify	No	No
	Kaufman et al. (2018)	SH	No	No	Fixed	Fixed (10%)	Did not specify	No	No
	Kolwey and Petroy (2022)	SH	No	Yes	Fixed	Not specified	Single-family	No	No
	Nadel and Fadali (2022)	SH, WH	No	Yes	Fixed	Fixed (5%)	Single-family Multi-family	Yes	No

Additionally, in answering the third research question, this research, for the first time, quantifies the improvement of thermal comfort possible across an entire building stock given a set of upgrade packages. While a number of studies have analyzed the impact of an upgrade on an individual building energy model [43–47], and Mavrogianni et al. analyzed the baseline thermal comfort of an entire building stock [48], no analysis has yet combined these two aspects. This research fills this gap by analyzing the baseline thermal comfort of an entire building stock and the change in thermal comfort in the building stock based on a set of envelope and heat pump system upgrades.

1.1.5 Broader Impacts

This research develops a tool and related analysis that contributes to an equitable electrification of the residential building sector in Los Angeles by providing targeted electrification upgrade recommendations for owners and landlords. In terms of equipment performance, the results from this study can be generalized to population centers with similar climates – such as San Diego and Western Mexico, cities along the Mediterranean, Cape Town, South Africa, Perth Australia, and along Chile and Peru's western coast. From a societal perspective, this research demonstrates how the tenets of energy justice can be integrated into a quantitative research study. This study aids in the development of not only a sustainable, but also a just energy system through equitable residential building electrification. The tool and methods developed herein can be used to improve energy equity research in related fields, such as those addressing other demand sectors like commercial buildings, transportation, and industry or research on energy supply from the local to the global level.

1.2 Background and Literature Review

This research spans several topics, including the energy transition, residential building electrification and energy justice. The following subsections provide background and context to understand these topics. First, it is first necessary to recognize the impact climate change is having on our planet and the contribution the built environment towards climate change. Second, a literature review of energy justice principles and their application is provided to show the rationale for vulnerable households outlined in the Energy Justice-Informed Study Design sector. Third, the theory underlying scenario development is outlined to underscore the importance of high-quality scenario design. Finally, an overview of energy modeling is given to show the different questions different model articulations can answer.

1.2.1 Climate Change and the Built Environment

Increased global greenhouse gas emissions have led to increases in the average global temperature [49]. Increasing global temperatures are already leading to devastating impacts including deforestation [50],

desertification [51], sea level rise [52], lack of access to drinking water [53], and forest fires [54]. In the United States, legislation at the federal, state, and local levels has been enacted to address these emissions. This legislation has called for the explicit reduction to building emissions such as Denver City Council's Bill 21-1310 which sets building performance standards and an electrification mandate [55] and President Biden's Executive Order 14057 which call for all federally-owned and leased building to be net-zero by 2045 [9]. Jurisdictions have also set implicit building emissions reduction goals through economy-wide emission reduction goals, such as California Senate bill 32, which calls for a 40% reduction in state-wide greenhouse gas emissions by 2030 [10].

Building emissions are classified into three different scopes [56]. Scope 1 emissions are those generated through the combustion of fossil fuels within the buildings themselves. Scope 2 emissions are those produced by the energy system in providing buildings with electricity (e.g., natural gas power plants). Scope 3 emissions are the life cycle emissions produced beyond energy usage (e.g., extraction of materials, construction, end of life) [57]. All three building emissions scopes must be addressed to achieve widespread building decarbonization. This study will focus on addressing Scope 1 emissions.

Almost all fossil fuels burned onsite in residential buildings can be attributed to space heating, water heating, cooking, and clothes drying [58]. Scope 1 emissions can be fully eliminated by replacing combustion-based technologies with electric ones. Currently, electric technologies exist that are many times more efficient compared to their combustion-based counterparts. Furthermore, these technologies are all commercially available. Therefore, the challenge to eliminating Scope 1 emissions from residential buildings is addressing the barriers that all households face in adopting these new technologies.

1.2.2 Energy Justice

The concept of energy justice is derived from the foundations of the environmental justice movement. Energy justice aims to understand how the development of the energy system has led to the marginalization of certain communities [16, 59, 60]. Energy justice has been written about widely, and there are several consistent tenets. McCauley et al. described the concept of energy justice as the aim to provide all households, 'across all areas, safe, affordable and sustainable energy' [16]. Jenkins et al. highlights the fact that energy justice focuses on both communities and the environment, thus describing energy justice as a combination of the natural science (e.g., energy systems) with the social science (e.g., energy policy) [61]. Heffron extends the concept beyond the use of energy, defining energy justice as the application of human rights across the entire life cycle of the energy system, from extraction to decommissioning [62]. Energy justice focuses both the distribution of benefits and burdens generated in the production and consumption of energy services [30], and the ability of communities to take part in

decision-making regarding the energy system [17, 18, 30].

Energy justice, more than simply a concept, can also be adapted as a tool to rectify inequities created by the energy system by informing policy [24, 30]. Hernández, following the work done by the First National People of Color Environmental Leadership Summit in their creation of the Principles of Environmental Justice, posited four energy justice rights that all governments must provide their citizenry [63]. They are the 1) right to healthy, sustainable energy production, 2) right to best available energy infrastructure, 3) right to affordable energy, and 4) right to uninterrupted energy service. Similarly, Sovacool and Dworkin used the concept of energy justice to develop a framework for identifying energy injustices and proposing solutions (Table 1.3) [30].

Table 1.3 Energy justice analytical applications to energy problems. Adapted from [64]

Topic	***Application to energy***	***Injustices***	***Solutions***
Energy efficiency	Energy efficiency: high penetration of efficient service	Inefficiencies involved in energy supply, conversion, distribution, and end-use	Fuel economy standards, energy efficiency labeling, industrial retrofits, utility-scale demand-side management, ascending block rate pricing, advanced metering and smart grids, training and capacity building, consumer education and awareness
Energy externalities	Wellbeing: less suffering, pain, externalities, and disasters associated with energy production and use	The imposition of negative social and environmental costs on society such as traffic congestion, the extractive industries affiliated with energy production, the resource curse, nuclear waste, air pollution, greenhouse gas emissions, and water consumption	Passage of a carbon tax, accurate price signals and tax shifting, and environmental bonds
Human rights and social conflict	Universal human rights: an obligation to protect human rights in the production and use of energy	The violation of civil liberties—in some extreme cases death and civil war—undertaken in pursuit of energy fuels and technology, as well as the contribution of energy production to military conflict	Extractive industries transparency initiatives, energy truth commissions and inspection panels, improved social and environmental impact assessments for energy projects, availability of legal aid to vulnerable groups

Table 1.3 Continued.

Topic	*Application to energy*	*Injustices*	*Solutions*
Energy and due process	Due process: free prior informed consent for the siting of energy projects; fair representation in energy decision-making	Approaches to energy siting that ignore or contravene free, fair, and informed consent, and/or do not conduct adequate social and environmental impact assessments	Better information disclosure, broader community involvement and participation
Energy poverty	Accessibility and subsistence: an energy system that gives people an equal shot of getting the energy they need, energy systems that generate income and enrich lives	Lack of access to electricity and technology, dependence on traditional solid fuels for cooking, and time-intensive fuelwood and water collection and processing of food in emerging economies, borne mostly by women and children	Social pricing and assistance programs as well as pro-poor public private partnerships for microhydro units, solar home systems, improved cookstoves, biogas digesters, and small-scale wind turbines, mechanical energy for pumping, irrigation, and agricultural processing
Energy subsidies	Libertarianism: energy decisions not unduly restricted by government intervention	Gross subsidies that involve an involuntary wealth transfer to recipients, essentially raiding the pocket books of the unwilling	Elimination of inappropriate subsidies, subsidy impact assessments, sunset clauses, and adjustment packages for those dependent on subsidies
Energy resources	Resource egalitarianism: an obligation to minimize resource consumption and ensure adequate reserves for future generations	Exhaustion of depletable energy reserves and fuels	Improved energy efficiency, establishment of national resource funds, commercial-scale deployment of renewable electricity and biofuels
Climate change	Intergenerational equity: an obligation to protect future generations from energy-related harms	A daunting suite of negative impacts from climate change including ocean acidification, food insecurity, climate refugees, and the increased frequency and severity of natural and humanitarian disasters	Greenhouse Development Rights, community-based adaptation, mitigation through stabilization wedges

While initial writings address energy justice in a philosophical manner, a growing number of studies are applying the concept of energy justice to a variety of real-world issues. Chapman et al. used energy justice to develop a set of equity factors (e.g., greenhouse gas reduction, health, employment, and electricity price impact), weigh these factors by relative equity and policy burden, to quantitatively evaluate the retirement of various coal power plants in Australia [64]. Similarly, Healy and Barry demonstrate the democratization of energy systems by analyzing fossil fuel divestment strategies [65]. Liljenfeldt and Pettersson examine the

distributional justice implications of windmill sitting [66]. Alvial-Palavicino and Ureta economizes energy justice to propose more just electricity tariffs [67].

However, the most common application of energy justice is the use of the energy justice tenets as first put forth by McCauley et al. [16] and used extensively by others [17, 26, 28, 29, 68, 69]. The original three energy justice tenets are distribution, recognition, and procedural justice [16] . However, several studies have added additional tenets this this list, including: restorative justice [18, 62], intergenerational justice [30, 70], and cosmopolitan justice [29, 62]. This thesis utilizes the tenets of distribution, recognition, and procedural justice to develop strategies that promote restorative justice (Figure 1.2). This approach is similar to phase of decision-making for applying energy justice, a framework developed Heffron and McCauley [71] and used by others (Figure 1.4) [72]. These four tenets of energy justice are defined in detail in the following paragraphs.

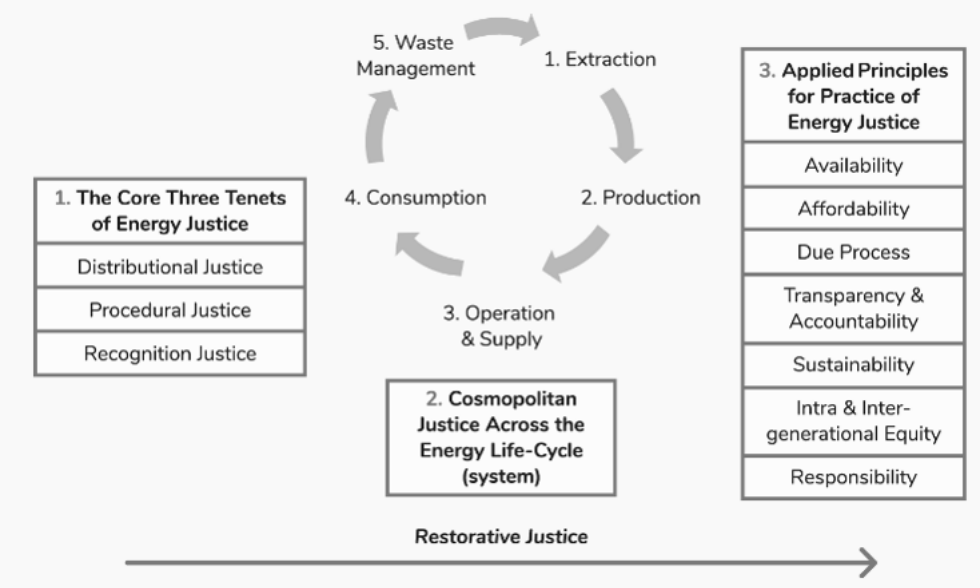

Figure 1.4 The Energy Justice Conceptual Framework. Adapted from [72, 73]

Distributional justice seeks to understand how the benefits and burdens of the energy system are shared amongst all who interact with the system [28]. The main benefit of this system is access to modern energy services, while energy-related subsidies provide additional benefits for some households [73]. On the other hand, the burdens are far more dispersed and exist at every point in the energy life cycle: during production, through transmission, to consumption, and at end-of-life [63]. Examples of these burdens include:

- Air and water pollution from the extraction and combustion of fossil fuels [28, 63, 74, 75].
- Energy sacrifice zones where the local environment and communities have been irrevocably damaged for the sake of energy development [63].
- Low-quality housing resulting from systemic divestment (e.g., redlining) which require more energy per unit service (e.g., increased energy to heat the same amount of space) leading to high energy burden and energy insecurity [63, 76, 77].

Knowing the impacts of the energy system on society, recognition justice seeks to determine the relationship between the different groups in this system, how the benefits and burdens are being allocated, the cost of bearing these burdens, and how, if any, remuneration is being offed to those who are disproportionately burdened [28, 29]. This tenet seeks to understand the impact of current and historical injustices on over-burdened communities [18]. Recognition justice seeks to include these over-burdened communities in the solution development process [26]. Just as distributional justice seeks to understand the burdens along the entire lifecycle of the energy system, recognition justice must think through the communities impacted from extraction, refining, manufacturing, transmission, and consumption of energy commodities [26]. Furthermore, recognition justice must seek to understand the distribution of any subsidies given across to this life cycle to understand which communities have not been able to access these benefits [26].

Next, procedural justice examines how decisions are made at all levels of energy policy. This not only refers to the current laws and regulations surrounding the energy system, but also due process through policies can be changed or remediated [26, 30]. Procedural justice seeks to answer the following questions. Who is given power to make decisions? Who is recognized in the decision-making process? What is the impartiality of those involved and the fairness of the process [29]. Some of the goals of procedural justice include local knowledge mobilization, greater information dissemination, and greater institutional representation [17]. With these tenets, it is now possible to identify all the negative impacts of the energy system, understand which communities are disproportionately affected by them, and then understand the decisions which lead to these injustices.

Having identified the burdens of the energy system (distributional justice), who has been most negatively impacted by these burdens (recognition justice), and understanding how the system has led to these inequities (procedural justice), the final tenet, restorative justice, seeks to rectify these issues (Figure 1.2). Restorative justice calls for active intervention, working with these communities to remediate these issues and correct historical injustices [18]. Heffron adds to this by saying that restorative justice

must seek to identify foreseeable inequities in energy projects that are in the planning and permitting process to avoid future issues [62].

To ensure no household is over-burdened or left behind in the transition to residential building electrification, I use the tenets of energy justice to guide the process of answering the three research questions outlined previous to create an energy justice-informed study design (Figure 1.3). First, through a review of the literature, I identified a set of household characteristics that are most associated with energy injustices in the residential building sector. Second, previous studies have shown that successful energy justice efforts have two key features: community involvement and regional specificity [17, 25, 28, 77, 78]. To achieve regional specificity, I decided to focus on a single city, Los Angeles, as a case study. In this way, I can focus on the unique regional characteristics, perspectives, and history to inform this research. To address community involvement, I have considered the perspectives of a variety of stakeholders from the Los Angeles community to help direct this research and its outcomes. Where possible, I will generalize my findings so that this research can be leveraged to impact communities across the globe. These two approaches are detailed in the sections that follow and then following these is an overview of the final, energy justice-informed study design.

1.2.2.1 Energy Justice Issues in the Residential Building Sector

Combing the 'what', 'who', and 'why' of distributional, recognition, and procedural justice, it is possible to identify specific energy justice issues in the residential building sector. Hernández demonstrates this by classifying three different types of burdens: structural, economic, and behavioral [63]. Structural burdens, such as poor housing quality due to redlining, lead to and compound economic burdens such as paying more energy to heat or cool a households based on poor insulation or drafty homes. Therefore, there are instances when the ultimate cause of energy justice issues in the residential building sector are not related to the energy system. Taking this example further, if a household has to pay a larger portion of their income to pay for energy bills, this household may be forced to make behavioral changes such as the decision to 'heat or eat,' or forgo medications, appropriate clothing, or any other number of sacrifices to pay energy bills. The toll of these decisions and their trade-offs compromise mental and physical health which only compound existing issues [63]. Similarly, the downstream impacts of energy justice issues in the residential building sector may appear to have little relation with the energy system.

In a review of the energy justice literature, I found four household characteristics that were most often associated with energy justice issues in the residential building sector (Figure 1.5). I also found that there is a significant amount of intersectionality in the ways these household characteristics impacted energy justice. For example, white households are less likely to experience poverty [79], and lower-income households are

receive a smaller portion of clean energy tax credits [80]. Therefore, white households, who generally have higher incomes levels will receive a larger portion of clean energy tax credits. Therefore, when looking to understand the equity impacts of a transition to residential building electrification it is critical that the methods used in this study be able to take as many of these household characteristics into account.

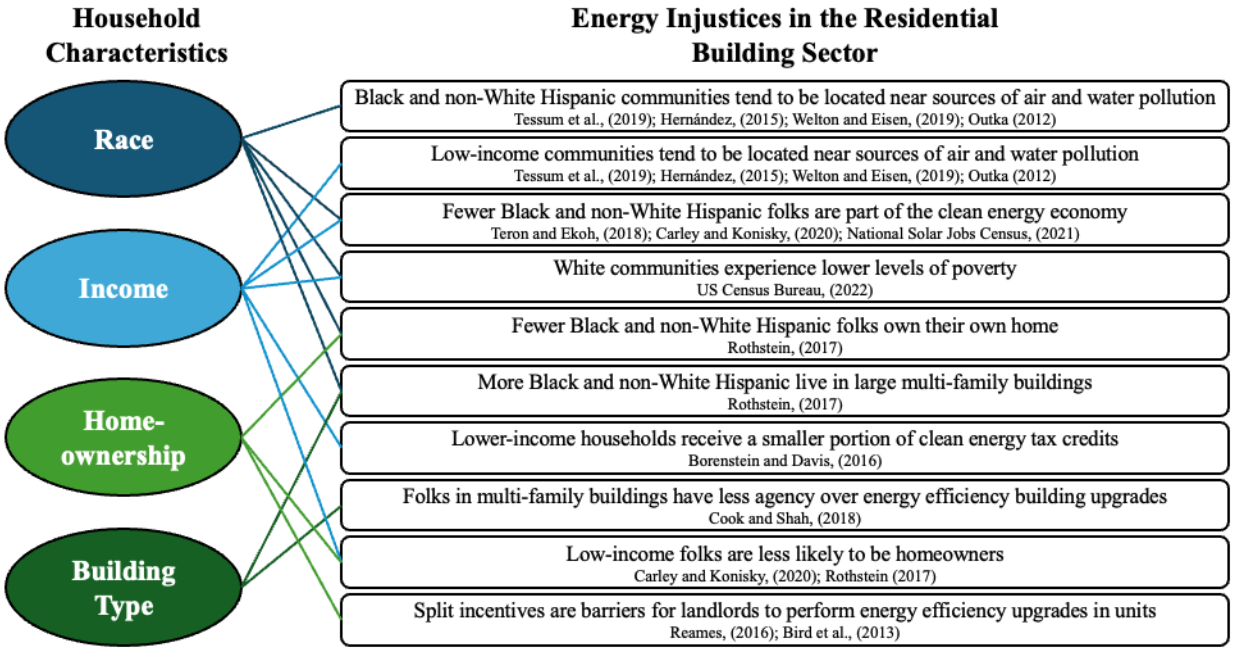

Figure 1.5 Household characteristics associated with energy justice issues in the residential building sector [18, 25, 28, 63, 74-77, 80-84]

1.2.2.2 Los Angeles as a case study

The City of Los Angeles, hereinafter referred to simply as Los Angeles, has many characteristics which make it an ideal case study to understand the equity implications of a transition to residential building electrification. 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 also access to Los Angeles-specific utility data [81]. 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 [82]. Thus, any change to this energy system will influence a significant portion of the California and U.S. populations. From a societal viewpoint, Los Angeles offers not only a highly diverse population in terms of race, income, homeownership, and residential building type, but also a population with extreme disparities across these dimensions [83]. Therefore, the lessons learned from the electrification in Los Angeles' residential building can be extrapolated nationally. Finally, 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 [12, 13].

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 [84]. I performed a description-based coding analysis of the notes from these meetings to determine the most common concerns expressed by these representatives regarding residential buildings. The background, methodology, results, and discussion from this coding analysis can be found in Appendix A. The main takeaways from this analysis were:

1. Affordability of proposed upgrades, both in terms of the capital and operating costs, was by far the most common concern expressed by residents. Therefore, it is key to understand the balance between the high purchase prices of many high-efficiency electric appliances and LADWP's plans to triple electricity rates in the next 25 years to fully understand the economic implications of a transition to residential building electrification ("Power Strategic Long-Term Resource Plan" 2022)[85].

2. Residents are worried existing building conditions and infrastructure will negate or seriously reduce the effectiveness of the proposed clean energy technologies. Therefore, any analysis must consider the current building characteristics in Los Angeles to provide the best recommendations for electrification upgrades.

3. Access to cooling and basic thermal comfort in residential buildings are basic human rights that must be addressed to address current inequities in Los Angeles. The increased penetration and use of cooling technologies could increase both capital and operating costs for residents, but the electrification of space heating via heat pumps could serve to both electric this end use and provide access to cooling technologies for households that do not currently have them.

4. 4. Renters are vulnerable in this transition given their lack of agency in decisions concerning unit retrofits. Furthermore, based on the split-incentive issue, landlords may not choose to pursue certain upgrades that may benefit renters, or may choose to not pass on savings. This issue tallies with findings from the literature review and the energy justice issues stemming from homeownership (Figure 1.5).

1.2.2.3 Energy Justice Definitions

Table 1.4 provides the definitions for various energy justice-related vocabulary that appear through this research.

Table 1.4 Household characteristics associated with energy justice issues in the residential building sector

Energy Justice Vocabulary	Definition
Energy Burden	Amount of household income spent to cover energy costs [86]
Energy Insecurity	"The inability to meet basic household needs" due to the high cost of energy [87]
Energy Poverty	A lack of access to basic, life-sustaining energy [72]
Just Transition	A transition away from the fossil-fuel economy to a new economy that provides "dignified, productive, and ecologically sustainable livelihoods; democratic governance; and ecological resilience" [88]

1.2.3 Scenario Development Process

Understanding the scenario development process is critical when analyzing different pathways to achieve equitable residential building electrification. Without this understanding, it will be impossible to develop high-quality scenarios needed to answer Research Question 1 from Figure 1.1. In this section, I describe the purpose of scenario analysis, provide an overview of the different stages of the scenario development process, and show how the scenario development process can be leveraged to address an energy justice-informed study design.

Scenario analysis is an important tool for understanding the implications of current and future developments by allowing us to compare possible futures side-by-side. Given the high level of complexity and uncertainty found in the energy system, scenario analysis is not a tool to predict the future, but rather a method to find a range of possible futures [22]. In the literature, the goals for scenario analysis are numerous and convey the many applications of this process in energy modeling. Scenario analysis can reveal impacts of changes to the energy system under stakeholder control – policy decisions [89], organizational response [90], and the achievement of specific objectives [38]. In parallel, scenario analysis assesses the impacts of uncertainty in the energy system outside of stakeholder control – population growth, gross domestic product growth [91], climate processes ([92]. An apt description of the purpose of scenarios, as described by Grundy, is to help us explore what the future of the energy system may look like, but more importantly understand the challenges of living in that future [93].

In a review of the literature, the scenario development process can be segmented into three primary stages: project scoping, variable scoping, and scenario scoping (Table 1.5). In project scoping, the scenario

development team outlines the purpose of the scenario analysis by identifying the key questions and characteristics. Along with this, the team decides the stakeholders that will be consulted in the scenario development process – this includes anyone from subject matter experts to community members to policy makers. Next, the variable scoping stage takes the themes identified in the project scoping and attempts to parameterize them using variables present in the energy model. Similarly, if an energy model has not yet been selected, the team can use these variables and the project scoping themes to determine the best model to use for their analysis. When evaluating variables and how they can change, it is important to understand the interdependence of variable in an energy model, their possible range, the exogenous data used to define them, and the control level stakeholders have over the choose variables. Just like the variable scoping stage, the scenario scoping stage uses the themes identified in project scoping to assign appropriate scenario types. Again, these scenario types could factor into the type of energy model selected for their analysis.

Table 1.5 Household characteristics associated with energy justice issues in the residential building sector

Stage	Guiding Question
Project Scoping	PS.1: What key questions do we want to answer? [20, 22, 94, 95]
	PS.2: What characteristics do we want to explore? [89, 94–96]
	PS.3: What stakeholders do we involve in the process? [20, 22, 94]
Variable Scoping	VS.1: What are the primary variables of interest? [20, 22, 89, 94]
	VS.2: Is there any interdependence of these primary variables?[20, 22, 23]
	VS.3: What is the range of possible values for these primary variables? [23, 89, 94–96]
	VS.4: What level of control do stakeholders have over the primary variables? [20, 22]
Scenario Scoping	.1: Is each scenario plausible or possible? [20, 22, 23]
	S.2: Based on key questions, should the scenarios be normative, descriptive, or both? [22, 23, 89]
	S.3: Based on the key questions, should the scenarios be trend-based, disruptive, or both? [22, 23, 89, 96]
Scenario Scoping	S.4: Based on the primary variables, what is the range of scenarios needed to answer the key questions? [22, 96]

In this research, I leverage the scenario development process to address three tenets of energy justice: distribution, recognition, and procedural justice. To answer guiding question PS.3 from Table 1.5, when identifying stakeholders to involve in the scenario development process we can address both recognition and procedural justice by addressing the following questions. For recognition justice, "Which groups have been excluded from decisions regarding the energy system?" For procedural justice, "How do we involve these historically disenfranchised groups moving forward?" To answer guiding questions PS.1 and PS.2 from Table 1.5, when identifying key questions and characteristics we can address the tenet of distributional justice by asking "What questions/characteristics do these historically disenfranchised want to explore? Finally, to answer guiding question VS.1 from Table 1.5, when selecting the primary variables

of interest, we can address the tenet of procedural justice by asking the questions "What are the most appropriate metrics to judge the effectiveness of these initiatives?" and "Are these metrics appropriate to the community's needs?" [19].

1.2.4 Energy Modeling

Energy modeling, combined with scenario analysis, enables us to explore the implications of the different pathways to residential building electrification. I leverage energy modeling to answer Research Questions 2 and 3 from Figure 1.1. Energy modeling will allow me to understand the changes in supply and demand of various energy commodities to help prepare for the uncertain consequences of this transition [20, 97]. Energy models can also be used to analyze the impact of both existing and proposed building decarbonization policies [98]. These insights will help policy makers and utilities ensure that energy is accessible, affordable, and supportive of clean energy policy goals. In this section, I describe the different analytical approaches and modeling methodologies that can be put into practices. I also describe how the type of model and its formulation can be leveraged to address an energy justice-informed study design.

Energy modeling frameworks vary widely in terms of scope, analytical approaches, and modeling methodology. The scope of an energy model refers to two different characteristics. First, the scope of an energy model can refer to its relationship to other models in a larger modeling framework. An energy model can act as a part of larger integrated assessment model that may include economic, climatic, political, and human health elements [99]. An energy model can also act independently without interaction from other sectors. Second, the scope of an energy model can encompass both supply and demand, or just one of these elements [100].

The analytical approach of an energy model is the process through which the model resolves. A simulation-based energy model answers the question "What would happen if...?" These models are used to understand the impact of different developments based on the input of exogenous data. These energy models have no foresight [99]. An optimization-based model answers the question "What needs to happen to achieve . . . ?" These models prioritize a user specified objective, regardless of the consequences in other sectors. These models have perfect foresight to achieve the stated objective [99]. A hybrid-based model uses an optimization approach to resolve the model within each timestep. However, this optimization does not drive towards a large goal across the model time horizon; this is referred to as myopic foresight.

The modeling methodology of an energy model is how the model handles interactions with other sectors, such as the economy, the environment, or other societal pressures. A top-down, or black-box model estimates the energy supplied and demanded at different points of the economy. These models are based on and rely upon historical data and trends and are therefore unable to forecast broad technological or

systemic changes. A major drawback to these models is the fact that they only provide an overall estimation of energy supply and demand, and thus individual entities cannot be analyzed [100]. A bottom-up, or white-box model calculates energy demand for each node. Using large datasets to define the characteristics of each entity, energy supply and demand profiles are generated and can be aggregated across the entire time. Given their complexity, these models are computationally complex and data-intensive [100].

Other important energy modeling characteristics include temporal and spatial resolution and scale and the data used to create different scenarios and projections. From a temporal perspective, it is important to understand both the temporal resolution, or length of a given time step in a model (e.g., hourly, yearly) and the temporal projection period which is the time horizon to which the model projects (e.g., from 2020 through 2050). From a spatial perspective, an energy model is scoped across an area of interest (e.g., contiguous U.S.) which is then subdivided into unit areas [100]. The more granular the constituent areas, the greater the resolution. Finally, it is key to understand the exogenous data being input into the energy model [100]. When evaluating the data source used by a model, it is critical to understand how frequently this data is being collected and the quality and generalizability of the data.

Given the range of energy modeling frameworks, choosing an existing model or choosing to develop a specific type of model depends on the use case. An excellent starting point is to work through the guiding questions for each of the different stages of scenario development (Table 1.5). Through this process, the types of scenarios needed to answer the key questions will be identified and this will begin to narrow the number of appropriate energy modeling frameworks. Establishing the key variables of interest, their range, interdependence, and level of control will further refine this list. Just as with scenario development, it is imperative to consider energy justice when evaluating possible energy modeling frameworks. We need to ensure that we can answer the key questions and explore the characteristics of interest of historically disenfranchised communities. Furthermore, we need to ensure that the energy modeling framework can be leveraged to create metrics appropriate to the community's needs [19].

1.2.4.1 LA100 Equity Strategies

This research was in part based on the work done in the LA100 Equity Strategies project conducted by the National Renewable Energy Laboratory (NREL) and the University of California – Los Angeles (UCLA) on behalf of the Los Angeles Department of Water and Power (LADWP). The goal of the LA100 Equity Strategies project was to ensure that all Los Angeles residents benefit from the clean air, good jobs, and economic opportunities available in a transition to a clean energy future [101]. As a member of NREL's building team for this project, I was part of a larger effort to create a customized and validated

building stock energy model for Los Angeles.

This custom model was based off the publicly available ResStockTM building stock energy model which is developed and maintained by the NREL residential buildings group [102]. The customization to this model included improving the model resolution, adjusting appliance saturation, and using weather data based on the four California Energy Commission climate zones present in Los Angeles. The baseline model was then validated against timeseries electricity use provided by LADWP. This model customization and validation was conducted by five other researchers and me. For this reason, these researchers are included as co-authors in the third, fourth, and fifth chapters of this thesis.

I then leveraged this customized and validated model to run the residential building electrification scenarios that serve as a foundation for this study. I built upon the work that had already been done for the LA100 Equity Strategies project. First, the LA100 Equity Strategies report only examined electrification of space heating systems through the installation of heat pump systems in the context of safe and comfortable home temperatures and resilience [103]. In this study, I expand the investigation electrification to include water heating, cooking, and clothes drying. Furthermore, I examine the electrification of space heating via lower cost electric equivalent systems. Second, I created the methodology for this research to report out the highly resolved capital costs associated with the upgrade packages examined. Additionally, the calculation of operating costs and subsequent calculation of simple payback period and energy burden in the LA100 Equity Strategies report used a fixed volumetric natural gas and electricity rate. In this study, I use the same rate structures used by LADWP and the Southern California Gas Company for electricity and natural gas, respectively, to calculate the operating costs, marginal net present value, and energy burden for each household simulated [104, 105]. Therefore, the work done as a part of this research both augmented the work done by the NREL buildings team for the LA100 Equity Strategies project and used that work as a foundation to create a significant amount of novel research in this area.

CHAPTER 2

INTERNAL CONSISTENCY AND DIVERSITY SCENARIO DEVELOPMENT: A COMPARATIVE FRAMEWORK TO EVALUATE ENERGY MODEL SCENARIOS

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Noah Sandoval, Janet L. Reyna and Amy E. Landis (2023). "Internal consistency and diversity scenario development: A comparative framework to evaluate energy model scenarios." Renewable and Sustainable Energy Reviews.

2.1 Preface

Chapter 2 was published in Renewable and Sustainable Energy Reviews with the following citation: Sandoval, Noah, Janet L. Reyna, and Amy E. Landis. "Internal Consistency and Diversity Scenario Development: A Comparative Framework to Evaluate Energy Model Scenarios." Renewable and Sustainable Energy Reviews 186 (October 1, 2023): 113632. https://doi.org/10.1016/j.rser.2023.113632. This chapter is presented exactly as published. This chapter and paper address research question 1: "How can we ensure the development of high-quality scenarios for energy modeling?" The Internal consistency and Diversity Scenario Development comparative framework was developed to both improve the theory underlining scenario development and to improve the practice of developing high-quality scenarios for energy models.

Using the Internal consistency and Diversity Scenario Development comparative framework, this chapter outlines the four evaluations of the scenario development process needed to achieve high-quality scenarios: development process, access, variable diversity, and scenario diversity. This process was used then used in Chapters 3, 4, and 5 to create the scenarios for electrification and electrification supportive strategies that are used to answer research questions 2 and 3. Additionally, several key aspects of the Internal consistency and Diversity Scenario Development comparative framework can used to address energy justice issues. The process by which stakeholders are selected is a key element of both recognition and procedural justice. Distribution justice can be addressed if these community stakeholders are elevated to guide project and variable scoping. If these voices direct the key questions to be answered, the characteristics to explore, and

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the primary variables of interest, they will also impact the variable type, variable control, scenario outlook, and scenario progression metrics. Therefore, not only can this comparative framework used to create high-quality scenarios, but it can also be leveraged to achieve energy justice outcomes.

The tenets of energy justice were addressed and incorporated into the scenario development process in multiple ways using the Internal consistency and Diversity Scenario Development comparative framework. First, in the Stakeholder Engagement metric of the Development Process evaluation, it is possible to address recognition justice by selecting stakeholders from vulnerable communities that are implicated in the results of the scenario analysis. Second, the Narrative Complexity metric in the Development Process evaluation can address distributional justice by outlining the key questions to be answered by the scenario analysis and the key characteristics of the scenarios themselves. These narratives can be focused on the negative burdens created by the energy system and possible solutions to remediate them. Third, the Variable Type and Variable Control metrics in the Variable Diversity evaluation address procedural justice by understanding the systemic changes that can be made to address the issues identified the development of the scenario narratives.

2.2 Abstract

Energy modeling frameworks and scenario analysis help us explore the potential impact of our actions and uncertainties in future energy systems. Despite their importance, there is no systematic procedure for evaluating the scenario development process. In a literature review, we identify two core elements of the scenario development process: internal consistency and diversity which are oftentimes missing from scenarios. To address this gap, we create the Internal consistency and Diversity Scenario Development (IDSD) comparative framework which aims to assess the feasibility and diversity of scenarios for a given energy model. With this framework, we review commonly used energy models and demonstrate our framework on their scenarios.

The IDSD comparative framework can serve several purposes absent from previous scenario development work by aiding energy modelers and report writers in crafting high-quality scenarios. First, the IDSD is a reflective tool which can improve the quality of the scenario development process, enabling a comparative assessment of energy models and scenarios. Second, the IDSD can provide guidance to modeling frameworks with existing scenarios and those still in development; this feedback will enable modelers to improve the development and the communication of the limitations of their scenarios. Third, this study has highlighted areas for improvement in the scenario development of some commonly used energy model frameworks. Finally, there is a complete lack of explanation regarding the stakeholder selection process. Addressing these identified items could increase opportunities for advanced energy

technology uptake and improve our options for achieving a more resilient energy system.

2.3 Introduction

The global energy system is currently situated along several inflection points – environmentally, technologically, politically, and economically – where the decisions and actions taken now could drastically alter the trajectory of the future. Environmentally, anthropogenic climate change is beginning to significantly impact temperature and weather patterns [49], and much of this is a direct result of energy sector emissions [106]. Technologically, the development of many advanced energy technologies can both reduce the carbon intensity of energy production and increase efficiency while remaining cost effective [107] and reliable [108]. However, the deployment of these technologies to combat climate change faces significant political and economic barriers [109]. Energy modeling frameworks can explore the tradeoffs of different technology deployment cases to provide an understanding of what future energy supply and demand could look like [110]. Furthermore, results from these modeling frameworks can help key energy system stakeholders make informed decisions. Energy modeling frameworks can offer valuable insight to future uncertainty and seek ways to build towards a more resilient, sustainable, and just energy system.

A fundamental component of energy modeling frameworks is the implementation of scenario analysis. Scenario analysis allows us to compare many possible futures side-by-side. Along with this, we can leverage scenario analysis to understand the implications of current and future actions. It is important to note that given the high level of complexity and uncertainty found in the energy system, scenario analysis is not a tool to predict the future, but rather a method to find a range of possible futures [22]. Scenario analysis is a powerful tool for variable exploration, but how can we assess quality and practicality of developed scenarios?

The process of creating a set of scenarios is called scenario development. Based on the literature, the most fundamental aspect of scenario development is project scoping. The first part of project scoping is to articulate the purpose of the scenario and the key questions to be answered. These questions can pertain to a wide variety of situations including: policy decisions [89], an organization's response to new development [90], the achievement of specific objectives [38], the increase in economic development of a country [**?**], or the changes in the climate processes [92]. Once the purpose and key questions have been solidified, the second part of project scoping is to outline the basic characteristics of each scenario - What variables to use? Their range and interdependence? What type of scenario outlook and progression to utilize? These two elements of project scoping are critical in ensuring high-quality scenarios.

In a review of the literature, we identified three types of studies which examine scenario development – individual model reviews, state-of-the-field reviews, and model inventories (Table 2.1). The first type of

analyses are detailed reviews of individual energy modeling frameworks and their respective reports which focus on the model methodology, scenario contents, and an analysis of past projections [111–115]. The state-of-the-field reviews survey large numbers of energy modeling frameworks to identify specific shortcomings of the field as a whole [41, 116–119]. Lastly, model inventories are reflective tools with the intention to be used by energy modelers to iterate and improve upon the development of both their modeling frameworks and scenarios [95, 120]. While these model inventories have been adapted to other analyses, they act simply as an auxiliary guide rather than comprehensive comparative framework [121, 122].

Table 2.1 Analytic capabilities of scenario development review types

Analytic Capabilities	Individual Model Review	State of the Reviews	Model Inventories
Analyze the internal consistency of scenarios			
Analyze the diversity of scenarios			
Provide targeted feedback for scenarios of a single model framework			
Compare the scenarios of different models			
Offer general scenario development guidance			
Key:			
Symbol			
Meaning	Can analyze and typically does this analysis	Can analyze but typically does not do this analysis	Cannot do this type of analysis

These previous studies evaluating scenarios from energy modeling frameworks lack several fundamental elements for comprehensively assessing scenario development. First, existing frameworks are unable to ensure the internal consistency of each scenario. We define internally consistent scenarios as coherent [21], plausible [110], focused descriptions [22] of possible futures [23]. The internal consistency of a scenario is closely connected with the scenario development process; only through the clear articulation of the

purpose, key questions, and characteristics can a scenario development team construct a scenario which has all the attributes of internal consistency listed above. Ensuring internal consistency is a key part of creating high-quality scenarios yet there exists no evaluation which focuses on this aspect of the scenario development process. While individual model reviews and model inventories could hypothetically gauge the internal consistency of a scenario, none of the studies we identified did so. At the same time, state-of-the-field reviews have no ability to do this type of analysis, because they provide a macro-level overview of the trends and gaps in the scenario analysis field rather than a detailed analysis of each scenario set (Table 2.1).

