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Addressing building related energy burden, air pollution, and carbon emissions of a low-income community in Southern California

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ABSTRACT

This study examines the impact of low-income assistance and electrification programs on a disadvantaged community in Southern California. An urban building energy model is paired with an AC power flow and electric distribution system degradation model to evaluate how the cost of energy, carbon emissions, and pollutant emissions change after applying building weatherization, energy efficiency, and electrification measures to the community. Results show that traditional weatherization and energy efficiency measures (upgrading lighting and appliances, improving insulation to current building code standards) are the most cost-effective, reducing the cost of energy and carbon emissions by 10–20 % for the current community. Heat pump water heaters offer a 40 % average reduction in carbon emissions and almost 50 % decrease in criteria pollutant emissions, but at a cost increase of 17–22 %. Appliance electrification also reduces carbon emissions 5–10 % but increases cost by 7 % to 25 %. For reducing carbon, government programs that support building electrification are most cost-effective when they combine switching from natural gas to electricity with high efficiency system. Electrifying hot water and appliances effectively reduces emissions but must be paired with improved low-income assistance programs to prevent increased energy burden for low-income families. The urban building energy model and electrical distribution simulations used in this study can be replicated in other low-income communities.

1. Introduction

Low-income and disadvantaged families are more likely to live in less energy efficient buildings [1], are less likely to have energy efficient appliances [2,3], and experience an energy burden[1] that is two to three times higher than average [4]. These challenges can reduce family health, safety, and security [5–7].

Low-income energy assistance programs designed to address these challenges through utility bill support, building weatherization, and energy efficiency have existed for decades. In California, 27 % of residential utility customers income qualify for assistance through these programs [8]. These programs operate amid a backdrop of aggressive environmental goals and shifting building performance standards. For example, California has aggressive state-wide carbon emissions reduction and renewable energy goals [9,10], is looking to decarbonize all buildings [11,12], and regularly updates the state-wide “Title 24’’ building energy efficiency code to support State energy and environmental goals. California’s most populated regions also have the worst air quality in the United States [13,14].

Prior analyses focused on single-family buildings have shown that building weatherization, energy efficiency, and electrification can reduce annual energy costs for low-income families across the U.S. by, on average, $670 [15], and up to $400 for Californians [16]. Simulation results suggest that these measures could reduce primary energy use by up to 30 % [15], and improve air quality [17,18].

A critical tool in evaluating the impacts of building measures is the physics-based building energy model (BEM). The value of this tool is evident in Wilson et al. [15,16] and Wei et al. [19]. Both authors use BEMs to evaluate cost-effective weatherization, energy efficiency, and electrification measures. Primary differences are that the study by Wilson et al. spans the United States using the ResStock™ model [20], while

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[1] Energy burden is the percentage of household income used on energy costs.

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Nomenclature

AC	ALTERNATING current
ACPF	AC power flow
AFUE	annual fuel utilization efficiency
BEM	building energy model
CARE	California alternative rate for energy
CO	carbon monoxide
CO_{2e}	equivalent carbon dioxide emissions
ERWH	electric resistive water heater
ESA	energy savings assistance
DEER	database for energy efficiency resources
DHW	domestic hot water
EPA	environmental protection agency
FFA	finished floor area
HVAC	heating, ventilation, and air conditioning
LIHEAP	low-income home energy assistance program
LIWP	low income weatherization program
NO_x	oxides of nitrogen, including nitric oxide (NO) and nitrogen dioxide (NO_2)
SCE	Southern California edison
SCG	Southern California gas
SDK	software development kit
TDV	time-dependent valuation
UBEM	urban building energy model
UEF	uniform energy factor
UHC	unburned hydrocarbons
WAP	weatherization assistance program

that by Wei et al. focuses on climate zones in California, includes renewable generation, and considers low-cost paths to zero net energy. Other examples include the examination of energy efficiency, weatherization, electrification, and onsite renewable generation to a community in Denver, CO [21], the effect of building electrification on the Texas electric grid [22], passive cooling measures for multifamily buildings in India [23,24], and numerous other studies focused on different facets of energy efficiency, weatherization, and electrification applied to BEMs [25–27].

A relatively new approach for moving beyond a single building to multiple buildings is urban building energy modeling (UBEM). UBEMs can capture areas ranging from a single city block to an entire city [28]. Examples of UBEM efforts using custom physical BEMs are presented in the literature [29–31]. Many efforts rely upon the EnergyPlus™ BEM engine [32] paired with U.S. Department of Energy (DOE) reference BEMs [33,34]. One common approach to UBEM involves the development of "archetypes" where buildings are clustered based of type, geometry, and other factors. Each cluster is then simulated using a single composite BEM, reducing total BEM simulations to improve model scalability. Examples of this approach are found in [35–41]. A second approach relies upon a fusion of BEMs and machine learning. Highly detailed BEMs are used to train machine learning tools, which then predict energy loads for unmodeled buildings [42–45]. A third method involves developing BEMs for each individual building in an area of interest. Examples of this method include the CityBES [46–49] and URBANopt™ [50–55] tools.

The impacts of building electrification extend beyond individual buildings to electrical infrastructure. Prior work has shown that building electrification will likely require expansion and upgrade of the electric generation, transmission, and distribution systems [21,22,56–58]. Recent efforts have accounted for infrastructure impacts designing buildings for a new community [55] or when examining the electrification of existing buildings [21]. These efforts have primarily been focused on evaluating distribution circuit voltage levels and quantifying the extent and duration of infrastructure overloads. Doulbeday et al. considers the cost of infrastructure when designing a new community [55]. Infrastructure upgrade costs, however, have typically not been accounted for.

The current BEM and UBEM literature also typically does not adequately address or include low-income energy assistance program evaluation or impacts. Literature on this topic typically focuses on evaluating the costs and benefits of federal weatherization programs [6,7,59], changes in program policy, the impacts of these programs on low-income families [60,61], and estimates on how to maximize program benefits [62]. Two articles from Bradshaw et al. used BEMs to evaluate the impact of low-income assistance program measures on building loads, utility bill cost, and carbon emissions [63,64].

This work adds to the existing literature by using a UBEM for the disadvantaged Oak View community located in Huntington Beach, California, to address three questions:

1. What suite of weatherization, energy efficiency, and electrification measures leads to lowest cost of energy, carbon emissions, and pollutant emissions?
2. To what extent do current low-income energy assistance programs support clean energy technology adoption?
3. How do clean energy technologies affect the cost of maintaining local energy infrastructure?

The approach uses a combination of an URBANopt model of the community building infrastructure paired with an OpenDSS AC power flow (ACPF) and degradation model for the local electric distribution grid. Building measures and technologies considered in this work include lighting, appliance, and plug load efficiency, envelope upgrades, space heating, and water heating measures. The economic analysis includes support from low-income energy assistance programs and potential electric infrastructure upgrades. This work does not consider space cooling systems or onsite generation.

2. The Oak View Community

The Oak View Community is home to approximately 8000 residents [65]. It consists of a commercial and industrial sector surrounded by residential areas and is ranked in the 73rd percentile of environmentally challenged census tracts in California, primarily due to high levels of diesel particulate matter, traffic, toxic releases, and proximity to hazardous waste handling sites [66]. Social factors that also contribute to this ranking include low educational levels, high housing burden, and high poverty rates. According to American Community Survey Data [67], 53 % of Oak View households have incomes of 45 % or less than the local county average, and 73 % have incomes below 66 % of the average.[2]

This study focuses on a section of the Oak View community, depicted in Fig. 1, comprising 286 residential and 31 commercial, industrial, and educational buildings. Residential buildings predominantly use natural gas for heating and domestic hot water, except for the five largest multifamily residential buildings, which use electric resistive heating systems. Only six residential and approximately half of non-residential buildings have central air conditioning. Most buildings were constructed before 1975. Many nonresidential buildings have undergone major renovations

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[2] Poverty limits are adjusted based on average local incomes. According to the American Community Survey [67] the average Orange County, CA household income for a family of three was $100,455, or 450 % the federal poverty level.

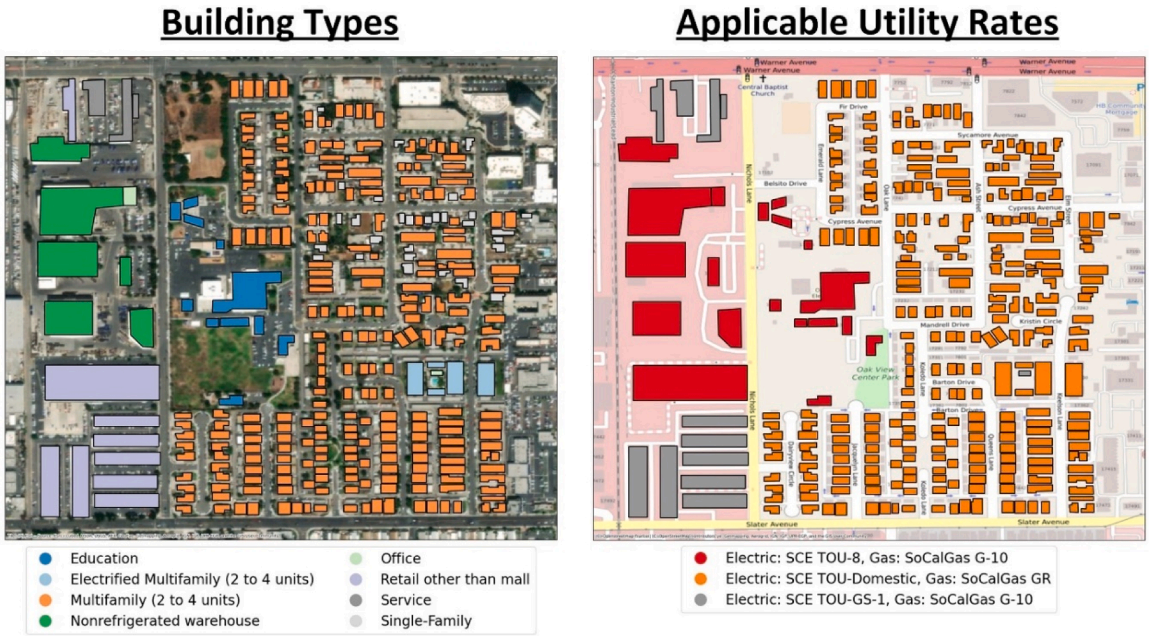

Fig. 1. Layout of the Oak View community, including building types, outlines, location, and applicable utility rates.

sometime in the past 20 years.

The Oak View community receives electricity and natural gas utility service from Southern California Edison (SCE) and Southern California Gas (SCG or SoCalGas), respectively. The right subfigure in Fig. 1 shows the applicable electric and natural gas utility rates [68,69]. Nonresidential electric rates vary based on peak annual electricity demand, with customers below 20 kW assigned to TOU-GS-1 and all others assigned to TOU-8.

3. Approach and methodology

This study uses a UBEM developed in [70] and an ACPF and electrical degradation models described in [70,71]. These models are used to evaluate the impact of energy efficiency, electrification, and weatherization measures on the Oak View community. The overall approach is summarized in Fig. 2. URBANopt is first used to simulate current energy use for all buildings, establishing baseline energy use. Then, this UBEM is used to simulate different clean energy technologies applied across the community. URBANopt outputs are fed into the ACPF to calculate distribution circuit voltages and ampacities. Circuit ampacities are then used to predict electric circuit component degradation. All results are then used to evaluate the total cost of energy (utility bills, equipment cost, and assistance funds), carbon emissions, and pollutant emissions for Oak View. Fig. 3 shows a diagram of model inputs, data flows between models, and model outputs. [70].

3.1. Urban building energy modeling & URBANopt

The Oak View UBEM is developed using the URBANopt software development kit (SDK) [50,72]. This SDK automates the construction and simulation of physics-based building energy models for multiple buildings. It is built on open-source tools EnergyPlus and OpenStudio® and offers various BEM workflows for residential and non-residential buildings [51,52,73,74]. The URBANopt SDK allows for the integration of clean energy technologies into individual buildings using EnergyPlus and OpenStudio measures. URBANopt also facilitates integration with other tools for analysis of electric vehicle integration, district energy systems, distributed energy resources, and electric distribution infrastructure.

The development of the Oak View UBEM “Baseline Model” mentioned in Fig. 2 is described in [70]. This model estimates how energy is used in the community today prior to the application of any clean energy measures. The bottom-up model was built by tuning individual BEMs using data from site visits, BEM simulation standards [75], survey data [76–78], and real utility energy use data. We used site visits to establish the condition of current Oak View buildings and current building energy systems. Using this information, we used BEM standards to develop bottom up building energy loads. These loads were compared against real utility energy use data from Oak View. Differences in predicted versus actual loads were resolved using Federal building energy survey data. High level BEM parameters used in the modeling are provided in Table 1. On an aggregated basis, annual residential electricity and natural gas predictions from the model were within 3 % of actual use, while monthly energy use was predicted to be within 10 %. Non-residential building energy data was tuned using commercial building energy use survey data [77].

In the Oak View UBEM, specific measures are applied based on building type (residential or non-residential) and existing systems. The community consists of three major building classifications: 1) residential buildings with natural gas appliances, domestic hot water (DHW), and space heating; 2) electrified residential buildings with standard appliances and electric resistive heating; and 3) non-residential buildings with natural gas for space heating and DHW. Fig. 1 shows the location and footprint of these different buildings. The clean energy technology and weatherization measures considered in this work are grouped into four categories: 1) lighting, appliance, and plug load improvements; 2) space heating; 3) water heating; and 4) envelope retrofits. Envelope retrofits include retrofitting Oak View buildings to meet building energy code standards, and the application of a novel cool coating [79]. Table 2 summarizes the building measures. Detailed technical and cost information can be found in supplemental material. The analysis does not include space cooling technologies due to high installation costs and limited support from low-income assistance programs (discussed further in Section 3.3).