The second way current studies fall short is in how they define and evaluate diversity. For this work, we define diversity in two ways, as both the complexity [123] and multi-dimensionality [94] of each scenario, as well as the range of diversity found across a set of scenarios [94]. Both types of diversity, like internal consistency, are inextricably tied to the scenario development process. It is critical when identifying the purpose of the scenario and articulating the key questions to be answered that the entire spectrum of variable and scenario characteristics be considered. Given the complexity of the energy system, it is important to consider the wide array of factors that impact any individual piece. It is crucial to explore all available variables to ensure that the goals of the scenario analysis are met. While individual model reviews and model inventories could analyze diversity, they typically do not. Just as with internal consistency, state-of-the-field reviews do not have the ability to report on the diversity of scenario sets due to their macro-level analysis of the field (Table 2.1).

The third gap in the previous work is the inability of existing approaches to assess their wider impact in the scenario development field. Of the types of studies mentioned, none can: 1) compare scenario sets side-by-side, 2) provide targeted feedback to each scenario set, and 3) offer general guidance to the scenario development field through the identification of trends and gaps (Table 2.1). Current studies are either too focused and cannot generalize their results (e.g., individual model reviews), or are too general and do not offer specific feedback and guidance to individual models (e.g., state-of-the-field reviews, model inventories). To ensure the development of high-quality scenarios, it is critical that we have an ability to learn from the strengths of other scenario development processes, get targeted feedback on our own processes, and learn from the greater energy modeling field.

In summary, there is currently no existing comprehensive comparative framework that evaluates the internal consistency and diversity of the scenarios used in energy models. Furthermore, none of the work currently available can compare the scenarios of energy modeling frameworks side-by-side, provide targeted recommendations for the scenario development for individual models, and identify trends and gaps across the field. Without a comparative framework to evaluate the scenario development process, the projections

of the future supply and demand of energy from these scenarios could prove unreliable. These unrealistic views of the future could provide decision makers and stakeholders with faulty information, spurring them to take inappropriate action. The consequences of this include missing opportunities in advanced energy technologies, a lack of understanding of the impacts of future developments, and on the whole, a less resilient energy system. Any of one of these could lead to significant social, economic, political, and environmental ramifications.

To bridge these gaps, in this study we propose the Internal consistency and Diversity Scenario Development (IDSD) comparative framework which has all the analytical capabilities outlined in Table 2.1. The IDSD can critique the quality of the scenario development process specifically in terms of the internal consistency and diversity of the scenarios. It is important to note that we are not critiquing the energy modeling frameworks themselves, but rather their scenario development and the reporting of those scenarios. In this way, we can compare the scenarios of all different types of energy modeling frameworks side-by-side. Beyond these comparisons, the IDSD can provide guidance to modeling teams working on both existing model frameworks and those still in development. The conclusions drawn from this evaluation will give energy modelers guidance to improve the development of their scenarios along with the communication of the limitations of their scenarios. At the same time, it will give insight to decision makers into the types of scenarios which are possible and the limitations of certain scenario types. This study includes an overview of the methods used to create the IDSD, the results of the comparative framework on five case studies, a discussion of the results and recommendations for the energy modeling field, along with a conclusion which summarizes the IDSD comparative framework and its implementation.

2.4 Methods

The following section outlines the methodology used in the IDSD comparative framework. The IDSD is composed of two distinct sections– Internal Consistency and Diversity. Internal Consistency is assessed through the Development Process and Access evaluations; Diversity is assessed by evaluating Variable Diversity and Scenario Diversity. To orient the reader of the purpose of each evaluation, we present a driving question, along with a series of evaluation metrics which are then used to answer that driving question (Table 2.2).

Table 2.2 Comparative framework outline

Section	Evaluation	Driving Question	Metric
Internal Consistency	Development Process	Is there a rigorous development process?	Stakeholder Involvement
			Narrative Complexity
			Data Utilization
	Access	Is the documentation accessible?	Public Availability
			Easy of Access
Diversity	Variable Diversity	Is the complexity of the scenario sufficient for its purpose?	Variable Type
			Variable Control
	Scenario Diversity	Is the range of possible futures found in the set of scenarios sufficient to meet the goal of the scenario analysis	Scenario Outlook
			Scenario Progression

Within each metric, there are several different classifications. For the Internal Consistency metrics, classifications were highlighted in green, yellow, and red to represent best, acceptable, and unacceptable practices, respectively. For the Diversity metrics, there is not a single preferable practice. Instead, Diversity is evaluated by whether the diversity found in the variables and scenarios used are adequate to fulfill the purpose of the scenario or the overall analysis. Each evaluation will include a set of reflection questions which can be used by scenario development teams to reflect on the results of the evaluations and give them guidance on how best to improve their scenarios.

2.4.1 Internal Consistency

When we evaluate the Internal Consistency of scenarios from energy modeling frameworks, we want to ensure that the futures posited are possible. Although scenarios, by their definition, are often exploring unlikely or edge-case futures, any scenario should be one that under some combination of events could exist. In practice evaluating internal consistency requires two steps. The first step to understand the process through which each scenario was developed. Therefore, the first Internal Consistency evaluation is the Development Evaluation. The second step is to analyze the accessibility of the relevant documentation and data surrounding the development process of the scenario. The process of collecting this information makes up our second evaluation, the Access Evaluation. Through the implementation of both evaluations, we can judge the Internal Consistency of any energy modeling framework scenario. The process of crafting these two evaluations is outlined in the next two sub-sections.

2.4.1.1 Development Process Evaluation

The driving question "Is there a rigorous development process?" summarizes the Development Process Evaluation. To answer this question, we define three metrics: stakeholder involvement, narrative complexity, and data utilization. We define internally consistent scenarios as coherent [21], plausible [110], focused descriptions [22] of possible futures [23]. In this definition, we use the words 'plausible' and 'possible', to acknowledge that some scenarios represent boundary conditions and are highly unlikely but are viable to some degree. Next, we utilize the term 'coherent' to convey the idea that the variables which define any scenario must be congruous with the scenario aim. Finally, we employ the phrase 'focused description' to communicate that each scenario must be purposeful both as an individual scenario, but also within the scenario set. Creating scenarios with these attributes requires a variety of perspectives, an understanding of the interactions and dynamics of the system, and thoughtful discussion regarding the future progression of the system as a whole. Thus, the Internal Consistency of a scenario cannot be confirmed unless an extensive development process is undertaken. Table 2.3 outlines these three metrics along with their classifications, criteria, and reflection questions.

Table 2.3 Scenario development evaluation metrics along with associated classifications, criteria, and reflection questions

Metric	**Classification**	**Criteria**
	Purposeful and Selective	Clear stakeholder involvement: purpose of stakeholder involvement clearly outlined; reason(s) for stakeholder selection clearly outlined.
	Purposeful	Clear stakeholder involvement: purpose of stakeholder involvement clearly outlined, but reason(s) for stakeholder selection unclear.
	Selective	Clear stakeholder involvement: purpose of stakeholder selection clearly outlined, but purpose of stakeholder involvement unclear.
	Basic	Clear stakeholders involvement, but purpose of stakeholder involvement and the reason(s) for stakeholder involvement unclear.
	None	No clear stakeholder involvement

Table 2.3 Continued.

Metric	Classification	Criteria
Stakeholder Involvement	Reflection Questions	- Was the documentation surrounding stakeholder involvement publicly available? - Was the documentation provided surrounding stakeholder involvement complete? - What was the purpose of the stakeholder involvement? - What was the criteria for stakeholder involvement? - How did the modeling team and stakeholders deal with dissent/disagreement? - What elements of the development process were stakeholders included in? - Were the most relevant perspectives from the energy system or community included in the stakeholder group? - What was the process for recruiting and working with stakeholders?
Narrative Complexity	Detailed	A scenario narrative exists and a discussion of why each variable was used is included.
	Basic	A scenario narrative exists, however, no justification for the variables are given.
	None	No scenario narrative exists, or simply, the values of the scenario variables are given
	Reflection Questions	- Was the documentation surrounding narrative complexity publicly available? - Was the documentation provided surrounding narrative complexity complete? - What was the purpose of each scenario, and how did each variable in that scenario contribute to that purpose? - For each scenario, were the variables used the most appropriate for the purpose of the scenario? Are there other variables available? - Are all key characteristics of the scenario analysis represented in the final scenario set?
Data Utilization	Detailed	Reference to the data set used to develop the major trends of the scenario along with a justification of why this data set was chosen.
	Basic	Reference to the data set used to develop the major trends of the scenarios.
	None	No reference to the data set used to develop the major trends of the scenarios.
	Reflection Questions	- Was the documentation surrounding data utilization publicly available? - Was the documentation provided surrounding data utilization complete? - What was the rationale for using a specific data set? - If no data set was used, where did the information which informed the scenarios originate?

Stakeholder Involvement - Stakeholder involvement is key for the effective development of each of the other characteristics. The range of the stakeholder group could include any of the actors within the energy system [22, 23, 90]. Those participating in scenario development can be central to the modeling group, or

they can be less involved and participate via interviews, charrettes, consultations, or focus groups [90, 94, 110]. Stakeholder involvement can come in a variety of different forms and the reason(s) for this involvement is variable as well. It is crucial that scenario development teams clearly communicate the purpose of this involvement as well as the process for selecting and working with these stakeholders.

Narrative Complexity - The narrative contextualizes the scenario by providing the outlook or subject of the scenario [89, 94, 96, 124], the trend(s) which define the scenario [22], and/or the construction of the scenario storyline [95]. For this study, we define variables as the specific parameters which are used to differentiate the non-baseline scenarios from the baseline. A detailed narrative is one which thoroughly explores the implications of specific future developments, considers all the variables which could impact this narrative, selects specific variables to define the storyline of the scenario, and then provides justification for this selection.

Data Utilization - Once a narrative has been developed, the next step is to quantify the major trends. This is accomplished by identifying the major variables which will be used to define the scenario and to quantify uncertainty. This can be done through the statistical analysis of historical trends [89, 95, 124], data from the literature [90], or input from subject matter experts [110]. Utilization of specific data sets along with a justification of why this specific data was used shows careful consideration of the implications of the impact the data will have on the scenario outcomes. Projections not founded in specific data sets are perceived as simple conjectures without thought to the repercussions of these speculations.

2.4.1.2 Access Evaluation

The driving question "Is the documentation accessible?" summarizes the Access Evaluation. To answer this question, we define two metrics: public availability and ease of access (Table 2.3). If the applicable information outlining the scenario development process is not available, it is impossible for a third party to judge the validity of the development process, and the Internal Consistency of the scenario cannot be confirmed. Table 2.4 outlines these two metrics along with their classifications, criteria, and reflection questions.

Public Availability - Availability of the main model report or model documentation could be restricted by a subscription fee or membership within a particular organization. Open access to all model documentation, reports, and data without any type of restriction is ideal [116, 125].

Ease of Access - When seeking information about the scenario development process, two factors lead to a high ease of access. First, the location of the information; it is easier to find information in the major report or main documentation as compared to the appendices or supporting material. Second, the guidance to the information. Information that can be found easily with precise guidance is preferrable to

Table 2.4 Access evaluation metrics along with associated classifications, criteria, and reflection questions

Metric	**Classification**	**Criteria**
Public Availability	Open	Requires no fee or subscription to access information.
	Mixed	Requires a fee or subscription to access some of the information.
	Closed	Requires a fee or subscription to access any of the information
	Reflection Questions	- If a fee or subscription is required, why is that fee or subscription necessary? - Are there ways to grant access to this information to certain parties while ensuring the information remains confidential (e.g., non-disclosure agreements)? - Are there other ways to receive compensation for this information so that it can be more publicly available?
Ease of Access	High	Information found with precise guidance in the final model report of model documentation.
	Medium-High	Information found with imprecise guidance in the final model report or model documentation.
	Medium-Low	Information found with precise guidance in appendices or other support materials.
	Low	Information found with imprecise guidance in appendices or other support materials.
	None	Information not found.
	Reflection Questions	- Were all the scenario development steps (Table 2.3) followed in the creation of these scenarios? If not, which were missing? - If all the steps were followed, is all information about this process available in the documentation? - Is the scenario development process referenced in the table of contents of the final model report or model documentation?

imprecise guidance where reading through many sections or documents to find the pertinent information is required [119, 126].

2.4.2 Diversity

Diversity, for the purpose of this paper, encapsulates two different ideas; the diversity found within each scenario and the diversity across the set of scenarios. It is important to note that when quantifying both types of diversity, we compare all the non-baseline scenarios to the baseline scenario. The diversity found within a non-baseline scenario is created through the different types of variables used to differentiate it from the baseline scenario. Therefore, the first diversity evaluation is the Variable Diversity Evaluation. Beyond this, Diversity can also be found across a set of scenarios in terms of the types of scenarios and variables used to differentiate the non-baseline scenarios from the baseline scenario. Thus, the second diversity evaluation is the Scenario Diversity Evaluation. The process of crafting these evaluations is outlined in the next two sub-sections.

2.4.2.1 Variable Diversity Evaluation

The driving question "Is the complexity of the scenario sufficient for its purpose?" summarizes the Variable Diversity Evaluation. To answer this question, we define two metrics: variable type, and variable control. The energy system is highly complex, thus the number and combination of variables we can perturb allow us to explore innumerable scenarios. In this evaluation, we want to ensure that the variables used in each scenario fulfill the purpose of the analysis. Table 2.5 outlines these metrics along with their classifications, criteria, and reflection questions to be used for all scenarios.

Variable Type - From an economic point of view, this metric evaluates whether the variable in question will alter the supply curve, the demand curve, or a combination of the two. For example, a decrease in the capital cost to build wind turbines will produce a horizontal shift in the supply curve, altering the price of electricity and thus the quantity demanded [127].

Variable Control - This metric evaluates the level of control or influence that energy system stakeholders (e.g., policymakers, utilities, energy consumers) have over the variable in question. By level of control, we mean the ability to dictate or influence a given variable, and thus its impact on the energy system. A variable with internal control is something that energy system stakeholders have complete control over, such as the ability to create a carbon tax [91]. A variable with limited control is a variable which can be indirectly influenced by energy system stakeholders. An example of limited control is the ability to use subsidies or fuel reserves to influence fuel prices, while other market pressures impact these prices as well. Whereas a variable where energy system stakeholders have little to no control over, such as

Table 2.5 Variable diversity evaluation metrics along with associated classifications, criteria, and reflection questions

Metric	**Classification**	**Criteria**
Variable Type	Supply Side	A variable whose primary impact is on the supply curve of an energy commodity.
	Mixed	A variable whose impacts cannot be ascribed to either the supply or demand of an energy commodity.
	Demand Side	A variable whose primary impact is on the demand curve of an energy commodity.
	Reflection Questions	- How many types of variables do you have in each scenario and across the scenario set? - Why did you choose these types of variables and not other for each scenario? - Do the types of variables used for each scenario help in answering the key questions?
Variable Control	External	A variable where energy system stakeholders have no direct control or influence over due to the large number of dependencies, the complexity of the phenomena, and/or the large number of parties involved.
	Limited	A variable where energy system stakeholders have limited but not direct control over due to the ability to somewhat influence the dependencies and/or other parties involved.
	Internal	A variable where energy system stakeholders have no control or influence over.
	Reflection Questions	- How many control levels do you have in each scenario and across the scenario set? - Why did you choose these control levels and not others for each scenario? - Do the control levels of the variables used for each scenario help in answering the key questions?

population growth, would be classified as external control [91]. We acknowledge that the differentiation between limited and external control can be highly subjective. For this analysis we took into consideration the scope of the energy modeling framework being analyzed and the context of the variable in the scenario in question to make these distinctions.

2.4.2.2 Scenario Diversity Evaluation

The driving question "Is the range of possible future found in the set of scenarios sufficient to meeting the goal of the scenario analysis?" summarizes the Scenario Diversity Evaluation. To answer this question, we define two metrics: scenario outlook and scenario progression. Within scenario outlook, a scenario's projection methodology is described as either descriptive or normative [23]. Scenario progression classifies the evolution of the modeled future as either trend or disruptive [23]. The purpose of a set of scenarios is to contrast the results of different scenario narratives [110, 128]. The range created by these different scenarios should be large enough to include a wide variety of futures, while at the same time being focused to effectively answer the key questions posed by the modelers. Table 2.6 outlines these two metrics along with their classifications, criteria, and reflection questions.

Table 2.6 Scenario diversity evaluation metrics along with associated classifications, criteria, and reflection questions

Metric	**Classification**	**Criteria**
Scenario Outlook	Descriptive	Scenarios with myopic or no foresight which do not resolve each time step to reach a predetermined final state.
	Normative	Scenarios which take specific variables and values into account to attempt to reach some final, predetermined state.
	Reflection Questions	- Does the goal of the scenario analysis include both exploratory and goal-based objectives? Why or why not? - Is the purpose of the scenario to determine the impact of an action or trend or is it to reach a goal?
Scenario Progression	Trend	Scenarios whose projections are based on the extrapolation of historical data and which could represent any plausible or exploratory trends.
	Disruptive	Scenarios whose projections have marked disruptions which cannot be attributed to or predicted by historical data.
	Reflection Questions	- Does the goal of the scenario analysis only include the projection of historical trends? If so, why? - Is the purpose of the scenario to model a significant disruption to the status quo or an exploratory future? Does this match the scenario projection? - For scenarios which model a significant disruption, what is the purpose of this disruption? How was this disruption identified and parameterized? - For scenarios which model an exploratory future, what trend(s) is/are driving this scenario? Why is/are this/these trend(s) valuable to monitor?

Scenario Outlook - This metric evaluates whether a scenario is descriptive, which simulates futures by resolving each time step irrespective of the evolution of the projection pathway, or normative, which begins with a final, stated goal and resolves each time step in an attempt to best meet that goal [23, 123].

Scenario Progression - This metric evaluates the evolution of the scenario. Trend scenarios use projections extrapolated from historical data, which represent plausible or even exploratory development. Disruptive scenarios include events that shock the energy system, which serve as boundary conditions for future energy trends [123].

2.5 Case Studies

In this section we present the results of the IDSD comparative framework for five case studies. Each case study is comprised of a commonly used energy modeling framework with an associated report. These are used together to understand the scenario development process. We begin with the IDSD Internal Consistency (Table 2.7) and Diversity (Table 2.8) results for the case studies. Next is an overview of each case study which includes a summary of the report and the energy modeling framework(s) used, a recap of the IDSD Internal Consistency and Diversity evaluations, and a brief analysis of the results. We present a comparative analysis of the trends across the case studies and major findings in the Discussion section.

Table 2.7 The case study results for the IDSD internal consistency evaluations.

		Development Process Evaluation			***Access Evaluation***	
Model and Report	**Scenario Type**	*Stakeholder Involvement*	*Narrative Complexity*	*Data Utilization*	*Public Availability*	*Ease of Access*
World Energy Model: 2021 World Energy Outlook	Baseline	Basic	Basic	Basic	Open	High
	Non-Baseline	Basic	Basic	Basic	Open	High
National Energy Modeling System: 2022 Annual Energy Outlook	Baseline	Purposeful	Basic	Basic	Open	High
	Non-Baseline	Purposeful	Basic	None	Open	High
Scout Model: Scout Core Measure Scenario Analysis	Baseline	Basic	Basic	Detailed	Open	High
	Non-Baseline	Basic	Basic	Detailed	Open	High
Various: LA100 Study	Baseline	Purposeful	Basic	Detailed	Open	High
	Non-Baseline	Purposeful	Basic	Detailed	Open	High
Asia-Pacific Integrated Assessment Model: SSP3: AIM Implementation of Shared Socioeconomic Pathways	Baseline	Purposeful	Detailed	Detailed	Open	High
	Non-Baseline	Purposeful	Detailed	Detailed	Open	High

Table 2.8 The case study results for the IDSD diversity evaluations.

		Scenario Diversity		**Variable Diversity** **Key: Each "·" symbol in these columns represents a variable which was altered from the baseline scenario"**					
Model and Report	**Non-Baseline Scenarios**	Scenario Outlook	Scenario Progression	Variable Type			Variable Control		
				Supply	Mixed	Demand	Internal	Limited	External
World Energy Model: 2021 World Energy Outlook	Announced Pledges	Descriptive	Trend	x x			x	x	
	Sustainable Development	Normative	Trend	x x			x	x	
	Net Zero Emissions by 2050	Normative	Trend	x x			x	x	
National Energy Modeling System: 2022 Annual Energy Outlook	High oil price	Descriptive	Trend	x				x	
	Low oil price	Descriptive	Trend	x				x	
	High oil gas supply	Descriptive	Trend	x				x	
	Low oil gas supply	Descriptive	Trend	x				x	
	High economic growth	Descriptive	Trend		x x				x x
	Low economic growth	Descriptive	Trend		x x				x x
	High renewable price	Descriptive	Trend	x				x	
	Low renewable price	Descriptive	Trend	x				x	

Table 2.8 Continued.

		Scenario Diversity		**Variable Diversity** **Key: Each "·" symbol in these columns represents a variable which was altered from the baseline scenario"**					
Model and Report	**Non-Baseline Scenarios**	Scenario Outlook	Scenario Progression	Variable Type			Variable Control		
Scout Model: Scout Core Measure Scenario Analysis	RB 1T-2T	Descriptive	Trend	x		x		x	x
	RB 1T-2T-3T	Descriptive	Trend	x		x		x	x
	RB 1T-2T-3T FS0	Descriptive	Trend	x		x x	x	x	x
	RB 1T-2T-3T FS20	Descriptive	Trend	x		x x	x	x	x
	HR 1T-2T-3T	Descriptive	Trend	x		·		x	x
	HR 1T-2T-3T FS0	Descriptive	Trend	x		x x	x	x	x
	HR 1T-2T-3T FS20	Descriptive	Trend	x		x x	x	x	x
	HR 3T FS0	Descriptive	Disruptive	x		x x	x	x	x
	HR 3T FS20	Descriptive	Disruptive	x		x x	x	x	x
Various: LA100 Study	High	Descriptive	Trend		x	x x x		x	x
	Stress	Descriptive	Trend		x	x x x		x	x
Asia-Pacific Integrated Model: AIM implementation of Shared Socioeconomic Pathways	SSP 1: 4.5 W/m2	Normative	Trend	x x	x x x x	x x		x	x x x x x
	SSP 1: 3.7 W/m2	Normative	Trend	x x	x x x x	x x		x	x x x x x
	SSP 1: 2.6 W/m2	Normative	Trend	x x	x x x x	x x		x	x x x x x
	SSP 2: 6.0 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 2: 4.5 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 2: 3.7 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x

Table 2.8 Continued.

		Scenario Diversity		**Variable Diversity Key: Each "·" symbol in these columns represents a variable which was altered from the baseline scenario"**					
Model and Report	**Non-Baseline Scenarios**	Scenario Outlook	Scenario Progression	Variable Type			Variable Control		
	SSP 2: 2.6 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 3: 6.0 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 3: 4.5 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 3: 3.7 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 4: 4.5 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 4: 3.7 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 4: 2.6 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 5: 6.0 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 5: 4.5 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 5: 3.7 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x
	SSP 5: 2.6 W/m2	Descriptive	Trend	x x	x x x x	x x		x	x x x x x

2.5.1 IDSD Internal Consistency And Diversity Evaluation Results

Table 2.7, Table 2.8 compare side-by-side the IDSD Internal Consistency and Diversity results for each of the five case studies conducted in this study, respectively. For Internal Consistency (Table 2.7), classifications which are highlighted in green, yellow, and red to represent best, acceptable, and unacceptable practices, respectively. Along with this, baseline and non-baseline scenarios were evaluated separately because of difference in the documentation level in some of the reports. For Diversity (Table 2.8), there is not a single, preferable practice. Instead, Diversity is evaluated by the number of different variable or scenario classifications provide sufficient diversity to answer the key questions of the analysis. It is important to also note that we only analyze the non-baseline scenarios in how they compare to the baseline scenario. We believe that the greatest insight can come from reviewing all metrics from each evaluation to understand how each scenario plays a part in addressing the purpose of the analysis.

2.5.2 Case Study 1: World Energy Outlook

The World Energy Outlook (WEO) is published in the fall of each year by the International Energy Agency with the purpose to provide "critical analysis of and insights on trends in energy demand and supply, and what they mean for energy security, environmental protection and economic development" [129]. The modeling framework used to generate the WEO is the World Energy Model (WEM) which is a large-scale, general equilibrium, simulation-based model which uses yearly time-steps to the year 2050 across the entire globe which is divided into 26 different regions/nations [130]. The baseline scenario is called the stated policies scenario, and it includes three other scenarios – announced pledges, sustainable development, and net zero emissions by 2050 scenarios [129].

What follows is a summary of IDSD evaluation of the 2021 WEO. For Internal Consistency, the report itself, all model framework documentation, and support materials were completely available online [129, 130]. All the scenarios were outlined with a basic narrative in the model documentation and main report [129, 130]. The data used to define both the baseline and non-baseline scenarios was found in the model documentation and main report [129, 130]. The WEM documentation refers to the collaboration with various other modeling groups, academic institutions, and expert reviewers, but does not go into the detail about the selection process of these stakeholders, nor their purpose. In terms of Diversity, the variables used to differentiate the non-baseline scenarios include the fuel cost and carbon tax which are both supply side variables. The carbon tax is classified as internal control, whereas fuel cost is classified as limited control [129, 130].

Based on the analysis of the 2021 WEO using the IDSD comparative framework (Table 2.7, Table 2.8), we offer the following recommendations to the WEO development team. First, while the 2021 WEO has

low access barriers, this report lacks some elements of a robust development process with basic narrative complexity and data utilization ratings. That being said, it is clear that many different expert stakeholders are involved, representing a variety of institutions. However, the purpose of their involvement and their selection process remains unclear. Second, while the 2021 WEO does feature both normative and descriptive scenarios, there are only trend-based scenarios. Finally, the 2021 WEO only considers supply-side variables. We therefore recommend that the WEO development team consider the reflection questions for the following metrics: stakeholder involvement, narrative complexity, data utilization, variable type, and scenario progression to ensure the Internal Consistency and Diversity of their scenarios and scenario set.

2.5.3 Case Study 2: Annual Energy Outlook

The Annual Energy Outlook (AEO) is published in the spring of each year by the US Energy Information Administration [131]. While an explicit purpose for AEO was not stated, the documentation does state that the 2022 AEO "explores long-term energy trends in the United States" [131]. The modeling framework used to generate the results for the AEO is the National Energy Modeling System (NEMS) which is a general equilibrium, simulation-based model which uses yearly time-steps to the year 2050 across the entire contiguous United States with a resolution of the nine US census divisions [132]. The purpose of NEMS is to "project the impact that energy, economic, environmental, and security factors can have on the U.S. energy system" [132]. The baseline scenario is called the reference scenario, with eight other scenarios – high oil price, low oil price, high oil and gas supply, low oil and gas supply, high economic growth, low economic growth, high renewable energy cost, and low renewable energy cost [131].

What follows is a summary of IDSD evaluation of the 2022 AEO. For Internal Consistency, the report itself, all model framework documentation, and supporting materials were completely available online [131–134]. For all scenarios, the AEO team conducted multiple working group meetings in the year leading up to the report for each of the major subsectors in their model (Industrial, Macroeconomic, Residential and Commercial Buildings, Petroleum and Natural Gas, Electricity, Coal, Renewables, and Nuclear). The purpose of these working groups is clearly articulated and there is ample documentation of the work done by each group [133]. That being said, the stakeholder selection process is unclear. A basic description of the development of the baseline scenario was available in the report narrative along with the data used to generate it [131]. Unfortunately, only a small amount of information was found about the development of the non-baseline scenarios in the report narrative. The creation of these scenarios appears to be a simple percent change in certain variables from the baseline scenario [134]. No information pertaining to the specific narratives nor the reasoning for the changes in variables was available for these scenarios. In terms

of Diversity, the variables used to differentiate the non-baseline scenarios include fuel cost, fuel supply, and asset capital cost which are classified as supply side and limited control variables, along with population growth and gross domestic product growth which are classified as mixed type and external control variables [131].

Based on the analysis of the 2022 AEO using the IDSD comparative framework (Table 2.7, Table 2.8), we offer the following recommendations to the AEO development team. First, while the 2022 AEO does have low access requirements and pursues extensive stakeholder involvement, the narrative complexity and data utilization of this report is lacking. Second, the 2022 AEO only considers descriptive and trend-based scenarios. Third, while the 2022 AEO does consider supply and mixed-type variables, no scenario features a scenario with multiple Variable Types. Lastly, the 2022 AEO does not consider internal control variables. We therefore recommend that the AEO development team consider the reflection questions for the following metrics: narrative complexity, data utilization, scenario outlook, scenario progression, variable type, and variable control to ensure the Internal Consistency and Diversity of their scenarios and scenario set.

2.5.4 Case Study 3: Scout Core Measure Scenario Analysis

The Scout model is a building energy model developed primarily by the U.S. Department of Energy's Building Technologies Office (BTO) [135]. While the Scout model is used for a variety of applications by BTO, for this study we are evaluating the Scout Core Measure Scenario Analysis [136]. The purpose of the Scout model is to "project the reductions in building operation-phase CO2 emissions and primary energy use through 2050 and compare these reductions against targets in the [U.S. Mid-Century Strategy]" [137]. Scout is a bottom-up, stock inflow model which uses the residential and commercial building sector energy end use and fuel type outputs from the 2020 AEO and then applies energy conservation measures to these technologies resulting in energy savings [136]. Therefore, this study has a similar temporal and spatial resolution and scope as the 2020 AEO. This study uses scenarios built upon combinations of three variables: increasing building technology efficiency (1T through 1T-2T–3T), carbon intensity of the electric power supply (RB – reference, HR – high renewable), and an incentive for fuel switching (FS0 – no incentive, FS20 – 20% incentive) [137]. See Table 2.8 for a full list of scenarios.

What follows is a summary of IDSD evaluation of the Scout Core Measure Scenario Analysis. For Internal Consistency, the analysis itself, along with all Scout model documentation and datasets used in the scenarios were fully available online [136]. Information about the model and its scenarios was prominent and easy to find in all the documentation [135, 137**?**]. While the number of scenarios and variable combinations make for a wide range of possible futures, the model documentation simply explained the difference between the different variable levels and did not provide a narrative for any of its scenarios.

Rather these scenarios are permutations of the three variables outlined previously [135–137]. Conversely, the model documentation went into great detail about the data used by the different variables with all the datasets available online [136]. Lastly, while the Scout model was developed by a group of researchers from the Department of Energy's Energy Efficiency & Renewable Energy Office, Lawrence Berkeley National Laboratory, the National Renewable Energy Laboratory, and several energy-related research consultants. However, there was no available documentation of the selection process nor the reason for their inclusion in this modeling effort [135, 138]. In terms of Diversity, the variables used to differentiate the non-baseline scenarios include fuel supply as a supply side variable, along with fuel switching and energy efficiency improvements for demand side variables [135–137]. The incentivized fuel switching variable would be classified as internal control level, carbon intensity of the grid would be classified as limited control, and building technologies would fall under the external control classification [135–137].

Based on the analysis of the Scout Core Measure Scenario Analysis using the IDSD comparative framework (Table 2.7, Table 2.8), we offer the following recommendations to the Scout team. First, while this study involves researchers from a variety of different research institutions, the Scout team could reflect more on their stakeholder involvement. Second, the narrative complexity of this study is limited and it only considers descriptive, trend-based scenarios. It is important to note that this is the only scenario analysis to include disruptive scenarios. These scenarios (HR 3T FS0 and HR 3T FS20) feature high renewable electricity generation, upgrading the existing building stock to the highest performing building technologies, and fuel switching

Lastly, this report does not consider mixed-type variables. We therefore recommend that the Scout development team consider the reflection questions for the following metrics: stakeholder involvement, narrative complexity, scenario progression, and variable type to ensure the Internal Consistency and Diversity of their scenarios and scenario set.

2.5.5 Case Study 4: LA100 Study

The LA100 Study was conducted by the National Renewable Energy Laboratory (NREL) for the Los Angeles Department of Water and Power (LADWP) with the purpose of informing "the city of Los Angeles, LADWP, and other stakeholders of the possible pathways to 100% renewable energy, and the implications of these pathways for the people who live and work in Los Angeles" [139]. The LA100 Study was created using a combination of demand models and historical demand data. The residential, commercial, and transportation demand sectors were modeled through a suite of tools developed primarily by the NREL: ResStock [102], ComStock [140], and EVI-Pro [141], respectively. The industrial demand sector along with the water system and outdoor lighting sectors were modeled using historical demand data

from LADWP [142, 143]. The city is divided into receiving stations, census tracts, and individual properties [139]. The baseline scenario is called the moderate scenario, with two other scenarios, high and stress, which each include different technology electrification levels (e.g., electric heating systems, electric vehicles, etc.) and energy efficiency improvements [139].

What follows is a summary of IDSD evaluation of the LA100 Study. For Internal Consistency, the study itself was fully available online [139] and had precise guidance to the scenario development process in Chapter 3 of the study [144]. Chapter 3 of this study began with a general outline of each scenario and then it went into great detail as to how the different scenarios were modeled along with the data used delineate these scenarios [144]. Chapter 2 of the report outlined the study approach and gave an overview of the proceedings of the LA100 Advisory Group. The purpose of the Advisory Group was to provide feedback and comment on the work done by the project groups. Along with this, the Advisory Group provided insights to help improve the project given their unique perspectives [145]. While the purpose of the Advisory Group was fully transparent, the selection process of the Advisory Group was unclear. Documentation of all these meetings along with attendees were available on the LADWP's website [146]. In terms of Diversity, the variables used to differentiate the non-baseline scenarios include gross domestic product growth for mixed type variables along with energy efficiency improvements, technology adoption, and demand response for demand side variables [144]. Gross domestic product growth is classified as an external control variable, whereas the remaining variables are classified as limited control [144].

Based on the analysis of the LA100 Study using the IDSD comparative framework (Table 2.7, Table 2.8), we offer the following recommendations to the LA100 team. First, the development process of the LA100 Study had basic narrative complexity, and the study team could review the reflection questions in this area. Second, the LA100 Study only featured descriptive and trend-based scenarios. Lastly, the LA100 Study did not consider supply-type and internal control variables. We therefore recommend that the LA100 team consider the reflection questions for the following metrics: narrative complexity, scenario outlook, scenario progression, variable type, and variable control to ensure the Internal Consistency and Diversity of their scenarios and scenario set.

2.5.6 Case Study 5: AIM implementation of Shared Socioeconomic Pathways

The Shared Socioeconomic Pathways (SSP) Framework was developed by the Intergovernmental Panel on Climate Change with five scenarios, each at different levels of mitigation and adaptation challenges [147]. Each scenario has a different marker scenario modeling framework to generate the scenario results. Each modeling framework is an integrated assessment model which incorporates a variety of different systems (e.g., energy, economic, land use, air quality) across the entire world with various regional divisions

and time steps through the year 2100 [147]. We chose to analyze the Asia-Pacific Integrated Model (AIM) which is the marker model for SSP3 – Regional Rivalry [148]. However, unlike other marker models, AIM has the capabilities to analyze all other SSPs. AIM is a general equilibrium model with a recursive dynamic solution algorithm [147]. In the AIM implementation of Shared Socioeconomic Pathways article, the authors generated 22 scenarios across two dimensions. The first dimension is comprised of the five SSPs which are distinguished by several socio-economic variables. The second dimension is comprised of six different climate conditions defined by their radiative forcing level in terms of W/m2. Each SSP features a baseline scenario and three to four non-baseline scenarios.

What follows is a summary of IDSD evaluation of the AIM implementation of Shared Socioeconomic Pathways. For Internal Consistency, all documentation for the AIM and the SSP Framework were fully available online [147, 148]. Detailed narratives were available and easily accessible. Not only did an introductory journal article outline the SSP Framework and the various scenarios [147], each scenario and the AIM modeling methodology was described in the AIM implementation of Shared Socioeconomic Pathways article [148]. This same journal article that introduced the SSP Framework also directed readers to where they could find the data used to project the variables in their scenarios [149–156]. Lastly, another journal article for the SSP Framework described the origins of the framework along with the expert teams, interdisciplinary teams, and modeling teams involved in its development [124]. Unfortunately, we found no information regarding the selection process of these different stakeholder groups. In terms of Diversity, the variables used to differentiate the non-baseline scenarios include energy intensity changes and technology adoption for demand-side variables, population growth, gross domestic product growth, land use change, and climate for mixed type variables, with fuel cost and asset capital cost for supply-side variables [149–156]. Of these variables, technology adoption, fuel cost, and asset capital cost would be classified as mixed control with the rest falling under the external control level [149–156]

Based on the analysis of the AIM implementation of Shared Socioeconomic Pathways using the IDSD comparative framework (Table 2.7, Table 2.8), we offer the following recommendations to the SSP team. First, the AIM implementation of Shared Socioeconomic Pathways only considers trend-based scenarios. Second, the AIM implementation of Shared Socioeconomic Pathways does not consider internal control variables. We therefore recommend that the SSP Framework and AIM development teams consider the reflection questions for the following metrics: scenario progression and variable control to ensure the Internal Consistency and Diversity of their scenarios and scenario set.

2.6 Discussion

Based on the case study results, we have identified four major findings. First, the scenarios in the 2021 WEO, and to some extent the scenarios of the 2022 AEO and the Scout Core Measure Scenario Analysis lack the documentation or elements of the Development Process required to verify the Internal Consistency of their scenarios and, moreover, do not have the complexity and richness found in other scenarios. Second, there is a significant gap in Scenario Diversity with regards to the number of modeling frameworks which include normative and disruptive scenarios. Third, there is a significant lack in Variable Diversity in terms of the level of control stakeholders have over these variables. Finally, there is a complete lack of explanation regarding the stakeholder selection process. The following section will discuss these four findings and provide guidance for improvement.

2.6.1 Documentation Gaps

Using the criteria defined in the IDSD, we have identified several areas that would significantly improve the Internal Consistency of the 2021 WEO and further strengthen that of the 2022 AEO and the Scout Core Measure Scenario Analysis report. All reports could use additional description of the Development Process in their documentation. For these reports, it is unclear whether the Development Process as defined by IDSD is truly limited in the narrative complexity, data utilization, and stakeholder engagement metrics, or whether this is just not well-described in the documentation. Regardless, either of these issues could limit the utility of these scenarios for other work. Given the widespread use of the data created by these modeling frameworks, improving the Development Process of these scenarios could result in a myriad of positive impacts on planning and policy making decisions that surround the energy system.

Given that three of five of the reports selected lacked either a satisfactory Development Process or level of documentation to verify Internal Consistency, it would not be surprising if other reports suffered from similar issues. Internally inconsistent scenarios can lead to a misunderstanding of the future and sub-optimal decisions. Therefore, our first recommendation is for the entire energy modeling community to use the Development Process evaluation to ensure that 1) there is thoughtful consideration of the perspectives which should be included in the scenario development, 2) each scenario and each variable within these scenarios serves a specific purpose in the scenario analysis, and 3) the data to describe the major trends in each scenario are examined and justified to match the goals of the scenario analysis. Beyond this, documentation of this development process is key to ensure a complete understanding of the scenario analysis, its utility, and limitations. To do this, we recommend that the energy modeling community considers the reflection questions in the Development Process evaluation and use the Access evaluation to ensure that the documentation of this process is both available and accessible. In this way,

energy modelers can ensure that the scenarios they develop will feature plausible, coherent, and focused descriptions of possible futures.

2.6.2 Scenario Diversity

The second major finding is that there is a lack of Scenario Diversity across most reports evaluated especially in terms of normative and disruptive scenarios. The 2021 WEO and the AIM implementation of Shared Socioeconomic Pathways were the only reports to include normative scenarios - the Sustainable Development, Net Zero Emissions by 2050, and SSP1 scenarios. The importance of these types of scenarios can be seen in the Net Zero Emissions by 2050 scenario which shows that to achieve this goal electricity would have to increase to be the majority energy source by 2050 and that clean energy and infrastructure investments would need to triple by 2030 [129]. These specific findings give energy system stakeholders benchmarks to hit and it demonstrates that these goals are attainable. These scenarios are important because they allow us to determine if pathways exist to achieve certain goals and the scale of action needed to do so. Whereas descriptive projections have no explicit direction and could miss key opportunities.

Similarly, there is an almost complete absence of disruptive scenarios. The Scout Core Measure Scenario Analysis was the only report to include any disruptive scenarios – the HR 3T FS0 and HR 3T FS20 scenarios. These were the only scenarios to explore the technical potential of technologies and simulate a marked disruption in their exogenous input data. By doing this, the authors of this study found that even through these unrealistic, boundary condition scenario definitions, it was impossible to hit 2050 carbon reduction goals for the U.S. residential building sector [137]. This is a powerful conclusion and it completely changes this discussion. Even with the most ambitious building technologies, high renewable electricity generation, and incentivized fuel switching this target cannot be met. Therefore, to achieve this goal other, possibly more aggressive, measures must be considered.

It is understandable that energy modelers would stray away from disruptive scenarios, using historical data to extrapolate trends is a conservative approach to building a scenario. However, the assumption that all variables will follow historical data is a highly unreliable assumption [157]. Furthermore, trend-based scenarios do not challenge conventional thinking [123], the implications of not doing this include not understanding the sensitivities of different disruptions. Rather, the energy modeling field will be greatly enriched by an influx of disruptive scenarios. Evaluating the impacts of different disruptions, of varying magnitudes, occurring at different points in time would spark discussion regarding the various inflection points in our energy, economic, and environmental systems.

Thus, our second recommendation is that more reports incorporate normative and disruptive scenarios to increase the Diversity of the futures which are modeled. Normative scenarios will provide alternative

pathways and challenge the status quo found in descriptive scenarios, while disruptive scenarios will open dialogue regarding the implications and impacts of the different types of system shocks and how we can position ourselves to best, if not anticipate then, respond to an inevitable shift.

2.6.3 Internal Control Variables

The third major finding is that there is a lack of Variable Diversity in terms of the scenarios which use internal control variables. Only the scenarios from the 2021 WEO and the Scout Core Measure Scenario Analysis have internal control variables. Thus, most energy modeling frameworks analyzed did not simulate a scenario where energy system stakeholders would have full agency. The 2021 WEO scenarios show that widespread carbon taxes are critical to reducing, if not eliminating, energy-related carbon emissions. The Scout Core Measure Scenario Analysis showed that even if the U.S. was to implement fuel switching incentives, this measure, even combined with other efforts would not be enough to fully decarbonize the U.S. residential building sector.

These findings show the magnitude of change that can be implemented relatively quickly through both policymaking and public and private energy programs. It is also possible to show the impact of these efforts in relation to other variables where we may only have limited control. We recognize that there are many factors in the energy system outside of direct stakeholder control and that it is critical to understand the uncertainty of these factors. However, we believe that it is just as important to understand the scale of impact that energy system stakeholder decisions can have on the energy system. This type of analysis allows for an understanding of what can and cannot be accomplished by different programs, policies, and initiatives.

Unfortunately, we found that the largest group of scenarios analyzed were scenarios with a single variable of either limited or external control. If this is representative of the larger energy modeling field, then the greatest proportion of scenarios we are generating are versions of the future where we have little to no control. The removal of agency in this scenario development process creates a spectrum of futures which we can both easily conceive of, but which also, paradoxically, have unavoidable consequences. Thus, our third recommendation is to urge the energy modeling community to subject each of their scenarios to the Variable Diversity evaluation of the IDSD framework to ensure that the futures they are constructing offer actionable pathways towards a more sustainable, reliable, and just energy system.

2.6.4 Stakeholder Selection Process

The final major finding was the complete of lack description or methodology of the stakeholder selection process across all the energy modeling frameworks we analyzed. While three of the five energy model

frameworks analyzed feature purposeful stakeholder involvement, not even one outlined the methods for their selection process. Without this information, it is impossible to judge if any stakeholders were not overlooked, nor if there was any selection bias by the scenario development teams. Thus, all scenario development teams have an opportunity to improve their stakeholder involvement by simply outlining the process by which they went about selecting those who collaborated on their work. Likewise, if no formal process was followed, these teams can immediately improve the quality of their work by developing and deploying a selection protocol. Our final recommendation is for all scenario development teams to document or begin to incorporate stakeholder selection to immediately improve the stakeholder involvement and internal consistency of their scenarios.

2.7 Conclusion

Due to a level of subjectivity in some of the different evaluation metrics along with different familiarity levels of those using this evaluation with the reports they are evaluating, we recommend that all future scenario analyses by scenario development teams utilizing the IDSD comparative framework implement inter-rater reliability approach to ensure rigorous analysis [158, 159]. While we understand that this is a time-consuming process, research has shown that the inclusion of a single round of reliability checks by an independent reviewer will increase the rigor of the analysis [160–162].

Our goal is that the IDSD comparative framework is used by the energy modeling community to improve the internal consistency and diversity of scenarios reported to the greater energy system stakeholder group. The focus on Internal Consistency and Diversity came out of a recognition of the deficiencies found across various major energy modeling framework reports. However, we understand that this is not a perfect tool and moreover we fully anticipate that as the scenario development process continues to improve, so will the scope of this comparative framework expand as other needs arise.

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CHAPTER 3

ACHIEVING EQUITABLE SPACE HEATING ELECTRIFICATION: A CASE STUDY OF LOS ANGELES

3.1 Preface

Chapter 3 is intended to be published as a peer-reviewed journal article. As of April 2024, it is under review with Energy and Buildings. However, as the peer-review process is not certain it may ultimately be published in another journal. Future edits may be made based on reviewer comments. This chapter and paper address part of research question 2— "What are the consequences for all households in a transition to residential building electrification?"—by evaluating all costs associated with electrifying residential building space heating systems to a variety of different efficiency levels. The Marginal Net Present Value Upgrade Analysis Model was developed to receive input data from various upgrade scenarios run with the ResStock™ model and report out highly detailed results. The results from this model can be used to show households' capital and operating costs associated with set of space heating system upgrades. Additionally, for each upgrade, this model outputs a marginal net present value, using a unique discount rate for each household.

This chapter details how current household characteristics, especially heating system type (e.g., ducted vs. non-ducted), cooling system type and presence, along renter/owner status, impact the costs associated with each upgrade. For the households where the upgrade with the best marginal net present value is the lowest efficiency system, the consequences include roughly equivalent capital costs initially, but increased operating costs, and they do not provide cooling to those who do not already have it. Given LADWP's Strategic Long-term Resource Plan, electricity prices in Los Angles are projected to increase 200%–500% in the next 20 years [85]. Given this projection, the negative long-term cost implications of installing these low efficiency upgrades are tremendous. While installing the higher efficiency heat pump systems will avoid increases in utility bills for residents, the high initial capital costs of these systems make them cost prohibitive for many households. This chapter details how these nuances impact vulnerable households—low-income households, renters, households in multi-family buildings, and households without cooling—and the barriers these households face in a transition to electrified residential buildings.

This chapter addressed two aspects of energy justice in both the methodology and the reporting of results: recognition and distributional justice. The methodology addresses the two most prevalent Los Angeles resident concerns outlined in the Introduction: affordability and the current residential building conditions. Affordability is addressed by improving the cost calculations of residential building

electrification upgrades through the calculation of variable baseline and upgrade HVAC costs, the inclusion of all capital costs (i.e., labor, material, and fuel switching costs), and the implementation of a variable discount rate. Current residential building conditions were addressed through the use of the ResStockTM residential building stock energy model which performs statistical sampling to determine the building characteristics used to simulate each representative dwelling unit. Addressing affordability and the current residential building characteristics are examples of distributional justice, where this research focuses on burdens imposed on households by the energy system. The reporting of results focuses on three of the four vulnerable households and one of the community concerns outlined in the Introduction: low-income households, renters, and households in multi-family buildings. By focusing on these vulnerable households, recognition justice is addressed by ensuring that those who are disproportionately impacted by the burdens of the energy system put at the forefront of this analysis.

3.2 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 rulemaking and will give insight into the impact residential building electrification can have on vulnerable communities.

3.3 Introduction

Electrification is an important strategy for reducing CO2 emissions [163, 164]. A shift towards more widespread electrification is evident at both the federal and state levels; specifically emphasizing a shift towards electric heating in buildings [9].Then in 2018, California's governor signed Executive Order

B-55-18, which mandated state-wide carbon neutrality by 2045 [165]. According to the California Air Resources Board, buildings are responsible for approximately a quarter of the state's greenhouse gas emissions [166]. 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 [167]. 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 [2–7]. However, the impacts of climate change are being felt disproportionately more by politically, economically, and culturally marginalized communities [168]. Yet, the policies set out to address climate change often neglect these same communities in the type of support they provide or the types of households who can access the benefits of these policies [168]. Integrating equity implications into the energy transition requires that we consider additional factors in addition to the physical systems.

Energy justice is based on the philosophy of the environmental justice movement, which was a response to the unequal distribution of environmental burdens especially on marginalized communities [16]. The goal of energy justice is to provide all households with modern, sustainable, and affordable energy services by addressing current energy inequities and ensuring that the benefits of future energy systems are justly shared with previously marginalized communities [16–19]. In a review of the energy justice literature, we identified four types of vulnerable households that bear a disproportionate amount of the burdens attributable to the energy system [18, 25, 28, 63, 74–77, 79, 80, 169–171]. These vulnerable households are households of color, low-income households, renters, and households living in multi-family buildings. Additionally, studies have shown that energy justice initiatives are most successful when they are regionally specific and have a focus on community engagement [25, 77, 172]. Therefore, studies on the city level, rather than that state or national level, will be more effective in achieving energy justice outcomes.

The City of Los Angeles, hereinafter referred to simply as Los Angeles, has many characteristics which make it an ideal case study to understand the economic impacts of the electrification of residential space heating. 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 [81]. 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 [82]. Thus, any change to this

energy system will influence a significant portion of the California and U.S. populations. 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 [83]. Therefore, the lessons learned from the electrification of space heating in Los Angeles' residential building can be extrapolated nationally. 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 [12, 13]. 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 [84].

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 [32–37, 173–179]. Table B.1 in Appendix B 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. [32], Billimoria et al. [34], Partridge [35], Kolwey and Petroy [36], and Nadel and Fadali [37] considered all installation costs and only one study by Asaee et al. [174] sized, and thus priced, both the baseline and upgrade space heating systems to the building being modeled. 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% [180–185]. Furthermore, the literature indicates that among a variety of other characteristics, households with lower incomes have a preference for higher discount rates [39, 40, 42, 186]. Third, existing studies only considered a narrow range of baseline and upgrade space heating technology configurations. Only Asaee et al. [174], Deetjeen et al. [175], Kelly et al. [177], and Nadel and Fadali [37] considered all major baseline space heating technologies, and not a single study considered upgrading to electric resistance heating systems. Furthermore, only

Deetjeen et al. [175], Billimoria et la. [34], Nadel [176], Hopkins et al. [33], and Nadel and Fadali [37] 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 'CO2-abatement costs' [173], 'tolerable capital costs' [174], or the addition of health and climate cost [175], 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 [32–36, 175, 179], only three studies ensured that both single- and multi-family households were modeled [32, 33, 37], only Nadel and Fadali [37] reported the impact of household income level on their results and not a single study disaggregated households by renter/owner status.

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 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. 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.

The high resolution of this model allows us to disaggregate the results to understand the implications of residential building space heating electrification for four types of vulnerable households: low-income households, renters, households in multi-family buildings, and households without cooling. Additionally, 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 for low- and moderate-income households [187]. This unprecedented allocation of federal funding will have a significant impact for any vulnerable 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.

3.4 Methodology

To quantify all costs associated with a transition to electrified space heating, we follow a four-step methodology. First, we demonstrate 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. Second, we outline 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 the first part. Next, we detail 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, we review 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.

3.4.1 Simulate Baseline Energy Consumption

ResStock is a physics-based, bottom-up, white box, residential building stock energy model developed by NREL [188]. ResStock defines the relative probability of 127 residential building characteristics (e.g., wall insulation R-value) through a set of conditional probability tables synthesized from 11 national data sources. 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 [189]. Appliance saturation levels were revised using the 2019 California Residential Appliance Saturation Study and correlated these saturations to both income and renter/owner status [190]. 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.

With these 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 [191]. 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 [192]. Finally, the model results were then successfully validated against Load Research Data provided by the LADWP (See Appendix B).

3.4.2 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 the previous section. The upgrade scenarios are summarized in Table 3.1. 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).

Table 3.1 Space Heating Electrification Upgrade Package Definitions

	Baseline Technology		
Upgrade Technology and Scenario Name	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 For households without ducts: MSHP SEER 17, 9.5 HSPF		
Mid-Efficiency Heat Pump	For households with ducts: ASHP SEER 18, 9.3 HSPF For households without ducts: MSHP SEER 25, 12.7 HSPF		
High-Efficiency Heat Pump	For households with ducts: ASHP SEER 24, 10.8 HSPF For households without ducts: MSHP SEER 33.1, 13.5 HSP		

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 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 [193], 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.

3.4.3 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 3.1. 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.

3.4.3.1 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 3.1).

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1-r)^t} \tag{3.1}$$

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.

3.4.3.2 Marginal 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 previously. This process is summarized in Figure 3.1 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.

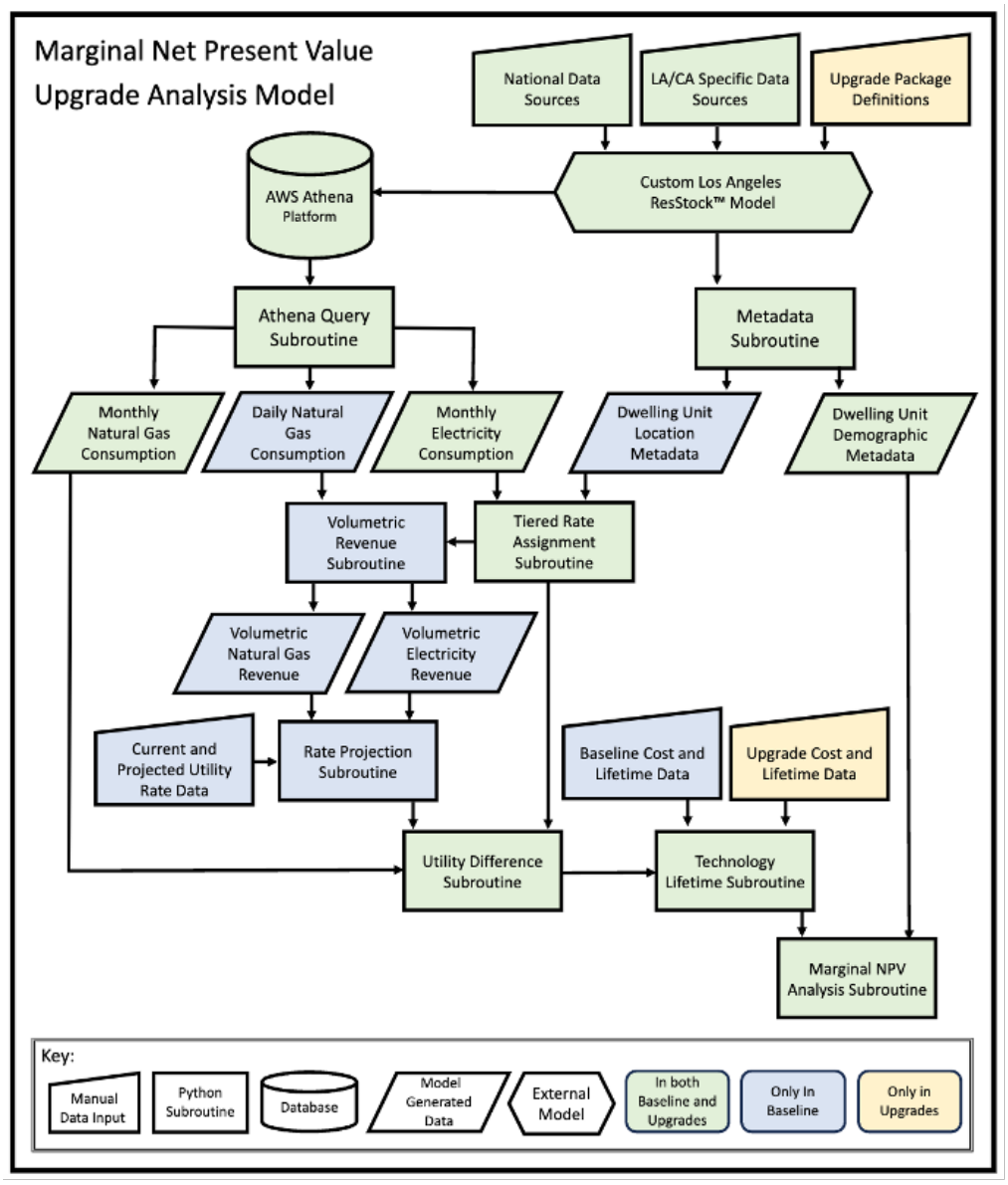

Figure 3.1 Software architecture diagram for the Marginal Net Present Value Upgrade Analysis Model

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 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 [194]. 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 3.1). 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 [195]. 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. All heat pump upgrades meet the EnergyStar rating to qualify for federal tax credits for energy efficiency home improvements ("Tax Credits for Your Home," n.d.). 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 [187]. 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 [187]. 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. Given the uncertainty the costs for heat pumps given that they their market share is growing each year, we performed a cost validation of the heat pump costs we used in this research [196] against data from TECH Clean California which is a state initiative to accelerate the adoption of clean water and space heating technologies [197]. Details of this cost validation can be found in Appendix B.

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 [198]. 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 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.

The discount rates used in existing studies that address the economics of residential building electrification are not appropriate to accurately quantify future costs and savings for vulnerable households. Existing studies that address the economics of residential building electrification use fixed discount rates for all simulated households. These fixed discount rates range from 1% to 10% (Patteeuw et al. 2015; Asaee, Ugursal, and Beausoleil-Morrison 2017; Mahone et al. 2019; Deetjen, Walsh, and Vaishnav 2021; Billimoria et al. 2021; Nadel 2016; Kelly, Fu, and Clinch 2016; Hopkins et al. 2018; Raghavan, Wei, and Kammen 2017; Partridge 2018; Nadel 2018; Kaufman et al. 2019; Kolwey and Petroy 2022; Nadel and Fadali 2022) [32–37, 173–179, 199]. However, when surveying over 1200 households, Newell and Siikamaki found the preference of payback periods for energy efficiency decisions varying widely [186]. This study

calculated that the implied discount rates of these households ranged from approximately 2.5% to 100%. Additionally, this study found that less educated households, larger households, households with lower incomes, and households of color exhibited higher discount rates. Therefore, the discount rates used in existing studies that address the economics of residential building electrification should be using variable discount rates and that the discount rates that these studies use may be too low for some households.

Similarly, the discount rates used to calculate the costs and savings for residential building technology upgrades in a variety of U.S. centric general equilibrium energy models do not match the findings of Newell and Siikamaki [186]. The discount rates used in these models varying more compared to existing studies on residential building electrification, with discount rates from 7% to 45% [180–183, 185, 200, 201]. Some of these are fixed across all residential building technology upgrades and some have different discount rates for different technologies. Regardless, these models use fixed discount rates that do not vary based on household demographics.

This research improves on existing studies that address residential building electrification by using a variable discount rate that assigns discount rate across a much larger range than that shown in existing studies. Given the focus of residential building technology upgrades in the U.S. centric general equilibrium energy models, I use range of discount rates found in these studies, 7% to 45%. Then given that Newell et al. found that low income households, one of the vulnerable households identified in the Chapter 1, have a preference for higher discount rates, I assigned each household a discount rate inversely proportional to their relative 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 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.

3.4.3.3 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 [32–37, 173–179, 199]. 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 [32–37, 173–179, 199]. 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 [202]. 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 3.2).

Table 3.2 Electricity and Natural Gas Rates for Rate Projection Sensitivity Analysis

	Utility Type	
Rate Projection	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

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 [203]. The CEC creates periodic California Energy Demand (CED) Forecasts for each major California utility, including LADWP [204]. 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 (Figure 3.2) [205]. 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). Performing this analysis, we can comment on how relative utility costs impact the ability to electrify space heating across the country by impacting the change in NPV of these different space heating electrification technologies.

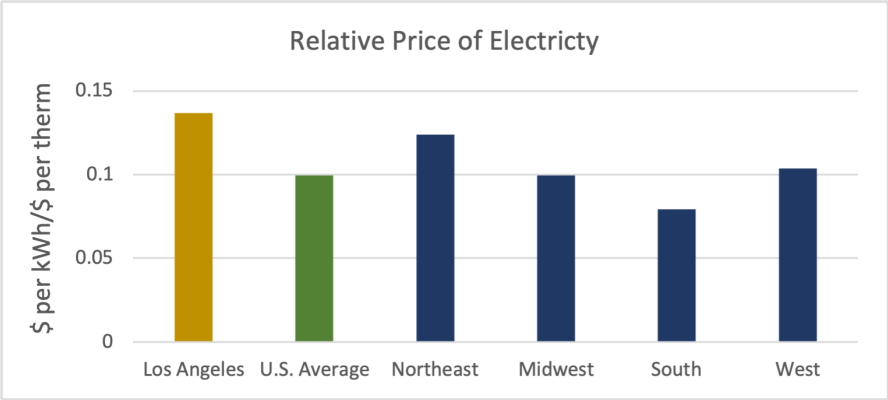

Figure 3.2 Electricity and Natural Gas Rates for Rate Projection Sensitivity Analysis

3.5 Results And Discussion

To understand the societal and equity impacts of a transition electrified space heating in the residential building sector, we focus our analysis of the results on the vulnerable households identified in Introduction: low-income households (0-80% AMI), renters, households in multi-family buildings, and households without cooling. For the results showing 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.

3.5.1 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 systems with a low-efficiency ASHP (Figure 3.3). 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 B.6 in Appendix B). 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.

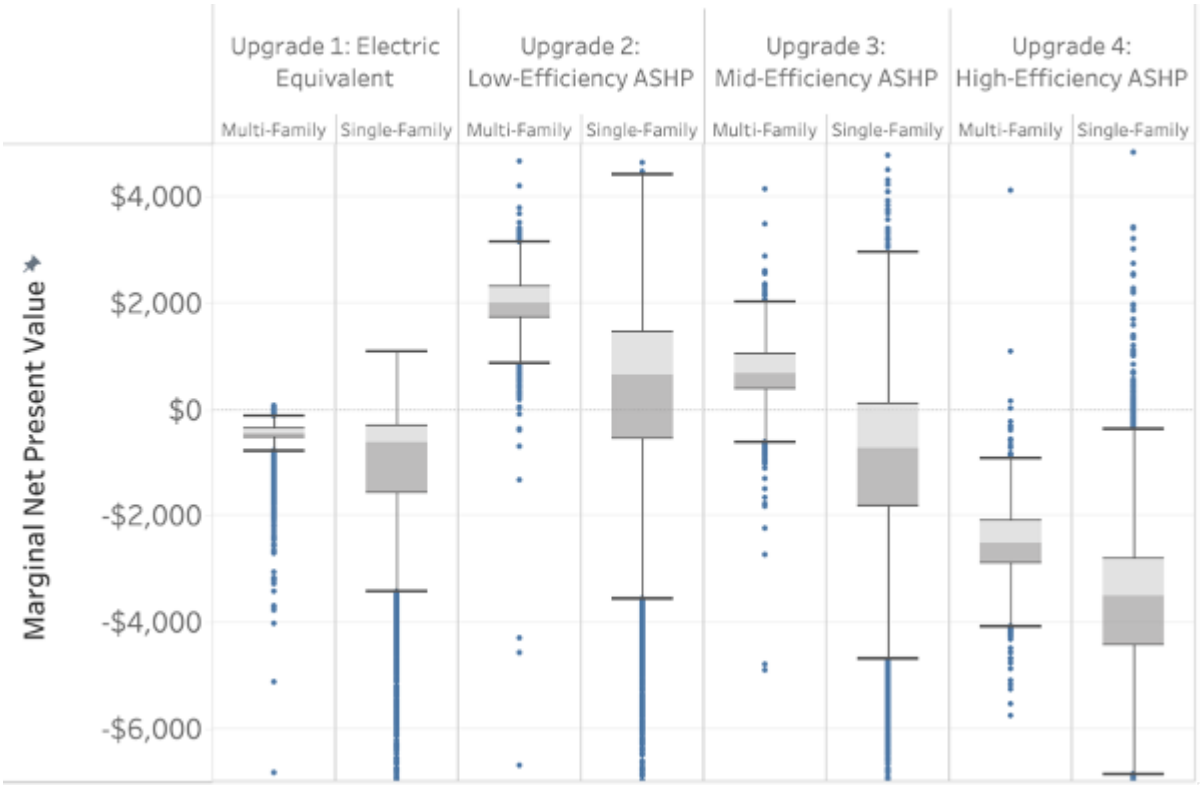

Figure 3.3 Distribution of marginal net present value of replacement for space heating electrification upgrades for buildings with natural gas furnaces with central ACs in the baseline

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 3.3).

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 B.7 in Appendix B). 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

Table 3.3 Interquartile range of the highest marginal NPVs for electrification upgrades in the most common non-ducted household types

Baseline HVAC System		Electrification upgrade with the highest marginal NPV	Marginal Net Present Value		
			75% Percentile	50th Percentile	25th Percentile
Natural Gas Furnace	Room AC	Electric Equivalent	-$490	-$524	-$799
Natural Gas Boiler	Room AC	Electric Equivalent	$286	$187	-$81
Natural Gas Wall/ Floor Furnace	Room AC	Electric Equivalent	$243	$145	-$29

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 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.

3.5.2 Upgrade Results For Homeowners Who Do Not Use Cooling In The Baseline

For owners who do not use cooling, space heating electrification increases costs (Figure 3.4). 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 B.8 in Appendix B)

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.

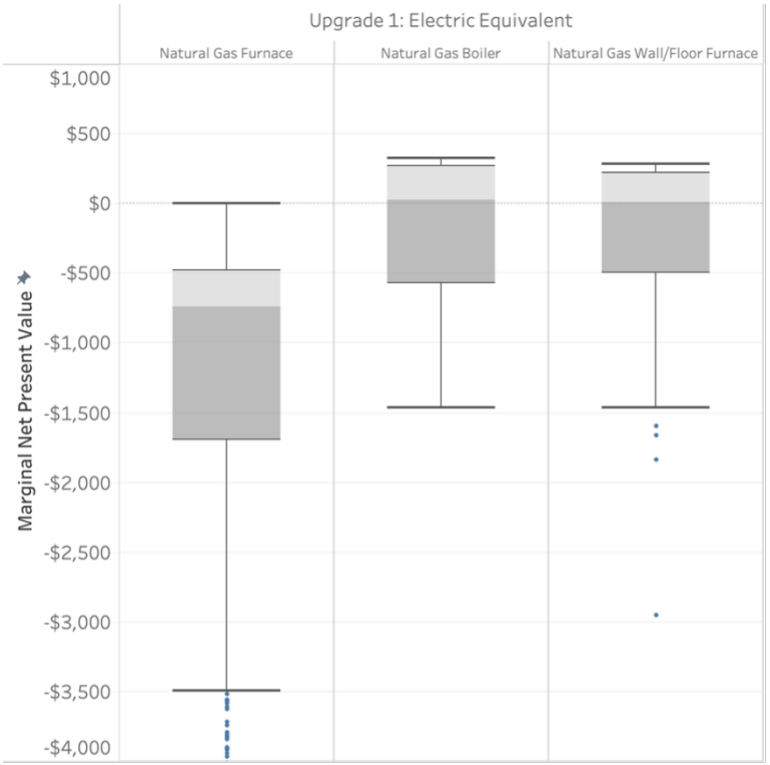

Figure 3.4 Distribution of marginal net present values for electric equivalent space heating electrification upgrades for households that do not have or do not use cooling

3.5.3 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 3.4). 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.

Table 3.4 Interquartile range of the highest marginal NPVs for electrification upgrades in the most common non-ducted household types

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	-$1,028	-$2,487	-$5,984
Natural Gas Boiler	$305	-$911	-$1,576	-$3,649
Natural Gas Wall/ Floor Furnace	$223	-$2,728	-$3,345	-$5,243

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 3.5).

Table 3.5 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

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 [206, 207].

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 B.10 in Appendix B). While IRA benefits can cover entire heat pump systems up to $8000, more modest support (from $1000-$3000) will 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 [208–210].

3.5.4 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 (Figure 3.5). 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 in Figure 3.5, the electrification upgrade that appears most favorable would be the highest efficiency heat pumps as compared to the results from Figure 3.4 which indicate that low-efficiency heat pumps and electric equivalent technologies are the best option. Rather than advocating for an electric equivalent system given the high capital costs of the heat pump systems, the results 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 Figure B.10 in Appendix B).

Table 3.6 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 discussed previously, 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.

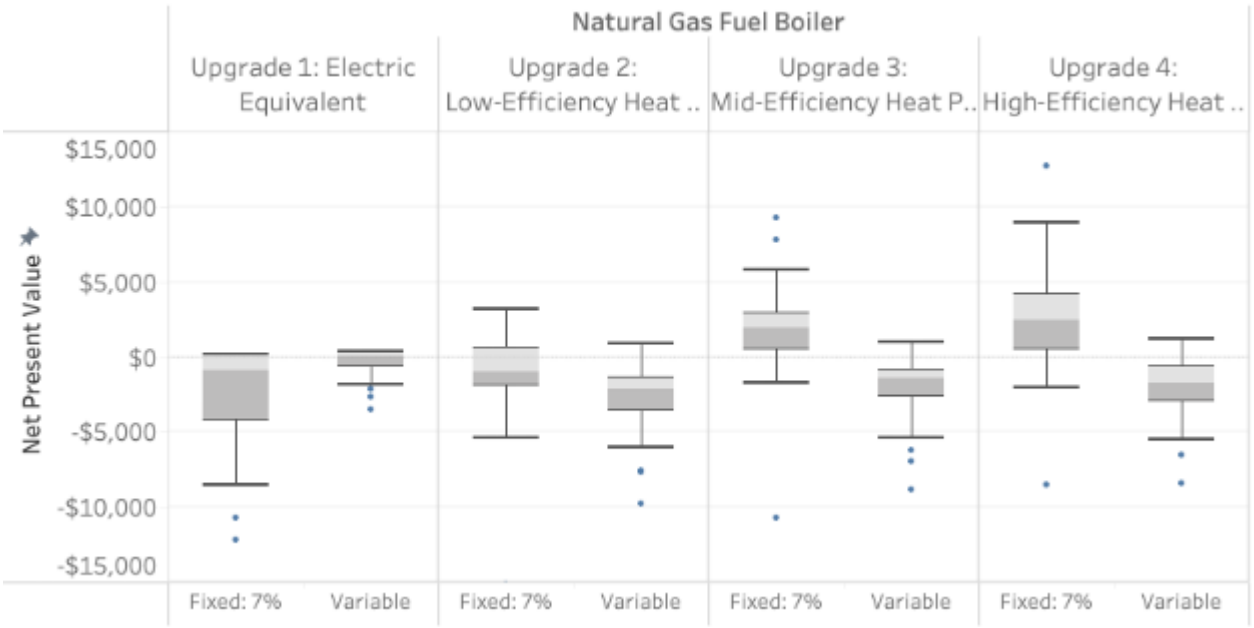

Figure 3.5 Distribution of marginal net present value for space heating electrification upgrades for buildings with natural gas boilers with room ACs in the baseline using fixed and variable discount rates.

3.5.5 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 (Figure 3.6). 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 in many other areas across the nation may make these heat pump upgrades more difficult.

Table 3.6 Recommended electrification upgrade differences between the variable discount rate and the fixed, low discount rate along with their associated increase in capital costs

Baseline HVAC System		Electrification upgrade with the highest marginal NPV		Median increase in capital costs
		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

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 B.15 in Appendix B). 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.

3.5.6 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 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 [211]. The highest income bin used by the

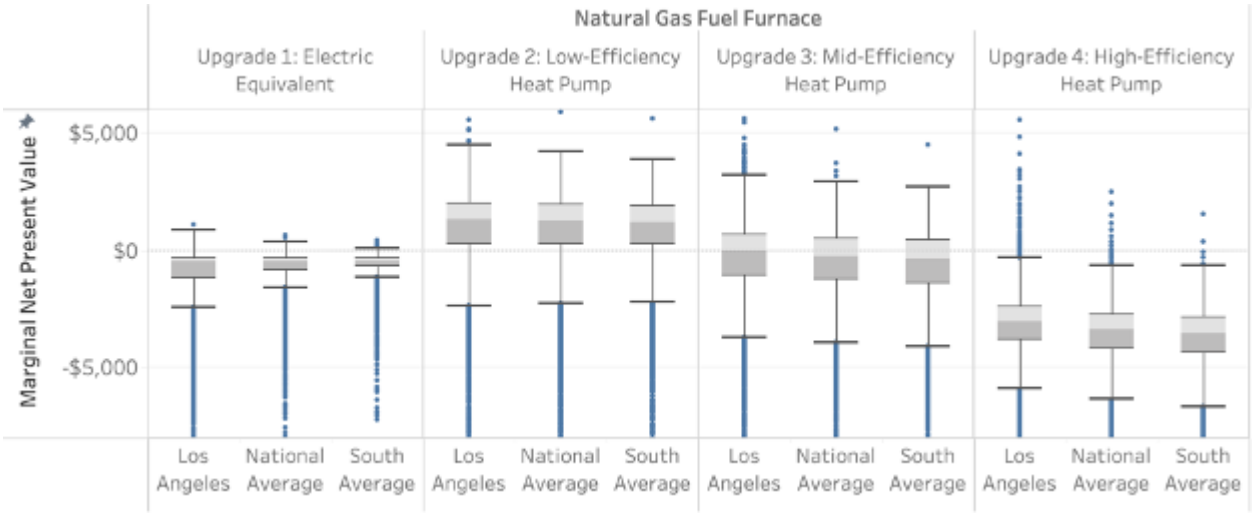

Figure 3.6 Distribution of marginal net present value for space heating electrification upgrades for buildings with natural gas boilers with room ACs in the baseline using fixed and variable discount rates.

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 3.7). These results include all households regardless of building type, cooling access or use.

Table 3.7 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 (LL = Landlord, O = Owner)

		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	
IRA Rebates	Baseline Space Heating Technology	LL	O	LL	O	LL	O	LL	O	LL	O	LL	O
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	-$1559	-$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

The results from Table 3.7 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 B.11 in Appendix B), combined with the capital cost savings (See Table B.12 in Appendix B), 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 (Figure 3. 7).

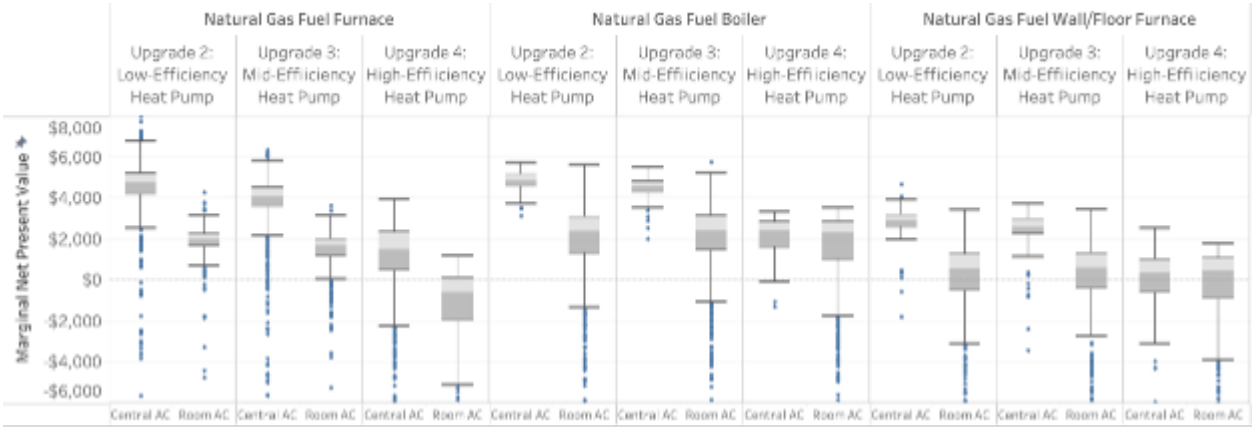

Figure 3.7 Distribution of marginal net present values, including IRA rebates, for space heating electrification Upgrades for low-income households (0-80% AMI) which did not have or did not use cooling in the baseline.

3.5.7 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 [32–34] (See Table B.13 in Appendix B). 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 [212]. Furthermore, while heat pumps have the ability to reduce utility bills throughout the entire year for all household types, 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. 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.

3.6 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 regarding 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 vulnerable households. 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:

1. 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.

2. For owners who do not already have or use cooling, space heating electrification increases costs. For these households, the electric 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.

3. 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.

4. 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.

5. 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.

6. 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.

3.7 Acknowledgements

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CHAPTER 4

ACHIEVING EQUITABLE WIDESPREAD RESIDENTIAL BUILDING ELECTRIFICATION – EXAMINING BARRIERS, STRATEGIES, AND OPPORTUNITIES USING LOS ANGELES AS A CASE STUDY

4.1 Preface

Chapter 4 is intended to be published as a peer-reviewed journal article. As of April 2024, it is in preparation to be submitted to Energy and Buildings. However, as the review process is not certain it may ultimately be published in another journal. Future edits may be made based on reviewer comments.

This chapter addressed two aspects of energy justice: recognition and distributional justice. The methodology address the two most prevalent Los Angeles resident concerns outlined in the Introduction: affordability and the current residential building conditions. Affordability is addressed by improving the cost calculations of residential building electrification upgrades through the examination of all electrification upgrades (i.e., space heating, water heating, cooking, and clothes drying), the calculation of variable baseline and upgrade HVAC and water heater costs, the inclusion of all capital costs (i.e., labor, material, and fuel switching costs), and the implementation of a variable discount rate. Current residential building conditions were addressed through the use of the ResStock^{TM} residential building stock energy model which performs statistical sampling to determine the building characteristics used to simulate each representative dwelling unit. Addressing affordability and the current residential building characteristics are examples of distributional justice, where this research focuses on the burdens imposed on households by the energy system. The reporting of results focuses on three of the four vulnerable households and one of the community concerns outlined in the Introduction: low-income households, renters, and households in multi-family buildings. By focusing on these vulnerable households, recognition justice is addressed by ensuring that those who are disproportionately impacted by the burdens of the energy system put at the forefront of this analysis.