3.2. ACPF and infrastructure degradation

The Oak View ACPF model was developed using the ACPF simulator OpenDSS [80]. OpenDSS can resolve three-phase voltage and current through distribution power lines and transformers. The distribution

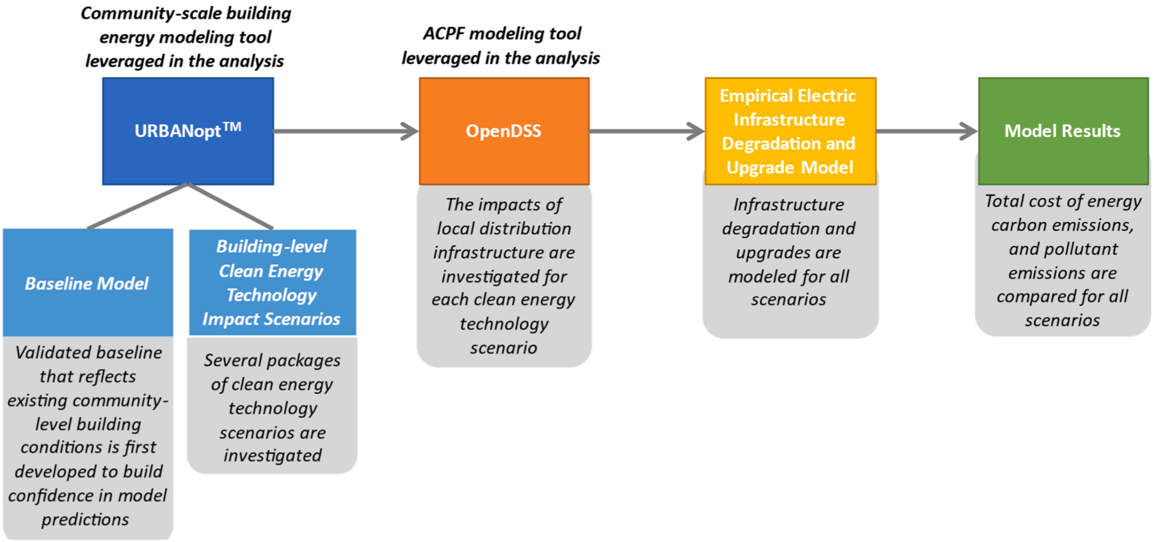

Fig. 2. Urban energy modeling approach used in the analysis, which includes community-level building energy modeling using URBANopt, and electrical distribution system analysis through OpenDSS.

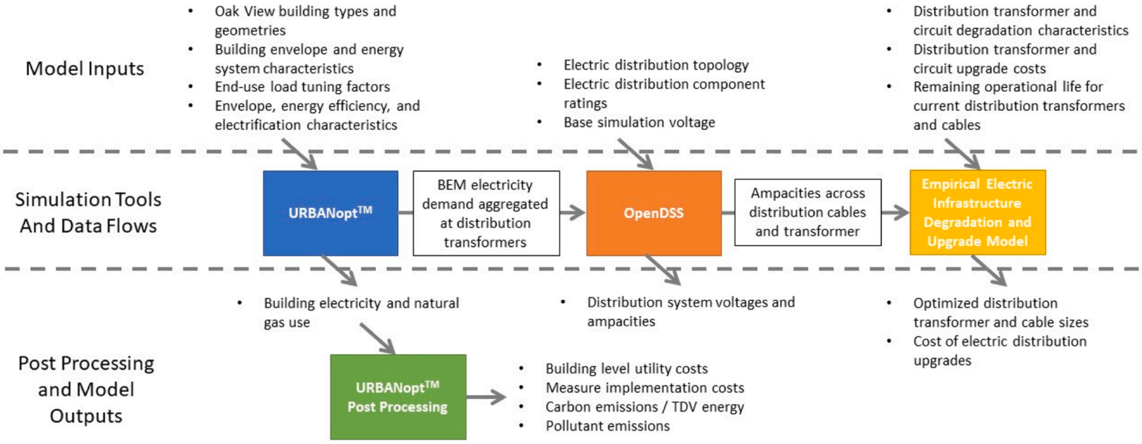

Fig. 3. Diagram of information flow between model components from model inputs to outputs.

Table 1
High level BEM parameters used to simulate different building types Fig. 1.

	Building template					
	Residential	Educational	Nonrefrigerated warehouse	Service	Office	Retail other than mall
Vintage / Title 24 Code	Pre-1985	2003	2003	2003	2003	2003
Wall assembly insulation (m^2 K/W / ft^2 °F h/Btu)	1.395 / 7.92	1.937 / 11.31	0.618 / 3.51	0.618 / 3.51	1.937 / 11.31	0.618 / 3.51
Wall radiative properties (Fraction)	Solar absorptance: 0.7, thermal absorptance: 0.9, visible absorptance: 0.7					
Roof assembly insulation (m^2 K/W / ft^2 °F h/Btu)	2.581 / 14.67	1.937 / 11.31	2.497 / 14.18	2.258 / 12.82	1.937 / 11.31	2.258 / 12.82
Roof radiative properties (Fraction)	Solar absorptance: 0.7, thermal absorptance: 0.9, visible absorptance: 0.7					
Window U-factor (W/m^2 K / Btu/h ft^2 °F)	7 / 1.233	4.37 / 0.77	7 / 1.233	7 / 1.233	4.37 / 0.77	4.37 / 0.77
Window solar heat gain coefficient (Fraction)	0.82	0.61	0.82	0.61	0.61	0.61
Window visible transmittance (Fraction)	0.25	0.25	0.25	0.25	0.25	0.25
Gas space heater efficiency (AFUE %)	Gas furnace: 0.80, Gas boiler = 0.78, Electric Baseboard = 1.00					
DHW efficiency (UEF %)	Gas tank: 0.6, Electric resistive tank: 0.8					
Cooling system coefficient of performance	Buildings with cooling systems: 2.8					

system topology was developed in two steps. First, SCE circuit maps were used to outline electrical distribution circuits [81,82]. Second, site visits were used to verify infrastructure and building connections. The topology of the ACPF model is shown in Fig. 4. Prior work has shown that all electrical distribution equipment is properly sized to meet current Oak View loads [70].

Results from the ACPF model simulations of hourly-resolved annual dynamic operation of the electric infrastructure are used to evaluate the degradation of distribution transformers and cables [71]. The transformers are modeled using an IEEE empirical thermal model [83]. The cable degradation model developed in [71] is integrated with a steady-state cable energy balance [84] and experimental cable insulation degradation model [85]. According to [85], the primary form of cable degradation is from the thermal aging of insulation material on the

Table 2
Summary of clean energy technologies considered for each of the building classifications.

Measure category	Residential	Already electrified residential	Nonresidential
Lighting, appliance, and plug load	• Replacement of compact fluorescent lighting (55 lumens/watt) to LED lighting (80 lumens per watt) • Upgrade appliances to ENERGY STAR® or high efficiency models (refrigerators, cook tops/ranges, dishwashers, clothes washers & dryers, smart power strips) • Electrification of gas appliances • Electrification of gas appliances using ENERGY STAR® appliances	• Replacement of compact fluorescent lighting (55 lumens/watt) to LED lighting (80 lumens per watt) • Upgrade appliances to ENERGY STAR® or high efficiency models (refrigerators, cook tops/ranges, dishwashers, clothes washers & dryers, smart power strips)	• Replacement of linear fluorescent lighting (88 lumens/watt) to linear LED lighting (130 lumens per watt) • Deployment of smart power strips
Space heating	• Upgrade to a condensing gas furnace • Electrification of space heating with electric baseboard heaters	• n/a	• Upgrade to a condensing heating system • Electrification of space heating with electric baseboard heaters
Water heating (DHW)	• Upgrade to a condensing gas water heater • Electrification of DHW with an electric resistive water heater (ERWH)[a] • Electrification of DHW with a heat pump water heater (HPWH - uniform energy factor = 3.75)	• Upgrade to a HPWH (uniform energy factor = 3.75)	• Upgrade to a condensing gas water heater • Electrification of DHW with an ERWH • Electrification of DHW with a HPWH (uniform energy factor = 3.75)
Envelope[b]	• Upgrade wall insulation to Title 24 mandatory levels • Upgrade wall insulation to Title 24 recommended levels • Upgrade roof insulation to Title 24 mandatory levels • Upgrade roof insulation to Title 24 recommended levels • Upgrade windows to Title 24 mandatory levels • Apply a novel cool coating to the building exterior		• Upgrade wall insulation to Title 24 mandatory levels • Upgrade roof insulation to Title 24 mandatory levels • Reduce space infiltration 30 % • Apply a novel cool coating to the building exterior

[a] Results show that ERWH are inferior to HPWHs in terms of total cost, carbon emissions, and pollutant emissions. However, ERWH installation costs are lower than HPWHs, are allowed under Title 24 building code, and are found inside the Oak View community.

[b] Envelope measures initially included residential unit sealing. However, simulation results predicted that sealing increased both cost and energy use. Further investigation found a mismatch between the procedural BEM generation process and the standard building sealing measure, producing this erroneous result. This issue was not addressed since prior studies have thoroughly examined building sealing, showing that reducing infiltration reduces heating load at rates comparable to improved attic and roof insulation [19,49]. As a result, effort was directed elsewhere.

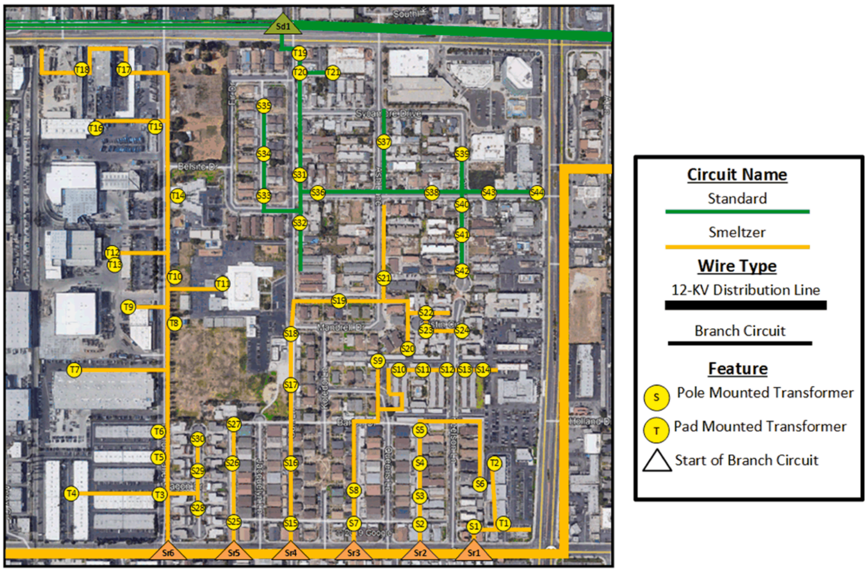

Fig. 4. Oak View Community electric distribution circuit topology.

cable exterior. The cable energy balance is used to predict cable temperature dynamics, which are then used to predict cable degradation. Degradation results for both transformers and cables are then used to predict whether equipment replacement is necessary. At replacement, the component size is optimized to achieve minimum net present value cost over the next 30 years. Complete details of the degradation models and infrastructure optimization model are discussed in Wang et al. [71]. Based on communication with SCE and prior analysis, we assumed that each distribution transformer start with 15 years of useful life left, and that all cables have no thermal degradation.

3.3. Low-Income energy assistance programs

The combined goals of Federal and California State low-income energy assistance programs are to reduce energy burden, improve health and safety, and reduce greenhouse gas emissions. Assistance programs provide reduced utility rates, and weatherization and energy efficiency upgrades. Both SCE and SCG offer discounted rates to households with incomes at or below 200 % of federal poverty limits [86,87]. These rates, known as California Alternative Rates for Energy (CARE) rates, reduce utility electricity rates by ~30 %, and gas rates by ~20 %.

Four weatherization and energy efficiency programs are considered in this work: the U.S. DOE Weatherization Assistance Program (WAP), the U.S. Department of Health and Human Services Low Income Home Energy Assistance Program (LIHEAP), the California Department of Community Services and Development Low-Income Weatherization Program (LIWP), and SCE and SCG Energy Savings Assistance Programs (ESA). At the time of this work, WAP, LIHEAP, and SCG ESA funds designated for use in Orange County were administered by the local non-profit organization Community Action Partnership—Orange County (CAPOC). A list of potential building and appliance improvements was provided to us by the CAPOC construction manager. Measures available through the LIWP and SCE ESA programs are listed online [88,89]. These programs support weatherization measures that meet mandatory Title 24 building energy efficiency standards, replacement of most major in-unit residential appliances with ENERGY STAR or other high efficiency models, and the repair and replacement of heating, cooling, and DHW systems. LIWP also supports electrification measures. These programs do not currently support weatherization measures beyond mandatory Title 24 standards, high efficiency cooking equipment, the novel cool coating, or shared laundry machines.

The application of these programs in multi-family buildings depends upon the income levels of all tenants. Low-income occupants have access to specific measures within their units, including lighting, appliances, and in-unit heating equipment. Whole building weatherization and shared energy systems are available when 60 % or more of the occupants qualify as low-income. Common area measures (i.e., lighting and laundry facilities) are provided when 80 % or more of the tenants are low income. Permanent building upgrades are restricted to properties committed to providing low-income housing.