4.2 Abstract

The decarbonization of residential building via electrification is imperative given that they represent over 5% of all CO_2-equivalent emission in the United States. Using Los Angeles as a case study, this paper models the techno-economics of three electrification upgrades at a variety of efficiency levels: water heating, cooking, and clothes drying. These three electrification upgrades along with the electrification of space heating systems are then put into the broad context of a full transition to residential building

electrification by comparing them the current natural gas technologies they are replacing. Results show that 1) vulnerable households will need to be supported to afford both the lowest and highest efficiency electrification upgrades and that a transition to the lowest efficiency electric technologies will exacerbate existing energy inequities, 2) our model projections align with the 2022 Strategic Long-Term Resource Plan developed by the Los Angeles Department of Water and Power (LADWP), and 3) if households transition to the lowest efficiency for all technologies, the grid will see a 40% and 50% increase in total annual and daily peak consumption, respectively. While this change will generate increased revenues for LADWP it will also require the augmentation of their energy generation, transmission, and distribution assets. While a full transition to the highest efficiency electrification will avoid have little impact on the grid, based on LADWP's projections, it will cause a six-fold in electricity rates to generate the funding LADWP has promised for building electrification incentives. Given these barriers, governments and utilities must find strategies to support households, especially vulnerable ones, in this transition to residential building electrification.

4.3 Introduction

Reducing the emissions attributed to residential buildings is a key element to mitigate the impacts of climate change [213]. To do this, it is necessary to address Scope 1 emissions which are the emissions generated in the operation of residential buildings through the on-site combustion of fossil fuels – primarily for space heating, water heating, cooking, and clothes drying [57]. Electrification of these technologies, along with the elimination of Scope 2 emissions, which are the emissions from utility electricity generation, are the primary proposed methods to reduce residential building greenhouse gas emissions [2–7, 57]. Presently, there are a wide range of proven technologies to achieve residential building electrification. In addition to electric equivalent technologies, there are many high-efficiency heat pump technologies for space and water heating that have been shown to operate reliably in in range of climates [12–15]. The primary gap in existing research is technology deployment, and more specifically, equitable deployment by 2050 to mitigate the worst impacts of climate change.

The economics of residential building electrification are well documented in the literature and are summarized in Table 4.1. However, while each study provides important insights, no one study has each of these four critical components: end uses that consume fossil fuels, inclusion of capital costs, use of a variable discount rate, and disaggregation of results by building type.

Only Mahone et al. [32] and Hopkins et al. [33] take into account all major end uses that consume fossil fuels in residential buildings: space heating, water heating, cooking, and clothes drying. Given decarbonization mandates at the federal [9], state [214], and local level [11], it is critical that any study

understand the implications of full residential building electrification to fully communicate the scale of financial implications for households who currently burn fossil fuels in their homes. See the dark blue column in Table 4.1.

Less than half of the identified studies include all capital costs associated with electrification, including material, labor/installation, and fuel switching [32, 34–37]. This misrepresentation of total costs could impact everything from the amount and type of subsidies for these upgrades to the size of a loan needed a household needs to cover these costs. All of which could impede electrification or further the economic inequities between communities. See the light blue column in Table 4.1.

No existing studies use a variable discount rate to calculate costs for households. Economic research has shown that households values future savings differently, therefore applying a fixed discount rate across a population, as these studies do, distorts how households account for increases in capital costs compared to future savings in operating costs. See the light yellow column in Table 4.1.

No existing study disaggregates results by building type, income level, and renter/owner status. The costs associated with each electrification upgrade will have implications for renters vs. landlords vs. owners, those living in single-family residences have different considerations compared to those living in multi-family buildings, and income level will be a huge determinant of whether or not an upgrade is even financially viable without external incentivization. See the dark yellow column in Table 4.1.

Table 4.1 Overview of residential building electrification economic modeling studies.

		Study Design			Reporting		
Model Type	Study	Electrification technologies	Includes all installation costs	Discount rate	Building Type	Income Level	Renter/ Owner
White-box, physics-based models	Patteeuw et al. (2015) [173]	Space heating, Water heating	No	Fixed (7%, 3.5%)	Single-Family	No	No
	Asaee et al. (2017) [174]	Space heating	No	Fixed (1%, 3%, 6%, 9%)	Single-Family	No	No
	Mahone et al. (2019) [32]	Space heating, Water heating, Clothes drying, and Cooking	Yes	Fixed (3.35%)	Single-Family Multi-Family	No	No
	Deetjen et al. (2021) [175]	Space heating	No	Fixed (7%)	Single-Family	No	No
	Billimoria et al. (2021) [34]	Space heating	Yes	Not specified	Single-Family	No	No
Black-box, econometric models	Nadel (2016) [176]	Space heating	No	Fixed (5%)	Did not specify	No	No
	Raghavan et al (2017) [199]	Water heating	No	Fixed (3%)	Did not distinguish	No	No
	Kelly et al. (2018) [177]	Space heating	No	Fixed (5%)	Single-Family	No	No
	Hopkins et al. (2018) [33]	Space heating, Water heating, Clothes drying, and Cooking	No	Fixed (5%)	Single-Family Multi-Family	No	No
	Partridge (2018) [35]	Space heating, Water heating	Yes	Fixed (5%)	Did not specify	No	No
	Nadel (2018) [178]	Space heating, Water heating	No	Fixed (5%)	Did not specify	No	No
	Kaufman et al. (2019) [179]	Space heating	No	Fixed (10%)	Did not specify	No	No
	Kolwey and Petroy (2022) [36]	Space heating	Yes	Not specified	Single Family	No	No
	Nadel and Fadali (2022) [37]	Space heating, Water heating	Yes	Fixed (5%)	Single-Family Multi-Family	Yes	No

While each of the studies in Table 4. 1 provide important insights, none have a specific focus on understanding how marginalized households will fair in this transition to residential building electrification. Sandoval et al. [215] presented the marginal net present value distribution of various space heating electrification upgrades disaggregated by income level, renter/owner status, and building type for Los Angeles. In this paper, the analysis done using Los Angeles as a case study in Sandoval et al. [215] is continued by examining the results of additional electrification upgrades, i.e. water heating, cooking, and clothes drying, at a variety of efficiency levels. The case study of this full suite of electrification upgrades is then compared Los Angeles' own plans for residential building electrification

In 2022, LADWP released their current Strategic Long-Term Resource Plan (SLTRP). This report outlines LADWP's roadmap to 100% clean energy by 2045 [85]. In this plan, LADWP developed a reference scenario and three other scenarios ("Cases"). These cases vary the future generation, energy storage, and transmission assets LADWP plans to build and maintain. Each of these cases is also subjected to a set of sensitivity analyses, one of which is change in electric load under different electrification projections which include building electrification and energy efficiency improvements. The High Load sensitivity analysis projects an average annual retail sales increase of 2.4%, whereas the Low Load sensitivity analysis projects a decrease of 1.6%. Based on their results, LADWP recommended Case 1 [85]. Case 1 is based on California's Renewable Portfolio Standard (RPS) which calls for the 100% of the state's electricity to come from carbon-free resources by 2045 [216]. Case 1 achieves 80% of this RPS target by 2030 with a natural gas phase out that concludes in 2035 and high building electrification and energy efficiency deployment.

Using Los Angeles as a case study, the goal of this research is to conduct a high-resolution techno-economic analysis of a transition to residential building electrification. The results of this study will inform households of the changes in costs they could experience in this transition. We analyze the individual costs to electrify a broad range of technology at the lowest and highest efficiency levels. Additionally, we examine the change in energy burden experienced by all households of full electrification at the lowest and highest efficiency levels. These results are then compared to LADWP's SLTRP to ensure the reliability of our approach and juxtapose our findings with their results. Our results are then analyzed from the perspective of the utility, LADWP. We determine the changes in annual electricity consumption by the Los Angeles residential building stock, but also the changes in the peak consumption, both in terms of the magnitude of the peak demand but its timing, for both high and low efficiency electrification scenarios. Just as in Sandoval et al. [215], we focus on analysis on four groups of vulnerable households: low-income households, renters, households in multi-family buildings, and households that do not use cooling. These vulnerable households were identified from a review of the energy justice literature and a coding analysis of concerns voiced by Los Angeles residents regarding the city's transition to clean energy

and electrification. In the discussion section, we put the results from this case study into the broad context of a full transition to residential building electrification, especially for these vulnerable households. We identify several barriers to this transition and provide possible strategies to overcome these barriers. Additionally, we identify several opportunities made possible through residential building electrification.

4.4 Methodology

Sandoval et al. [215] developed a techno-economic model to evaluate the costs associated with electrification upgrades applied to a residential building stock, called the Marginal Net Present Value Upgrade Analysis Model. Sandoval et al. [215] used this model to examine the costs for households as they electrify their space heating systems. This research adds to that analysis to by examining the three remaining major electrification upgrades found in residential buildings: water heaters, cooking ranges, and clothes dryers. The model was updated to include the capital costs and lifetimes for the three technologies explored herein. The capital costs used in this study can be found in Appendix C. The lifetime of these technologies are those used in the U.S. Energy Information Administration's residential building modeling efforts [198]. Three sensitivity analyses were conducted on various economic parameters in this research: a variable vs. fixed discount rate, a variety of utility rate projections, and the relative price of electricity compared to natural gas. In this way, we create a comprehensive overview of the economic implications of a transition to residential building electrification by evaluating the four major electrification upgrades found in the residential building sector.

For each of the three technologies evaluated in this chapter – water heaters, cooking ranges, and clothes dryers – a set of electrification upgrades was developed at various efficiency levels. Table 4.2 outlines these different upgrade packages based on the baseline technologies being electrified and the different efficiency levels of the upgrade electric technologies. The combined energy factor (CEF) and uniform energy factor (UEF) are given for each of the baseline and upgrade technologies for clothes dryers and water heaters, respectively. For each of these upgrades, the capital costs included the cost to run a single, dedicated electric circuit. The only exception is for the electric tankless water heaters upgrades. Electric tankless water heaters require one to three dedicated electric circuits based on the number of occupants in the household. The greater the number the occupants, the greater the hot water demand, the more electric power draw of these systems, and the need for additional circuits. Based on the household size, the cost of these additional circuits is factored into the total capital costs for this particular upgrade.

Table 4.2 Electrification upgrade technologies and associated efficiency levels for water heating, cooking, and clothes drying

Technology	***Efficiency Level***	***Baseline Technology (Efficiency)***	***Upgrade Technology (Efficiency)***
Water Heater	Low	Natural Gas Storage Standard (0.59 UEF)	Electric Standard (0.92 UEF)
		Natural Gas Storage Premium (0.67 UEF)	
		Natural Gas Tankless (0.82 UEF)	Electric Tankless (0.99 UEF)
	Mid	Natural Gas Storage Standard (0.59 UEF)	Electric Premium (0.95 UEF)
		Natural Gas Storage Premium (0.67 UEF)	
	High	Natural Gas Storage Standard (0.59	Electric Heat Pump (2.3 UEF)
		Natural Gas Storage Premium (0.67 UEF)	
		Natural Gas Tankless (0.82 UEF)	
Cooking Range	Low	Natural Gas Standard	Electric Standard
	High	Natural Gas Standard	Electric Induction
Clothes Dryer	Low	Natural Gas Standard (2.39 CEF)	Electric Standard (2.90 CEF)
	Mid	Natural Gas Standard (2.39 CEF)	Electric Premium (3.93CEF)
	High	Natural Gas Standard (2.39 CEF)	Electric Heat Pump (5.20 CEF)

In addition to the analysis performed in Sandoval et al. [215], this research evaluates the energy burden associated with a full transition to both high and low efficiency electrification. Equation 4.1 below describes the calculation used to determine how the energy burden of each household was simulated.

$$HouseholdEnergyBurden = \frac{AnnualEnergyCosts}{AnnualHouseholdIncome} \tag{4.1}$$

The annual energy costs were calculated by the Marginal Net Present Value Upgrade Analysis Model. The model applied LADWP's tiered electricity rates and Southern California Gas Company's volumetric natural gas rates to each households simulated annual consumption of electricity and natural gas [104, 105, 215]. Annual household income was calculated for each households as a function of household occupancy, renter/owner status, building type, vintage, and income bin based on the Public Use Microdata Samples from the 2019 American Community Survey [217]. Energy burden was calculated for each household in Los Angeles if all natural gas space heaters, water heaters, cooking ranges, and clothes dryers were electrified with either the lowest or highest efficiency level equipment as outlined in Table 4.2.

4.5 Results And Discussion

The results from the three residential electrification upgrades – water heating, cooking, and clothes drying – calculated in this chapter along with the results from Sandoval et al. [215] that examined the

electrification of space heating are broken down into five sections. First, we evaluate the impact of the lowest efficiency electrification upgrades on households. Second, we evaluate the impact of the highest efficiency electrification upgrades on households. Third, we calculate the energy burden if all natural gas end uses were upgraded to the lowest and highest efficiency electric technologies. Next, these results are put into context through a comparison with LADWP's 2022 Strategic Long-Term Resource Plan. Finally, the impact of low- and high-efficiency residential building electrification on the electric grid is assessed, including the annual change in electricity consumption and the timing and magnitude of peak electricity consumption in Los Angeles. Throughout, we analyze the results with a focus on the four groups of vulnerable households: low-income households, renters, households in multi-family buildings, and households that do not use cooling. In this way, we are able to identify any barriers that these households may face that may not be an issue for other households.

4.5.1 Impact Of Electrification On Households With Low Efficiency Electrification

In Los Angeles, electrifying the most common natural gas equipment in residential households with the lowest efficiency electric upgrade option increases all costs for most households. Table 4.3 shows that upgrading natural gas cooking ranges, standard efficiency storage water heaters, and furnaces with the lowest efficiency electric equivalent technology will increase costs both at the time of installation and throughout their lifetimes for most households. Most, if not all, of the increase in capital costs can be attributed to the cost of fuel switching, rather than the equipment itself (See Table C.1 in Appendix C). This results in a negative marginal net present value for each of these three upgrades when compared to costs associated with the baseline natural gas equipment. The notable exception are households with natural gas premium storage water heaters. Most of these households will experience a positive marginal net present value. While this upgrade will increase operating costs, electric standard storage water heaters have a significantly lower capital cost.

Table 4.3 Costs for lowest efficiency space heating, water heating, cooking range, and clothes dryer electrification upgrades

Baseline Natural Gas Technology	***Lowest Efficiency Electrification Upgrade***	***Technology Saturation***	***Increase in Capital Costs***	***Interquartile Range***	
				Increase Annual Operating Costs	***Net Present Value***
Furnace	*Electric Furnace*	*52.0%*	$4671	-2*to*255	-1,259*to*−393
Boiler	*Electric Boiler*	*6.90%*	-$3171	$1 to $170	-$258 to $287
Wall/Floor Furnace	*Electric Floor Furnace*	*7.36%*	-$2461	$1 to $154	-$246 to $215
Standard Storage Water Heater	*Electric StorageWater Heater*	*53.1%*	$20	$104 to $372	-$1,164 to -$348
Premium Storage Water Heater	*Electric Storage Water Heater*	*23.2%*	-$620	$143 to $416	-$664 to $193
Tankless Water Heater	*Electric Tankless*	*1.72%*	-$803 $604 $2905	$98 to $279 $253 to $598 $382 to $835	-$744 to -$210 -$1892 to -$778 -$2645 to -$1399
Cooking Range	*Electric Standard Range*	*77.8%*	$270	$22 to $49	-$423 to -$341
Clothes Dryer	*Electric Standard Clothes Dryer*	*30.8%*	-$180	$54 to $123	-$180 to $41

For the remaining, less prevalent upgrades, there is a different trend. Electric boilers, wall/floor furnaces, standard efficiency tankless and storage water heaters, and clothes dryers all have lower capital costs compared to the baseline natural gas equipment they are replacing, even when considering the cost of fuel switching. However, for each of these technologies, there is an increase in operating costs. While these technologies are less common in the Los Angeles residential building stock as compared the technologies in Table 4.3 , over 53% of households have at least one of these technologies.

Low efficiency residential building electrification will have an impact some but not all vulnerable households. Most renters will see increased operational costs for all the electrified technologies. However, several of these technologies including electric boilers, wall/floor furnaces, premium storage water heaters, and clothes dryers have lower capital costs compared to the natural gas equivalent technology. Therefore, with the electrification of these end uses, landlords could take advantage of these lower costs while increasing their tenants' utility bills.

4.5.2 Impact Of Electrification On Households With High Efficiency Electrification

While electrifying the most common natural gas equipment with the highest efficiency upgrade options can decrease operating costs for some technologies, the increases in capital costs are significant (Table 4.4). Similar to the low efficiency upgrades, this results in a negative marginal net present value for most upgrades. However, the median marginal net present values of these upgrades range from $200 to 2000 less (more negative) compared to electrifying with the lowest efficiency equipment. This means that owners and landlords will have much less incentive to install these technologies if pushed to electrify. These high capital costs and negative marginal net present values will be exacerbated if a household needs to electrify multiple appliances. The notable exception is that most owners with a natural gas premium storage water heater will experience a positive marginal net present value. Additionally, regardless of baseline technology, upgrading to an electric storage heat pump water heater provides the best marginal net present value of all water heater upgrades with a median marginal net present value of $76. This is the only technology in the set of highest efficiency upgrades options that produces the best marginal net present value of all efficiency levels.

Table 4.4 Costs for highest efficiency space heating, water heating, cooking range, and clothes dryer electrification upgrades

Baseline Natural Gas Technology	Highest Efficiency Electrification Upgrade	Technology Saturation	Increase in Capital Costs	Interquartile Range	
				Increase Annual Operating Costs	Net Present Value
Furnace with Central AC	Air Source Heat Pump (SEER 24, 10.8 HSPF)	23.60%	$7,787	-$755 to -$235	-$3824 to -$2425
Boiler with Room AC	Mini-Split Heat Pump (SEER 33.1, 13.5 HSPF)	1.59%	$1,773	-$542 to -$188	-$1533 to $294
Wall/Floor Furnace with Room AC	Mini-Split Heat Pump (SEER 33.1, 13.5 HSPF)	1.74%	$3,652	-$561 to -$211	-$3598 to -$1570
Standard Storage Water Heater	Electric Storage Heat Pump	53.10%	$490	-$89 to -$36	-$522 to -$366
Premium Storage Water Heater	Electric Storage Heat Pump	23.20%	-$150	-$46 to $0	$21 to $157
Tankless Water Heater	Electric Tankless	1.72%	-$80	$98 to $279	-$744 to -$210
			$60	$253 to $598	-$1892 to -$778
			$290	$382 to $835	-$2645 to -$1399
	Electric Storage Heat Pump		$1,200	-$22 to $40	-$1480 to -$1290
Cooking Range	Electric Induction Range	77.80%	$1,140	$14 to $37	-$1263 to -$1192
Clothes Dryer	Electric Heat Pump Clothes Dryer	30.80%	$540	-$11 to $33	-$674 to -$597

Compared to low-efficiency electrification, high-efficiency electrification will impact different groups of marginalized households differently. Most renters could see a decreases of anywhere from $200 to 750$ in annual utility bills with an upgrade to high-efficiency space heating, $40 to 90$ for an upgrade to an electric storage heat pump water heater. However, the high capital cost of these technologies could make these upgrades unattainable, especially for low-income households, even if the marginal net present value is positive. Finally, for those without cooling, while high efficiency electrification does provide cooling through the installation of air-source and mini-split heat pumps, these technologies come with a capital cost from $1,500 to $10,000 or more depending on the existing space heating equipment. Finally, there

were not any significant difference for those households living in multi-family buildings compared to single-family buildings.

4.5.3 Impact Of Electrification On Household Energy Burden

While Table 4.3 and Table 4.4 show the relative costs associated with electrifying each of the major natural gas end uses in the Los Angeles residential building stock, these data do not communicate the impact of electrifying multiple end uses in a single household. In Los Angeles, over more than 70% of households will need to electrify at least two end uses, and more than half will have to electrify at least three. Therefore, it is critical to understand how these costs will add together for residents. Figure 4.1 shows the impact of the change in operating costs via the change in energy burden if all natural gas end uses were upgraded with either the lowest or highest efficiency electric technologies. These results are disaggregated by income level as defined by area median income (AMI).

Figure 4.1 shows that electrification via the lowest efficiency electric technologies will exacerbate existing energy inequities. Currently in Los Angeles, households with lower incomes face higher energy burdens compared to those with higher incomes (Figure 4.1 – Baseline Energy Burden). This problem is only exacerbated if households electrify with the lowest efficiency electric upgrades (Figure 4.1 – Low Efficiency Electrification Energy Burden). The increase in energy burden of low-income households (0-80% AMI) is approximately two and four times greater than the increase in experienced by moderate- (80-120% AMI) and high-income (+120% AMI) households, respectively. Therefore, a transition to low-efficiency electrification will escalate current inequities, increasing the energy burden the most for the most marginalized households. This is true, regardless of where residents live in Los Angeles, but is most prominent in the South and East Los Angeles communities, which are already classified by the state as disadvantaged communities [218]. While the price of electricity in Los Angeles is high relative to other parts of the country, we conducted a sensitivity analysis in which we adjusted the price of electricity to be more similar to other parts of the county [215]. While this made the increase in utility bills smaller for a switch to low-efficiency electric equipment, these alternative rates still created an increase in operating costs compared to the baseline.

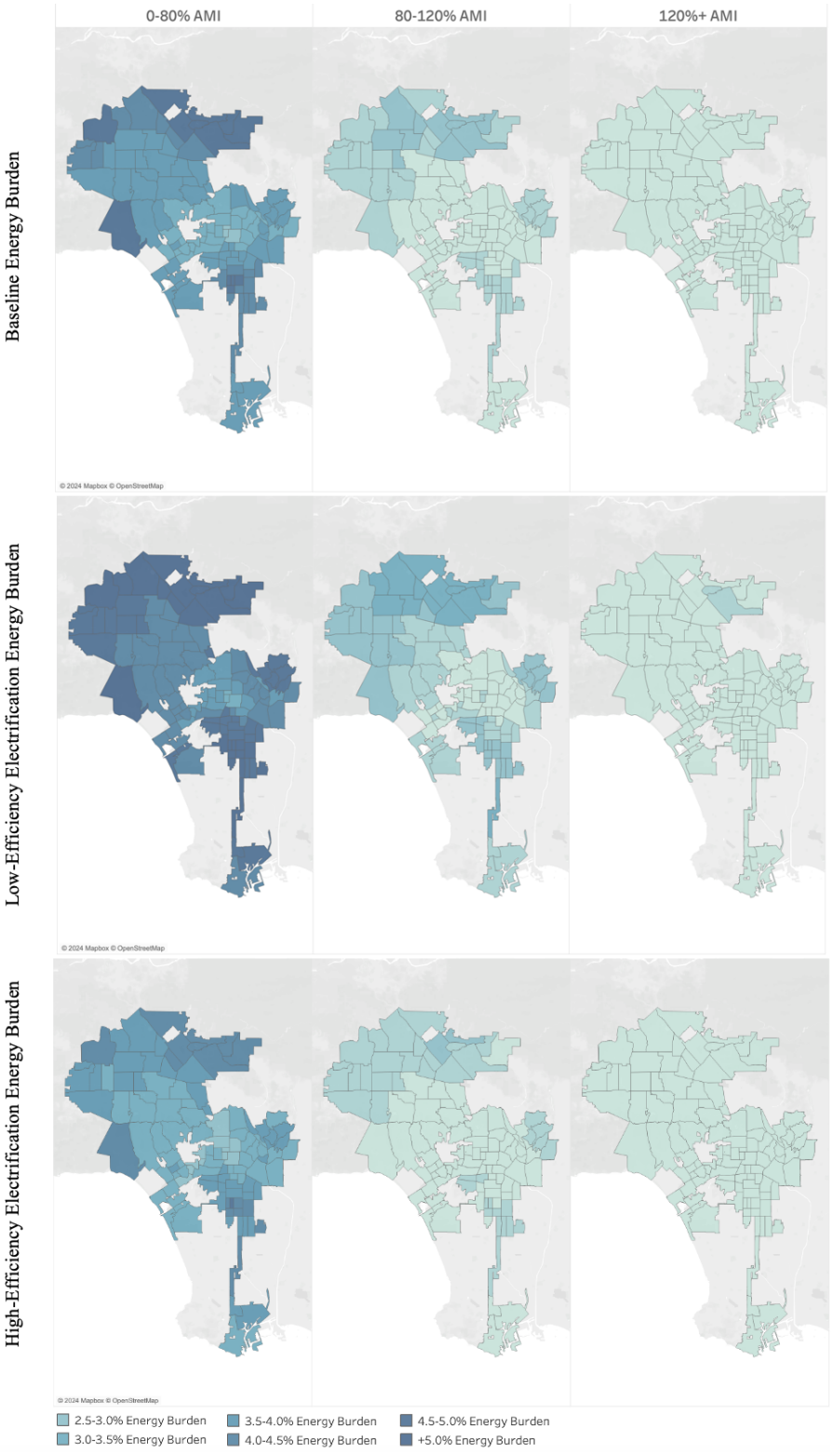

Figure 4.1 Current energy burden in Los Angeles neighborhoods compared to energy burden with lowest and highest efficiency electrification upgrades disaggregated by AMI

Conversely, electrification via the highest efficiency electric technologies eases current energy inequities (Figure 4.1 – High Efficiency Electrification Energy Burden). Low-income households stand to benefit the most from high efficiency electrification. The decrease in energy burden for these households is three times more compared to moderate- and high-income households. Renters would also benefit from these upgrades because they decrease operating costs. However, landlords may not be incentivized to purchase high-efficiency systems due to high capital costs.

4.5.4 Comparison To LADWP Strategic Long-Term Resource Plan

The results from Case 1 of LADWP's SLTRP align with the results from this study. Under the baseline assumption for building electrification in Case 1, LADWP projects that annual electricity consumption will increase by over 3,000 GWh. This lies between the low- and high-efficiency electrification scenarios reported previously in this study, which predict an increase of 4,000 GWh and a decrease of 0.2 GWh, respectively. Based on this, it is possible to extrapolate that LADWP projects that residential building electrification will be accomplished with low to moderate efficiency equipment.

To achieve widespread residential building electrification, LADWP plans on offering customers a variety of incentives to pay for a portion of the retail price of electric equipment: 40% of water heaters and clothes dryers, 35% of cooking ranges, and 25% of space heating technologies. LADWP plans to cover the cost of residential building electrification incentives through increased electricity sales. While LADWP has committed $6 billion to residential building electrification incentives, they also predict $8.4 billion in revenues from increased electricity sales. While incentives will reduce initial costs for households (See Table 4.3 and Table 4.4), the anticipated increases in operating costs will amount to more throughout the lifetime of these technologies. As previously discussed, lower efficiency electrification will disproportionately burden low-income households and renters. Despite the decrease in capital costs due to these incentives LADWP plans on offering low-income households will see the greatest increases in energy burden compared to moderate- and high-income households (Figure 4.1). Similarly, renters will experience increased operating costs, while their landlords will benefit from the both the lower capital costs of the lower efficiency equipment and the incentive provided by LADWP (Table 4.3). Additionally, to achieve the least expensive carbon-free energy system LADWP projects that electricity rates will increase from their current rate of 20¢/kWh to 65¢/kWh by 2045.

Unfortunately, a transition to high efficiency electrification also has drawbacks. LADWP projects that increasing the efficiency of the electric technologies and the energy efficiency of residential buildings will continue to stagnate or even decrease LADWP's retail electricity revenues. This along with their plans for 100% carbon-free energy necessitate the increase in rates from their current level to 120¢/kWh. In this

case, marginalized households will have access to systems which are up to four times more efficient compared to their baseline technologies and will still pay more for the same energy service. This does not consider the increased capital costs associated with these systems, even considering the incentives provided by LADWP.

4.5.5 Impact Of High And Low Efficiency Electrification On The Grid

The electrification of households across Los Angeles could change total annual electric demand, peak demand, and the diurnal and seasonal timing of peak demand. Each of these factors is important to the utility in terms of the revenues they can expect to receive but also the ability of their generation, transmission, and distribution systems to meet the load throughout the year. Figure 4.2 shows the daily electricity consumption of the baseline, low-, and high-efficiency electrification upgrade packages.

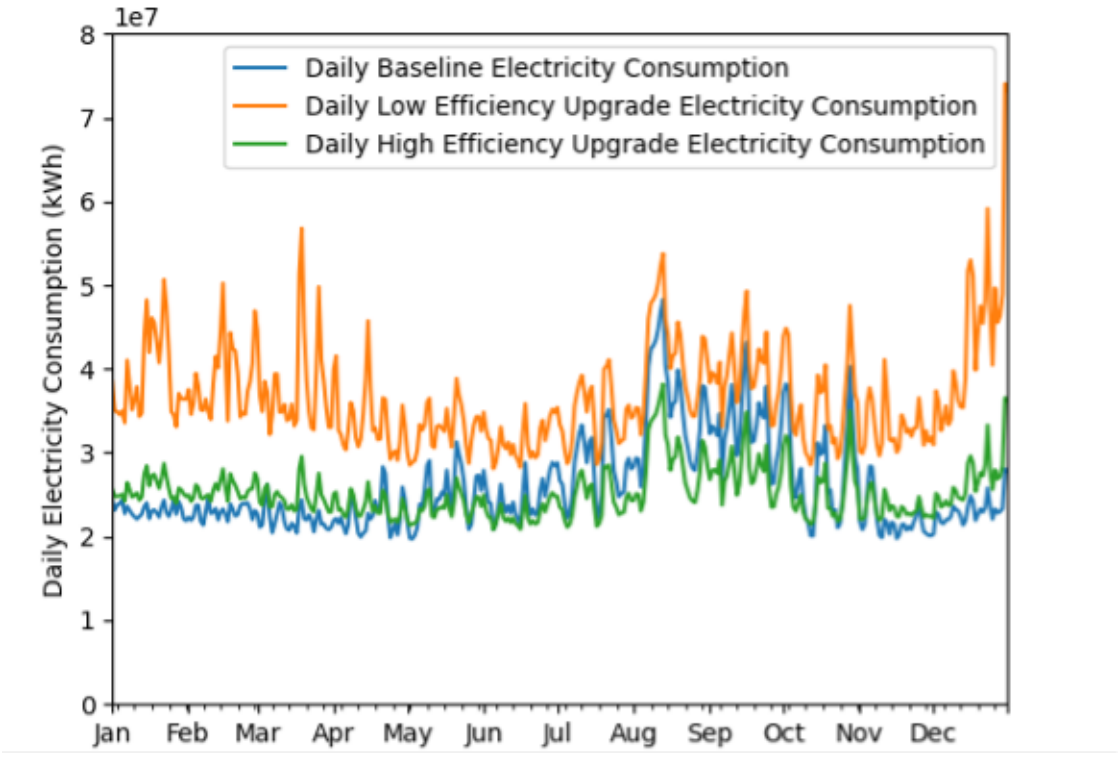

Figure 4.2 Daily Electricity consumption for the Los Angeles residential building stock under baseline, low-, and high-efficiency electrification scenarios.

Residential building electrification via the lowest efficiency upgrade scenario will both increase the maximum daily electricity consumption of the Los Angeles residential building stock and change the timing of peak consumption (Figure 4.2). Using low efficiency electric technologies, the maximum daily electricity consumption will increase by more than 50% and will shift from mid-August to the middle of the winter (Table 4.5). Also, the hour of peak consumption shifts from early afternoon to morning, too early to be

served by intermittent renewable power generation [219]. Therefore, more energy will be needed during a time of day where less renewable energy generation is possible. The result is an increased reliance on non-renewable fuels which consequently diminishes the decarbonization effect of electrification. See Figure C.1 and Figure C.2 in Appendix C for the daily load curve during summer and winter peak consumption days.

Table 4.5 Timing of maximum daily and hourly consumption for the lowest efficiency electrification scenario compared to the baseline

Scenario	Date of Maximum Daily Consumption	Hour of Maximum Consumption on Date of Maximum Daily Consumption	Consumption on Date of Maximum Daily Consumption	Consumption on Hour of Maximum Consumption on Date of Maximum Daily Consumption
Baseline	August 13th	3:00 PM	48.3 GWh	2.43 GWh
Lowest Efficiency Electrification	December 30th	7:00 AM	74.1 GWh	3.99 GWh

Under the current electricity rate structure in Los Angeles, increased electricity consumption with a transition to low efficiency electrification will result in households being reclassified into higher electricity rate tiers. This reclassification and resulting increase in operating costs is not captured in the previous results (Table 4.3, Figure 4.2), but could either increase energy burden or force households to forego energy services or other expenses (e.g., medications, quality food) whose absence could lead to further mental, physical, or emotional health issues [63].

Conversely, annual residential electricity consumption can, paradoxically, be lowered through the by replacing natural gas technologies with the most efficient electric technologies. The electrification of water heating, cooking, and clothes drying with even the highest efficiency devices will increase electric loads. However, when electrifying space heating with the highest efficiency technologies—heat pumps—the efficiency of space cooling also increases. Due to the high utilization of space cooling in Los Angeles, this results in a net annual decrease in electric loads (Table 4.6). Additionally, given the high efficiency of heat pumps, the previously peak daily consumption decreases by over 20% (Table 4.6).

The contrast between the impacts of low and high efficiency electrification on the grid have wide ranging implications. While not generalizable across the entire United States, high efficiency electrification can maintain the status quo of a mid-afternoon summer peak across other cooling-dominated regions. With rising summer temperatures, high efficiency heat pumps will help decrease or maintain current summer electric peaks [12–15, 213]. This decrease in annual demand could allow for more households to

Table 4.6 Timing of maximum daily and hourly consumption for the highest efficiency electrification scenario compared to the baseline

Scenario	Total Annual Electricity Consumption	Change in Total Annual Electricity Consumption	Date of Maximum Daily Consumption	Consumption on Date of Maximum Daily Consumption
Baseline	9,450 GWh	N/A	August 13th	48.3 GWh
Highest Efficiency Electrification	9,240 GWh	-2.25%	August 13th	38.2 GWh

have access to cooling services, a key equity metric, all while not placing increased pressure on electricity generation and delivery infrastructure [220]. For heating-dominated regions that will shift to winter peaking, a transition to low-efficiency electric technologies could put extreme pressure on the current grid. In these regions, high efficiency space and water heating are critical in making electrification feasible.

4.6 Conclusion

In this research, we used Los Angeles as a case study to determine the economic impact of widespread residential building electrification on individual households and the grid. From an analysis of the results of this study, we found that households, especially vulnerable ones, and the grid will face barriers in their transition to residential building electrification. This is true regardless of whether the residential building sector is electrified via the lowest or highest electric technologies.

Low efficiency electrification will increase both annual and peak daily electricity consumption in Los Angeles by more the 40% and 50%, respectively. While this will provide increased revenues for LADWP, some portion of these revenues will need to be invested in the augmentation of its energy generation, transition, and distribution assets. While high efficiency electrification will not put this stress on LADWP, to provide the promised incentives for residential building electrification, rates will increase six-fold.

Many of the lowest-efficiency electrification upgrades and almost all the high-efficiency ones will increase capital costs for households. To successfully decarbonize residential buildings, improving the affordability of these technologies is imperative, especially for marginalized households. The monies to provide incentives to make these technologies more affordable could be generated from taxes such as the provisions in the Inflation Reduction Act of 2022, or through programs like California Air Resources Board's cap-and-trade program.

Affordability could also be improved through the creation of equitable rate structures. These rate structures could discount both fixed and volumetric electricity rates for vulnerable households. Additionally, utilities could create electrification specific rate structure to incentivize residential building

electrification

In addition to affordability, there are a number of other barriers that may hinder widespread residential building electrification, such as physical and cultural installation barriers. Physical installation barriers include the lack of capacity to add additional circuits to power the electric equipment, the size of existing ducts that were designed to deliver higher outlet air temperature from combustion-based space heating equipment, and space limitations for installing the larger heat pump storage water heaters and outdoor condensers in multi-family buildings. Cultural installation barriers including the lack of familiarity with the operation and performance of high-efficiency electric equipment for both residents and installers and reluctance by some households to convert from gas cooktops. In a series of focus groups conducted by Gordon et al. regarding the transition away from natural gas cooking ranges in the U.K., respondents noted many perceived advantages of gas cooktops, such as controllability and ease of use, convenience, efficiency and responsiveness, familiarity and reliability [221].

Overall, there exist several opportunities in widespread residential building electrification. An electrified building stock has incredible demand flexibility potential. The ability to pre-heat or pre-cool thousands of homes, along with the ability to pre-heat millions of gallons of hot water represents an immense thermal battery that can be leveraged by a utility. With internet-connected controls for equipment, utilities can shift these loads to smooth both winter and summer peaks [222]. The ability provide access to cooling through the electrification of space heating with heat pumps. In Los Angeles, over half of residential building units lack access to cooling [220]. Providing cooling through heat pumps yields myriad benefits that could outweigh the additional costs associated with the upgrades.

4.7 Acknowledgements

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CHAPTER 5

COOLING – NOT WEATHERIZATION – PROVIDES AN EFFECTIVE ELECTRIFICATION SUPPORTIVE STRATEGY FOR RESIDENTIAL BUILDINGS IN LOS ANGELES

5.1 Preface

Chapter 5 is intended to be published as a peer-reviewed conference proceeding. As of April 2024, it has been accepted for the ACEEE Buildings Summer Study and is currently under review. However, as the peer-review process is not certain it may ultimately be published in another journal. Future edits may be made based on reviewer comments. This chapter and paper address research question 3: "Can electrification supportive strategies improve the transition to residential building electrification?" Two electrification supportive strategies – improvement of the building envelope and installation of heat pumps to provide cooling – were examined independently and together. These electrification strategies were selected based on specific concerns and solutions voiced by community members in a coding analysis of the LA100 Equity Strategies project's steering committee meetings (See Appendix A) The steering committee was composed of representatives from community-based organizations from across Los Angeles. While other strategies such as demand response programs or residential solar also show promise as electrification supportive strategies, and as the anti-oppression activist, Regan Byrd, states, marginalized communities collectively not only have expertise in their own oppression, but in solutions for disrupting this oppression [27].

This chapter describes how these two important electrification supportive strategies improve the transition to residential building electrification (Figure 5. 1). The goal of the first electrification supportive strategy, improved building envelope performance, was to determine if the capital costs of this upgrade could be recovered through the decrease in utility costs associated with reduced heating loads and cooling loads for those who use cooling. It was determined that in the mild climate of Los Angeles where space conditionings loads are minimal, this strategy would not be cost effective. Therefore, the focus of this chapter is on the second electrification supportive strategy, the installation of heat pumps to both provide cooling and electrify space heating systems, and the combination of the two strategies. Given the high capital costs of heat pumps, the primary goal of these analyses is to determine the reduction in thermal stress resulting from these upgrades, with the secondary goal being the cost-effectiveness of the upgrades. Thus, this chapter focuses on the use of Standard Effective Temperature (SET) as a thermal comfort index and its novel application in this research. For each electrification supportive strategy, a set of upgrade packages was developed. These upgrade packages are analyzed specifically for the vulnerable households

outlined in the Introduction – low-income households, renters, households in multi-family buildings, and households without cooling – to ensure that any barriers for these households are identified and mitigated.