Household income eligibility for these programs ranges from below 200 % to 300 % of federal poverty limits. Due to limited income data, a cutoff of 200 % was applied to all programs. The number of eligible families was estimated using American Community Survey data. For privacy reasons, the allocation of these families to buildings was done randomly. No further information on this allocation is provided to prevent any accidental overlap between modeled and actual family locations.

Low-income assistance programs require measures that reduce energy burden and increase health and safety [89,90].Typically, improvements beyond mandatory building code levels, and higher efficiency space and water heating systems are not supported unless these systems were previously installed at a building. To accommodate the examination of higher efficiency equipment and electrification, a modeling assumption was made: funds that would have been available are assumed to partially offset installation costs of measures that are not typically supported by assistance programs; building owner and tenants covering any remaining costs. However, if electrification measures reduce energy burden, it is assumed that LIWP funding will cover all equipment costs.

3.4. *Recent and emerging technology support programs*

Multiple clean building technology support programs have been established in the last few years. These programs apply to nearly all residents, but support levels depend on household income. California programs include the Building Initiative for Low-Emissions Development (BUILD) program [91], and the Technology and Equipment for Clean Heating (TECH) Initiative [92]. The BUILD program provides incentives for new building construction or major renovation. The primary incentive is the “Base GHG” incentive, which credits developers based on avoided carbon emissions at $150 per tonne avoided greenhouse gas emissions [93]. The TECH Initiative provides direct incentives to reduce the cost of installing heat pump systems. Incentives vary geographically. A residential SCE customers can receive up to $3100 towards the installation of a heat pump water heater (HPWH) and up to $1400 to support building electrical upgrades [94]. At the time of this work, the BUILD program was yet to be finalized, while TECH Initiative rebates were fully utilized in certain utility territories [94].

Other support programs initiated through the Inflation Reduction Act of 2022 (IRA) [95] include 1) a 30 % tax credit on the installation of a HPWH with UEF of 3.3 or higher, up to $2000, and 2) the proposed Home Owner Managing Energy Savings (HOMES) rebate program. This program provides funding to state energy offices to operate clean energy technology rebate programs. Rebates are capped at the lesser of $4000 or 50 % of project costs for energy savings $\geq$ 35 %. Incentives increase to $8000 or 80 % of project costs when improvements benefit low or moderate-income households. Since most state programs were under development during this work, we based incentivized building technologies on ENERGY STAR Multifamily New Construction guidelines [96]. Note that the High-Efficiency Electric Home Rebate (HEEHR) Program specified in the IRA is not explicitly captured in this work since the incentive type is similar in structure to the California TECH Initiative.

For our analysis, we assume that the TECH Initiative funds can be used in place of low-income assistance funds for DHW systems—all other measures supported by these low-income programs are unaffected. We assume that the IRA HPWH tax credits are applied on top of low-income assistance funding. For the HOMES program, we assume that the newly available funding replaces low-income assistance funding.

3.5. *Evaluation criteria*

3.5.1. *Cost of energy*

The cost metric used in this work is the percent difference in total cost before and after each building measure, as shown in Eq. (1). Total cost is described in Eq. (2) and is taken as the net present value of equipment and weatherization installation costs, utility bills, and assistance or technology support funds. Net present value (NPV) is calculated using a discount rate of 6.5 % over 10 years. This metric is referred to as “change in NPV cost.” Whenever building and weatherization costs exceed available assistance and support funding, we assume that the difference is funded using an 80 %/20 % debt/equity split, with debt funded through a 10-year loan at 6.5 % interest.

$$\Delta\ Total\ Cost = \frac{Total\ Cost - Total\ Cost_{Baseline}}{Total\ Cost_{Baseline}} \cdot 100\ \% \tag{1}$$

$$\begin{aligned} Total\ Cost = NPV(&Equipment\ and\ Weatherization\ Costs - Subsidies \\ &+ Utility\ Bills) \end{aligned} \tag{2}$$

This work assumes that new measures are only installed when the previous system reaches the end of its life, or is “burned out.” The $Total\ Cost_{Baseline}$ in Eq. (2) includes the replacement cost based on mandatory Title 24 energy efficiency standards. The opposite scenario where measures are implemented before prior system failure, or “early replacement” was found to increase cost in all scenarios except for interior lighting and smart power strip upgrades. Utility bills are calculated using URBANopt BEM outputs and SCE and SCG rates. Utility bills were projected for ten years using a 3 %[3] annual utility rate escalation. Fig. 5 illustrates the results, showing the total utility bill intensity and the fraction attributed to electric bills. Utility bill intensity is defined as the sum of annual building electricity and natural gas utility bills, divided by building finished floor area (FFA). Non-residential and commercial buildings exhibit the highest utility bill intensity.

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[3] Data from the U.S. Energy Information Administration [107] shows that the ten-year residential utility escalation rate over the past five years can vary between 0.6 % and 4 % for electricity, and −0.4 % and 5.1 % for natural gas. The 3 % rate was assumed based on upward retail rate price volatility while being below peak escalation rates.

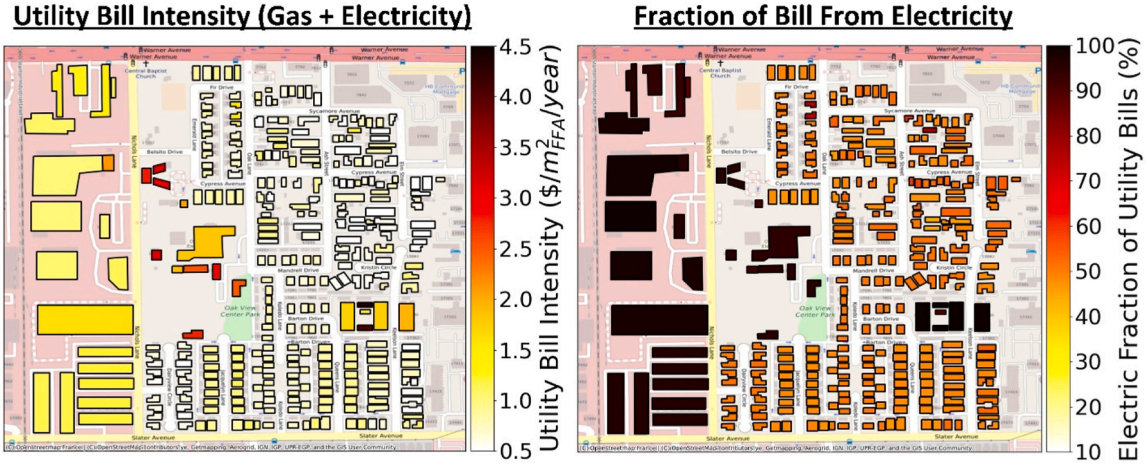

Fig. 5. Baseline utility bill intensity for each building and the fraction of bill intensity due to utility electricity demand. Utility bill intensity is total annual electric and natural gas utility cost divided by building finished floor area (FFA). The results show that non-residential and electrified residential buildings have the highest utility bill intensity. Energy use results presented in Section 3.5.2 show that 20 % to 30 % residential energy is associated with electricity while these results show electricity driving 50 % to 60 % total utility bills.

3.5.2. *Carbon emissions*

Carbon emissions from building energy use come from non-renewable fuel combustion in building heating systems and appliances, and from utility power plants. California's electricity and natural gas carbon emission rates are expected to decrease annually until 2050 [10,97]. Electric grid carbon intensity also varies by the hour and across seasons. The time-dependent valuation (TDV) of energy captures these trends and dynamics, estimating hourly costs, primary energy content, and carbon emissions for utility electricity and natural gas from 2022 to 2052 [97]. TDV factors were initially developed to support California's building energy efficiency code Title 24 and are used to predict primary energy use in buildings through 2052 [98]. TDV energy is used as the metric to evaluate carbon emissions due to its connection with non-renewable energy content.

Figs. 6 and 7 illustrate the application of TDV energy values to the baseline Oak View model. Fig. 6 displays the split between site energy and TDV energy for residential and non-residential buildings, with or without space cooling. Gas end uses are represented in shades of red, electricity in shades of green. Results highlight that residential energy use is primarily driven by gas DHW, while non-residential energy use is dominated by plug loads and interior lighting. There is a qualitative similarity between the TDV energy use splits and site energy. Fig. 7 shows TDV energy intensity for all buildings, including the fraction attributed to electricity use. The highest TDV intensity buildings are in the Oak View residential sector, mainly due to natural gas usage. Comparing Figs. 4 and 7 reveals that residential electricity accounts for over 50 % of energy burden while contributing 20 % to 30 % of carbon emissions and TDV energy.

A final metric used to evaluate technologies and weatherization measures is the levelized cost of avoided carbon (or the cost of carbon). This cost represents the cost paid by building owners, residents, and local businesses to reduce carbon emissions by investing in clean building technologies. Carbon emissions are calculated using TDV energy multiplied by carbon emissions from natural gas combustion for 2022 through 2023 TDV values. Levelized avoided carbon is the net present value of the change in carbon emissions between the baseline community and the community after installing a clean energy technology (Eq. (4)). Levelized cost of avoided carbon is calculated by dividing the change in net present value of total cost of energy (Eq. (2)) by levelized avoided carbon This metric is shown in Eq. (3) and has units of $\frac{\$}{tonne\ CO_{2e}}$. This metric represents the cost each ratepayer pays to reduce building-related carbon emissions.

$$Levelized\ Cost\ of\ Carbon = \frac{Total\ Cost - Total\ Cost_{Baseline}}{NPV(Avoided\ Carbon)} \tag{3}$$

$$Levelized\,Avoided\,Carbon = NPV(Carbon\,Emissions - Carbon\,Emissions_{Baseline}) \tag{4}$$

A separate version of this same metric is calculated where change in total cost is replaced with weatherization and energy efficiency assistance plus clean energy technology support funding. This metric quantifies the cost efficacy of different programs for reducing building related carbon emissions. Aside from some California programs, the goals of these programs are the reduction of energy burden and improved health and safety for low-income households, not to economically reduce carbon emissions.

3.5.3. *Pollutant emissions—NO$_X$*

Criteria pollutant emissions that we examine come from combustion processes used for electricity generation, water and air heating, and residential appliances. We use pollutant emission factors based on average electric grid emission rates from the United States Environmental Protection Agency (EPA) [99], and experimental results from appliances and heaters [100–106]. Table 3 provides emissions factors for nitrogen oxides (NO$_X$), which are used to calculate annual NO$_X$ emission inventories for all Oak View buildings. Emissions factors for carbon monoxide and unburned hydrocarbons are available for residential appliances and heating systems but not for electricity generation and are not included in this study.

Resolving air quality impacts requires models operating across far larger geographic areas than that of the community considered here. However, prior work considering both the electric grid and air quality response to building electrification has shown that building electrification reduces the exposure of low-income and disadvantaged communities to air pollution [18]. This suggests that the change in direct emissions from the community due to natural gas combustion is the

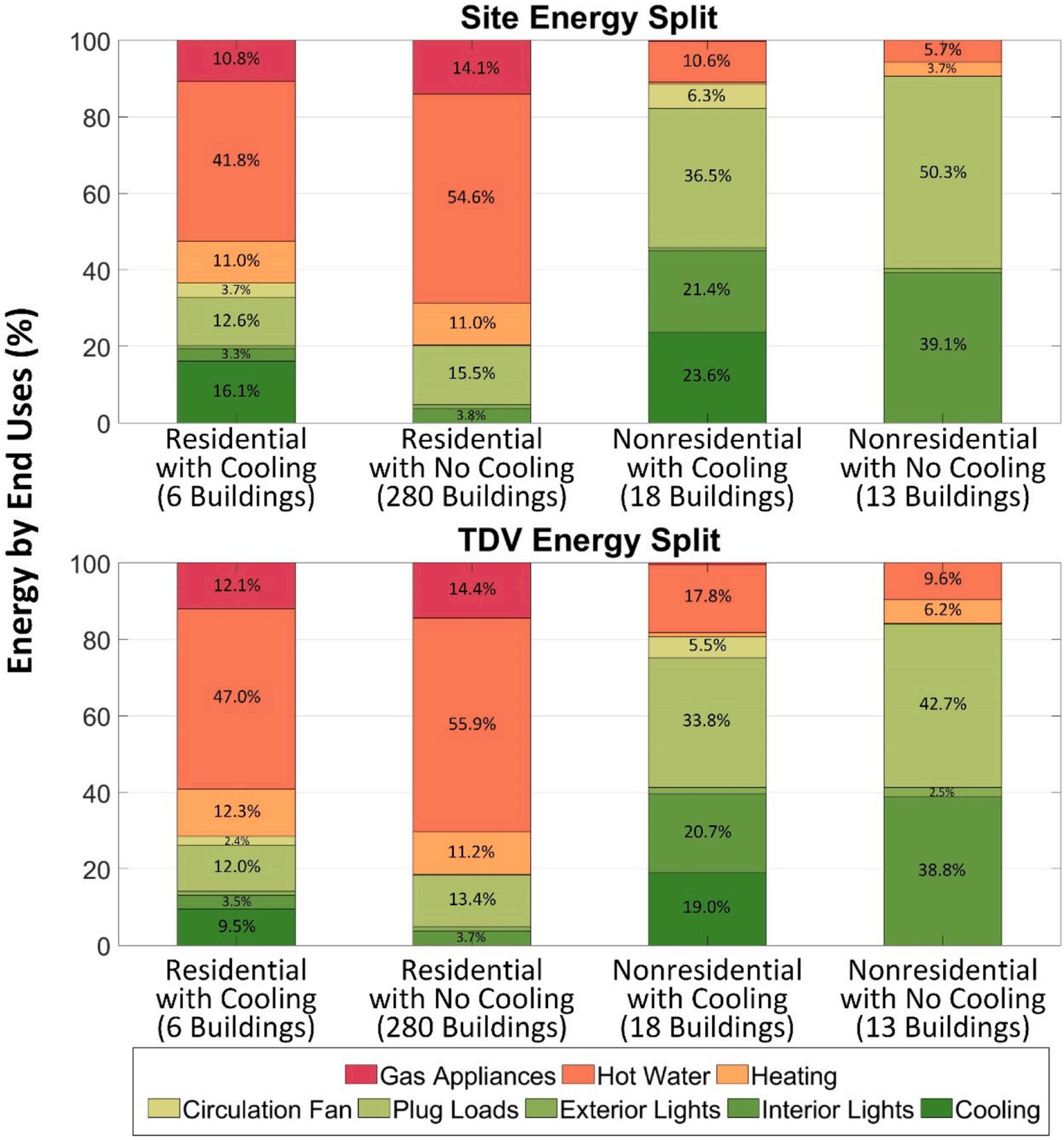

Fig. 6. A comparison between site energy and TDV energy use for Oak View residential and non-residential buildings. The figure is derived from results originally presented in [70]. This figure shows the difference in TDV energy use between residential and non-residential buildings where DHW dominates energy use in residential buildings while plug loads and interior lighting dominate non-residential.