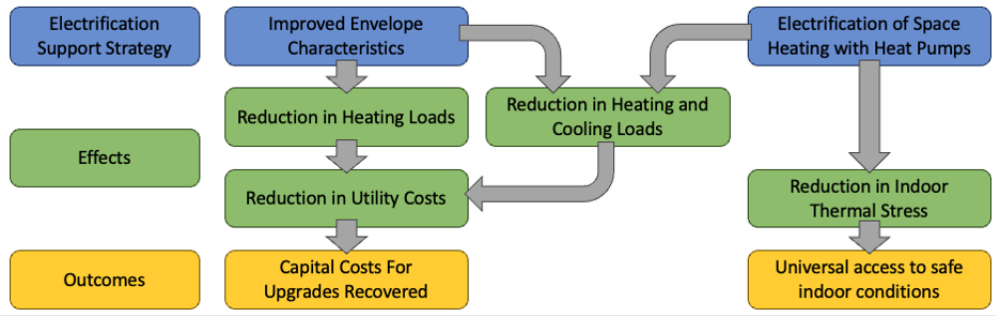

Figure 5.1 Electrification supportive strategies and their mechanisms to achieve specific outcomes

This chapter addressed two aspects of energy justice: recognition and distributional justice. The methodology addresses the three most prevalent Los Angeles resident concerns outlined in the Introduction: affordability, the current residential building conditions, and access to cooling/basic thermal comfort. Affordability is addressed by improving the cost calculations of residential building electrification upgrades through the calculation of variable baseline and upgrade HVAC, the inclusion of all capital costs (i.e., labor, material, and fuel switching costs), and the implementation of a variable discount rate. Current residential building conditions were addressed through the use of the ResStockTM residential building stock energy model which performs statistical sampling to determine the building characteristics used to simulate each representative dwelling unit. Access to thermal comfort is addressed through electrification strategies 2 and 3 which examine if the use of heat pumps to electrify space heating and improve indoor thermal conditions. Addressing affordability, the current residential building characteristics, and access to cooling/basic thermal comfort are examples of distributional justice, where this research focuses on the burdens imposed on households by the energy system. The reporting of results focuses on three of the four vulnerable households and two of the community concerns outlined in the Introduction: low-income households, renters, households in multi-family buildings, and households without access to cooling. By focusing on these vulnerable households, recognition justice is addressed by ensuring that those who are disproportionately impacted by the burdens of the energy system put at the forefront of this analysis.

5.2 Abstract

The high costs of an electrified residential building sector will be borne by both households and utilities. To ease this transition, this research examines two electrification supportive strategies 1) improved envelope characteristics and 2) space heating electrification via heat pump systems to provide cooling.

Using Los Angeles as a case study, we use the residential building stock model, ResStock^{TM}, to understand the changes in energy consumption and thermal comfort conditions of these two electrification supportive strategies. We found that the first electrification supportive strategy, improved envelope characteristics by themselves, are not an effective strategy in Los Angeles' mild climate. The second electrification supportive strategy, space heating electrification via heat pump systems to provide cooling, could be combined with the first to improve indoor thermal comfort for households. We found that some households are more at risk than others because they may not use or have access to cooling technologies when outdoor temperatures become dangerously hot. To mitigate the risks associated with unsafe indoor conditions, we simulated a suite of building envelope and heat pump space heating and cooling system upgrades to understand their effect on thermal conditions, especially for those households that currently do not have or use cooling. Given the results, we found that for Los Angeles households envelope improvements by themselves do not lead to meaningful improvements in indoor thermal conditions. However, the installation and use of a heat pump space heating and cooling system at any efficiency level can substantially increases the time households spend in "livable" thermal conditions. The installation and use of any type of heat pump will increase costs for households. This study provides novel comparison between housing upgrades that provide mechanical cooling and building weatherization. Furthermore, it provides quantitative data to support ongoing qualitative research on the importance of access to cooling technologies. This research has implications for building science researchers who seek to improve building energy and comfort models at a population scale as well as policymakers who seek to mitigate health risks due extreme heat exposure.

5.3 Introduction

Two of the primary concerns voiced by Los Angeles' residents when asked about a transition to 100% clean energy and the decarbonization of the building, transportation, and energy sectors were 1) the current conditions of residential buildings and 2) access to cooling and basic thermal comfort (see Appendix A). With the prospect of residential building electrification as a means to decarbonize the residential building sector, residents had two issues about the current conditions of their households. The first was the infrastructure of their homes to be able to support these upgrades (e.g., electric panel constraints). The second was the effectiveness of any heating or cooling technology upgrade given the perceived poor quality of the thermal envelope of their homes. While the first issue is addressed in the Chapters 3 and 4 and in the conclusion, the second issue will be addressed in this chapter. The second major concern of residents was ensuring access to cooling for all households in Los Angeles. This concern is not unjustified as one major impact of climate change is the increased frequency and severity of heat waves [164] and that the most common weather-related event resulting in death in the U.S. is extreme heat [223].

Therefore, reducing heat exposure in residential buildings is imperative to public health and to do this we need to understand the mechanisms that drive unsafe indoor temperatures.

Thermal comfort indices have been developed to understand the conditions under which humans are comfortable while living and working in buildings. A variety of thermal comfort indices have been developed to suit a range of needs in this field [224]. ASHRAE Standard 55 outlines acceptable thermal comfort conditions for buildings and other occupied spaces [225]. One aspect of ASHRAE Standard 55 is the use of Standard Effective Temperature (SET), first proposed by Gagge et al. [226], to normalize varying environmental conditions into a single thermal comfort metric. The SET of single thermal zone in a building is calculated using indoor air temperature, mean radiant temperature, water vapor pressure, air velocity, occupant metabolic rate, and their clothing level (Equation 5.1) [227]. These variables are used in conjunction to calculate the dry-bulb temperature of a hypothetical standard environment at 50% relative humidity, where air and skin temperature are the same.

$$SET = T_{sk} - \frac{Q_{sk} - wh_{es}(P_sk - 0.5P_{s,SET})}{H_{hs}} \tag{5.1}$$

Where h_{ws} is the comprehensive heat transfer coefficient of the standard environment (W/m^2-°C); Tsk is the skin temperature (°C); whes is the comprehensive evaporative heat transfer coefficient of the standard environment (W/m^2-Pa); P_{sk} is the vapor pressure on the skin surface (Pa); $P_{s,SET}$ is the steam pressure corresponding to SET °C and 50% relative humidity (Pa); and Qsk is the skin heat loss (W/m^2).

The existing literature that leverages SET as a thermal comfort metric can be broken into three areas. The first area is the use of SET in conjunction with other thermal comfort models to develop adaptive thermal comfort models for a particular building or region of interest. These field studies compare occupant comfort survey data with the measured building conditions (e.g., temperature, humidity) to develop a comfort model that gives a range of comfortable conditions [228]. These models have been used in a variety of applications including office buildings [229–232], prefabricated buildings [233], and transitional spaces [234]. These studies allow building managers to understand the current conditions experienced by occupants in their buildings. Furthermore, results from these studies outline the levers that can be adjusted to ensure that indoor conditions remain inside a range that will be comfortable for occupants. However, one limitation to these studies is that they do not consider the impacts different building upgrades would have on the thermal comfort.

The second area is the use of SET is in building energy simulations to approximate the thermal comfort conditions in both existing and planned buildings to inform baseline conditions and the impact of different building upgrades on thermal comfort. In many of these studies, one or more of the variables in Equation

5.1 are assumed and the results from these studies are less rigorous compared to the measured data collected in field studies. The impact on thermal comfort of a wide variety of building characteristics have been evaluated in this way including impact of HVAC presence and operation [43, 46], window shading and glazing [44], roof materials and shapes [45], and photovoltaic-Trombe walls [47]. These studies demonstrate that using SET in building energy modeling can help improve not only building energy performance but also ensure occupant comfort given the building design or retrofits. However, these studies are limited in that they are case studies and do not examine population-level effects.

The final area, with smallest existing research, is the use of SET in building stock energy modeling to simulate the widespread change in thermal comfort of upgrades across a larger building stock. Mavrogianni et al. [48] simulated nearly 30,000 unique buildings by varying the building and occupant characteristics of 15 residential building geometry archetypes. The thermal comfort within each building was calculated under a variety of occupant behavior patterns using different ventilation schedules and shading scenarios. This study found that occupant window operation behavior along with daytime shading and night cooling were significant factors in mitigating indoor overheating risk. While the study provides insights on thermal comfort as a function of occupant behavior and building characteristics, it does not address the impacts of building upgrades on thermal comfort.

An advantage of using SET in building energy models is the ability to predict the change in baseline thermal comfort given certain upgrades. Mavrogianni et al. took the use of SET in building energy modeling beyond isolated case studies and applied it to an entire building stock [48]. However, no study currently exists that has modeled the thermal comfort characteristics of an entire building stock and described the improvement from the baseline of these thermal comfort characteristics under specific upgrade scenarios (Figure 5.2). Therefore, combining the simulation of upgrades across an entire residential building stock with the calculation of SET for the baseline and upgrades for each household will us to determine the effectiveness of the strategy to deploy heat pumps to both provide cooling and electrify space heating equipment.

To determine the effectiveness of the electrification supportive strategies outlined previously, this research will perform three analyses. First, we use a building stock energy model to simulate the energy performance and thermal conditions of a large existing building stock. In this way we can determine the effectiveness of the first electrification supportive strategy, improved envelope characteristics, in reducing the energy consumption required to heat and cooling households. Second, we analyze the impact of various upgrades on improving thermal conditions. Third, we calculate the costs associated with the upgrades that succeed in improving thermal comfort. In this way, we can recommend the most cost-effective upgrades that improve thermal comfort to households based on their baseline building characteristics. In each of

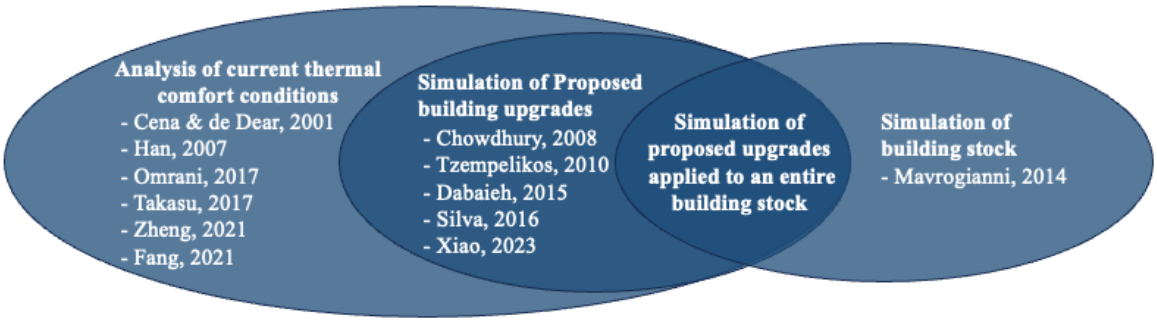

Figure 5.2 Trends and gaps in the use of standard effective temperature as a thermal comfort index

these analyses, we will address issues of equity by focusing on four cohorts of vulnerable households – low-income households, renters, households in multi-family buildings, and household which do not have access to or do not use cooling in the baseline. When assessing the results, we will address each of these cohorts to ensure that no household is left behind or over-burdened in the attempt to improve the thermal comfort for all Los Angeles households. The research has implications for building science researchers who seek to improve building energy and comfort models at a population scale as well as policymakers who seek to mitigate health risks due extreme heat exposure.

5.4 Methodology

To achieve the aims of this study, we developed a four-part methodology. First, we outlined the reasons for choosing the City of Los Angeles, hereinafter referred to simply as Los Angeles. Second, we developed a customized building stock energy model to simulate the energy use and indoor thermal comfort of the current residential building stock in Los Angeles. Third, we developed and model a set of energy retrofit upgrade packages that simulate the two electrification supportive strategies we hope to decrease energy usage and improve baseline thermal comfort conditions. Finally, we assess the change in energy usage of upgrade packages and compare this to the thermal comfort improvement where relevant.

5.4.1 Los Angeles As A Case Study

Los Angeles has many characteristics that make it an ideal case study to understand the impact of residential building upgrades on thermal comfort. Los Angeles is one of the largest metropolitan areas in the United States; more than 1% of the U.S. population lives in Los Angeles [82]. Thus, any change to the thermal comfort across its building stock will benefit a significant portion of the California and U.S. populations. Furthermore, Los Angeles shares a similar climate with other major cities in southern California, northwestern Mexico, the Mediterranean, southwestern South Africa, and western Australia.

Thus, the findings from this study can be extrapolated and used in these areas as well. Finally, in the LA100 Equity Strategies study conducted by the National Renewable Energy Laboratory (NREL) and the University of California Los Angeles, 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 some of the most common concerns included access to cooling, health and safety of current residential buildings, and the quality of current infrastructure in marginalized communities to support any proposed upgrades [84].

5.4.2 Custom Los Angeles ResStock™ Model

ResStock™ is a physics-based, bottom-up, white box, residential building stock energy model developed by NREL [188]. ResStock defines the national relative probability of 157 residential building characteristics (e.g., wall insulation R-value) through a set of conditional probability tables synthesized from 11 different national sources. For this study, the probability of some of these national characteristics were customized to Los Angeles.

The custom Los Angeles ResStock model included refined probability distributions for model geography, appliance saturation, and weather. We improved the ResStock model geographic resolution from the U.S. Census Bureau's Public Use Microdata Areas to the census tract level. We revised the appliance saturation levels, which are based on the U.S. Energy Information Agency's 2015 Residential Energy Consumption Survey, using the 2019 California Residential Appliance Saturation Study [190]. These new saturation levels were correlated to both income and renter/owner status to improve the characterization of housing in low-to-moderate income and disadvantaged communities. 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—zones 6, 8, 9, and 16.

With these customizations, we were able to simulate the hourly energy use of all major energy end uses for a representative sample of dwelling units in the Los Angeles. First, ResStock sampled 50,000 dwelling units to approximate the residential building stock of Los Angeles. Second, the characteristics and weather files associated with each dwelling unit are fed into the building energy modeling platform OpenStudio®, which leverages the EnergyPlusTM modeling engine and NREL's high-performance computer to generate hourly energy use for all major end uses [192]. These hourly load profiles are then validated against Load Research Data provided by LADWP. Finally, we downselected this building stock to only include occupied dwelling units. Lastly, we configured the ResStock model to output each of the variables needed to calculate SET (Equation 5.1) and to output the hourly SET (Equation 5.1)for each household for the entire year. This process produced the baseline scenario and the ability to understand the current energy

consumption and thermal conditions of residential buildings across Los Angeles.

5.4.3 Scenario Upgrade Development

With the baseline scenario simulated, we defined a set of electrification supportive upgrade scenarios based on two factors: 1) improving envelope characteristics, and 2) adding or upgrading the efficiency of heat pump systems in households. The goal of improving envelope characteristics will increase the energy efficiency of electrified space heating systems, decreasing the operational energy and cost required by these systems. While heat pump space systems, beyond providing high-efficiency cooling service, can also serve to electrify space heating systems. If both the cooling and heating systems in a home can be replaced by a heat pump system, the lifetime costs of these systems are similar to that of replacing the baseline systems [33, 34, 175, 176]. Additionally, these two strategies were applied together as both are shown to improve thermal comfort [235–241]. These upgrade packages are described in following paragraphs.

We implement three envelope upgrade packages in addition to the electrification of the space heating systems with electric equivalent systems. The first envelope upgrade is the deployment of cool roofs. Cool roofs are considered because they are both required by the Los Angeles Municipal Code for all new construction and roof replacement and because community-based organizations advocated for their utilization in marginalized communities in Los Angeles [11, 84]. The second envelope upgrade is based on the findings from Wilson et al., which identified drill-and-fill wall cavity insulation for frame constructions and a 25% reduction in infiltration through air sealing as two of the most cost-effective building envelope improvements [188]. The final envelope upgrade package is to bring all existing building up to cod with the 2022 CEC Residential Building Standards for new constructions. The CEC building standards set the minimum requirement for wall, attic, and roof insulation, windows, and infiltration [242]. Additionally, CEC building standards require mechanical ventilation for any residential building that has an air leakage value below 7 ACH50. Therefore, mechanical ventilation is added to any dwelling unit that achieved this infiltration level in the second and third envelope upgrade packages. Table D.1 in Appendix D outlines each of the three envelope upgrade packages in detail.

We implemented two types of heat pump space heating and cooling technologies both at a low- and high-efficiency level. The two types of heat pumps are air-source heat pumps (ASHP) for ducted households, and mini-split heat pumps (MSHP) for non-ducted households. For the low-efficiency heat pump cooling technologies, we took the guidelines for minimum efficiency heat pump technologies based on 2022 CEC building code standards for residential retrofits [242]. For the high-efficiency heat pump cooling technologies, we based our selection on the highest efficiency, commercially available products listed in the Air-Conditioning, Heating, and Refrigeration Institute's Directory of Certified Product Performance [243].

We sized the heat pump space heating and cooling systems to meet the entire cooling load of the dwelling unit at design temperature following the Air Conditioning Contractors of America's (ACCA) Manual J [191]. For heat pumps, they are sized to cooling plus some oversizing for heating per ACCA Manual S [244]. Table D.2 in the Appendix D outlines each of the four cooling upgrade packages in detail.

Table 5.1 outlines the 12 upgrade scenarios we simulated by combining these different envelope improvement and heat pump system upgrade packages. HP0E0 is compared to HP0E1, HP0E2, and HP0E3 to determine the effectiveness of improved envelope characteristics as the first electrification supportive strategy. Then the baseline scenario outlined in the previous section is compared to HP1E0 and HP2E0 to calculate the costs associated with providing cooling through the electrification of space heating with heat pumps. The remaining scenarios blend these two electrification supportive strategies to determine if there is any synergy between the two, specifically in regard to improving thermal comfort.

Table 5.1 Upgrade scenario parameterization based on improved envelope and heat pump upgrade packages

	HVAC System Upgrade from Baseline		
Envelope Improvement	Electric Equivalent Space Heating Technologies (HP0)	Low-Efficiency Heat Pump (HP1)	High-Efficiency Heat Pump (HP2)
No Change (E0)	HP0E0	HP1E0	HP2E0
Cool Roof (E1)	HP0E1	HP1E1	HP2E1
Low-Cost Envelope (E2)	HP0E2	HP1E2	HP2E2
Title 24 Envelope (E3)	HP0E3	HP1E3	HP2E3

5.4.4 Model Generated Data Analysis

To understand how the various upgrade packages will impact households in Los Angeles we have used three metrics to assess their relative costs and two metrics to assess thermal comfort. The cost metrics those are computed using the Marginal Net Present Value Upgrade Analysis model whose methodology is outlined in Sandoval et al. [215]. Thermal comfort is assessed by maximum SET to assess acute thermal stress and the annual SET distribution to assess chronic thermal stress. The method for determining these metrics is described in the following paragraph.

The Athena query subroutine obtained the hourly SET timeseries stored on the Amazon Web Services. This subroutine performs two functions. First, it determined the maximum SET experienced by each household throughout the year. Second, it summed the number of hours each household experienced across an array of SET ranges. This subroutine created a distribution of SETs across the entire year for each household. Importantly, this function allows us to calculate the number of hours each household spent below and above a SET of 86°F, because the U.S. Green Building Council defines a "livable temperature" as within a SET range of 54ºF–86°F [245].

5.5 Results and Discussion

5.5.1 Electrification Supportive Strategy 1: Improved Envelope Characteristics

Based on resident concerns about poor housing quality, the first electrification supportive strategy examined was improved envelope characteristics. The concept of this electrification supportive strategy is that the improvement of the thermal envelope of a home will decrease unwanted heat transfer to the environment, thus reducing the space heating and cooling energy use and decreasing the annual utility bill. Figure 5.3 compares the annual utility bills of the electric equivalent space heating upgrade alone (HP0E0) with the annual utility bills of the same space heating upgrade with each of the envelope improvements (HP0E1, HP0E2, HP0E3).

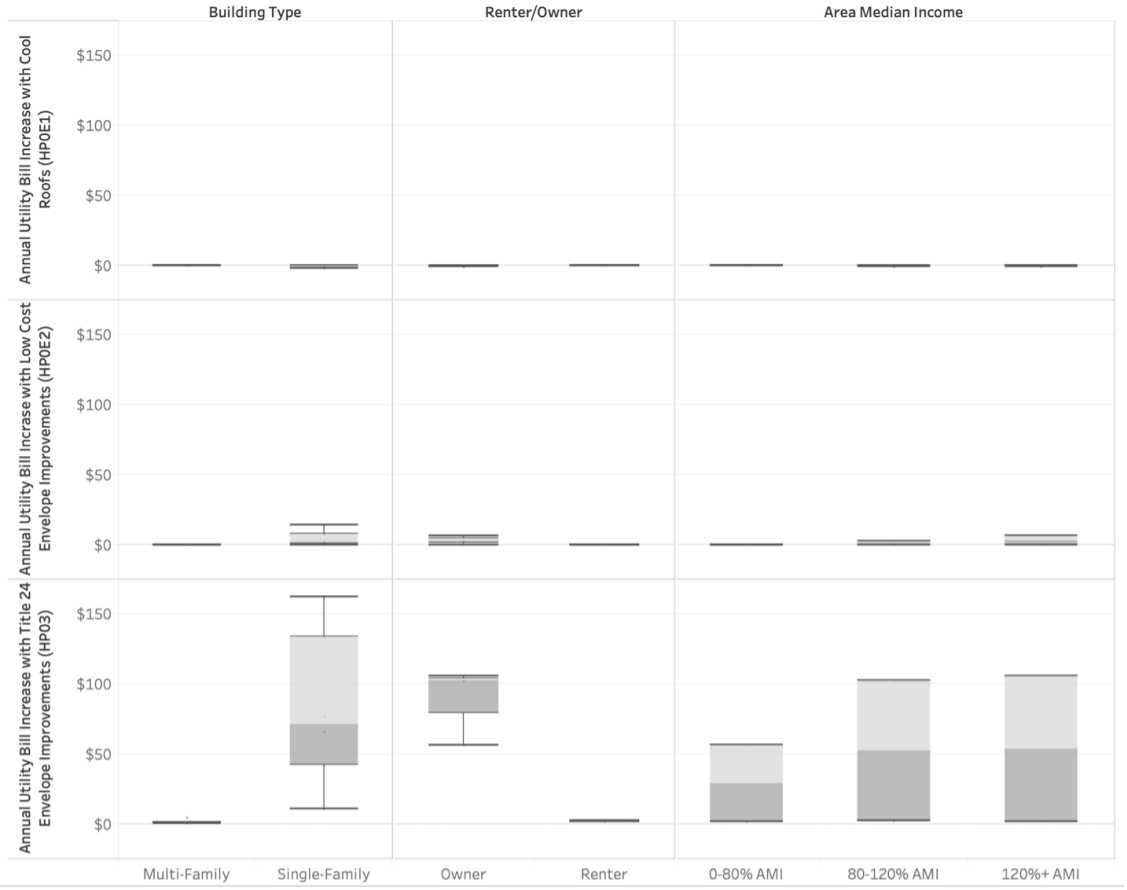

Figure 5.3 Median increase in annual utility bill for different envelope improvements paired with electric equivalent space heating upgrades disaggregated by building type, owner/renter status, and area median income

Figure 5.3 shows that while cool roofs (HP0E1) provide a very small decrease in annual utility bills for some cohorts, the lower infiltration and higher insulation levels of the HP0E2 and HP0E3 envelope packages increase utility bills. This increase comes from increased cooling loads in the summer. In Los

Angeles' mild climate, the improved envelope characteristics trap heat inside a household's thermal envelope during the warmer months, thus necessitating increased cooling. Therefore, we found that in Los Angeles improved envelope characteristics are not an effective electrification supportive strategy.

5.5.2 Electrification Supportive Strategy 2: Universal Access To Cooling Via The Electrification Of Space Heating With Heat Pumps

The analysis of this electrification supportive strategy contains three elements. The first element is to determine which households are experiencing uncomfortable indoor temperatures. The second element is to determine which upgrades improve the thermal comfort of households that experience uncomfortable indoor temperatures. The last element is to determine the costs associated with providing the upgrades that do improve thermal comfort for households.

5.5.2.1 Thermal Comfort And Cooling Use In Los Angeles

We analyze the thermal comfort results from the baseline scenario in two different ways. First, we determine the maximum SET experienced by each dwelling unit (Figure 5.4). These results give insights into the most acute thermal stress experienced in each dwelling unit.

Figure 5.4 shows that the most significant factor impacting acute thermal discomfort is whether a household uses cooling. This includes households that only cool a portion of their total home area. The average difference between the maximum SET experience by a household that uses cooling and one that does not is nearly 13°F. Over 99.9% of households that do not use cooling will experience a SET above 86°F and over 67% these residents will experience a maximum SET above 95°F. While there are differences in households with different incomes, renter/owner status, and building type, those differences are negligible compared to cooling use.

The second way we analyzed thermal comfort in the baseline scenario was by calculating the frequency each dwelling unit spent in various SET °F ranges (Figure 5.5). These results allow us to understand if there is chronic thermal stress experienced by certain households. Figure 5.5 sums the hours each simulated household spends in a series of SET °F ranges and then disaggregates these households' cooling use.

Along with the acute thermal stress experienced by households that do not use cooling (Figure 5.4), Figure 5.5 shows these households also experience chronic thermal stress throughout the year. These results show that households that do not use cooling experience a SET above 86°F 17.8% of the year; this equates to approximately 65 days. Those who do use cooling experience these same conditions only 1.1% of the year, 60 days fewer than those who do not use cooling. Given these results, we know that there are buildings across Los Angeles that experience temperatures above "livable" conditions for many weeks, if not months, of the year.

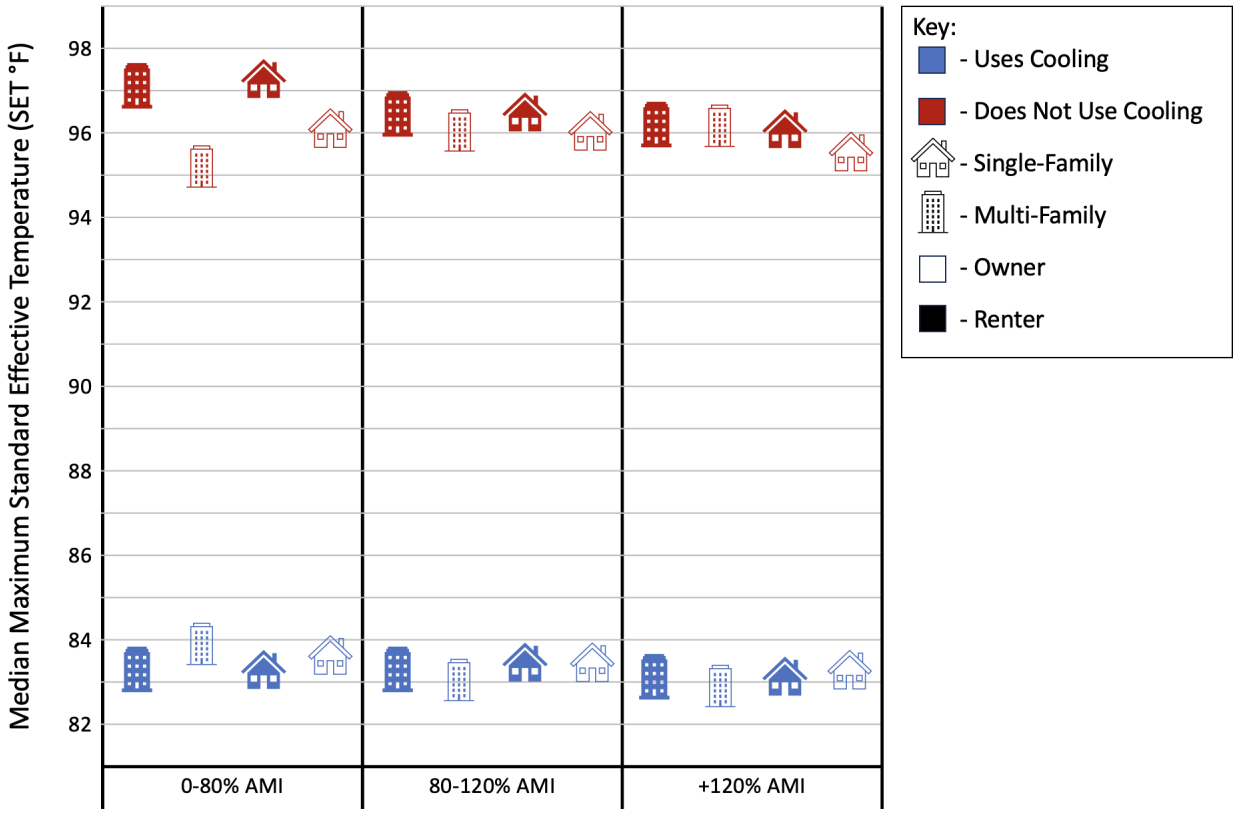

Figure 5.4 Median maximum SET disaggregated by cooling use, income, building type, and renter/owner status

These results show that the most important factor in determining thermal comfort in a household is whether a household uses cooling. This issue is critical because over 48% of Los Angeles households do not have or use their cooling equipment. While income level and renter/owner status do not significantly impact the results of acute or chronic thermal stress, 15% more low-income households do not use cooling compared to high-income households, 11% more renter-occupied households do not use cooling compared to owner-occupied households, and 5% more households in multi-family residences do not use cooling compared to those living in single family residences. Therefore, more of these household types will experience higher indoor air temperature for longer periods of time throughout the year. Upgrades to residential buildings across Los Angeles are imperative to reduce both the acute and chronic thermal stress currently being experienced by many households.

5.5.2.2 Impact Of Upgrades On Thermal Comfort

The first set of upgrades that could be deployed to improve the thermal comfort of Los Angeles residents are improvements to the building envelope (i.e., HP0E1, HP0E2, and HP0E3 scenarios). As

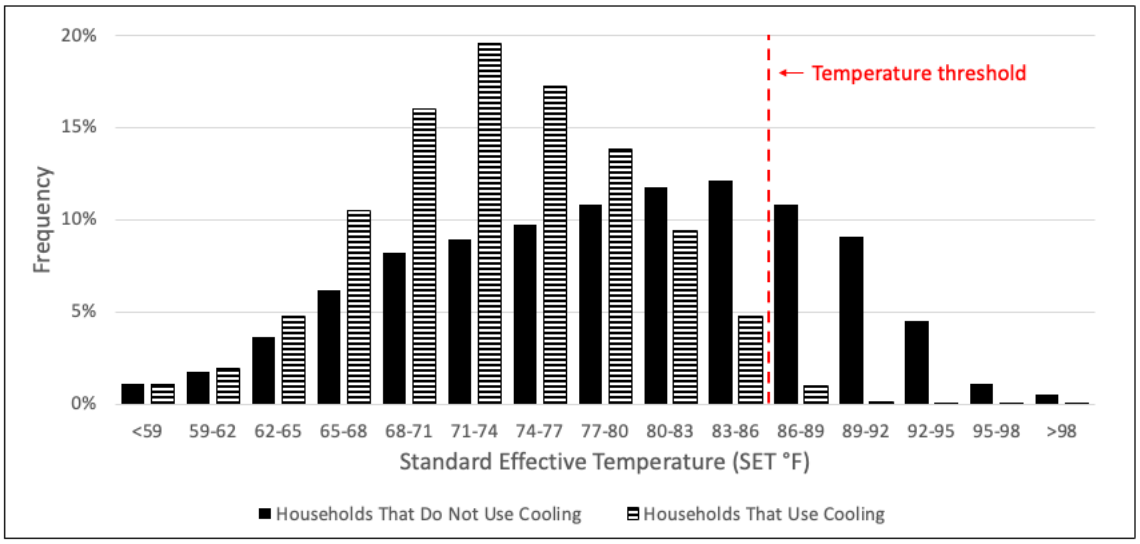

Figure 5.5 Annual hourly SET distribution disaggregated by cooling use

previously noted, if a household used cooling in the baseline scenario, then they were far less likely to experience SETs above a "livable temperature" threshold. Given this, most of these households do not need significant intervention to ensure safe and comfortable home temperature. Therefore, when analyzing the impacts of these upgrades, we only examined those households that do not have or do not use cooling in the baseline scenario. Figure 5.6 shows the frequency of hours spent in various SET °F bins of all the households that do not use cooling in the baseline scenario compared to the envelope only upgrade scenarios (HP0E1, HP0E2, and HP0E3 scenarios).

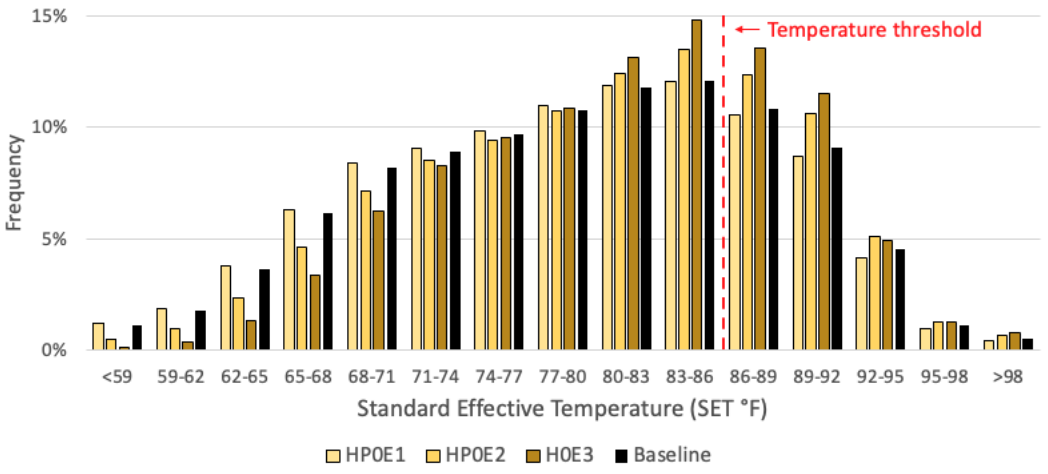

Figure 5.6 Annual hourly SET distribution for households without cooling in the baseline scenario compared to those households after envelope only upgrade scenarios (HP0E1, HP0E2, HP0E3)

Based on the results in Figure 5.6, improving the envelope characteristics of households that do not use cooling in the baseline scenario does not significantly improve thermal comfort. In fact, the upgrade scenarios that improve the insulation and air tightness of households, HP0E2 and HP0E3, increase the frequency of unsafe SET. While seemingly counter-intuitive, we found that improving these envelope characteristics is not only more effective in keeping warm air out, but it just as effective at keeping it trapped inside. Given Los Angeles' climate, in our simulations, during the warmer months, natural cooling from the late evenings through the early mornings is reduced by increasing the envelope performance. In practice this could be mitigated to some extent by increased natural ventilation through purposeful occupant behavior (e.g., opening of windows and doors), which is not explicitly modeled in this study. Installing cool roofs, upgrade scenario HP0E1, marginally decreases the number of hours above a SET above 86°F compared to the baseline scenario because this upgrade reduces the amount of solar heat gain without insulating or air sealing the envelope.

Given these results, upgrades beyond envelope improvements alone must be implemented to improve the thermal comfort of households that do not use cooling. Figure 5.7 shows the frequency of hours spent in various SET °F bins of all the households that do not use cooling in the baseline scenario compared to the HP1E0 scenario, which models upgrading households without cooling in the baseline with the low-efficiency heat pump space heating and cooling systems.

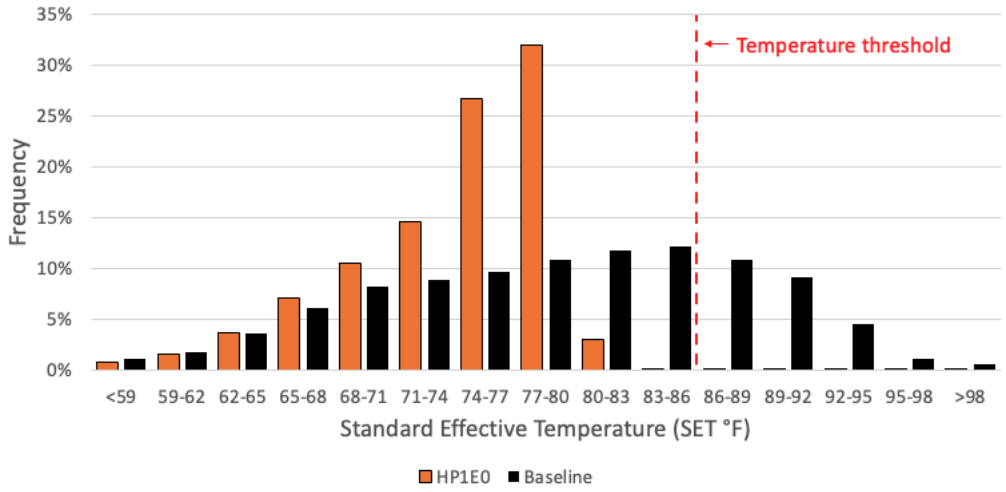

Figure 5.7 Annual hourly SET distribution for households without cooling in the baseline scenario compared to the low-efficiency heat pump space heating and cooling upgrade (HP1E0)

Figure 5.7 shows that the addition of even the lowest efficiency heat pump space heating and cooling systems significantly increases the number of hours spent within the "livable temperature" threshold for households without cooling. This is true even without improved envelope characteristics. In our

simulations, if a cooling technology is installed or upgraded, the new system will always attempt to meet the cooling load of the household regardless of household's behavior in the baseline scenario. Beyond this, any type of cooling upgrade also decreases the median maximum SET experienced by households without cooling (See Table D.3 in Appendix D). Therefore, we conclude that exposure to both chronic and acute thermal stress can be mitigated by the addition and use of any type of heat pump space heating and cooling system for homes in Los Angeles. This may not be the case of all households, especially those with high energy burdens who may not be able to pay for cooling even if they have access to cooling technologies.

To better understand the relationship between envelope characteristics and cooling upgrades on thermal comfort, Figure 5.8 compares the baseline scenario with the scenarios with the highest performance envelope improvements (HP0E3), the highest-efficiency heat pump (HP2E0), and these two upgrade packages combined (HP2E3).