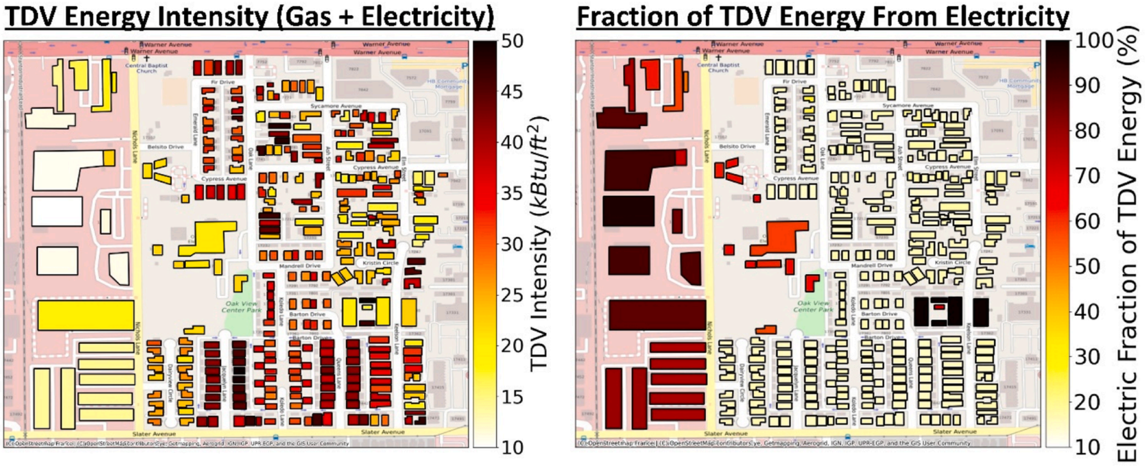

Fig. 7. TDV energy intensity for each building and the fraction of TDV intensity associated with utility electricity imports. The maps show that residential buildings have a higher energy use intensity, which is primarily driven by gas use.

Table 3
Summary of NO_x pollutant emission factors and sources for electricity and natural gas use.

Source	Units	NO_x
Utility Electricity [99]	kg/MWh delivered	0.189
Gas cooktop burner [100,101]	ng/J fuel combusted	53.9
Gas oven burner [101,102]		51.3
Space heater [101]		56.1
Low NO_x gas tank water heater [101,104,105]		7.8
Tankless gas water heater [106]		22.0
Gas clothes dryer [101]		13.9

critical metric to consider over and above that of utility electricity generation pollutant emissions.

4. Results

Results presented in this section are unique to the Oak View community. Factors that influence results are a relatively low carbon electric grid [99] coupled with relatively high retail electricity prices [107].

4.1. Residential—individual measures

Residential building results are separated into groups based on income and building type:

1. Tenants Below 200 % Poverty Limits: Buildings deeded as low-income properties, occupied with only low-income tenants.
2. Tenants Above 200 % Poverty Limits: Buildings occupied by tenants above household income limits.
3. Mixed Income & Electrified: Electrified residential buildings with mixed-income tenants.
4. All Residential Buildings.

Change in TDV energy and NPV cost for select measures applied to the Oak View community are shown in Fig. 8. Bars show the average change per group of buildings. Whiskers, or the "error bars," show the span of results produced by individual BEMs. Complete results for every measure are provided in the supplemental material, including mandatory wall and roof insulation; both measures produce modest cost savings and have a similar impact on TDV energy as recommended insulation levels. Window results are also absent from Fig. 8, but are available in the supplemental material. Window upgrades were found to provide minimal TDV energy savings while substantially increasing costs unless covered by low-income assistance programs.

Moving from top to bottom, the results show that cost-effective envelope upgrades for the community are limited to mandatory Title 24 measures (not shown). Additional insulation and cool coating were found to increase total cost. The cool coating increases TDV energy while recommended insulation measures produce modest energy savings that each make them more costly. Prior work has shown that cool coatings can produce significant financial, energy, and comfort benefits [79,49] . However, since most Oak View buildings lack air conditioning, the value of a cool coating is not realized by considering cost and energy alone.

Domestic hot water (DHW) measures generally increase cost. Among the three measures, only the condensing gas water heater reduces utility bills, but the higher capital cost results in a net increase in the total cost of energy. The electric resistive water heater (ERWH) decreases TDV energy by ~20 % but significantly increases the total cost of energy 75–100 %. HPWHs offer the most significant reduction in TDV energy, but utility bills may increase if replacing a conventional gas DHW system. If used to replace an ERWH, HPWH systems decrease both cost and TDV energy by up to 30 %.

Fig. 9 shows which heating type achieves lowest TDV energy at each Oak View building. This figure also shows the normalized heating load based on heater selection (top right) along with the TDV energy associated with condensing gas and baseboard electric space heaters (bottom right). Baseboard electric heating is less energy intensive than gas heating between 8 AM and 5 PM. Buildings with heating loads that peak between these hours achieve lower TDV energy with electric resistive systems. However, upgrading or electrifying residential building heating systems in Oak View generally increases costs – condensing gas heaters have much higher equipment costs while baseboard heaters increase total utility bills.[4]

Interior and exterior lighting were found to decrease both cost and TDV energy. LED adoption decreases equipment costs due to longer bulb life than incandescent or compact fluorescent and lowers utility bills. In general, the appliance upgrades described in Table 2 were found to typically increase costs while decreasing TDV energy. Appliance electrification in this community achieves lower TDV energy when compared to higher efficiency natural gas appliances but increase total energy cost due to higher utility bills. The lone instance where an appliance upgrade led to lower total cost occurred in the mixed income electrified building. This result is due to residential unit density—shared

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[4] Space heating heat pumps were not included in this work due to cost challenges. These systems will be included in subsequent work.

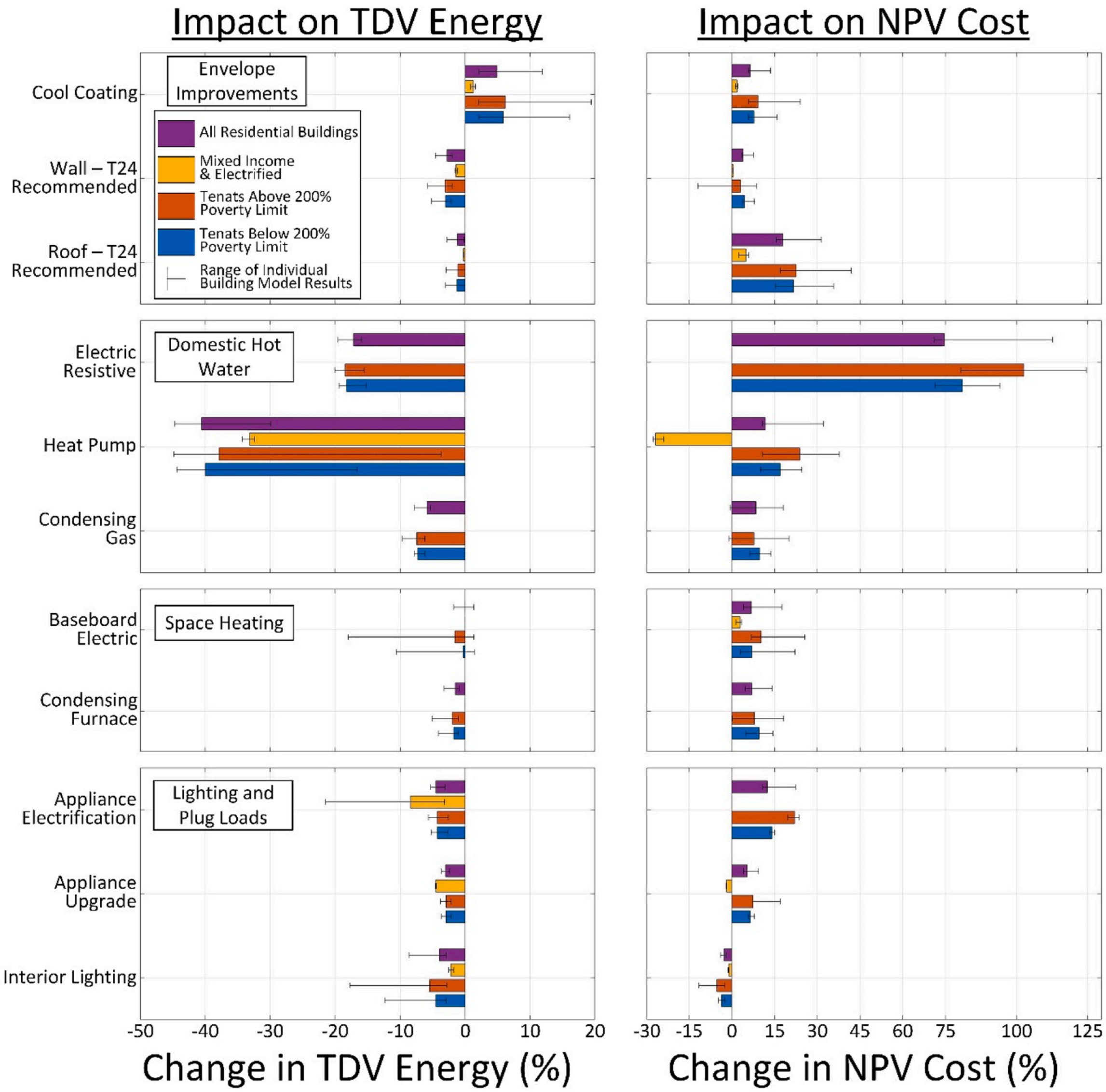

Fig. 8. Change in TDV energy and NPV cost for select measures for Oak View residential buildings. Each bar represents the average change for each building classification. The error bars represent the 5 % to 95 % percentile for individual BEM results.

laundry facilities are implicitly assumed to have higher utilization at buildings with more residential units, maximizing the benefit of high efficiency laundry machines.

Negative appliance results for Oak View are partially due to the assumption that many appliances are replaced simultaneously. High efficiency clothes washing and drying appliances placed in common building areas are relatively expensive and not supported by low-income assistance programs. These cost premiums offset the financial benefit of other high efficiency appliances that are supported through low-income assistance programs, like ENERGY STAR refrigerators, dishwashers, and smart power strips. Additionally, the appliance upgrade bundles included other relatively high-cost appliances, such as gas ovens, which are not covered by ENERGY STAR.

The levelized cost of avoided carbon emissions for Oak View property owners and low-income tenants caused by adopting individual measures is shown in Fig. 10. Results are arranged from lowest to highest cost of avoided carbon. The figure uses a logarithmic axis to capture the wide cost range. Mandatory Title 24 envelope and lighting measures have a negative cost of avoided carbon due to assistance from low-income programs that cover upgrade costs coupled with slight reductions in utility bills and TDV energy. Except for lighting measures, mandatory window, wall, and roof improvements only achieve a negative cost due to replacement or burnout, or when the prior windows or wall/roof insulation must be replaced. Fig. 8 and supplemental results show that these measures produce marginal cost and energy benefits. If replacement of these measures occurs before burnout, the levelized cost of carbon would quickly turn from negative to positive. This is captured in Fig. 11, which shows the cost of carbon based on low-income assistance programs that support envelope improvements and upgrades.

Of the measures that increase cost, the HPWH system has the lowest cost of avoided carbon at approximately \$200 per tonne CO_2 due to higher capital cost and increased utility bills. Aside from the recommended Title 24 wall insulation levels, the cost of carbon for all other measures exceeds \$1000 per tonne CO_2.

Costs of avoided carbon for previously electrified Oak View buildings are, in general, similar to results shown in Fig. 10. Key differences are that HPWH and appliance upgrades achieve a cost of carbon of -\$1000 and -\$600 per tonne due to lower utility bills while decreasing TDV energy. This appliance result is primarily due to higher use of shared laundry facilities in multifamily residential buildings with more

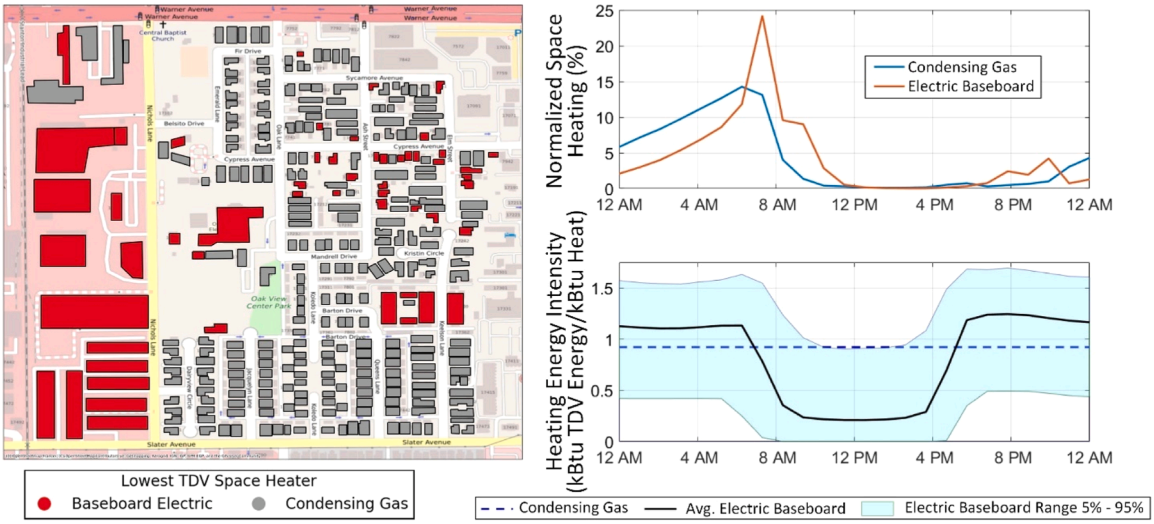

Fig. 9. Map of Oak View indicating which space heater type achieves lowest TDV energy reduction. The difference in space heater type is primarily due to the matching of space heating load profile with the TDV energy intensity of utility electricity and the grid. The top right figure shows the normalized space heating load for all buildings with lower TDV energy with a condensing gas or electric baseboard heater. The bottom right figure shows the average TDV energy intensity for a condensing gas heater or an electric baseboard system. The electric baseboard range represents variations in TDV energy for an electric baseboard space heater due to variations in electric grid operations.

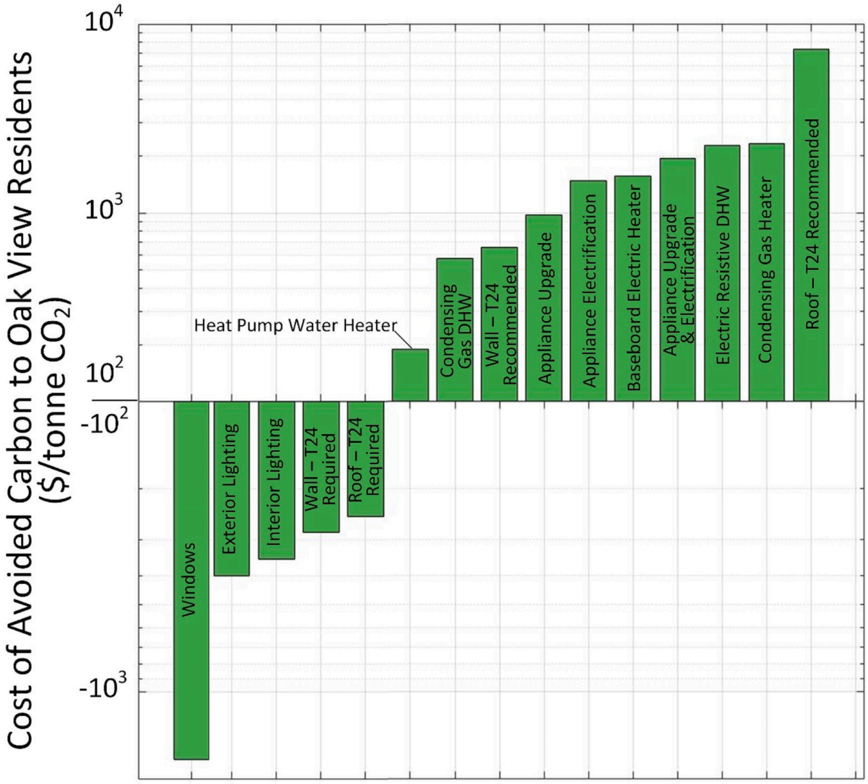

Fig. 10. Cost of carbon imposed on an Oak View building owner and low-income tenant who adopts an individual clean energy technology or weatherization measure. Results are presented using a logarithmic y-axis to show the range in results across the different measures. A logarithmic axis is used due to the extreme difference between low and high cost of carbon measures.

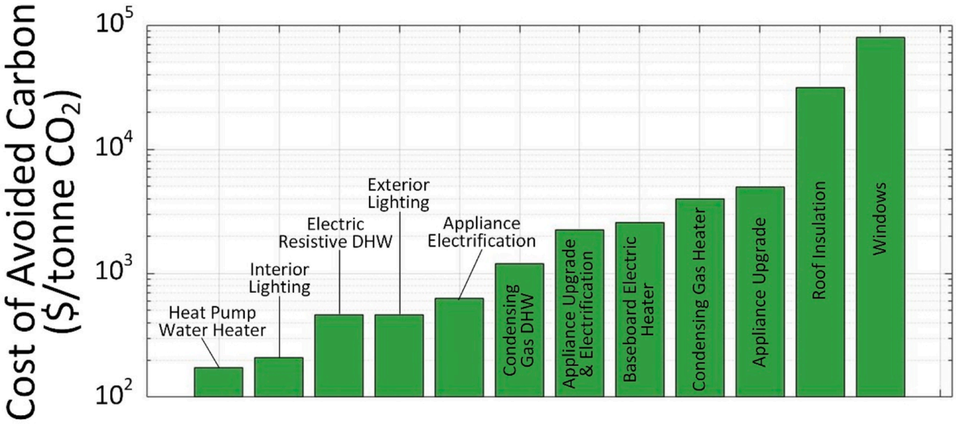

Fig. 11. Costs of avoided carbon for low-income tenants and properties in the community based on low-income weatherization and energy efficiency programs. The amount of invested funds is based on supporting measures that reduce utility bills for low-income households. A logarithmic axis is used due to the extreme difference between low and high cost of carbon measures.

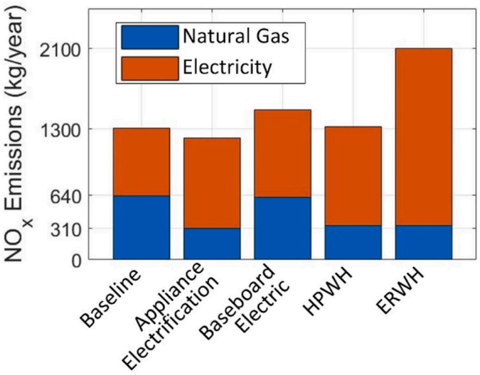

Fig. 12. Building related pollutant emissions for the Oak View community. Results include the baseline emissions level compared against electrification options. All other measures except for the condensing gas water heater were found to have a marginal impact on pollutant emissions. If the condensing gas water heater is tankless, NO$_x$ emissions from on-stie natural gas combustion increase approximately 30 %.

residential units. Cost of avoided carbon for buildings with tenants above federal poverty limits are like those shown in Fig. 10 and are in the supplemental results.

Results from the Oak View model show that the use of current low-income assistance programs can typically only be used to support mandatory Title 24 envelope improvements and upgrades to lighting and appliances located inside residential units. Regardless, the cost of avoided carbon due to investment from low-income energy assistance programs is presented in Fig. 11. Note that these results will always be positive since the utility bill savings benefits are realized by the tenant and not the low-income assistance programs. Of these measures, only lighting, appliance upgrades, roof insulation, and windows are fully funded using assistance program resources. All other measures assume partial funding based upon what would have otherwise been available for a similar, funded measure (e.g., partial funding of a HPWH in place of a fully funded conventional gas tank water heater). The costs of avoided carbon are ordered from lowest to highest cost and are plotted using a logarithmic scale.

The lowest cost investment for Oak View is for HPWHs, followed by interior lighting. Under current assumptions, program funding for HPWHs is capped by the cost of a conventional gas water heater, or approximately 55 % of the HPWH cost. For appliance electrification, the basic appliance option achieves the lowest cost of avoided carbon at a cost of slightly over $1000 per tonne CO$_2$.

There is a large cost difference between envelope improvements for building owners/tenants and low-income assistance programs. While Fig. 10 shows negative cost of carbon for tenants and building owners, Fig. 11 displays costs up to $90,000 per tonne CO$_2$ avoided. This difference stems from the replacement approach used in the model, where envelope investments occur only when required, and are divided between building maintenance and weatherization premium costs. Since mandatory insulation levels and window properties exist under Title 24, the premium cost to meet current codes is $0. However, when low-income weatherization funds are used, the maintenance cost is shifted to assistance programs, resulting in the cost of carbon shown in Fig. 11. Note that the goal of low-income weatherization programs includes enhanced health and safety. These factors are not directly addressed in this work.

Pollutant emission results for select measures are shown in Fig. 12. This figure shows the annual NO$_x$ emissions from natural gas at all residential buildings in Oak View, and emissions from powerplants. This figure only shows the change in emissions for electrification technologies since all other measures aside from the condensing gas water heater had little to no effect on annual NO$_x$ emission rates. Depending on the water heater type, pollutant emissions from buildings increase by approximately 30 % (on-demand water heater) or decrease by 10 % (tank water heater with low NO$_x$ burner).

The results show that appliance and DHW electrification measures both reduce natural gas NO$_x$ emissions by 45 % but increase electricity related NO$_x$ emissions. Appliance electrification and HPWH systems result in a net reduction in pollutant emissions while ERWH systems produce a net increase.

4.2. Non-Residential—individual measures

Fig. 13 presents the TDV energy and total cost results for non-residential buildings, categorized by those with and without space cooling. Recommended insulation levels for roof and walls are shown, while results for mandatory levels are provided in the supplemental material. Mandatory insulation levels follow a similar trend as residential buildings, slightly reducing cost and TDV energy. Fig. 13 shows that upgrading roof insulation to recommended levels increases costs across all non-residential buildings. However, installing recommended wall insulation decreases both cost and energy for all non-residential buildings. The cool coating decreases cost and energy for buildings with space cooling. The cost and energy reduction from applying a cool coating to nonresidential buildings with space cooling are the largest for any envelope improvement applied to any building type, residential or non-residential.

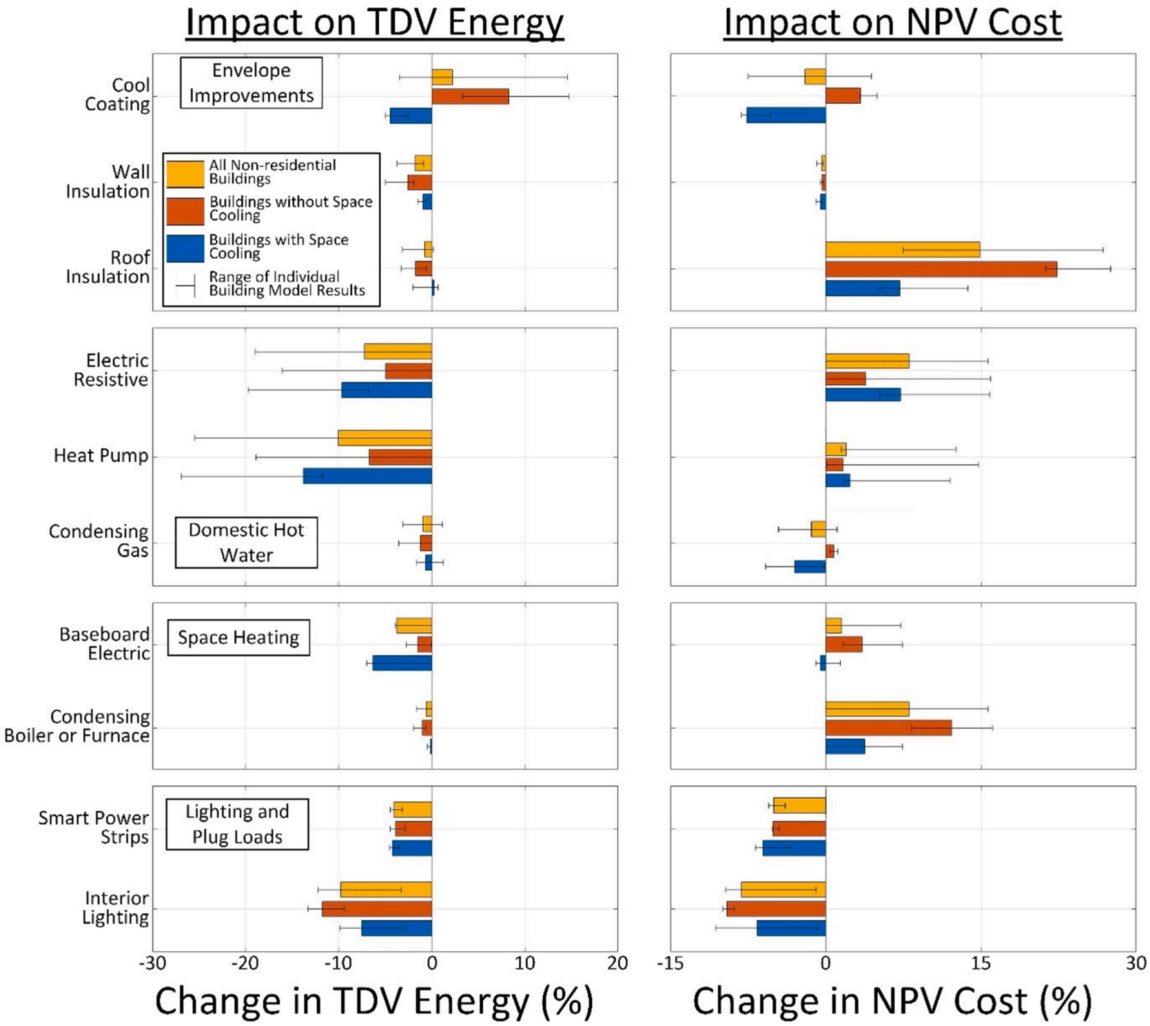

Fig. 13. Change in TDV energy and NPV cost for select measures for non-residential Oak View buildings. Each bar represents the average change for each building classification. The error bars represent the 5 % to 95 % percentile for individual BEM results.