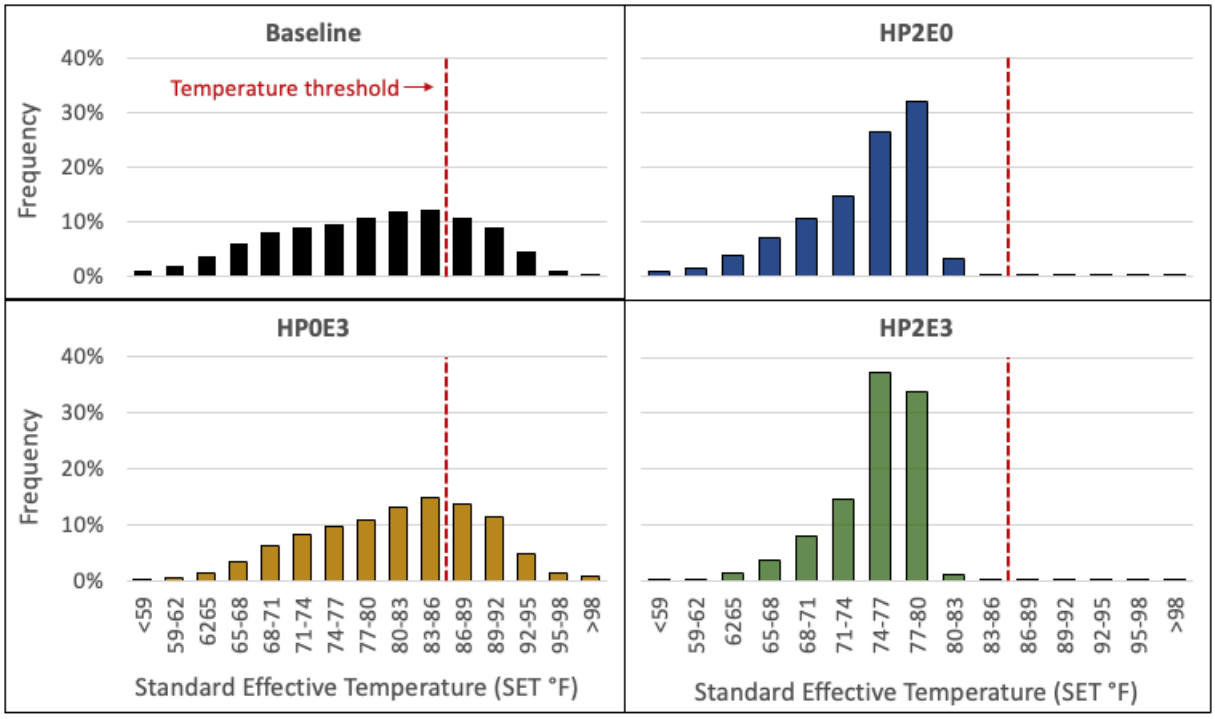

Figure 5.8 Factor analysis of annual hourly SET distribution for households without cooling in the baseline scenario compared to the upgrades with greatest envelope and cooling packages

The factor analysis in Figure 5.8 shows that there are some synergistic benefits to pairing cooling access with building envelope improvements. Scenario HP2E3 exhibits the most narrow distribution of SET of any scenario. Not only are the hours spent in extremely high SETs eliminated through the addition of cooling, but there are also even fewer hours spent in extremely low SETs due to the improved envelope characteristics. It is critical that this synergy is further explored for building stocks in more extreme

climates. While the combination of building envelope improvement and cooling provides the best thermal comfort results, it is clear that heat pumps by themselves can significantly increase in the number of hours at a "livable" temperature. Therefore, in the following section we will only examine the costs associated with adding cooling as a means to electrify.

5.5.2.3 Cost Analysis Of Adding Cooling Services

Cost To Use Existing Cooling Equipment - 49% of Los Angeles households do not use cooling in their households. However, 51% of the households that do not use cooling have access to cooling equipment. There are many reasons why a household that has access to cooling equipment would choose not to use it (e.g., in need of costly repairs), but a critical reason is the additional utility costs to run these systems. These data, from the Residential Energy Consumption Survey, are simply a binary response from households and do not go into details as to why they do not use these systems[246]. Figure 5.9 shows the distribution of the increase in annual utility bills households would experience if they chose to use the fully operational cooling systems that were not used in the baseline scenario.

Figure 5.9 shows that the most common type of households that have but do not using cooling equipment are low-income, are renters, in multi-family buildings. While these households will not see as high of utility bill increases compared to higher income households, owners, and single-family homes, most will nevertheless have annual utility bills hundreds of dollars higher than they are currently. For lower income folks, this increase could be unaffordable. To put this in context, for low-income households (0-80% AMI), this represents an increase in energy burden by 0.75%, which is greater than the baseline energy burden of high-income households in this same situation (+120% AMI) (See Table D.3 in Appendix D).

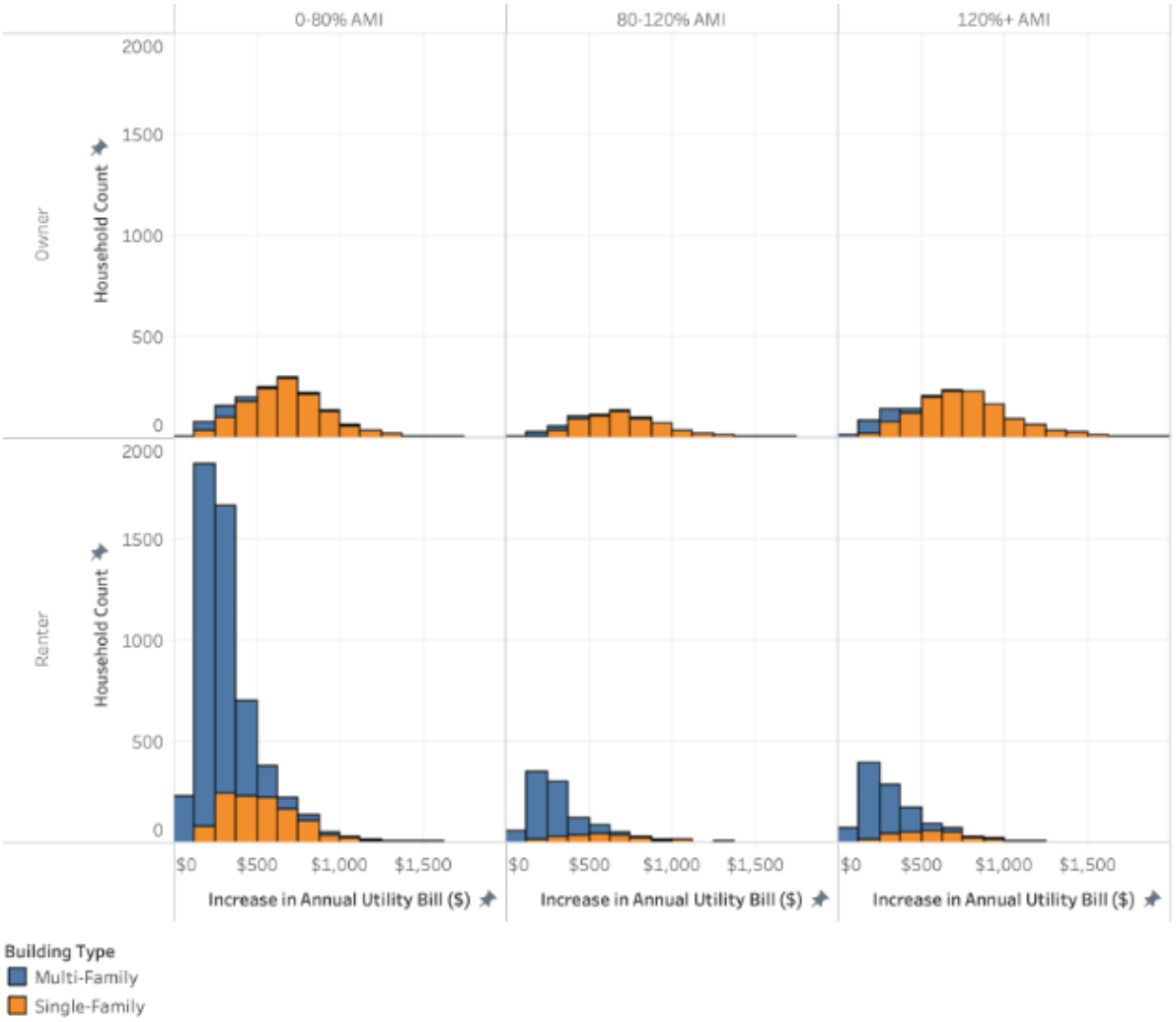

Figure 5.9 Distribution of increase in annual utility bills ($) for cooling households that have cooling systems they do not use in the baseline, disaggregated by income, renter/owner status, and building type

Upgrade Costs For Households Without Cooling Systems In The Baseline - The next analysis is to calculate the costs for households that do not have access to cooling technologies. Given the previous results, we will only examine the costs associated with the upgrade scenarios that add cooling systems for households that did not have cooling in the baseline (HP1E0, HP2E0). We will not examine the costs of these cooling system upgrades with any envelope improvements given their minimal impact on thermal comfort (Figure 5.6 and Figure 5.8). These results are broken down to reflect the various roles found in residential buildings: owners and renters.

Operating Costs For Renters - Renters are the most vulnerable population when considering universal cooling because they have the most limited agency in providing passive or active cooling strategies for themselves. These households are entirely subject to decisions made by their landlords. For renters, the

most important factor in accessing cooling is the increased operating costs for the cooling system. In this analysis, we assume that utility bills are not covered in a tenant's rent. We acknowledge that this is not always the case. Figure 5.10 shows the annual increase in operating costs for low- and moderate-income renters for the upgrade scenarios HP1E0 and HP2E0.

Unsurprisingly, the highest efficiency heat pump systems create the smallest increase in annual operating cost for renters. Most of these households will see an increase in utility bills, though in a few cases, utility bills decrease due to the increased efficiency of and thus bill reduction for space heating with heat pump systems. Most low-income households will see their annual utility bills increase by approximately $250 and $150 with an upgrade to low- and high-efficiency heat pumps, respectively. While $10–$20 a month may not seem to be a significant increase, to an already energy burdened household, this could mean nonpayment of rent, a utility disconnection, or sacrifices with food, clothes, or medication, all of which could negatively impact mental, physical, and emotional health [206, 247, 248]

Operating Costs For Owners - The first expense an owner would consider is the change in capital costs associated with any upgrade. Figure 5.11 shows the change in capital costs for low- and moderate-income owners for the upgrade scenarios HP1E0 and HP2E0.

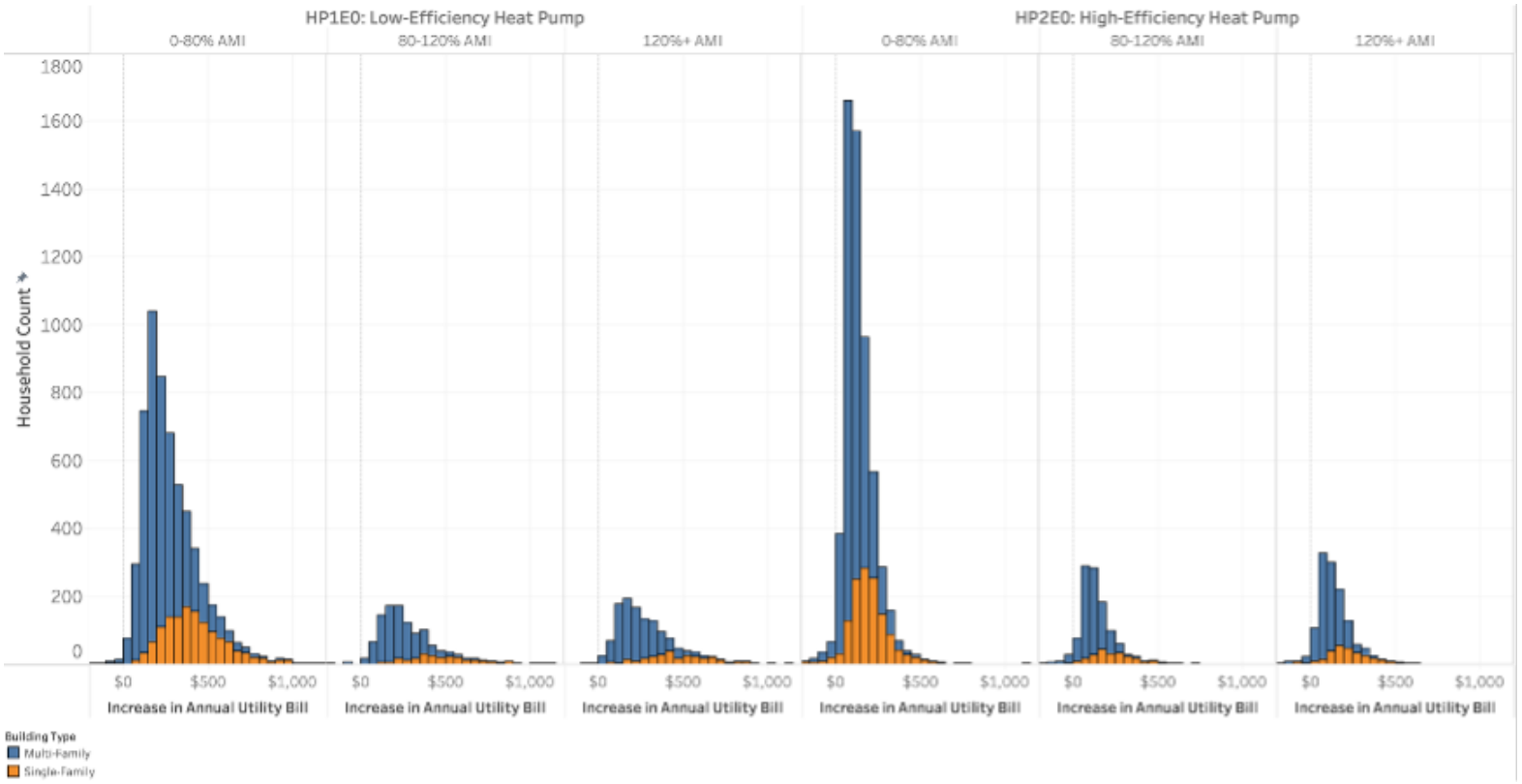

Figure 5.10 Distribution of increase in annual utility bills ($) for renters that did not have cooling equipment in the baseline, disaggregated by income and building type

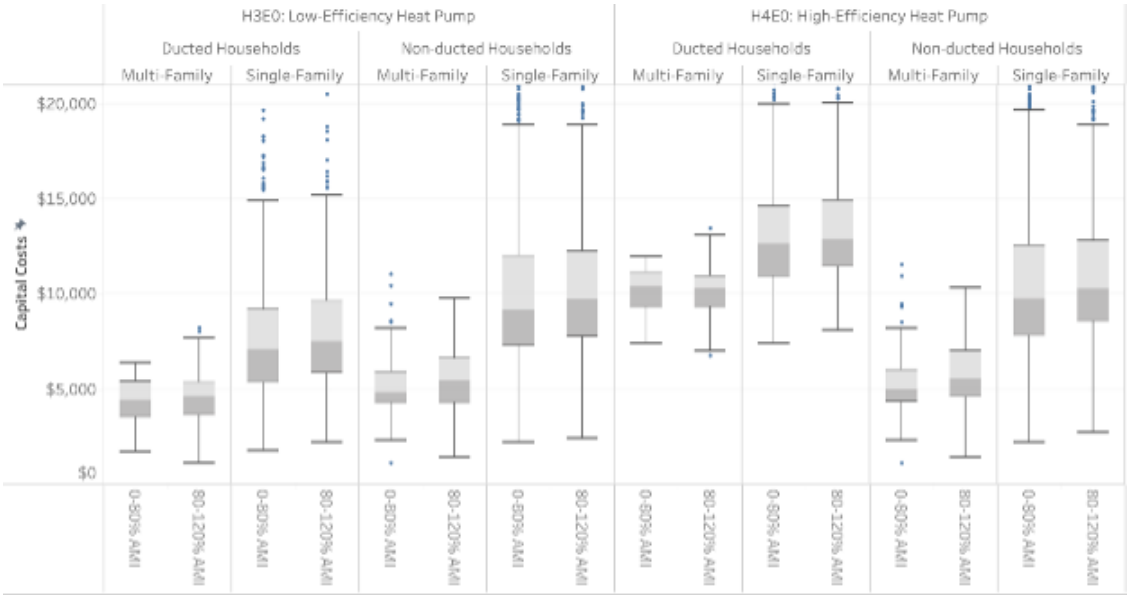

Figure 5.11 Distribution of capital costs ($) for owners that did not have cooling equipment in the baseline, disaggregated by income and building type

Unsurprisingly, based on the results from Figure 5.11, the lowest median capital costs for households without cooling in the baseline scenario are found with the low-efficiency heat pump scenario (HP1E0), regardless of the system's type (i.e., ducted or non-ducted households). We did find that multi-family households require heat pump systems that are thousands of dollars less than single-family households; this is probably because multi-family households are generally smaller compared to single-family ones. Furthermore, we found that non-ducted housing units should opt for the highest efficiency systems given the fact that the difference in capital costs between the low- and high-efficiency systems is negligible. This is due to the fact that the capital cost of mini-split heat pumps is more heavily dependent the size of the load being delivered, due to the cost of individual head units, as compared to the efficiency of the systems [196]. Ducted housing units will see an increase in capital costs of over $5,000 upgrading from the low- to high-efficiency systems.

While these costs are significant, if you consider the IRA High Efficiency, Electric Home Rebate Program, most low-income households (0-80% AMI) could see most if not all the capital costs of the heat pumps covered by the point-of-sale rebates available through this program. The primary exception to this is single-family homes, especially those that do not have ducts, or ducted households that opt to install the highest efficiency heat pump systems. Moderate-income households (80-120% AMI) will face a larger barrier even with these rebates given that only 50% of the capital costs are covered. Therefore, these households should anticipate spending thousands of dollars even considering the avoided cost associated

with not having to replace a fossil-fueled space heating system.

The second expense an owner would consider is the change in operating costs associated with any upgrade. Figure 5.12 shows the annual increase in operating costs for low- and moderate-income owners for the upgrade scenarios HP1E0 and HP2E0.

In Figure 5.12, similar to renters (Figure 5.10), we see that most households will see an increase in utility bills and the highest efficiency heat pump systems create the smallest increase in annual operating cost for owners. We also see that in some cases, there is even a bill savings due to the increased efficiency of and thus bill reduction for space heating and cooling for these combined systems. Most low-income households will see their utility bills increase by approximately $500 and $250 with an upgrade to low- and high-efficiency heat pumps, respectively – twice the increase compared to renters of the same income level. $20–$40 a month will be a significant increase for these households and will only increase energy burden and energy insecurity.

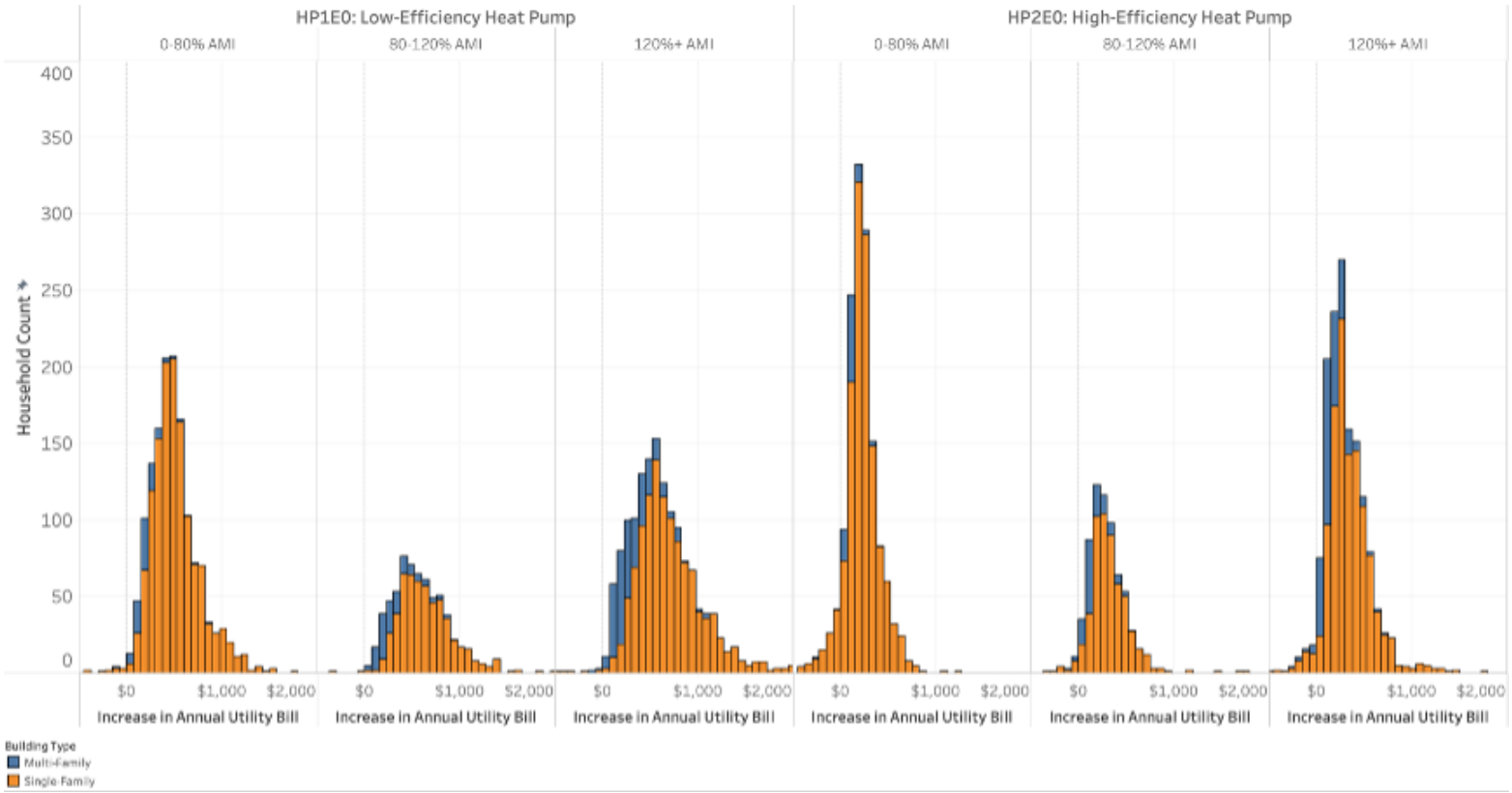

Figure 5.12 Distribution of increase in annual utility bills ($) for owner that did not have cooling equipment in the baseline, disaggregated by income and building type

5.5.3 Limitations And Future Work

This study is limited by the ResStock modeling framework, the scenario development process, and the cost modeling assumptions. First, given the current ResStock model articulation, we cannot accurately calculate SET for partial space conditioning systems. Thus, we are unable to calculate the baseline thermal comfort of those households who utilize partial space conditioning strategies in their homes. Additionally, due to this limitation we chose to model all upgrades with full space conditioning to be able to calculate SET for these upgrades. This is not a realistic representation of how households will necessarily choose to cool their homes. Another limitation in household characteristics sampled by ResStock is that the income associated with each household is associated with the tenants and not the landlord. Given this, we cannot be certain that a household's landlord would or would not qualify for certain incentives.

Second, using the Internal Consistency and Diversity Comparative Framework set out by Sandoval et al., we found that the stakeholder involvement process conducted in this study could be improved [193]. While the authors 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 influence the selection process. More purposeful and selective stakeholder engagement would serve to improve the quality of the scenario development process and any subsequent findings.

Finally, there were multiple aspects of the cost modeling that could be altered to improve accuracy. In calculating capital costs, a limitation of this study is that we assumed that each household would have capacity in their electric panel to accommodate this additional circuit. Therefore, while we were trying to quantify total fuel switching costs, in some cases we did not capturing the necessary expense of an electric panel upgrade, which could increase upgrade costs by thousands of dollars. Similarly, when upgrading natural gas heating system, 4% of affected households would become fully electric. For these households, when considering the operating costs, we did not subtract the daily meter charges that these households would not pay. Finally, we only considered households with natural gas heating systems when upgrading to heat pump technologies. Propane and other heating fuel sources were ignored because they represent less than 2% of the building stock.

5.6 Conclusion

In this work, we used Los Angeles as a case study to demonstrate the effectiveness of electrification supportive strategies to both ease the transition to residential building electrification and address resident concerns. First, we investigated a set of building envelope upgrade packages to reduce the heating load associated with electrified space heating systems. Second, we investigated the same set of building envelope upgrade packages along with a set of heat pump system upgrade packages to mitigate extreme chronic and

acute thermal stress in homes. These results provide quantitative data to support ongoing qualitative research on the importance of access to cooling. This research has implications for building science researchers who seek to improve building energy and comfort models at a population scale as well as policymakers who seek to mitigate health risks due extreme heat exposure. The conclusions from this research are:

1. Nearly half of Los Angeles residents do not have access to or do not use cooling. This number is increased if a household is low-income, rents, or lives in a multi-family building. These households experience both acute and chronic thermal stress throughout the year and it is critical that interventions are implemented to ensure that these households have access to functioning cooling systems and have the means to use them during warm periods of the year.

2. For Los Angeles, improved envelope characteristics increase rather than decrease annual utility bills. In some cases, these envelope improvements can have a dampening effect that can increase chronic thermal stress. To be an effective electrification supportive strategy, we recommend these upgrades be accompanied by the electrification of space heating via a heat pump system.

3. The installation and/or the use of any heat pump system has the ability, given full operation, to reduce the maximum SET to within the range of a "livable temperature" as defined by the U.S. Green Building Council. This finding supports observational data that the main deterrent to heat-related mortalities in the home is the access to and use of air conditioning [239, 241]. Additionally, in Los Angeles, significant envelope improvements do not need to accompany these heat pump systems to ensure their ability to provide adequate cooling.

4. In Los Angeles, building envelope performance improvements do not improve thermal comfort by themselves. However, they do have some limited synergistic impact in conjunction with cooling systems on improving the thermal comfort for households.

5. Los Angeles has an ordinance in place that requires the installation of a cool roof if a roof need to be replaced. However, we found that this upgrade also increases the number of hours a household spends below a typical heating setpoint and will thus increase heating loads during colder periods of the year. Despite these increases, cool roofs yield a net decrease in annual energy use.

6. Electrifying space heating with heat pumps is especially important for households that do not currently have access to cooling equipment. These households are the most at risk for experiencing conditions that are not "livable." However, there are significant costs associated with these upgrades and all vulnerable households will struggle to afford these costs without assistance.

7. Mechanisms like the IRA High Efficiency, Electric Home Rebate Program provide significant financial incentives that can cover the entire cost of these systems for most low-income owners and landlords (especially multi-family households and households with ducts). These incentives make them more attractive compared to traditional AC systems.

8. For most of the households that did not have cooling equipment in the baseline, installing a heat pump system will increase their energy burden. Options need to be explored to assist householdsespecially low-income onesto ensure that they can afford to use the cooling technologies installed in their homes. If not, this equipment could go unused, and the unsafe indoor thermal conditions currently plaguing Los Angeles residents will persist.

5.7 Acknowledgements

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CHAPTER 6
CONCLUSION

The goal of this research was to explore viable pathways to achieve residential building electrification and outline the possible consequences of these pathways, while ensuring no household is over-burdened or left behind in this transition. Guided by the aforementioned research questions, this work accomplished this goal by 1) developing a set of high-quality residential building electrification scenarios leveraging the Internal consistency and Diversity Scenario Development comparative framework, 2) creating a novel, high-resolution techno-economic model to evaluate the costs associated with the upgrades outlined in each scenario, and 3) evaluating the effectiveness of electrification supportive strategies that run in parallel with the electrification upgrades. Additionally, in answering each research question, an energy justice-informed study design was implemented to understand the impacts of these proposed changes on vulnerable households.

6.1 Research Question 1: Scenario Development

The first research question, "How can we ensure the development of high-quality scenarios for energy modeling?" was addressed in Chapter 2. This study concluded that scenario development, when practice is guided by theory, is an invaluable tool in the energy modeling field. Furthermore, scenario development should always seek to be an iterative process where developers return repeatedly to the project, variable, and scenario scoping stages throughout the formulation of the scenario analysis to ensure the best results. However, many of the prominent energy models that guide decision making, like the Annual Energy Outlook, have significant areas of growth when subjected to an analysis of their scenario development process. High-quality scenario development is critical to understand the transition to equitable residential building electrification; a transition where there are many uncertainties.

High-quality scenario development can ease the barriers to equitable residential building decarbonization by involving stakeholders from marginalized communities. Legislative mandates across the United States are mandating decarbonization and electrification; many vulnerable communities could be further marginalized in this process if we are not conscientious in this process. If intentional and meaningful stakeholder involvement is difficult in the current decision making structures, procedural justice calls for an examination of these structures and possibly changes to them to ensure a wide range of stakeholders can participate in rulemaking. As Regan Byrd, an anti-oppression activist, states marginalized communities collectively are experts in their own oppression due to lived experience, but also

they are experts on solutions for disrupting oppression [27]. Therefore, scenario development can promote restorative justice through the inclusion of these marginalized voices, understanding their needs, goals, and keeping them on the forefront of this transition.

The intellectual merit and technical contribution of this research was the development of the Internal consistency and Diversity Scenario Development comparative framework. This framework enables critique the scenario development process of any type of energy model and provide guidance to improvement for both existing scenario analyses and those still in development. This framework can also be used to compare scenario analyses side-by-side to determine different strengths and weaknesses in models. The utilization of this framework will help energy modelers better communicate their findings and the limitations of their models and results. Additionally, this framework will give insight to decisions makers into how scenarios analyses can be used effectively to guide the decision making and solution development processes.

6.2 Research Question 2: Scenarios For Equitable Residential Building Electrification

The second research question was addressed in Chapters 3 and 4. Research question 2 investigated "What are the consequences for all households in a transition to residential building electrification?" Chapter 3 addresses research question 2 by singling out the electrification of space heating given the wide range of HVAC configurations in a given building stock: different fuel sources, different heating and cooling equipment types, and different efficiency levels. This study concluded that, in Los Angeles, the most cost-effective space heating electrification upgrade are electric equivalent technologies for most households. The main exception are owners who replace both a natural gas furnace and a central AC system with a low-efficiency heat pump system. The result is that, if these findings are used by households to make decisions on the electrification of their space heating systems, low-efficiency electric equivalent systems will be installed in more households who are low-income, live in multi-family buildings, or who are renters – all vulnerable households. Given the cost of electricity in Los Angeles, these systems will create increases in utility bills, exacerbating energy burden issues, especially for low-income households. Electrifying with these technologies for these vulnerable households would violate two of the energy justice rights posited by Hernández: the right to the best available energy infrastructure and the right to affordable energy [63]. While these two issues can be resolved by upgrading to higher efficiency space heating systems (i.e., heat pump systems), these technologies come with capital costs that far exceed those associated with the electric equivalent systems. These increase costs could put them beyond the reach of many of these vulnerable households.

Chapter 4 addresses research question 2 by evaluating the remaining end uses that will need to be electrified: water heating, cooking, and clothes drying. Additionally, this chapter provides a high-level

perspective on the challenges of widespread residential building electrification for both residential retail electric customers and the utility in Los Angeles, LADWP. This study has a similar conclusion to that of Chapter 3. Low-efficiency electrification, while incurring the lowest capital costs, has widespread negative consequences. For households, these low-efficiency electric technologies will exacerbate current inequities by increasing utility bills and energy burden, The increase in energy burden is greatest for low-income households. For the utility, not only does low-efficiency electrification create increases the total annual electricity by 40% and peak daily electricity consumption by 50%, but also the timing of the daily peak electricity consumption changes. The timing of this peak consumption changes from mid-afternoon in the summer to early morning in the winter. While these changes will increase revenues for LADWP it will also require the augmentation of their energy generation, transmission, and distribution assets. Additionally, meeting an early morning winter peak could be especially difficult for LADWP to manage given that fewer renewable generation sources are available during this time [219]. Therefore, meeting this demand could require a higher reliance on energy generation from fossil fuels, decreasing the decarbonization impact of these changes. While a full transition to the highest efficiency electrification will actually decrease have little impact on the grid, based on LADWP's projections in the, it will cause a six-fold in electricity rates to generate the funding LADWP has promised for building electrification incentives.

The intellectual merit and technical contribution of this research was the development of the Marginal Net Present Value Upgrade Analysis Model. While this model improved on existing studies that evaluate the economics of residential building electrification through the examination of all electrification upgrades (i.e., space heating, water heating, cooking, and clothes drying), the inclusion of all capital costs (i.e., labor, material, and fuel switching costs), and the variable pricing of both HVAC and water heating systems, the main technical contribution of this model is the implementation of the variable discount rate. For the first time, a non-fixed discount rate was used to calculate the marginal net present value for the various electrification upgrades analyzed in this research. Assigning a unique discount rate to each household will improve the accuracy of these economic metrics that calculate lifetime costs and savings associated with any upgrade. No two households are the same, including how each household values future savings. It is imperative that each household is not assigned the same discount rates to ensure that the preferences of each household is taken into account in these calculations.

6.3 Research Question 3: Electrification Supportive Strategies

The third research question, "Can electrification supportive strategies improve the transition to residential building electrification?" was addressed in Chapter 5. This study concludes that access to and use of heat pump space heating and cooling technologies for Los Angeles residents who currently do not

have cooling is an invaluable electrification supportive strategy. However, even though Los Angeles residents clearly value access to cooling, there are significant costs associated with these upgrades and all vulnerable households will struggle to afford these costs without assistance. Without assistance, the equipment could go unused and the 'unlivable' indoor conditions currently plaguing many Los Angeles residents could persist. While I found that in Los Angeles, the improvement of insulation and infiltration levels alone was not a beneficial electrification supportive strategy, upgrading to cool roofs did show some limited energy savings. Results showed that cool roof increases the number of hours a household spends below both heating and cooling setpoints. While this does increase heating loads during colder periods of the year, the savings attributed to the decreased cooling loads in the warmer months yield a net decrease in annual energy use. Additionally, Los Angeles has an ordinance in place that requires the installation of a cool roof if a roof need to be replaced and LADWP has a rebate to help offset the increased costs of this upgrade [249].

The intellectual merit and technical contribution of this research was the use of SET to determine the change in thermal comfort based on a set of upgrades applied across an entire building stock. It is important to understand the current thermal comfort conditions across an entire building stock. This understanding can help identify the households most in need of interventions to improve thermal comfort. From here, it is possible to evaluate how upgrades can improve the thermal comfort in individual buildings that experience unsafe indoor conditions. Combining these two aspects elucidates pathways to achieve widespread access to safe indoor conditions. This research fills this gap and the results from this research can both direct interventions towards the households that currently experience the greatest thermal stress and identify specific upgrades that are shown to improve on these baseline conditions.

6.3.1 Overcoming Barriers To Equitable Residential Building Electrification

There are many types of the barriers to residential building electrification highlighted by this and other research. These include high equipment capital costs, rate structures, physical installation barriers, and cultural installation barriers. There are a variety of strategies that can be applied to address the issue(s) in each barrier.

6.3.1.1 High Equipment Capital Costs

As shown in the results of this study, many of the lowest-efficiency electrification upgrades and almost all the high-efficiency ones will increase capital costs for households. To successfully decarbonize residential buildings, improving the affordability of these technologies is imperative, especially for marginalized households. One strategy is the use of legislation to raise money to cover some or all the capital cost of

these systems for qualifying households. The High Efficiency, Electric Home Rebate Program, one of the provisions of the 2022 Inflation Reduction Act, is one example. Households receive point-of-sale rebates of either 100% or 50% of total capital costs (i.e., material and installation) based on the income level of the household [211]. For heat pump systems, incentives are capped at $8,000. While this program will completely change the outcomes for households that are able to participate, in the case of Los Angeles, the funds allocated for this program will allow for less than 1% of the qualifying households to access these benefits. However, there are other options for generating monies for these programs. One program that has been successful has been the auction revenues from the California Air Resources Board's cap-and-trade program which has generated over $24 billion in revenues which have been directed into programs which reduce greenhouse gas emissions [250]. A similar strategy is if a government agency or utility were to cover the initial capital costs of the equipment and engage in a lease-to-own program with the customer. Efficiency Vermont, one such example, offers 0% interest loans to qualifying households to assist in electrification and energy efficiency upgrades [251]. After their initial investment to cover capital costs, the government agency or utility can recover costs through the payments made by the customer. While the program does not accrue interest on these investments, the initial capital can be reused again and again to cover the cost of upgrades for other households; increasing the impact of the funds.

Another strategy would be to reduce the initial investment that governments or utilities would need to provide for incentive programs. While the High Efficiency, Electric Home Rebate program covers a significant portion of the total capital costs for qualifying households, results from this study and from Part 1 have shown that smaller incentives ($500–$4000) are sufficient in making the capital cost of high-efficiency electric technologies equivalent to the fossil fuel baseline technologies that they would replace [215]. Furthermore, results from this research show that in general low-income families live in smaller households that require the smaller and less costly space heating and cooling systems [215]. Therefore, if these incentive caps can be reduced, they can be spread out to a larger number of households. A further measure could be to offer a tiered incentive structure where incentives increase as the efficiency of the technology increases. This would both steer consumers towards the more efficient technologies and address the high capital cost of the highest efficiency systems.

Regardless, to make the higher efficiency upgrades more accessible, given the preference for high discount rates by low-income households, the incentives need to be supplied as close to the time of purchase as possible. Benefits from some energy efficiency incentive structures, such as the federal tax credits for energy efficiency, can come months later and do not benefit those who have low tax liability [252]. These types of rebates also limit access by increasing the time burden associated with these programs to fill out paperwork, they may require language fluency and an a more detailed understanding of the tax system.

Additionally, if incentives are not provided directly to the consumer (e.g., midstream incentives), they must be passed on, in part, to the consumer to ensure they are not pocketed by the manufacturer or installer.

6.3.1.2 Rate Structures

Currently, many rate structures follow a volumetric block structure—households that use more electricity pay more per unit energy. While this incentivizes energy efficiency, it disincentivizes widespread electrification. Similarly, some utilities use time-of-use schedules or demand charges. The higher the energy consumed during a specific period, whether that is a specific time of day for time-of-use schedules, or in any given time period for demand charges, the greater the utility bill for a household. With more electric equipment in a household, there is a greater chance of overlapping use resulting in a higher demand charges or high electricity use during peak periods resulting in higher electricity prices for time-of-use schedules, both of which disincentivize electrification. These increased rates and demand charges will be especially impactful on the energy burden of low income households, which already face energy insecurity [253]. Therefore, to equitably electrify, it is critical to rethink how electricity is priced.

There are many different strategies that can be employed to price electricity for marginalized households. One strategy is to vary either fixed or volumetric rates by income level or another metric of disadvantage or marginalization. One example of this practice is the bill rider used to pay for the California Solar initiative, which is funded through a utility bill surcharge from which low-income customers are exempt [254]. Each utility or public utilities commission could review the various elements attributable to the cost of electricity and stratify these charges based on income or other metrics. A second strategy would be to create electrification specific rate structures which could combat regressive demand charges. For customers who fully electrify, utilities could offer different rate structures that lower or eliminate demand charges, knowing that the electric utility will generate more volumetric revenue given the increase in electric equipment in the household [255]. Additionally, these rate structures could leverage time-of-use rates or demand response mechanisms to shift load indirectly and directly throughout the day to lower costs in both the short term, when deploying costly energy generators to meet the load, and in the long term, given that a smaller generation fleet will be required.