Unlike residential results, the condensing gas water heater reduces energy and cost compared to the conventional gas DHW system for educational, manufacturing, and office buildings that also have space cooling. HPWH's achieved the deepest TDV energy reduction but increased cost slightly.

Baseboard electric heating systems consistently reduce TDV energy compared to the baseline and condensing gas options. This was summarized in Fig. 9, which showed that buildings with peak heating at or after 8AM have lower TDV energy intensity with baseboard electric systems. Nonresidential BEM heating thermostat setpoints switch from 64°F to 70°F at 8AM, resulting in peak heating just as electric resistive energy intensity drops below condensing gas. Although a switch in heating system type generally increases cost, some of the educational and office buildings achieve lower costs with this system type due to lower replacement costs paired with relatively low heating loads.

Plug load and lighting measures prove highly effective in reducing energy use and cost. Interior lighting and smart power strips achieve TDV energy reductions comparable to the HPWH measure and decrease total cost of energy. Exterior lighting reduces TDV energy but does not yield significant cost savings due to relatively high installation costs.

4.3. Lowest cost and lowest emission community designs

Individual measure results were used to create optimal combinations of clean energy technologies and weatherization measures that minimize total cost, pollutant emissions, and TDV energy. Various combinations of measures applied to the Oak View UBEM were tested to identify the most effective mix.

The lowest total cost design for all buildings includes interior lighting and mandatory Title 24 envelope measures. Designs for buildings with electric resistive heating also in HPWHs and high-efficiency electric appliances. Non-residential buildings also include smart power strips and cool coatings for buildings with space cooling.

For pollutant emissions, measures such as energy efficiency and condensing gas technologies were found to reduce total NO_x emissions, resulting in a 10–20 % reduction within the community. Fig. 12 shows that appliance electrification and HPWH scenarios showed little to no change in total NO_x emissions due to the shift of emissions from the community to utility power plants. Recall that prior research found that building electrification in Southern California can lead to improved air quality [18]. Furthermore, the average NO_x emission rate of the California electric grid has been decreasing steadily over the years [99,108,109]. Assuming this trend continues with the integration of more renewable energy systems, electrification can eliminate on-site NO_x emissions and transition to a lower-emission energy source located away from populated areas. As a result, we assume that the lowest pollutant emission design aligns with the lowest TDV energy design.

All lowest TDV energy designs include lighting upgrades, HPWHs, mandatory Title 24 envelope measures, appliance electrification and upgrades, and space heater upgrades tailored to each building. For

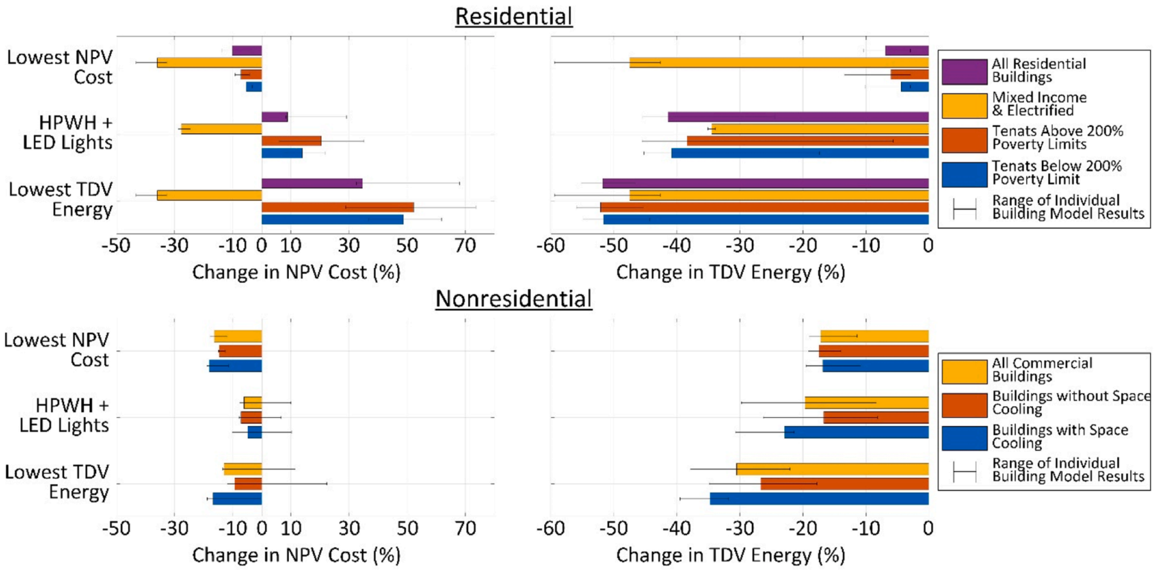

Fig. 14. The cost and energy results of the optimal mix of investments that produces the lowest NPV and TDV energy designs for residential and non-residential buildings in the Oak View community. An intermediate HPWH+LED Lights design is included as an intermediate scenario between lowest NPV and lowest TDV energy designs.

previously electrified buildings, the lowest TDV design also matches the lowest cost design. During the assembly of the lowest TDV energy design, we found that appliance and space heater upgrades increased cost substantially with modest reductions in TDV energy. Conversely, lighting and HPWH upgrades produced deep reductions in TDV energy with relatively small increases in cost. To balance cost and energy reductions, an ``intermediate'' lowest TDV scenario includes only HPWH and LED lighting upgrades.

Fig. 14 illustrates the change in total cost and TDV energy for these two design goals across residential and non-residential Oak View building subgroups. For residential buildings with gas heating systems (blue and red-orange bars in the top subfigures), the lowest cost measures reduce cost and energy by less than 10 %. The intermediate lowest TDV energy scenario reduces TDV energy by over 40 % but increases cost by 15–20 %. The lowest TDV energy scenario reduces energy by approximately 50 % but increases cost more than 50 %. For already electrified buildings, the lowest cost and lowest TDV energy scenarios match, both reducing cost and energy by 35 % and 45 % respectively.

Non-residential building designs consistently reduce total cost regardless of the design goal. LED upgrades and power strips offset the higher costs of other low TDV energy measures. Simulation results suggest that total energy cost can be reduced by up to 20 %, accompanied by a 20–30 % decrease in TDV energy.

For a typical Oak View residential building, the lowest cost and lowest TDV energy designs do not align. The lowest cost design yields minimal savings in cost and energy, while the lowest TDV energy design leads to an unacceptable increase in cost. However, Fig. 14 demonstrates that most energy savings achieved in the lowest TDV energy design can be obtained through HPWH and lighting measures alone. Fig. 15 provides information on the relative cost and energy contribution of each individual measure included in the lowest TDV energy design for low-income families in the Oak View community. Interactive effects were captured by simulating the measures incrementally. Additional charts for other residential groups can be found in supplemental material.

Fig. 15 illustrates the cost and energy contribution of each measure when implemented in a low-income residential unit. HPWH and lighting upgrades achieve a 41 % reduction in TDV energy at a 14 % cost increase. This cost increase occurs due to the higher HPWH installation cost and utility bills. Appliance electrification reduces TDV energy by 4 % but increases cost by over 20 %. Additional upgrades to appliances, space heating, and the envelope result in a cost increase of nearly 15 % and a TDV energy decrease of approximately 6.6 %. Appliance and space heater electrification cost increases occur primarily due to higher utility bills.

Fig. 16 shows the cumulative cost of carbon for the lowest TDV energy scenario in Oak View residential buildings. The graph displays the cost of carbon for both tenants and building owners (left) and considers low-income assistant program investment (right). The cost of carbon is analyzed based on income and building type, with buildings housing tenants below the 200 % poverty limit shown in the top left, buildings

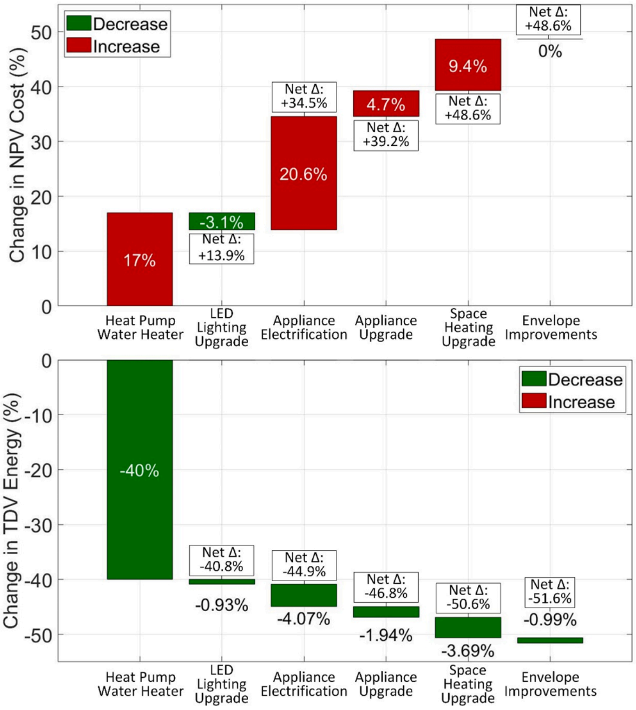

Fig. 15. Waterfall chart showing the relative contribution of the different measures that make up the lowest TDV energy design for low-income families living in Oak View.

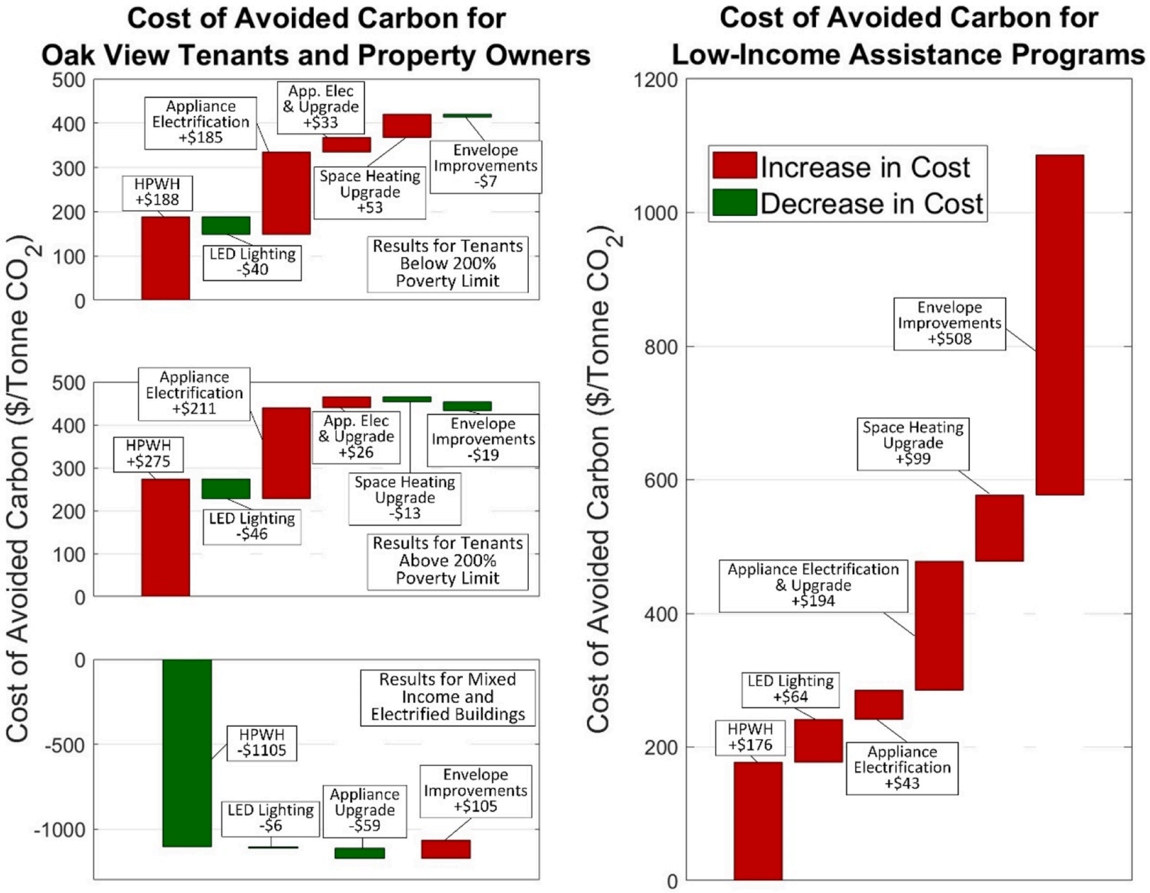

Fig. 16. Cost of carbon for residential building upgrades necessary to achieve lowest TDV energy across the Oak View community. The figure on the left shows the cost of carbon for tenants and building owners. The figure on the right shows the cost of carbon based on low-income weatherization and energy efficiency investment. Results show the cumulative effect of adoptions of new technologies and envelope upgrades specified for the lowest TDV energy designs.