6.3.1.3 Physical Installation Barriers

There are three physical installation barriers that hinder residential building electrification. The first is the capacity in electric panels to add additional circuits to power the electric equipment replacing fossil fuel combustion equipment [222]. The U.S. Department of Energy has recognized this issue and has put forward the Equitable and Affordable Solutions to Electrification prize competition. This competition has

recognized six finalists with a variety of solutions [256]. One of these finalists, the NeoCharge and Redwood Energy team have developed a strategy to address this issue. Their strategy involves a smart switch where two 240V circuits (e.g., laundry and EV) can share the same outlet and each be powered intermittently when the other is not needed [257].

The second physical installation barrier is the size of ducts is existing residential building. Ducts designed for combustion-based space heating equipment will be smaller because of the high outlet temperatures possible from these technologies. Heat pumps do not produce as high of outlet temperatures and thus cannot deliver the same heating load given the same flow rate [258]. One strategy to deal with this issue is to have a more continuous operation of the heat pump. Preheating spaces and different cycling/dead band strategies could both provide sufficient heating and distribute the load more evenly throughout the day. In heating dominated locations, residential building electrification will almost certainly mean a switch to a winter peak and these operation changes could help reduce the severity of this peak.

The final physical installation barrier involves obstacles for multi-family and single-family attached buildings to deploy outdoor condensers for space heating and cooling and space limitations to install heat pump water heaters. For large multi-family buildings, there may not be space to deploy the outdoor condensers needed for heat pumps for all units without taking up balcony space or changing the buildings aesthetics [255]. One possible strategy to address this barrier are wall mounted all-in-one heat pumps that do not require an outdoor condenser unit. One example is the Ephoca AIO wall mounted heat pump air conditioner which simply requires the installation of a set of intake and outlet air vents through an exterior wall [259]. These systems can be installed as standalone systems or be integrated into existing ductwork. Furthermore, energy recovery ventilators can be added to increase the efficiency of these systems. One drawback of these systems is their cost - nearly $4,000 for a single unit – especially if multiple units are needed to in a households [259].

Heat pump water heaters, the most efficient water heaters, pose a similar issue in that they are larger when compared to similar combustion-based versions due to the addition of the integrated fan, condenser, and evaporator. Furthermore, results from this study show that tankless electric water heaters create enormous electric load and increase utility bills far more than any other technology examined. Therefore, converting as many of these as possible to heat pumps is important for an equitable transition to electrification. Unfortunately, the space constraints for transitioning from tankless water heaters to heat pump storage water heaters is even greater. One possible solution is the use of phase change materials in water heater tanks to increase the heat capacity of the tank, therefore allowing the tank size to decrease [260, 261].

6.3.1.4 Cultural Installation Barriers

Cultural barriers can also hinder widespread residential building electrification. First, the lack of familiarity with the operation and performance of high-efficiency electric equipment has been shown to be a barrier to their adoption for both residents and installers. Residents, unfamiliar with new technology, may not understand the potential savings these electric upgrades can offer, nor how they operate compared to 'in-kind' technology [222, 262, 263]. Similarly, those installing and servicing this equipment may lack the experience to 1) correctly install these systems, which could impact their performance [222], or 2) confidently install these systems, which could increase the time required for installation and thus installation labor costs [262].

This issue is so important that the Northeastern Regional Assessment of Strategic Electrification report dedicated an entire section to address the need for marketing, outreach, and education related to the benefits of high-efficiency electric replacement technologies [263]. This report highlights the success of the 2014 Solar Benefits Colorado initiative which was a joint effort between several municipalities in the greater Denver area which worked with local automotive dealerships and photovoltaic installers to help them understand the synergistic benefits of residential solar and electric vehicle adoption. These entities, better equipped to answer consumer questions about a transition to these clean energy technologies, were able to significantly increase their sales. In Boulder County that year, the number of electric vehicle purchases tripled [264]. A similar strategy could be used for heat pumps, where educating contractors, installers, and technicians on the benefits of heat pumps and correct installation practices could multiply the impact with each of these individuals advocating for these technologies to hundreds of consumers, rather than educating consumers, who are likely to purchase only a handful of these systems in their lifetime.

The second cultural installation barrier we have identified is the reluctance by some households to convert from gas cooktops. In a series of focus groups conducted by Gordon et al. regarding the transition away from natural gas cooking ranges in the U.K., respondents noted many perceived advantages of gas cooktops – controllability and ease of use, convenience, efficiency and responsiveness, familiarity and reliability [221]. This study specifically called out how some focus group participants noted how transitioning away from gas cooktops would impact their cultural culinary backgrounds – from the inability to cook certain food on electric cooktops to the inability to pass down cooking practices between generations [221, 265]. To ensure an equitable transition to residential building electrification, these cultural concerns must be considered.

6.3.2 Opportunities In Residential Building Electrification

While there are many barriers to widespread residential building electrification, there are also multiple opportunities. An electrified building stock has incredible demand flexibility potential. The ability to pre-heat or pre-cool thousands of homes, along with the ability to pre-heat millions of gallons of hot water represents an immense thermal battery that can be leveraged by a utility. With internet-connected controls for equipment, utilities can shift these loads to smooth both winter and summer peaks [222]. This is especially helpful give the increased penetration of intermittent renewable energy generation; rather than curtailing excess wind and solar, this energy can be stored in electrified homes in ways combustion technologies could never match [222]. Furthermore, smoothing utility peak demand could decrease the occurrence of outages—a benefit to both the utility and its customers. Finally, as mentioned previously, smoothing daily peaks will also be beneficial to households by decreasing demand charges.

Another opportunity in residential building electrification is the ability to provide access to cooling through the electrification of space heating with heat pumps. In Los Angeles, over half of residential building units lack access to cooling [103]. According to a 2022 Berkeley IGS Poll, nearly two-thirds of Los Angeles County residents "believe extreme heat poses a serious threat to their and their family's health and safety" [266]. From 1993 to 2023, extreme heat caused the most weather-related fatalities in the U.S. [267]. This issue will only be exacerbated by increasing average summer temperatures and the increase in extreme weather events as a result of climate change [164]. Exposure to extreme heat can lower productivity, increase healthcare costs, aggravate pre-existing conditions, and lead to hospitalization or death [239, 240, 268–270]. Qualitative studies show that having and using an air conditioner is the greatest factor in preventing heat-related fatalities in the home, especially during a heat wave [239–241]. Sandoval et al. corroborated these findings with a quantitative building energy modeling analysis of occupant thermal comfort across the Los Angeles residential building stock [215]. Therefore, providing universal access to cooling through space heating electrification using heat pumps yields myriad benefits that could outweigh the additional costs associated with the upgrades.

6.4 Future Work

Improving the Marginal Net Present Value Upgrade Analysis Model could improve result accuracy. One such improvement to the Marginal Net Present Value Upgrade Analysis Model is changing how the model assigns discount rates to each household. Currently, the discount rate assigned to each household to calculate the marginal net present value is based on a linear scale inversely proportional to income. While this is an improvement on existing literature examining the economics of residential building electrification, there are many assumptions with this method. We know that household characteristics beyond income

impact discount rate. Thus, surveys could be conducted to see how a broader range of factors impact a household's value of future savings to create a more representative discount rate for each household. Another issue with the model is that I did not consider the space heating electrification upgrades for buildings with shared heating systems. These systems are in approximately 15% of residential buildings in Los Angeles and may be even more prevalent in cities in colder climates. The complexity of both these systems and their required electrification upgrades along with the determination of who would bear the costs associated (e.g., residents vs. building owners) was beyond the scope of this research. Additionally, research could be done to quantify the benefits of cooling (e.g., reduced healthcare costs) to counteract the costs associated with installing and operating these systems. These benefits could then be incorporated into the model to further justify their validity as an electrification supportive strategy.

Improvements to the ResStock modeling infrastructure could also increase the accuracy of the results in this research. The addition of electric panel capacity as a household characteristic would be a valuable addition to understanding the total costs associated with residential building electrification. With this improvement, the Marginal Net Present Value Upgrade Analysis Model could add the cost to upgrade an electric panel or purchase smart switches to the total capital cost. Other household characteristics that could identify vulnerable households could be added to the household characteristics in the ResStock model would improve our ability to assess energy justice outcomes. While the energy justice literature shed light on four types of households that I describe as vulnerable, i.e. households of color, low-income households, renters, and households in multi-family buildings, there are a wide array of other households that may struggle in a transition to residential building electrification. Examples include single-parent households, the elderly, caregivers, households with language barriers, households with immigration challenges, and households with individuals that have physical, emotional, or mental disabilities. Household members which identify with any of these characteristics will face unique challenges in a transition to residential building electrification. Therefore, to achieve a truly equitable transition, we will need to consider the needs of these households in this process and include these characteristics in the models we use.

For both the Marginal Net Present Value Upgrade Analysis and ResStock models, a similar customization to other cities and regions could help understand and achieve energy justice outcomes. Multiple studies have shown that successfully energy justice initiatives are regionally specific and involve the local community [25, 77, 172]. Therefore, using these powerful models to do similar analyses across the nation will better ensure an equitable transition to residential building electrification.

One of the key impediments to obstacles to equitable residential building electrification are the types of metrics and indicators currently used in energy justice initiatives across the nation [19]. Program metrics are a key part of procedural justice, given that they provide data to judge the effectiveness or utility of an

initiative. Metrics, just like any other governing structure, can be altered to favor one group over another, therefore developing metrics with a wide range of community stakeholders is critical. In terms of achieving equitable residential building electrification, metrics include both those that identify qualifying households and those that evaluate the success of interventions.

Many of the current indicators to identify vulnerable communities lack the specificity to adequately address community needs. While both simple (e.g., income level) and complex (e.g., CalEnviroScreen) indicators based in demographic, socioeconomic, or environmental factors can be powerful tool, it is possible to more accurately capture the needs of a specific household by focusing on the community's needs [218]. One example is heating or cooling slope. This indicator measures the amount of additional energy required to heat or cool a household given a 1°F change in outdoor temperature [271]. Utilizing smart meters and weather data, utilities could this indicator to identify the least efficient households to prioritize for weatherization programs. Taking this a step further, utilities could measure behavior adaptations to extreme weather to see how long before households are turning on heating and cooling services [63]. This could be used to identify households which are experiencing energy insecurity; these homes could be sent a representative from the utility who could provide information on utility bill assistance, weatherization, or AC efficiency upgrades [272].

Currently, the metrics used to evaluate the success of energy justice initiatives are quite limited. Metrics such as number of homes weatherized or the estimated energy savings of retrofits do little to address the specific concerns voiced by Los Angeles residents. Given two neighboring households that are equal in every way except the access to cooling, a successful intervention will look different for each of them. By adding cooling to House A that did not previously have it, an increase in energy consumption should be viewed as a success. Whereas House B which already has cooling could be weatherized and in this case a decrease in energy consumption would be viewed as a success [19]. A single, generalized metric cannot capture the nuances of these different outcomes.

One strategy to address this is the creation of a series of metric which align with community needs, with the most pressing need being the priority. Table 6.1 gives an example of set of prioritized electrification and energy efficiency upgrades. Households could qualify for intervention either via the metric associated with each intervention or a more generic metric (e.g., income level). If a household qualifies with a generic metric, then they would receive the highest priority intervention that they need given their unique circumstance (e.g., if they have and use their cooling equipment and a smart meter, but do not have an electric storage water heater, they would receive intervention 3 – the installation of a heat pump water heater). In this way, the residential building sector will slowly transition to being fully electrified in parallel with the community's concerns being addressed.

Table 6.1 Example of a prioritized set of electrification and energy efficiency upgrades based on community input

Community concern	Intervention priority	Metric to identify qualifying households	Primary intervention	Reason for intervention	Metric to evaluate success
2*1: Universal access to cooling equipment	1	Access to cooling	Installation of heat pump space heating and cooling system and smart meter	Electrify space heating and provide cooling	Smart meter to monitor cooling use during heat waves
	2	N/A - Applies to all households	Installation of smart meter	Ensure all households have access to and use cooling	Smart meter to monitor use during heat waves
2: Affordable Electrification	3	Households with natural gas storage water heaters	Installation of heat pump water heaters	The electrification upgrade with the highest marginal net present value	Number of units installed, scope 1 emissions reductions
3: Current building conditions/ infrastructure	4	Households with the highest cooling/ heating slope	Basic air sealing (i.e., weatherstripping, caulking) and drill and fill insulation	Ensure households can retain conditioned air to reduce utility bills	Change in cooling/ heating slope
2: Affordable Electrification	5	households with natural gas clothes dryers	Installation of electric standard clothes dryers	Upgrade with lower replacement cost compared to baseline technologies	Number of units installed, scope 1 emissions reductions

In summary, understanding equitable pathway to residential building electrification is extremely important and complex. This thesis shows that many electrification pathways could unnecessarily burden vulnerable communities. And while there are barriers such as rate structures and cultural concerns around these upgrades, there are many existing strategies and benefits that show considerable promise. The electrification of space heating with high efficiency heat pumps for those without cooling technologies is one example. This strategy would provide immediate access to cooling those who currently lack this critical service and would avoid high operating costs in the future. However, it is clear that while this strategy and many other high-efficiency electrification upgrades are the most beneficial to vulnerable households in the long run, these upgrades need to be accompanied by incentives to assist these households with the costs to install these technologies. Through the continued implementation of the energy justice tenets to identify burdens, recognize marginalized households, and address the systems that caused these issues, we can consciously involve these vulnerable communities in the development of a more just energy system.

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APPENDIX A

LA100 EQUITY STRATEGIES STEERING COMMITTEE MEETING NOTES CODING ANALYSIS

A.1 Introduction

The recent Los Angeles 100 Equity Strategies study, commissioned by the Los Angeles Department of Water and Power (LADWP), was conducted by the National Renewable Energy Laboratory (NREL) and University of California – Los Angeles (UCLA). In this study, the research team held a series of meetings with a steering committee made up of representatives from 14 community-based organizations (CBO) across Los Angeles [84] (Table A.1). The goal of these meetings was both to understand resident concerns with city's effort to decarbonize it energy, transportation, and building sectors and to also ensure that community voices were heard to provide direction to the project and prioritize energy equity outcomes [31]. The goal of this coding analysis was to take the stakeholder engagement work done by the LA100 Equity Strategies research team and learn about community concerns in relation decarbonization via the electrification of residential buildings.

Table A.1 Community-based organizations which composed the LA100 Equity Strategies steering committee

Steering committee member community-based organizations
Alliance of River Communities
City of LA Climate Emergency Mobilization Office
Climate Resolve
Community Build, Inc.
DWP-NC MOU Oversight Committee
Enterprise Community Partner
Esperanza Community Housing Corporation
Los Angeles Alliance for a New Economy
Move LA
Pacific Asian Consortium in Employment
Pacoima Beautiful
RePower LA
The South Los Angeles Transit Empowerment Zone
South LA Alliance of Neighborhood Councils Strategic Concepts in Organizing and Policy Education

A.2 Methods

We followed a two-part methodology to conduct the coding analysis of resident concerns in Steering Committee meetings held as a part of the LA100 Equity Strategies project. The first part was the collection of the meeting notes which served as the qualitative used in this analysis. The second part was

the analysis of resident concerns through a description-focused coding strategy. The methods for these two steps are outlined in the subsequent sections.

A.2.1 Data Collection

The LA100 Equity Strategies research team conducted a series of 20 Steering Committee meetings between November 2021 and May 2023 [31]. The meeting notes from these meetings are publicly available on the LADWP's LA100 Equity Strategies website [84]. The comments from CBO representatives which were captured in these meeting notes served as the qualitative data for this work.

A.2.2 Coding Analysis

We used a description-focused coding strategy to understand residents' concerns pertaining to the residential building sector with the city's decarbonization plan [273]. First, we developed a set of codes we believe would be relevant to resident concerns around electrification and decarbonziation. These initial codes are show in the first column of Table A.2. Second, we reviewed meeting notes and identified all resident concerns pertaining to residential buildings. We found 151 relevant resident comments. While identifying these concerns, we tagged each concern with one of the initial codes we delineated. In this process, we used in vivo coding to adapt our coding system by subdividing codes into more specific categories and adding clarifying details to codes [274]. The final set of codes used in this coding analysis are in the second column of Table A.2.

Table A.2 Initial and final codes used in coding analysis

Initial Codes	***Final codes after in vivo coding***
Health and Safety	General Health and Safety
	Air Quality and Pollution
	Access to Cooling/Resident Comfort
Affordability	Affordability of capital and operating costs of proposed upgrades
	Rebates/Incentives
Infrastructure	Current building infrastructure/conditions
Renter/Landlord dynamics	Renter/Landlord dynamics
Resilience	Resilience

A.3 Results

Table A.3 shows the number of resident concerns which were identified for each of the final codes outlined in Table A.2 and the percentage of each in relation to the total number of identified resident concerns. The percentages sum to more than 100 percent because some resident comments were tagged with multiple codes when they addressed multiple issues.

Table A.3 Coding analysis results

Final codes after in vivo coding	***Count***	***Percent***
General Health and Safety	6	3.97%
Air Quality	6	3.97%
Access to Cooling/Resident Comfort	26	17.2%
Affordability of capital and operating costs of proposed upgrades	53	35.1%
Rebates/Incentives	4	2.55%
Current building infrastructure/conditions	37	24.5%
Renter/Landlord dynamics	15	9.93%
Resilience	6	3.97%

A.4 Discussion

Based on the results from Table 3, the primary concern of residents was affordability, with over 40% of the concerns referencing the change in cost associated with the building upgrade being proposed by the city. One resident put this succinctly when they shared, "How much will all of this cost [84]?" Cost concerns can be broken into two categories. One resident addressed the first when saying "many property owners do not have the capital to front all the costs. [We need to] explore options for gap financing to ensure property owners can participate in retrofit programs" [84]. High capital costs especially of solar panel, high efficiency space and water heating systems must be addressed to ensure an equitable transition to residential building electrification. Along with this, we need to consider the impact on operating costs. "Bill stability is the critical equity issue" [84]. This is a critical point because as residents shift towards complete residential building electrification, it must be noted that in LADWP's Strategic Long-Term Resource Plan they estimate that electricity rates will increase from their 2022 level of just over 20¢/kWh to over 64¢/kWh by 2045 and increase of over 68%. Given these concerns and LADWPs plans for electricity rates, it is critical we understand the impact electrification will have on residents' utility bills.

The next most important community concern was the conditions of current household infrastructure. As one resident voiced "years of deferred maintenance on older building is a barrier to deep energy efficiency or electrification retrofits" [84]. Many of the comments on current household conditions focused on the ability of current residential buildings to effectively incorporate proposed upgrades. One resident commented, "[We] can't have a rooftop solar conversation with having a conversation about where we find resources to replace roofs in order to install solar" [84]. Another noted, "many multifamily affordable housing owners have older properties with deferred maintenance that might not have the infrastructure to support things like upgraded cooling systems" [84]. These residents are worried that the city is overlooking existing issues that will negate or seriously reduce the effectiveness of clean energy technologies. Therefore, we must take into account the current building characteristics in Los Angeles to provide the best

recommendations for electrification upgrades

The next most common concerns of residents were the themes of indoor comfort and universal access to cooling to ensure safe and comfortable temperature in their homes. As one resident said: "Low-income people and especially low-income elderly people are important to prioritize because they may not have access to air conditioning. [...]. The ability to run air conditioning during a heat wave can save lives, keep medicine from going bad, and keep small businesses afloat that require cooling" [84]. Another resident stated, "rising energy costs to keep homes at a comfortable living temperature is a community concern" [84]. Therefore, along with decreasing dangerously high indoor air temperatures in homes by understanding the impact of improved envelope characteristics and access to cooling technologies, we must also consider the costs associated with retrofits. This shows the intersectionality of the major concerns voice by residents – affordability and comfort. These residents are not alone in their concerns. According to the 2022 Berkley IGS Poll, nearly two-thirds of Los Angeles County residents "believe extreme heat poses a serious threat to their and their family's health and safety" [266]. Given resident concerns, along with pure space heating electrification we will also examine adding cooling by installing heat pumps which provide both space heating and cooling.

The fourth most common concern residents voiced was the difficult dynamics in the renter-landlord relationship. One resident shared, "Installing such equipment becomes challenging when renters require approval or buy-in from landlords to purchase and install home upgrades" [84]. As another resident stated "There are split incentives and renters don't have influence over insulating the buildings, along with other infrastructure issues" [84]. Again, we see the interconnect of these concerns – renters' lack of agency and concerns with current infrastructure. Given these concerns, we must disaggregate the building stock to understand which households are renters versus owners and provide the cost data that is relevant to all resident roles – landlords, renters, and owners – to understand the challenge each group faces in a transition to residential building electrification.

APPENDIX B

CHAPTER 3: SUPPLEMENTAL INFORMATION

B.1 Literature Review

There is an existing body of work on modeling the consumer economics of space heating electrification retrofit upgrades in residential buildings. Focusing on studies that examined the costs for homeowner, landlords, and renters of retrofitting existing homes, these studies fall into two categories: white-box physics-based models and black-box econometric models. White-box physics-based modeling studies leverage state or national survey data to generate unique building energy models where electrification upgrades can be simulated. While these types of studies report out on the household level and the building energy usage data generated can be aggregated to understand specific trends, they do require significant computational resources to develop. Black-box econometric modeling studies generate lower resolution results by applying building and technology saturation characteristics to a residential building stock. These models generate overall building stock energy usage data which can be averaged across generalized sections of the building stock. These types of studies require much less development work, but their resolution is restricted to the data they use which is usually at the state, regional, or national level. Table B.1 gives an overview of all these studies, their study design, and reporting metrics

Table B.1 Overview of space heating electrification economic modeling studies

		Study Design						***Reporting***		
Study Type	***Study***	*Includes all installation costs*	*HVAC sizing and pricing*	*Discount Rate Type (Value)*	*Baseline Space Heating Technology*	*Upgrade Space Heating Technology*	*Analyze those with and without Cooling*	*Building Type*	*Income Level*	*Renter/ Owner*
White-box physics-based models	Patteeuw et al. (2015)	No	Mixed	Fixed (7%, 3.5%)	Baseline not analyzed	ASHP GSHP	No	Single-Family	No	No
	Asaee et al. (2017)	No	Variable	Fixed (1%, 3%, 6%, 9%)	All technologies	AWHP	No	Single-Family	No	No
	Mahone et al. (2019)	Yes	Fixed	Fixed (3.35%)	Fuel furnaces	ASHP MSHP PTHP3	No	Single-Family Multi-Family	No	No
	Deetjen et al. (2021)	No	Mixed	Fixed (7%)	All technologies	ASHP	Yes	Single-Family	No	No
	Billimoria et al. (2021)	Yes	Fixed	Not specified	Fuel furnaces	ASHP	Yes	Single-Family	No	No
Black-box econometric models	Nadel (2016)	No	Fixed	Fixed (5%)	Fuel furnaces	Did not specify	Yes	Did not specify	No	No
	Kelly et al. (2016)	No	Fixed	Fixed 5%	All technologies	ASHP	No	Single-Family	No	No
	Hopkins et al. (2018)	No	Fixed	Fixed (5%)	Fuel furnaces	ASHP	Yes	Single-Family Multi-Family	No	No
	Partridge (2018)	Yes	Fixed	Fixed (5%)	Fuel furnaces	ASHP	No	Did not specify	No	No
	Nadel (2018)	No	Fixed	Fixed (5%)	Fuel furnaces	ASHP MSHP	No	Did not specify	No	No

Table B.1 Continued.

		Study Design						***Reporting***		
Study Type	***Study***	*Includes all installation costs*	*HVAC sizing and pricing*	*Discount Rate Type (Value)*	*Baseline Space Heating Technology*	*Upgrade Space Heating Technology*	*Analyze those with and without Cooling*	*Building Type*	*Income Level*	*Renter/ Owner*
	Kaufman et al. (2019)	No	Fixed	Fixed (10%)	Fuel furnaces	ASHP	No	Did not specify	No	No
	Kolwey and Petroy (2022)	Yes	Fixed	Not specified	Fuel furnaces	ASHP	No	Single Family	No	No
	Nadel and Fadali (2016)	Yes	Fixed	Fixed (5%)	All technologies	ASHP MSHP	Yes	Single-Family Multi-Family	Yes	No

B.2 Load Research Data Validation

Model validation was completed by comparing load research data (LRD) from LADWP with data produced by the custom Los Angeles ResStock model. The LRD from LAWDP was for the year 2012, therefore in our validation of the baseline scenario we used 2012 actual meteorological year weather data. The one caveat is that the residential stock is supposed to represent 2020. Therefore, once our validation was completed, we used modified 2012 weather data to represent weather in 2020.

The validation for the comparison to LRD from LADWP was done in various ways: load duration curves, seasonal load shapes, and high load days for each season. In terms of load duration curves, the custom Los Angeles ResStock model compares well to the LRD (Figure B.1). Across the load duration curve, our model is almost entirely within 10% of the LRD data, and our model is less than 10% off the peak of the load duration curve.

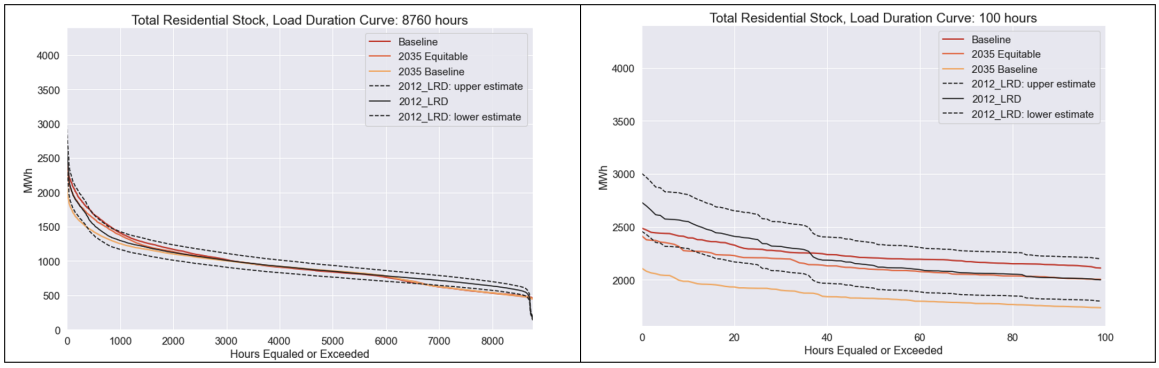

Figure B.1 Left) 2012 load duration curve comparison, Right) Comparison to the top 100 hours of the 2012 load duration curve.

The seasons are for winter, summer, and the shoulder season. Winter for 2012 is defined by months 1, 2, 3, and 12. Summer for 2012 is defined by months 5, 6, 7, 8, and 9. The shoulder season for 2012 is defined by months 4, 10, and 11. Similar to the load duration curve, the seasonal load shapes for the custom Los Angeles ResStock model compare favorably to the LRD with some exceptions (Figure B.2). The summer weekend cooling load is a little high, the winter morning weekday and weekend peak is more pronounced than in the LRD, and in general the shoulder season weekday baseload is lower than in the LRD. These trends are similar to those for the average seasonal high load day load shape comparison (Figure B.3).

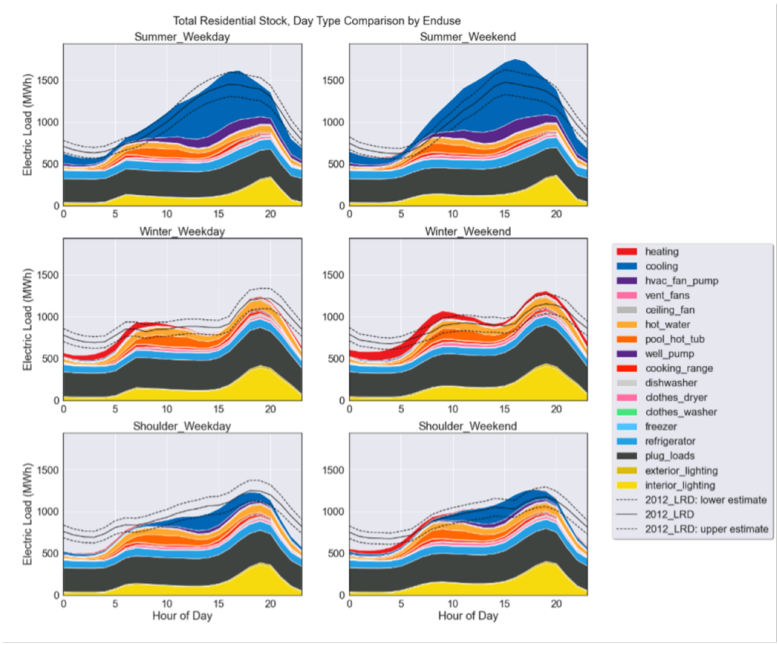

Figure B.2 Baseline seasonal average stacked end-uses

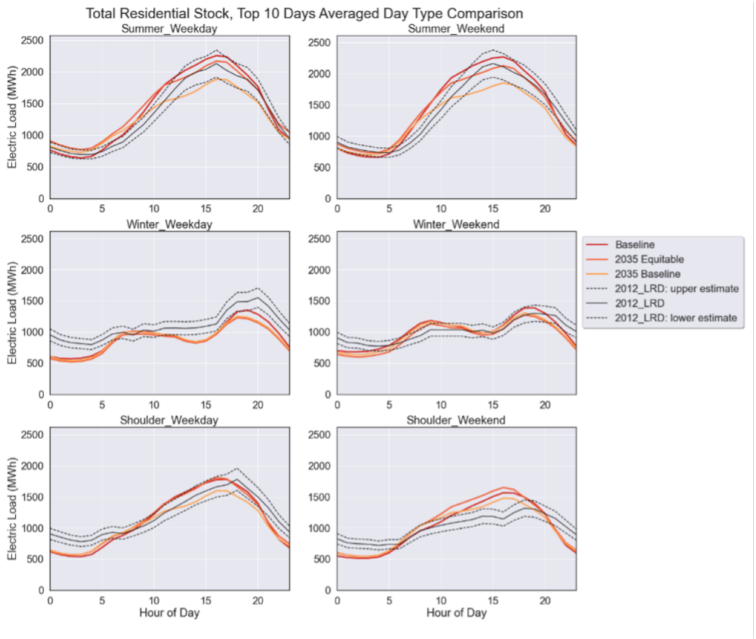

Figure B.3 Average of top 10 highest load days for each season by scenario

B.3 Internal Consistency and Diversity Comparative Framework Evaluation

Table B.2 outlines the classification and rationale for that classification for each of the metrics in the Internal Consistency and Diversity Comparative Framework as developed by Sandoval et al. [193].

Table B.2 Baseline seasonal average stacked end-uses

Metric	Classification	Rationale
Stakeholder Involvement	Purposefull	Stakeholders in this project include scientists and engineers at the NREL, a group of advisory committee members from LADWP, a group of steering committee members who are representatives from Los Angeles community-based organization. While this represents a diverse array of perspectives which aided in the development of the different electrification upgrade scenarios, the authors of this study did not partake in the selecting these individuals or organizations and thus cannot comment on the selection process of these stakeholders.
Narrative Complexity	Detailed	A detailed description of the purpose for each variable (space heating and cooling technology, discount rate, and rate projection) is available in the methods section.
Data Utilization	Detailed	A detailed description of the data used to represent each variable (space heating and cooling technology, discount rate, and rate projection) is available in the Methods section.
Public Availability	Limited	Journal publication requires access
Ease of Access	High	All scenario information can be found in the Methods section and Appendix A.
Variable Type	Only demand side variable	The inclusion of only demand side variable is sufficient to answer the research questions of this study because the research questions only pertain residential building space heating and cooling technology characteristics and their impact on capital and operating costs.
Variable Control	Internal and limited variables	This study features multiple internal control variables, where the types of cooling technology (e.g., code-minimum equipment) upgrades are governed by current laws. This study also features limited control variables looking at upgrades that residents can currently opt into. This study did not investigate external control variables because the purpose of this study is to examine different building space heating electrification upgrades.
Scenario Outlook	Descriptive	All the scenarios in this study aim to understand what would happen given the implementation of certain building upgrades. We were not trying to reduce energy consumption to a certain level or obtain a minimum cost/payback period. Therefore, we did not find it necessary to include a normative scenario.
Scenario Progression	Disruptive	This study only examines the impact of a complete change to electrified space heating in Los Angeles. This change would create a significant disruption to the status quo by reducing natural gas markedly in the colder months and increasing electricity demand in the colder months for the electric equivalent upgrade and year-round in the heat pump upgrades.

B.4 Detailed Overview of Cashflow Creation

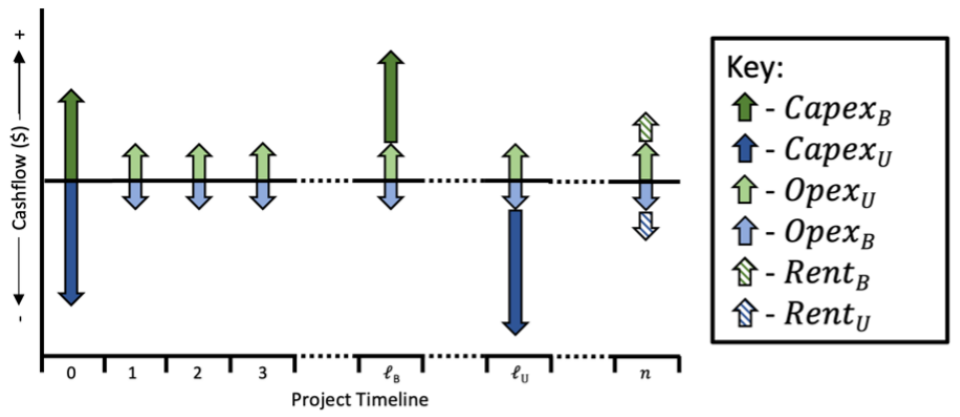

Figure B.4 Illustrative cashflow for space heating electrification upgrade.

Figure B.4 shows a cashflow with the various costs and timing of these costs of a space heating electrification upgrade as modeled in this study. At t=0 , a household installs a space heating upgrade instead of the baseline technology which did exist in their dwelling unit previously. Therefore, the household avoids the cost of the baseline technology (Capex_B) and incurs the cost of the upgrade technology (Capex_U). To determine the difference in capital costs at t=0, these two capital costs are added and subtracted to the cashflow, respectively. Here we also calculate the difference in capital costs for each building in each upgrade scenario. The net upgrade capital cost, Capex_diff, is calculated as shown in Equation B.1. This difference in capital costs is especially relevant to owners and landlords.

$$Capex_{diff} = (Capex_{B,equip} + Capex_{B,install}) - (Capex_{U,equip} + Capex_{U,install} + Capex_{U,fs}) \quad \text{(B.1)}$$

Where $\text{Capex}_\text{B,equip}$ and $\text{Capex}_\text{U,equip}$ are the equipment costs of the baseline and upgrade systems, respectively, $\text{Capex}_\text{B,install}$ and $\text{Capex}_\text{U,install}$ are the installation costs of the baseline and upgrade systems, respectively, and $\text{Capex}_\text{U,fs}$ is the cost of fuel switching for the upgrade system.

At t=1 through t=n , the household pays the difference in operating costs of the baseline (Opex_B) and upgrade (Opex_U) space heating systems. Here we also calculated the annual change in utility bills by summing the difference in these terms from t=1 through t=12 . The net annual upgrade operating cost, $\text{Opex}_\text{annual diff}$, is calculated as shown in Equation B.2. This difference in operating costs is especially relevant to owners and renters.

$$Opex_{annualdiff} = \sum_{t=1}^{12}(Opex_{B,t} - Opex_{U,t}) \tag{B.2}$$

Where $\text{Opex}_{\text{B,t}}$ and $\text{Opex}_{\text{U,t}}$ are the operating costs at time, t , for the baseline and upgrade systems, respectively.

Finally, these systems need to be replaced after the end of their average lifetime. Replacing these systems depends on the average lifetime of the equipment being replaced and the remaining time in the projection period. If the average lifetime of the system is smaller than the remainder of the projection period, the baseline or upgrade space heating system will be replaced and the full capital costs of these systems will be avoided or incurred at t=l

$$Rent = Capex * \frac{r(1+r)^r}{(1+r)^r - 1} \tag{B.3}$$

Where Capex is the capital cost of the rental equipment, r is the monthly interest rate, and n is the length of the rental in months.

B.4.1 Rate Projection and Operating Costs

To calculate future energy prices for both natural gas and electricity, the NPV Upgrade Analysis Model generates the current and projected volumetric revenues from for electricity and natural gas (Figure 3.1 – Volumetric Revenue Subroutine) and then uses these to create electricity and natural gas rates for the entire projection period (Figure 3.1 - Rate Projection Subroutine). The Volumetric Revenue Subroutine begins by calculating the simulated electric and natural gas volumetric revenues by multiplying the current LADWP and Southern California Gas Company rates by the monthly electricity consumption and the daily natural gas consumption generated by the Custom Los Angeles ResStock model, respectively. This data is stored on the Amazon Web Services' (AWS) Athena Database platform. Using python, we were able to query the data from AWS to determine daily natural gas consumption, monthly electricity consumption, and the zip code for each dwelling unit simulated (Figure 3.1 – Athena Query Subroutine). For general residential electric service in Los Angeles, tiered electricity rates are assigned based on both your zip code and the maximum monthly electricity consumption from the previous year – the higher the consumption, the higher the price per kilowatt-hour. Los Angeles residents can also opt-in to a time of use electricity rate [104]. While the NPV Upgrade Analysis Model can be augmented to do this analysis, this was not a part of this study. For natural gas, Southern California Gas Company prices household consumption on a more traditional tiered structure where each household pays a baseline rate up to the daily therm allowance and then the non-baseline rate for any consumption beyond that [105]. Next, using the same

energy consumption data generated by the Custom Los Angeles ResStockTM model and EIA's 2023 Annual Energy Outlook (AEO) rate projection for the entire projection period (2022 to 2050) [202]. the model calculates the AEO electricity and natural gas volumetric revenues for the base year (2022) and for the entire projection period (2023 to 2050). Following this, the model calculates the difference between the volumetric revenues LADWP and Southern California Gas Company with the AEO base year volumetric revenues. This difference is then applied to the projected AEO volumetric revenues to determine the projected LADWP and Southern California Gas Company volumetric revenues for the entire projection period. Figure B.5 graphically represents the calculations performed by the Volumetric Rate Subroutine.