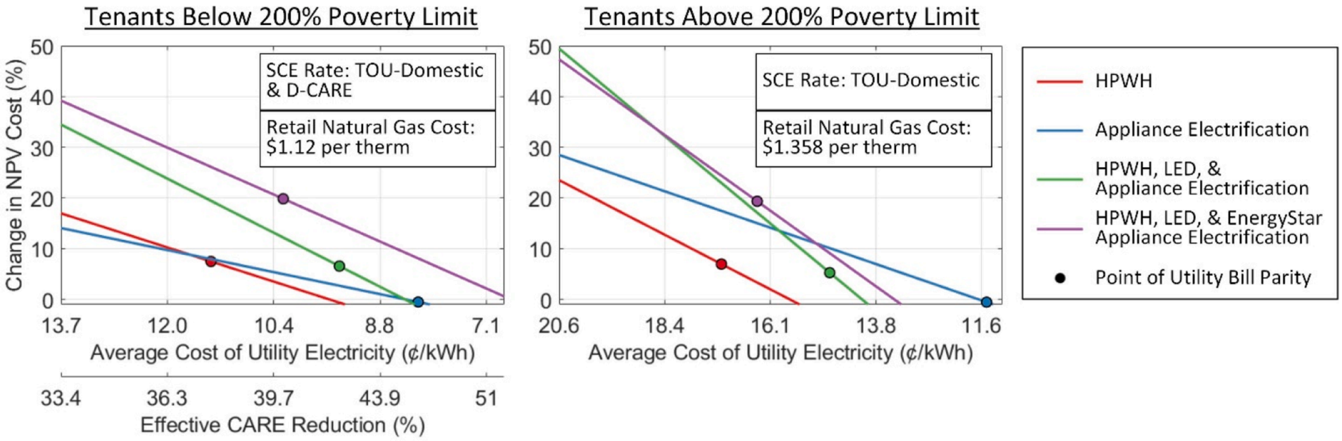

Fig. 17. The financial effect of reducing the cost of utility electricity on residential Oak View buildings that undergo electrification. The figure on the left focuses on families below the 200 % poverty limit and provides the effective CARE rate reduction. The figure on the right focuses on families above this poverty limit. Dots indicate the point at which electrification does not increase total utility bill cost (electricity + gas). Results are based on current SCE retail residential rates. According to simulation results, Oak View tenants below the 200 % poverty limit pay $13.7 per kWh electricity and $1.12 per therm natural gas. Tenants above the 200 % poverty limit pay $20.6 per kWh electricity and $1.358 per therm natural gas.

above the 200 % poverty limit in the middle left, and mixed-income tenants in already electrified buildings in the bottom left. Results for low-income assistance funds show only increases in cost since the benefits of these programs are realized by tenants, not the funding agencies.

By combining the effect of multiple measures at Oak View buildings, higher cost measures are balanced by lower cost, higher impact measures. For example, the cost of carbon for appliance electrification (from $1500 to $2300 per tonne, depending on income level), drops when paired with HPWH and lighting measures (from $350 to $400 per tonne). This same effect is observed for low-income assistance funds.

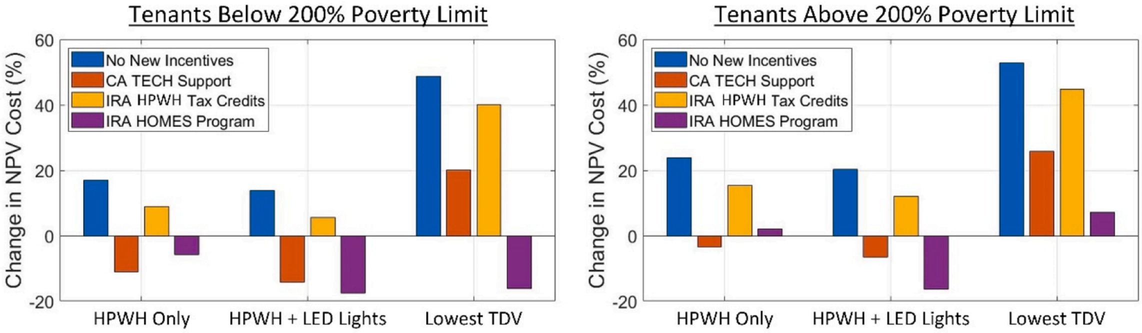

Fig. 18. Change in total cost for HPWH-based measures after applying funds available through new and emerging clean energy technology support programs. Results are shown for Oak View families above and below the 200 % household income poverty limit.

Note the cost of carbon for previously electrified residential buildings falls below -$1000 per tonne CO_2 due HPWHs reducing both cost and TDV energy.

4.4. *Expansion of low-income support programs*

Previous results show that electrification of DHW and appliances are effective in reducing TDV energy, carbon emissions, and pollutant emissions in Oak View buildings. However, these measures generally result in increased energy costs. This section explores how different utility rates and assistance programs can mitigate higher costs.

Fig. 17 illustrates how reducing the cost of utility electricity affects total cost for various electrification measures. The results are divided between Oak View tenants below and above the 200 % federal poverty limit. Natural gas rates also depend on income level and are $1.12 per therm for low-income residents, and $1.358 per therm for all else. Since certain electrification measures have a higher cost of installation, the point at which utility bill parity occurs is indicated with a dot. Under current CARE rates, the average actual discount applied to low-income ratepayers is 33.4 %.

For the HPWH, utility bill parity occurs when average utility electricity is reduced by $0.025 per kWh for ratepayers below the 200 % poverty limit (or a 38 % CARE reduction), and $0.04 per kWh for all else. For appliance electrification, rates must be reduced to $0.06 per kWh for low-income ratepayers, and $0.09 for all others. Reductions for mixed measures float between the upper appliance electrification and lower HPWH limits.

At utility bill parity, HPWHs continue to increase total cost due to higher equipment costs. The support programs described in Section 3.4 (TECH program, IRA tax credits, and HOMES) are designed to reduce the cost to install HPWHs and other clean energy technologies. The cost impact of these programs on Oak View property owners and tenants is shown in Fig. 18. This figure shows the application of these programs to the HPWH only, the HPWH and lighting upgrade measures, and the lowest TDV set of technologies. Results are shown for households above and below federal poverty limits (electrified homes are excluded).

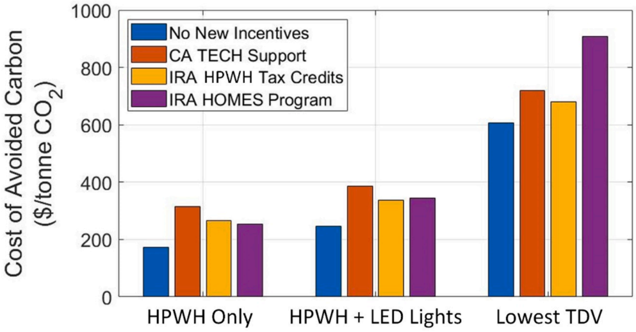

Fig. 19. Cost of carbon across Oak View residential buildings after applying funds available through new and emerging clean energy technology support programs. The cost of carbon considers the funds invested from new State and Federal incentive programs.

These results indicate that the new and emerging clean energy technology support programs provide significant cost savings benefits to Oak View tenants and property owners. In the case of the California TECH program, funding the purchase of a HPWH offsets both the HPWH installation premium and higher utility bills. This result is due to the assumption that a HPWH is installed to replace a failed gas tank DHW system. Since the property owner would need to install a new water heater, TECH funds offset the HPWH installation cost while reducing costs to maintain the property. These savings fully offset higher electric utility bills. When applied to the lowest TDV system design, TECH funds shrink the increase in cost from 50 % to 20 % despite only supporting HPWHs.

The IRA HPWH tax credit provides a similar benefit to TECH funding but is not sufficiently large to offset the equipment and utility bill cost premium for the buildings analyzed in the Oak View community. Finally, the IRA HOMES program is most effective at offsetting equipment premiums and higher utility bills for all technology scenarios analyzed for the Oak View community.

The cost of avoided carbon based on low-income assistance program funding applied to Oak View residential buildings is shown in Fig. 19. These results include the impact of TECH and IRA support. Cost of carbon increases for the TECH and IRA programs since these programs provide additional funding for clean energy technologies. Recall, however, that the utility bill benefits are experienced by the tenant, not the low-income assistance program, resulting in an increased cost of carbon as assistance increases.

Under the HPWH only scenario, TECH program funding completely offsets the cost to purchase and install a HPWH at a cost of $300 per tonne. The HOMES program, which covers 80 % of the cost, has a cost of approximately $250 per tonne. The IRA HPWH tax credits cost credit falls between TECH and HOMES incentives. Since this tax credit is stacked on top of existing low-income weatherization and energy efficiency funding, the isolated cost of carbon for the IRA HPWH tax credits is between $40 and $60 per tonne CO_2. As expected, adding additional measures (lighting, appliance electrification, etc.) increase the cost of carbon.

4.5. *Impact of measures on energy infrastructure*

The ACPF determined voltage and ampacity levels in the community and assessed distribution circuit degradation. The analysis showed that voltage levels were within acceptable limits of 0.95 to 1.05 p.u. for all measures (results that are consistent with prior work [21,110]). Only electrification measures caused circuit degradation. Fig. 20 illustrates the necessary upgrades for three different electrification scenarios over

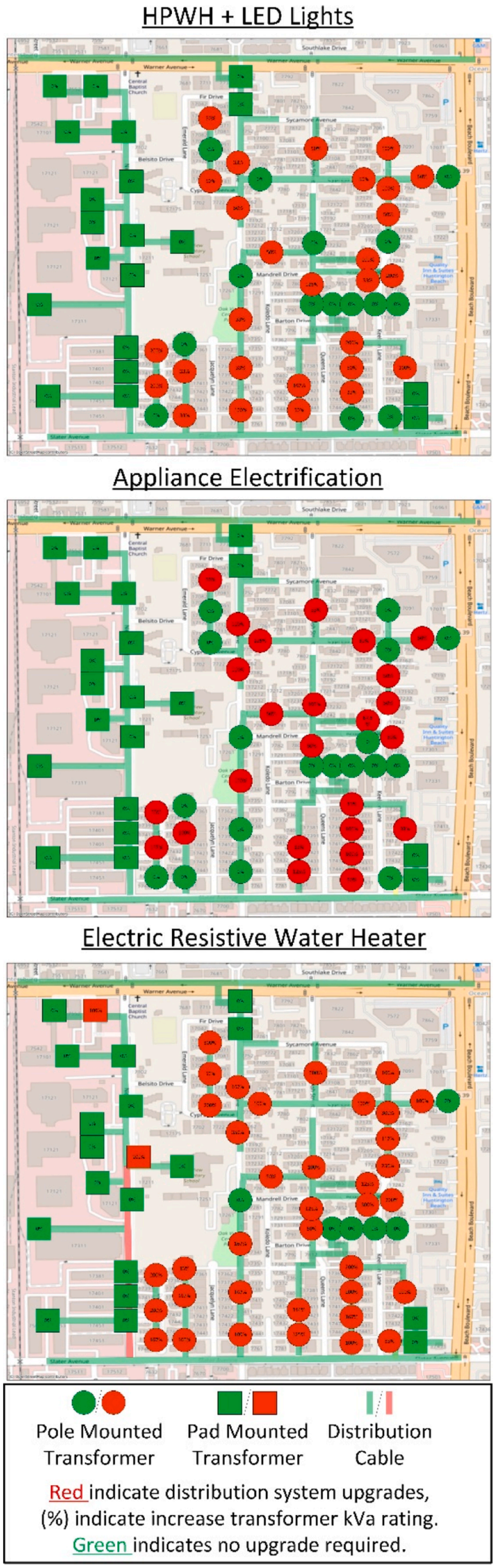

Fig. 20. Required electric distribution upgrades that occur within the next five years due to the following electrification measures: A) HPWH plus lighting, B) appliances, and C) ERWH systems. For reference, peak electrical demand for the entire community is 2.33 MW prior to measure implementation. Appliance electrification and HPWH measures increase peak demand to 2.47 and 2.83 MW, respectively. The ERWH measure increases peak demand to 3.46 MW.

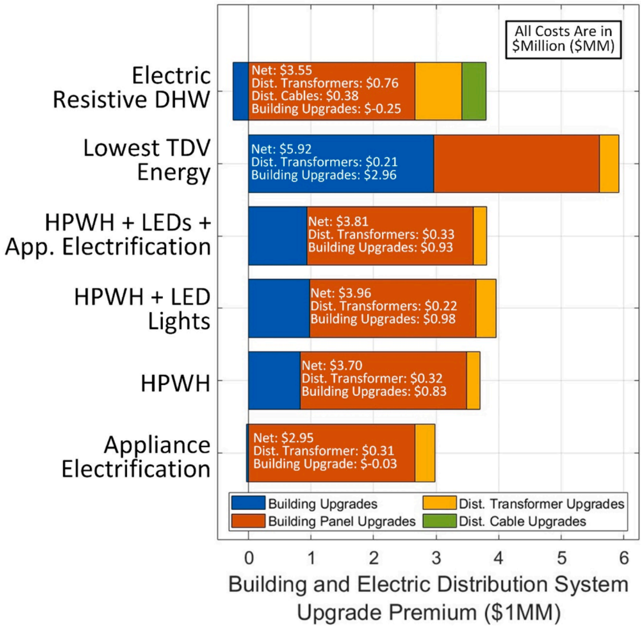

Fig. 21. Total up-front investment cost including energy technologies and weatherization measures at each individual building, panel and other building upgrades, and electric system distribution upgrades.

the next 15 years. Upgrades were determined using the model of [71]. HPWH and appliance electrification require transformer replacements, while ERWH leads to transformer failures and one cable overload. HPWH and appliance electrification upgrades would be required within five years of measure implementation while ERWH upgrades would be required within one year. These degradation results do not consider other potential load increases, such as electric vehicles or new space cooling.