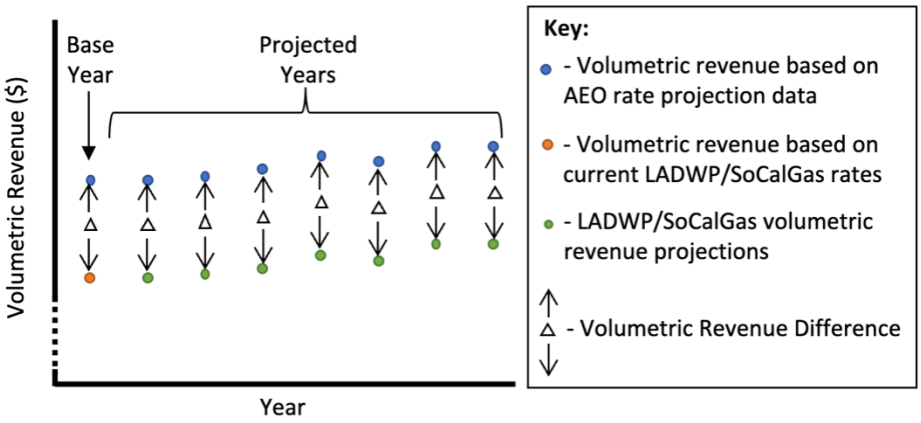

Figure B.5 Graphical representation of rate projection calculation using AEO and Los Angeles specific rates

The Rate Projection Subroutine then takes the projected electricity and natural gas volumetric revenues and computes the percent difference between the base year and each year in the projection period. The percent difference for each year in the projection period is then applied to the current LADWP and Southern California Gas Company rates to generate natural gas and electricity rates for the entire projection period. The operating costs for the baseline and electrification upgrade scenarios for each simulated dwelling unit are then calculated in the Utility Difference Subroutine by multiplying the natural gas and electricity consumption for each dwelling unit by their respective rate. The difference between these operating costs creates an initial cashflow for the electrification upgrade in question.

B.4.2 Capital Costs

Using a technology cost library along with the unique household characteristics of each simulated dwelling unit, we calculated the changes in capital costs associated with each upgrade scenario. In the Summer and Fall of 2022, we collected capital cost data for all baseline and upgrade technologies. For this study, we defined capital costs to include the purchase, installation, labor, and fuel switching costs. For

each natural gas appliance that was replaced with an electric one, the cost of fuel switching included capping the existing natural gas line and running one or more dedicated electric circuits to the electric technology based on its type and size. 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 necessary expense of an electric panel upgrade which could cost residents hundreds if not thousands of dollars more. Along with an overview of the cost data, the following section goes into detail about the development of this cost library including the search methodology and data sources. Also, note that capital cost is broken down into fixed and variable costs based on each technology. Along with the capital cost data, we found the lifetime data for all baseline and upgrade technologies based on data from the EIA [198].

The Technology Lifetime Subroutine takes the initial cashflow created by the Utility Difference Subroutine. For each dwelling unit, it takes the baseline cost and lifetime data and calculates the avoided cost of technology and adds this amount at t = 0, in the cashflow and then again at t=l, where l represents the lifetime of the technology. If the technology's next lifetime extends beyond the projection period, we added the avoided monthly fee for renting that technology, with a market interest rate of 5%, through the end of the projection period. The same process is done for the electrification upgrade technology which will replace the baseline technology, however instead of adding this value, the cost of the upgrade is subtracted from the cashflow.

B.5 Cost Library and Search Methodology

The methodology to determine the costs of the upgrade technologies is as follows. First, we reviewed the data from various technology cost databases (Table B.3). A summary was created for each upgrade including technology type, fuel type, efficiency, capacity, and other relevant features. Next, the raw data from these sources was collected which included all the features mentioned in the summary along with the types of costs available, total project costs, material costs, labor costs, hourly labor rates, and labor hours (Data available upon request). From this summary and data collection, we were able to decide if a particular data source or combination of data sources could supply all the upgrade costs needed for a particular upgrade. Next, these costs were compared to local hardware retailers and online wholesalers/suppliers (Table B.4), to determine if the costs were within a reasonable range. If a particular data sources or a combination of data sources could not supply the upgrade costs due to a lack of information or if their costs were outside an acceptable range based on the local hardware retailer or wholesaler/supplier prices, we found the lowest cost from the retailer or wholesaler and used this for the equipment price. Installation costs were either included in total project costs if this was the information

available. If not, installation costs were calculated by determining the type of labor needed (e.g., electrician), the associated hourly rate for that labor type, and the labor hours, along with fuel switching costs.

Table B.3 Cost Databases

Name	Who (Where)	Data Collection Method (Year)	Type of Cost Data	Technologies
eTRM	California Technical Forum (California)	Various (Itron Report 2010-2012), (RSMeans, various), (Data collected from online retailers/ wholesalers/suppliers, various)	Material Costs Labor Costs Labor Hours	Wall insulation, ceiling insulation, water heating, cooking range, clothes drying, HVAC (ASHP, MSHP, furnace, wall/floor furnace, AC, Room AC)
LBL Cost Data	LBL (Primarily CA, MA, and NC)	Survey to contractors with incentives for completion, 2020	Total Project Costs	Water heating, air sealing, wall insulation, ceiling insulation, windows, clothes drying, HVAC (ASHP, MSHP, NG furnace, AC)
National Residential Efficiency Measures Database	NREL (Nationwide)	2010	Total Project Costs	Water heating, cooking range, clothes drying, air sealing, wall insulation, ceiling insulation, windows, HVAC (ASHP, baseboards, boilers, MSHP, furnaces, wall/ floor furnaces, AC, room AC)
Navigant	Navigant Consulting (MA)	Contractor survey, webscraping, rebate program invoices, 2018	Total Project Costs	Water heater, HVAC (furnaces, boiler)
Building construction costs with RSMeans data	RSMeans (Nationwide)	Various	Material costs, hourly labor rate, labor-hours, material and labor factors	Water heating, wall insulation, ceiling insulation, lighting, windows, HVAC (boiler, furnace, fan coil AC, ASHP)

B.5.1 Cost Library

While most data sources had information on space heating technologies all their cost data was either associated with models that were significantly less efficient as compared to the upgrades that we used in this study or was very dated. Therefore, we went beyond these sources to find what we believed to be the most accurate cost data. For heat pumps, the only source with efficiencies close to what we used was a

Table B.4 Local Hardware Retailers and Online Wholesalers/Suppliers

Local Hardware Retailers	
Home Depot	www.homedepot.com
Lowes	www.lowes.com
Online Wholesalers/Suppliers	
Consumers Supply Company	www.consumersplumbing.com
Supply House	www.supplyhouse.com
National Pump Supply	www.nationalpumpsupply.com
AC Wholesalers	www.acwholesalers.com
The Furnace Outlets	www.thefurnaceoutlets.com
Craft Supply	www.thecraftsupply.com
Oswald Supply	www.oswaldsupply.com
eComfort	www.ecomfort.com
HighSEER	www.highseer.com

regression created with the LBL Cost Data. For ASHP, this regression was based on HSPF and capacity. Whereas MSHP costs were only based on capacity. For Natural Gas Wall and Floor Furnaces and Electric Baseboards, while several online wholesalers/suppliers had some cost information, Home Depot supplied the most comprehensive information from which we were able to develop regression models for sizing. For the remaining technologies, online wholesalers/suppliers provided the most recent and comprehensive pricing information from which we were able to create reliable regression models. A breakdown of all the costs used in the NPV Upgrade Analysis Model are shown in Table B.5.

Table B.5 Equipment and Installation costs for all space heating technologies and associated fuel switching

Technology	Cost Type	Cost Breakdown
Low-Efficiency ASHP (SEER 15, 8.5 HSPF)	Total Costs	Unit Cost: $2250 Variable Cost: $160 Variable Unit: kbtu-h
Mid-Efficiency ASHP (SEER 18, 9.3 HSPF)	Total Costs	Unit Cost: $4250 Variable Cost: $160 Variable Unit: kbtu-h
High-Efficiency ASHP (SEER 24, 10.8 HSPF)	Total Costs	Unit Cost: $7950 Variable Cost: $160 Variable Unit: kbtu-h
Low-Efficiency MSHP (SEER 17, 9.5 HSPF)	Total Costs	Unit Cost: $2330 Variable Cost: $300 Variable Unit: kbtu-h
Mid-Efficiency MSHP (SEER 25, 12.7 HSPF)	Total Costs	Unit Cost: $2330 Variable Cost: $300 Variable Unit: kbtu-h
Low-Efficiency MSHP (SEER 33.1, 13.5 HSPF)	Total Costs	Unit Cost: $2330 Variable Cost: $300 Variable Unit: kbtu-h

Table B.5 Continued.

Technology	Cost Type	Cost Breakdown
Electric Furnace	Equipment Costs	Unit Cost: $825 Variable Cost: $5.6 Variable Unit: kbtu-h
	Installation Costs	Labor Hours: 10 Hourly Rate: $140
	Fuel Switching Costs	Labor Hours: 2.25 Hourly Rate: $130
Electric Boiler	Equipment Costs	Unit Cost: $805 Variable Cost: $19.6 Variable Unit: kbtu-h
	Installation Costs	Labor Hours: 10 Hourly Rate: $140
	Fuel Switching Costs	Labor Hours: 2.25 Hourly Rate: $130
Electric Baseboards	Equipment Costs	Unit Cost: $26 Variable Cost: $11.8 Variable Unit: kbtu-h
	Installation Costs	Labor Hours: 2 Hourly Rate: $140
	Fuel Switching Costs	Labor Hours: 2.25 Hourly Rate: $130
3*Electric Wall Furnace	Equipment Costs	Unit Cost: $295 Variable Cost: $8.8 Variable Unit: kbtu-h
	Installation Costs	Labor Hours: 2.5 Hourly Rate: $140
	Fuel Switching Costs	Labor Hours: 2.235 Hourly Rate: $130
Natural Gas Furnace (76% and 80% AFUE)	Equipment Costs	Unit Cost: $620 Variable Cost: $6.3 Variable Unit: kbtu-h
	Installation Costs	Labor Hours: 10 Hourly Rate: $140
Natural Gas Furnace (92.5% AFUE)	Equipment Costs	Unit Cost: $970 Variable Cost: $8.0 Variable Unit: kbtu-h
	Installation Costs	Labor Hours: 10 Hourly Rate: $140
Natural Gas Boiler (76% and 80% AFUE)	Equipment Costs	Unit Cost: $1385 Variable Cost: $21.1 Variable Unit: kbtu-h
	Installation Costs	Labor Hours: 10 Hourly Rate: $140
Natural Gas Boiler (90% AFUE)	Equipment Costs	Unit Cost: $1830 Variable Cost: $20.4 Variable Unit: kbtu-h
	Installation Costs	Labor Hours: 10 Hourly Rate: $140
Natural Gas Wall and Floor Furnace	Equipment Costs	Unit Cost: $745 Variable Cost: $11.9 Variable Unit: kbtu-h

Table B.5 Continued.

Technology	Cost Type	Cost Breakdown
	Installation Costs	Labor Hours: 2.5 Hourly Rate: $140
Dedicated Electric Circuit	Total Costs	Labor Hours: 2.25 Hourly Rate: $130

B.6 HVAC Heat Pump Cost Validation

Of all the technologies listed above, the cost data for mini-split heat pumps (MSHP) and air source heat pumps (ASHP) has the highest uncertainty. This uncertainty is due to the fact that these technologies are some of the least mature in terms of wide-spread manufacturing and installation across the US. To compound this, the efficiency level of the heat pumps we are modeling is incredibly high. The data we used to model these costs is from the LBL Cost Data which was collected by surveying contractors about a number of the energy efficiency and technologies upgrade projects the completed. For the ABC Typology project, a regression was done on the cost to install these heat pumps and these regressions were used in our project as well. For ASHP, 317 data points were used to generate a set of regression equations based on capacity (tons) and HSPF. For this project, we modeled a SEER 26.1, 11 HSPF ASHP which based on the regressions called for a base cost of $9440 with a unit cost of $160/kbtu-h. For MSHP, 187 data points were used to generate a single regression equation solely based on capacity (tons). For this project, we modeled a SEER 33.1, 13.5 HSPF MSHP which based on the regression called for a base cost of $2330 with a unit cost of $300/kbtu-h.

To validate this data, we compared the modeled prices of installed ASHP and MSHP HVAC units in our model with data from TECH Clean California which is a state initiative to accelerate the adoption of clean water and space heating technologies [197]. From their website, it is possible to access the data they have collected from the projects which were completed and incentivized through this program [197]. For ASHPs and MSHPs, the cost for 695 and 178 different projects, respectively, were reported and used in this cost validation. Our first step to validate our modeled costs data was to compare the cost distributions of the BAU and Equity scenarios we modeled in this project to the TECH Clean California data. See Figure B.6, Figure B.7, and Figure B.8.

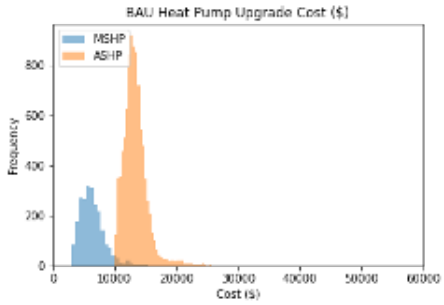

Figure B.6 BAU Scenario Heat Pump Upgrade Cost Distribution

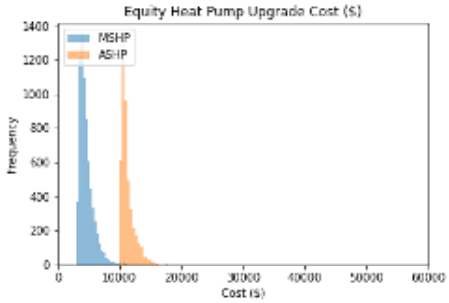

Figure B.7 Equity Scenario Heat Pump Upgrade Cost Distribution

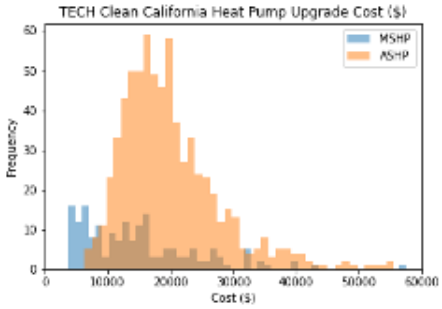

Figure B.8 TECH Clean California Heat Pump Upgrade Cost Distribution

While the general trends of MSHPs being less expensive overall as compared to ASHP systems held true for all three datasets, the TECH Clean California data showed much higher costs. To verify if this was true, we then normalized the costs of these systems to their capacity (in kbtu-h). See Figure B.9, Figure B.10, and Figure B.11.

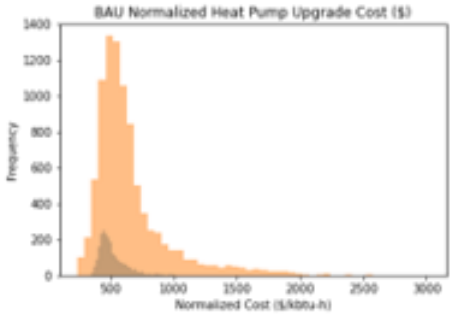

Figure B.9 Normalized BAU Scenario Heat Pump Upgrade Cost Distribution

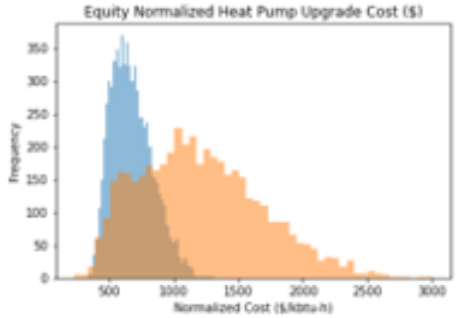

Figure B.10 Normalized Equity Scenario Heat Pump Upgrade Cost Distribution

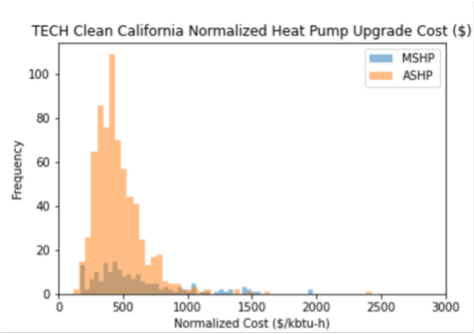

Figure B.11 Normalized TECH Clean California Heat Pump Upgrade Cost Distribution

With this normalization, we see that the BAU scenario and TECH Clean California data very similar distributions for both heat pump types. For ASHP, we see an average cost at approximately $500/kbtu-h with positively skewed distribution. For MSHP, we see an average cost of slightly below $500/kbtu-h also with a positively skewed distribution. However, the costs for the Equity scenario do not align as well and are much greater per kbtu-h for both ASHPs and MSHPs. To understand this, we next compared the

household size in terms of conditioned area. See Figure B.12, Figure B.13, and Figure B.14.

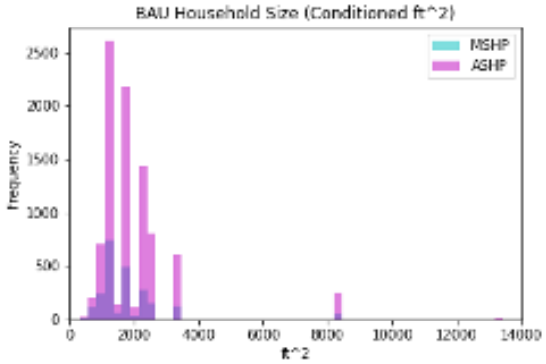

Figure B.12 BAU Scenario Household Size Distribution

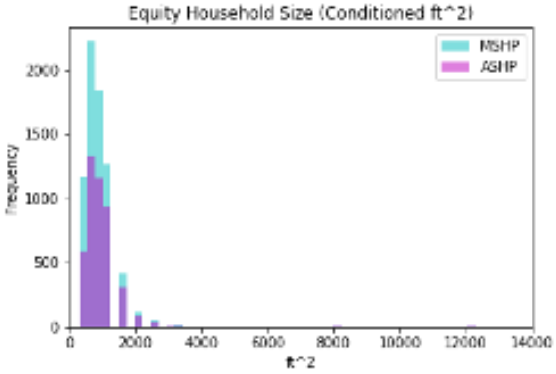

Figure B.13 Equity Scenario Household Size Distribution

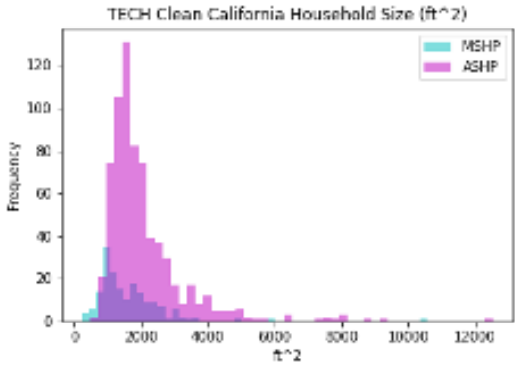

Figure B.14 TECH Clean California Household Size Distribution

From this comparison, we see that a majority of the households in the BAU scenario and the TECH Clean California data are between 1000-3000 square feet in size. Whereas most households in the Equity scenario are between 500-1500 square feet in size. For these smaller households, the sizes of these HVAC systems are going to be smaller. Therefore, the costs are going to be dominated by the large base costs of both ASHPs and MSHPs. This tallies with the larger cost per kbtu-h which we saw in the normalized costs figure (Figure B.9, Figure B.10, Figure B.11). With this data comparison, we are confident that the cost data we used based on the LBL cost data regressions for ASHP and MSHP is reasonable given the corroboration of these costs with the TECH Clean California cost data.

B.7 Additional Results Figures

Table B.6 Median Capital Cost Savings for Owners of households which have and use their Central AC systems (Note: Negative values indicate an increase in capital costs compared to baseline natural gas systems)

			Upgrade 1: Electric Equivalent	Upgrade 2: Low-efficiency Heat Pump	Upgrade 3: Mid-efficiency Heat Pump	Upgrade 4: High-efficiency Heat Pump
Baseline HVAC System		Building Type	Owner	Owner	Owner	Owner
Natural Gas Furnace	Central AC	Multi-Family	-$484	-$829	-$2,251	-$5,615
		Single-Family	-$461	-$3,487	-$5,594	-$8,988

Table B.7 Median Annual Operating Cost Savings for Owners of households which have and use their Room AC systems (Note: Negative values indicate an increase in operating costs compared to baseline natural gas systems)

		Upgrade 1: Electric Equivalent	Upgrade 2: Low-efficiency Heat Pump	Upgrade 3: Mid-efficiency Heat Pump	Upgrade 4: High-efficiency Heat Pump
Baseline HVAC System		Owner	Owner	Owner	Owner
Natural Gas Furnace	Room AC	-$16.1	-$51.6	-$90.2	-$266.2
Natural Gas Boiler	Room AC	-$62.8	$220.6	$427.3	$544.8
Natural Gas Wall/Floor Furnace	Room AC	-$48	$228.8	$428.2	$532.4

Table B.8 Median Annual Operating Cost Savings for Owners of households which do not have or do not use cooling systems (Note: Negative values indicate an increase in operating costs compared to baseline natural gas systems)

	Upgrade 1: Electric Equivalent	Upgrade 2: Low-efficiency Heat Pump	Upgrade 3: Mid-efficiency Heat Pump	Upgrade 4: High-efficiency Heat Pump
Baseline Space Heating Technology	Owner	Owner	Owner	Owner
Natural Gas Furnace	$121	$0	$16	$36
Natural Gas Boiler	-$95	-$2	$17	$25
Natural Gas Wall/Floor Furnace	-$83	$7	$26	$34

Table B.9 Median Capital Cost Savings for Owners of households with natural gas boilers which have and use their room AC systems (Note: Negative values indicate an increase in capital costs compared to baseline natural gas systems

			Upgrade 1: Electric Equivalent	Upgrade 2: Low-efficiency Heat Pump	Upgrade 3: Mid-efficiency Heat Pump	Upgrade 4: High-efficiency Heat Pump
Baseline HVAC System		Building Type	Owner	Owner	Owner	Owner
Natural Gas Boiler	Central AC	Multi-Family	$303	-$821	-$821	-$1,004
		Single-Family	$323	-$3,713	-$3,626	-$4,229

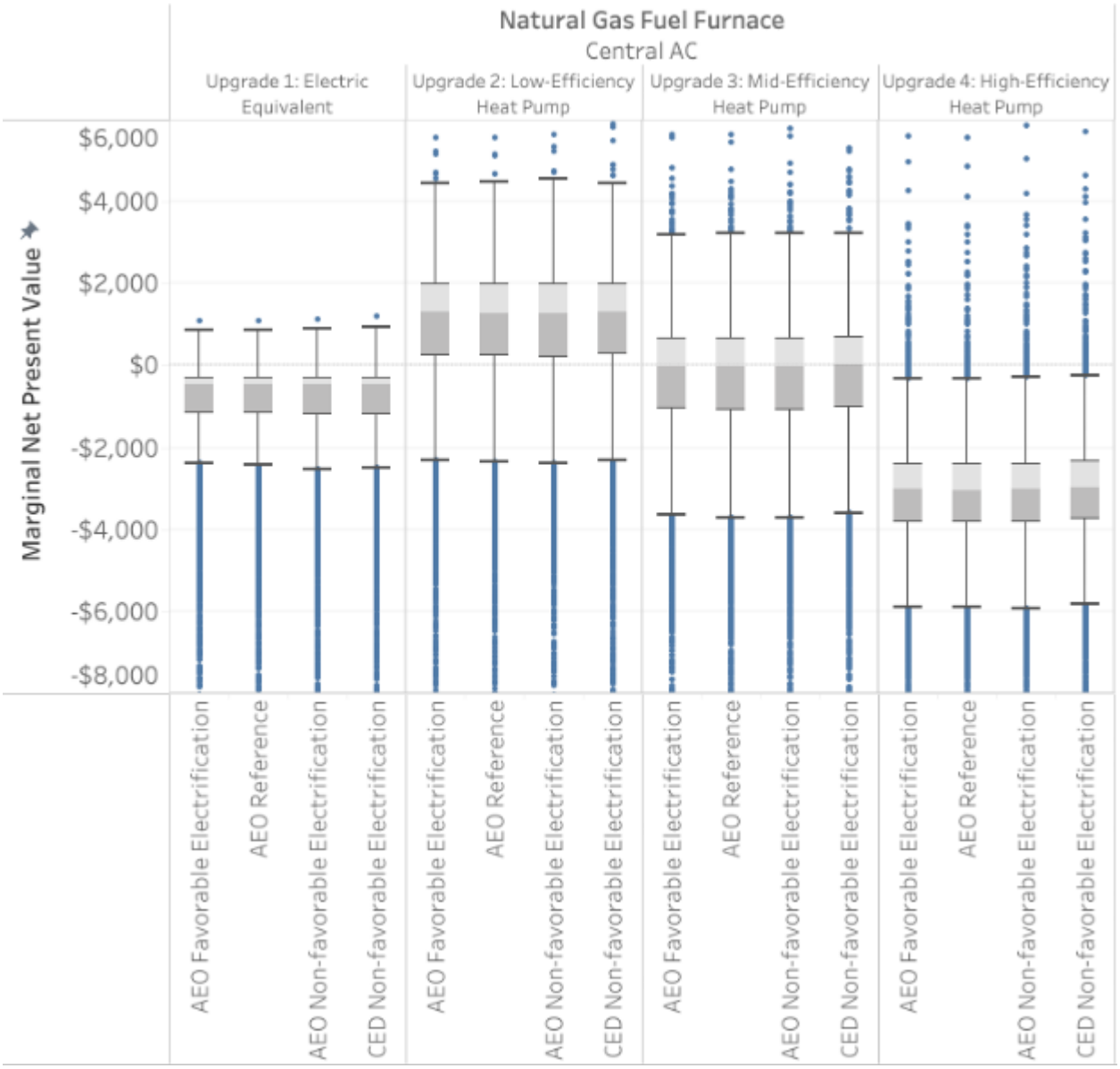

Figure B.15 Rate Projection Sensitivity Analysis for households which have and use Natural Gas Furnaces and Central AC systems.

Table B.10 Median Annual Operating Cost Savings for Renters (Note: Negative values indicate an increase in operating costs compared to baseline natural gas systems)

		Upgrade 2: Low-efficiency Heat Pump			Upgrade 3: Mid-efficiency Heat Pump			Upgrade 4: High-efficiency Heat Pump		
Utility Bill Assistance Eligibility	Baseline Space Heating Technology	25th Percentile	50th Percentile	75th Percentile	25th Percentile	50th Percentile	75th Percentile	25th Percentile	50th Percentile	75th Percentile
Eligible	Natural Gas Furnace	-$2.4	$6.9	$40.5	$8.4	$52.4	$130.4	$20.7	$106.4	$230.7
	Natural Gas Boiler	-$24.6	-$2.9	$18.7	-$9.9	$4.3	$44.9	-$4.7	$10.7	$66.6
	Natural Gas Wall/Floor Furnace	-$19.7	$0.3	$31.2	-$6.4	$12.1	$69.8	-$2.4	$20.1	$101.5
Ineligible	Natural Gas Furnace	-$6.8	$6.8	$55.9	$11.9	$77.3	$200.6	$31.6	$162.7	$360.1
	Natural Gas Boiler	-$32.2	$0.0	$35.4	-$7.5	$18.4	$86.5	-$0.6	$31.5	$122.7
	Natural Gas Wall/Floor Furnace	-$39.6	$0.8	$52.0	-$10.5	$22.0	$111.9	-$2.7	$37.9	$148.8

Table B.11 Median Annual Operating Cost Savings for Owners and Landlords of households that qualify for IRA benefits that do not use or do not have cooling in the baseline (Note: Negative values indicate an increase in annual costs compared to baseline natural gas systems)

	Upgrade 2: Low-efficiency Heat Pump				Upgrade 3: Mid-efficiency Heat Pump				Upgrade 4: High-efficiency Heat Pump			
	Landlord		Owner		Landlord		Owner		Landlord		Owner	
Baseline Space Heating Technology	0-80% AMI	80-120% AMI	0-80% AMI	80-120% AMI	0-80% AMI	80-120% AMI	0-80% AMI	80-120% AMI	0-80% AMI	80-120% AMI	0-80% AMI	80-120% AMI
Natural Gas Furnace	$0	-$1	$2	$0	$8	$6	$17	$15	$16	$16	$33	$32
Natural Gas Boiler	-$2	$0	-$1	-$3	$3	$9	$16	$12	$7	$15	$23	$23
Natural Gas Wall/Floor Furnace	-$1	$1	$7	-$2	$5	$10	$26	$10	$9	$16	$33	$20

Table B.12 Median Capital Cost Savings for Owners and Landlords of households that qualify for IRA benefits that do not use or do not have cooling in the baseline (Note: Negative values indicate an increase in capital costs compared to baseline natural gas systems)

	Upgrade 2: Low-efficiency Heat Pump				Upgrade 3: Mid-efficiency Heat Pump				Upgrade 4: High-efficiency Heat Pump			
	Landlord		Owner		Landlord		Owner		Landlord		Owner	
Baseline Space Heating Technology	0-80% AMI	80-120% AMI	0-80% AMI	80-120% AMI	0-80% AMI	80-120% AMI	0-80% AMI	80-120% AMI	0-80% AMI	80-120% AMI	0-80% AMI	80-120% AMI
Natural Gas Furnace	$2,781	$835	$3,579	$404	$3,237	$307	$2,988	-$651	$2,065	-$1,297	-$516	-$2,146
Natural Gas Boiler	$3,865	$1,131	$3,314	$178	$3,921	$1,110	$3,412	$181	$3,762	$937	$2,647	-$570
Natural Gas Wall/Floor Furnace	$1,964	-$758	$1,225	-$1,766	$2,022	-$722	$1,290	-$1,700	$1,880	-$1,114	$567	-$2,571

Table B.13 Comparison of parameters and results from NPV Upgrade Analysis Model with previous studies

	Parameters and results from previous studies							***Parameters and results from Marginal NPV Upgrade Analysis Model***			
Previous Study	*Location*	*Building Type*	*Baseline*	*Upgrade*	*Economic Metric*	*Discount Rate*	*Results*	*Baseline*	*Upgrade*	*Economic Metric*	*IQR*
Billimoria et al. (2018)	Oakland, CA	Single-family	Furnace AFUE 95% SEER 14 Central AC	ASHP SEER 18	Net Present Savings (through 15 years)	Not Specified	$1,469	Furnace AFUE 92.5% SEER 13	ASHP SEER 18, 9.2 HSPF	Marginal NPV	-$1453 to $489
								Furnace AFUE 92.5% SEER 15	ASHP SEER 18, 9.2 HSPF	Marginal NPV	-$1704 to $1339
Hopkins et al. (2018)	Los Angeles Basin, CA	Single-family	Furnace AFUE 80% SEER 13 Central AC	ASHP 10.5 HSPF	Net Lifecycle Savings	5%	$1,458 to $892	Furnace AFUE 80% SEER 13 Central AC	ASHP SEER 24, 10.8 HSPF	Marginal NPV	-$4150 to -$2761
Mahone et al. (2019)	Southern CA	Single-family	Furnace AFUE 80% SEER 14 Central AC	ASHP SEER 18, 10 HSPF	Life Cycle Savings	3.5%	$2106 to $7056	Furnace AFUE 80% SEER 13 Central AC	ASHP SEER 18, 9.2 HSPF	Marginal NPV	-$1425 to $326
								Furnace AFUE 80% SEER 15 Central AC	ASHP SEER 18, 9.2 HSPF	Marginal NPV	-$1723 to $991

APPENDIX C

CHAPTER 4: SUPPLEMENTAL INFORMATION

C.1 Capital Cost Library

While most data sources had information on space heating technologies all their cost data was either associated with models that were significantly less efficient as compared to the upgrades that we used in this study or was very dated. Therefore, we went beyond these sources to find what we believed to be the most accurate cost data. For heat pumps, the only source with efficiencies close to what we used was a regression created with the LBL Cost Data. For ASHP, this regression was based on HSPF and capacity. Whereas MSHP costs were only based on capacity. For Natural Gas Wall and Floor Furnaces and Electric Baseboards, while several online wholesalers/suppliers had some cost information, Home Depot supplied the most comprehensive information from which we were able to develop regression models for sizing. For the remaining technologies, online wholesalers/suppliers provided the most recent and comprehensive pricing information from which we were able to create reliable regression models. Table C 1 shows the final capital cost data which was used in the marginal net present value upgrade analysis model.

Table C.1 Cost data used in the marginal net present value upgrade analysis model

Technology	Cost Type	Cost Breakdown
Electric Standard Storage Water Heater	Equipment Costs	Unit Cost: $440
	Installation Costs	Labor Hours: 2.25 Hourly Rate: $130
Electric Premium Storage Water Heater	Equipment Costs	Unit Cost: $740
	Installation Costs	Labor Hours: 2.25 Hourly Rate: $130
Electric Heat Pump Storage Water Heater	Equipment Costs	Unit Cost: $1400
	Installation Costs	Labor Hours: 2.25 Hourly Rate: $130
Electric Standard Tankless Water Heater	Equipment Costs	Unit Cost: $235 Variable Cost: $445 Variable Unit: Occupant bin
	Installation Costs	Labor Hours: 2.25 Hourly Rate: $130

Table C.1 Continued.

Technology	Cost Type	Cost Breakdown
Electric Standard Cooking Range	Equipment Costs	Unit Cost: $630
	Installation Costs	Labor Hours: 2.25 Hourly Rate: $130
Electric Induction Cooking Range	Equipment Costs	Unit Cost: $1500
	Installation Costs	Labor Hours: 2.25 Hourly Rate: $130
Electric Standard Clothes Dryer	Equipment Costs	Unit Cost: $580
	Installation Costs	Labor Hours: 2.25 Hourly Rate: $130
Electric Premium Clothes Dryer	Equipment Costs	Unit Cost: $850
	Installation Costs	Labor Hours: 2.25 Hourly Rate: $130
Electric Heat Pump Clothes Dryer	Equipment Costs	Unit Cost: $1300
	Installation Costs	Labor Hours: 2.25 Hourly Rate: $130

C.2 Additional Results Figures

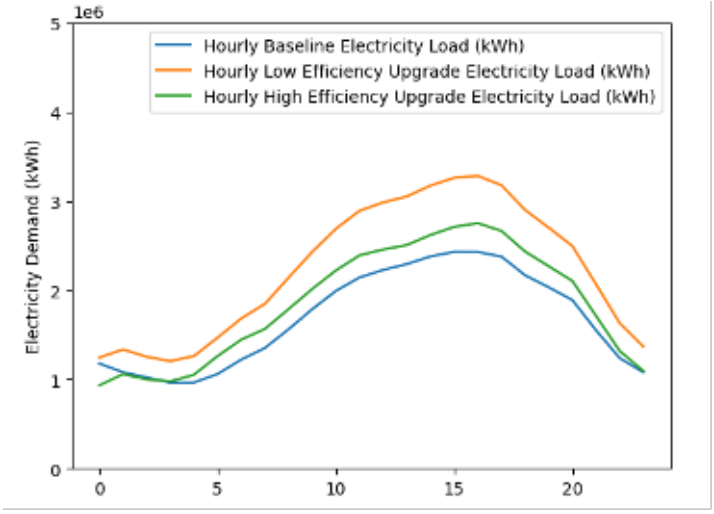

Figure C.1 Hourly electricity consumption for Los Angeles building stock on day of peak summer day consumption

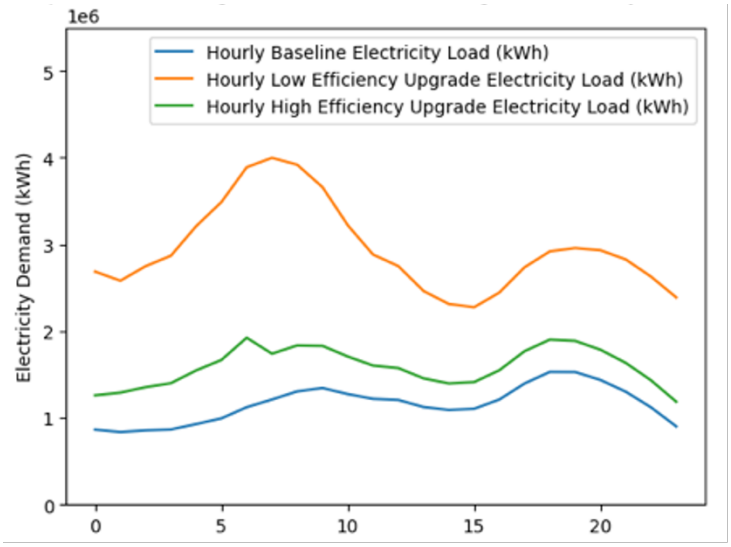

Figure C.2 Hourly electricity consumption for Los Angeles building stock on day of peak winter day consumption

APPENDIX D

CHAPTER 5: SUPPLEMENTAL INFORMATION

D.1 Methodology

Table D.1 Envelope Improvement Upgrade Packages

Upgrade Package	Upgrade Technology	Applicability
E1 – Cool Roofs	White or reflective roof material	All roof types (singles, metal, tile)
E2 – Cost Effective	25% Infiltration Reduction	All dwelling units
	Drill and Fill Wall Insulation	Dwellings with wood stud construction and below R-13 wall insulation.
	Mechanical Ventilation	Dwelling units upgraded to an infiltration level of 7 ACH 50 or less.
E3 – Title 24 New Construction	Infiltration Reduction to 5 ACH50	All dwelling units over 5 ACH50 before upgrades.
	Wall insulation	All dwelling type with wall insulation levels below Title 24 new construction requirements based on wall construction, building type, and CEC climate zone.
	Windows	All dwellings with windows below the Title 24 new construction requirements based on Solar Heat Gain Coefficient and area-weighted average U-factor.
	Attic Insulation	All dwelling type with attic insulation levels below Title 24 new construction requirements based on building type and CEC climate zone.
	Roof Insulation	All dwelling type with attic insulation levels below Title 24 new construction requirements based on roof finish and building type.
	Mechanical Ventilation	All dwelling units.

Table D.2 Scenario parameterization based on heat pump efficiency and type

	Low-Efficiency Heat Pump Systems (HP1)		High-Efficiency Heat Pump Systems (HP2)	
	Ducts	No Ducts	Ducts	No Ducts
Heat Pump System	ASHP: SEER 15, 9 HSPF	MSHP: SEER 17, 9.5 HSPF	ASHP: SEER 24, 10.8 HSPF	MSHP: SEER 33.1, 13.5 HSPF

D.2 Additional Results

Table D.3 Median change in energy burden for households with cooling systems who do not use them in the baseline

	Uses Cooling	0-80% AMI	80-120% AMI	120%+ AMI
Baseline Energy Burden (%)	No	3.21	1.50	0.73
Change in Energy Burden (%)	No	0.74	0.29	0.14

APPENDIX E

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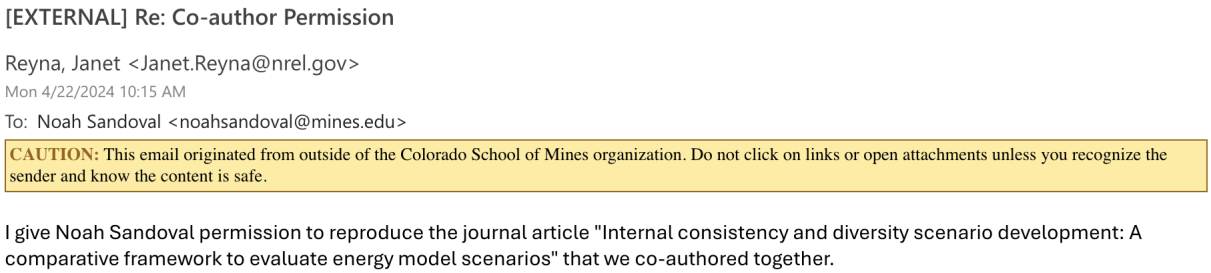

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