Building electrical panel improvements are likely also necessary to support building electrification.[5] Panel upgrade cost estimates are based on an engineering report on building electrification in the City of Palo Alto, California [111]. This work estimates that a panel upgrade from 100 amps to 200 amps for a single-family home costs $4256, and the same upgrade for a multifamily building cost $2744 per residential unit. Note that each additional $1000 in equipment cost increases total cost of energy by 11 % for low-income residents and 9 % for others. Combining all measures and potential upgrades, Fig. 21 shows the combined upfront cost for Oak View, including building measure premiums, panel upgrades, and electric distribution circuit upgrades. Building panel upgrade costs remain constant at $2.67 million. Electric distribution circuit upgrades range from $0.21 to $0.31 million for appliance electrification and HPWH measures. In total, the most significant capital requirement is panel upgrades required to electrify residential buildings.

These results represent investment from different parties. Regardless, all costs are likely to eventually be borne by the ratepayer as electric infrastructure upgrade costs are added to the utility rate base. Assuming a 30-year monetization period and a 7.5 % rate of return, appliance electrification and HPWH upgrades increase annual electricity costs by $15 to $24 per year per ratepayer (1 % to 2 % total cost increase). ERWH, with higher ampacity requirements, leads to an increase of nearly $84 per year (8 % total cost increase).

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[5] Most residential buildings were built without cooling and with gas system hookups. Visual inspection of exterior electrical panels indicates original equipment. Oak View residents have reported issues with building circuit breaker trips while using portable and standalone air conditioning units, or other electrical appliances.

5. Discussion

The three key contributions of this work are 1) the analysis of weatherization, energy efficiency, and electrification measures applied to a low-income community in Southern California, 2) the examination of low-income assistance programs towards supporting these building measures, and 3) the prediction of electric distribution circuit degradation and cost impacts due to the application of these measures. The main outcomes from this work are that there are a limited number of building measures applied to the Oak View community that can reduce cost, carbon, and pollutant emissions. Electrification of gas DHW and appliance systems produces the largest drop in carbon and pollutant emissions but increases utility bills for the Oak View community. As a result, these measures are likely ineligible for support under current low income weatherization and energy efficiency programs. Providing more generous utility rate discounts would eliminate bill increases due to electrification but would not eliminate additional equipment costs associated with electrification. These costs can be offset with new and emerging electrification support programs. Electrification is projected to degrade electric distribution utility equipment in Oak View. However, costs to offset degradation are relatively low - $\leq$2 % of current Oak View utility energy costs.

Limitations of our work include:

1) **Location dependence**: Oak View has a temperate climate and access to high cost, low-carbon electricity. The findings likely apply to other areas in California, but additional analysis may be necessary for implementation beyond the state.
2) **Instance in time**: Results are based upon current equipment and weatherization costs and incentives and do not consider future cost trends.
3) **Thermal boundaries**: Many HPWHs sources heat from ambient outdoor air. In reality, HPWHs are installed inside the building and would require ductwork to access exterior air. Most Oak View gas tank DHW systems are in garages next to exterior walls, or in mechanical rooms/closets separate from residential units. If HPWHs are installed with insufficient ventilation or ambient temperatures drop below the design point, HPWH performance will decrease. If the HPWH sources heat from conditioned areas, HPWH operation could result in additional space heater operation, reducing carbon emission savings created by DHW electrification.
4) **One hour time step**: Simulation time step does not capture the extremity of DHW consumption dynamics. Typical HPWHs also contain a backup electric resistive element that is triggered during large hot water draws. Analyzing the community at the hourly time-step likely misses dynamics that may result in electric resistive operation, which would reduce TDV energy savings and increase cost.
5) **Limited building measures**: This work does not include renewable distributed energy resources, active cooling technologies (i.e., reversible heat pumps), and other weatherization measures included in other work [49]. We also consider appliance upgrades as a bundle, mixing some economic and non-economic measures.
6) **Occupant thermal comfort**: Since we do not consider active cooling technologies, we do not resolve building occupant comfort. This consideration will become more important as extreme heat events occur more frequently.
7) **Split incentive:** Roughly 80 % of Oak View residents rent. Recent DOE survey results show that nearly 80 % of renters pay their own utility bills [112]. Since the utility bill reduction is experienced primarily by the ratepayer, a property owner does not have a direct incentive to invest in clean energy technology or weatherization [113]. This work does not resolve the challenge of this split incentive, which must be accounted for when implementing clean energy technology support programs.
8) **Availability of assistance funding:** CARE rate support is open to all income qualified ratepayers. All other programs, however, are budget limited and can only aid a certain number of families each year. These budget limitations were not considered in our work. If assistance budgets remain constant, supporting more expensive HPWH systems over conventional gas DHW heaters could reduce the number low-income families benefiting each year from weatherization and energy efficiency programs.

While our analysis focuses on Oak View, the approach can be applied to other disadvantaged communities in the U.S.

Based on our analysis, electrification efforts in Oak View should prioritize HPWHs over ERWH due to significant cost increases and distribution upgrades with the latter. However, a split incentive issue arises as ERWH systems cost less upfront. If not addressed, electrification of water heating could burden low-income Oak View renters and hinder carbon reduction potential. Title 24 permits electric resistive water heaters when tank size falls below a certain threshold, and other state energy codes are more permissive of residential electric resistive water heaters. Care must be taken to ensure that, when climate and utility cost conditions are similar to Oak View, electrification efforts prioritize higher efficiency heat pumps to avoid an unnecessary increase in energy burden for low-income families.

Widespread electrification of Oak View, especially with less efficient technologies, would increase the energy burden for low-income Oak View households under current rate structures. Further CARE rate reductions are needed for utility bill parity, or upfront incentives that offset both equipment and utility bill premiums must be provided. Escalating utility gas rates in California may drive future electrification in Oak View. However, this scenario achieves carbon reduction through an increased energy burden on low-income households. Finding ways to further reduce electricity costs for low-income families would improve equity and enable electrification.

Cost of carbon calculations support our findings that deeper carbon reductions often come at a higher Oak View ratepayer cost. Shifting funding from envelope improvements to electrification measures would enhance the carbon reduction effectiveness of low-income support programs and reduce the impact of higher energy costs. However, it is vital to analyze this shift carefully to ensure that it does not compromise program goals of enhancing health and safety.

Weatherization and energy efficiency measures in communities like Oak View have a small impact on cost and emissions reductions. Even unbundling appliance upgrades for ENERGY STAR appliances supported by LIHEAP and WAP only results in 10–15 % TDV energy reduction and 10–20 % cost reduction for residential buildings in Oak View. The lack of cooling loads contributes to this limited effect. The health and safety benefits of these measures are not addressed in our work. Regardless, there is significant potential to reduce carbon and pollutant emissions in low-income communities with a few targeted measures.

6. Summary and conclusions

This work analyzes building energy efficiency, weatherization, and electrification measures in a disadvantaged community in coastal Southern California. The goals were to determine the most cost-effective measures for energy, carbon, and pollutant reductions, assess support from low-income energy assistance programs, and evaluate their impact on the local electrical distribution system. The analysis incorporated incentives from the Inflation Reduction Act of 2022. A combined urban building energy and AC power flow model was used to examine upgrades in building envelope, DHW, space heating systems, and plug and lighting loads. Key findings include:

- Traditional low-income energy assistance measures (weatherization, efficient appliances, lighting upgrades) have limited impact on cost, carbon, and pollutant reductions in the community. These measures reduce costs and emissions by 10–20 % over the current community.

These results are influenced by the temperate climate and lack of building space cooling systems.

- Of the various measures examined in this work, the HPWH produces the largest reduction in carbon emissions and the 2nd largest reduction in pollutant emissions. When used to electrify a gas tank DHW, carbon emissions over the next 30 years are projected to drop by over 40 %, on average, while pollutant emissions from buildings are cut in half. However, due to the relatively high cost of California retail electricity, the HPWH increases total cost of energy by 17 % for low-income households, and 22 % for all others in the community. Pairing HPWHs with LED interior lighting achieves 80 % of the carbon reduction potential estimated in this work. When used to replace an ERWH, HPWHs decrease cost nearly 30 % and carbon emissions by nearly 35 %.
- HPWH and appliance electrification have a similar impact on the Oak View electric distribution systems, with transformer replacements and upgrades increasing Oak View ratepayer energy costs by 1 % to 2 %. Interestingly, electric distribution transformer degradation remains the same when both HPWHs and appliance electrification are implemented simultaneously.
- ERWHs also display significant TDV energy reduction potential but increase cost of energy 70 % to 100 % when replacing a gas tank DHW. Widespread deployment results in immediate distribution transformer upgrades, and in one instance, a distribution cable upgrade, resulting in a projected 7.5 % cost of energy increase for the community.
- Current low-income utility rate reduction programs, which reduce the cost of electricity by ~30 %, are insufficient for supporting electrification in this community. Holding utility gas costs constant, utility electricity must be reduced by 35 % to 45 % to achieve utility bill parity after building electrification.
- Incentives that offset 80 % or more of total HPWH installation costs across Oak View have the potential to eliminate any cost increase associated with electrifying residential buildings. However, incentives provided to property owners may not directly translate into savings for low-income renters.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used GhatGPT 3.5 in order to edit and improve the readability of the publication. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Robert Flores: Writing – original draft, Funding acquisition, Conceptualization. **Sammy Houssainy:** Writing – review & editing, Software. **Weixi Wang:** Writing – original draft, Formal analysis. **Khanh Nguyen Cu:** Writing – review & editing, Software. **Xiao Nie:** Writing – original draft, Data curation. **Noah Woolfolk:** Writing – original draft, Formal analysis. **Ben Polly:** Writing – review & editing, Funding acquisition. **Ramin Faramarzi:** Funding acquisition, Conceptualization. **Jim Maclay:** Writing – review & editing, Funding acquisition. **Jaeho Lee:** Writing – review & editing, Funding acquisition. **Jack Brouwer:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Some data is private and can be shared. Other data sets will be made available upon request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.adapen.2024.100169.

References

[1] Brown MA, Soni A, Lapsa MV, Southworth K, Cox M. Low-income energy affordability: conclusions from a literature review. Oak Ridge, TN (United States): Oak Ridge National Lab.(ORNL); 2020. https://doi.org/10.1088/2516-1083/abb954.

[2] Xu X, Chen Cf. Energy efficiency and energy justice for U.S. low-income households: an analysis of multifaceted challenges and potential. Energy Policy 2019;128(February):763–74. https://doi.org/10.1016/j.enpol.2019.01.020.

[3] R. Cluett, J. Amann, and S. Ou, “Building better energy efficiency programs for low-income households,” 2016. Available: https://www.southeastsdn.org/wp-content/uploads/2019/11/Building-Better-Efficiency-Programs-for-Low-Income-Households.pdf.

[4] A. Drehobl, L. Ross, R. Ayala, A. Zaman, and J. Amann, “How high are household energy burdens? An assessment of national and metropolitan energy burden across the United States,” no. September, pp. 1–80, 2022.

[5] Child Health Impact Working Group, “Unhealthy consequences: energy costs and child health-a child health impact assessment of energy costs and the low income home energy assistance program,” no. April 2007.

[6] Schweitzer M, Tonn B. Non-energy benefits of the US Weatherization Assistance Program: a summary of their scope and magnitude. Appl Energy 2003;76(4): 321–35. https://doi.org/10.1016/S0306-2619(03)00003-5.

[7] M.A. Brown, L.G. Berry, R.A. Balzer, and E. Faby, “National impacts of the Weatherization Assistance Program in single-family and small multifamily dwellings,” 1993.

[8] California Energy Commission, “Energy equity indicators tracking progress,” 2018. Available: https://www.energy.ca.gov/sites/default/files/2019-12/energy_equity_indicators_ada.pdf.

[9] F. Pavley and E. Garcia, *Senate Bill 32 California Global Warming Solutions Act of 2006: emissions limit.* 2016.

[10] N. Bautista, “08/28/18- Senate Floor Analysis for Bill No. SB 100,” Sacramento, 2018.

[11] L. Friedman, M. Stone, R. Bloom, C. David, and H. Stern, *Assembly bill 3232 zero-emissions buildings and sources of heat energy.* 2018. Accessed: Sep. 30, 2019. Available: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB3232.

[12] H. Stern and L. Friedman, “Senate bill 1477 low-emissions buildings and sources of heat energy.” Accessed: Mar. 04, 2020. Available: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB1477.

[13] Razeghi G, Carreras-sospedra M, Brown T, Brouwer J, Dabdub D, Samuelsen S. Episodic air quality impacts of plug-in electric vehicles. Atmos Environ 2016;137: 90–100. https://doi.org/10.1016/j.atmosenv.2016.04.031.

[14] U.S. Environmental Protection Agency, "Nonattainment areas for criteria pollutants (Green Book) | US EPA." Accessed: Feb. 21, 2023. Available: https://www.epa.gov/green-book.

[15] Wilson EJH, Harris CB, Robertson JJ, Agan J. Evaluating energy efficiency potential in low-income households: a flexible and granular approach. Energy Policy 2019;129(January):710–37. https://doi.org/10.1016/j.enpol.2019.01.054.

[16] E.J.H. Wilson et al., "Energy efficiency potential in the U. S. single-family housing stock," 2017. Available: http://www.nrel.gov/publications.

[17] Abel DW, et al. Air quality-related health benefits of energy efficiency in the United States. Environ Sci Technol 2019;53(7):3987–98. https://doi.org/10.1021/acs.est.8b06417.

[18] Zhu S, Mac Kinnon M, Carlos-Carlos A, Davis SJ, Samuelsen S. Decarbonization will lead to more equitable air quality in California. Nat Commun 2022;13(1). https://doi.org/10.1038/s41467-022-33295-9.

[19] Wei M, et al. Approaches to cost-effective near-net zero energy new homes with time-of-use value of energy and battery storage. Adv Appl Energy 2021;2(March):100018. https://doi.org/10.1016/j.adapen.2021.100018.

[20] E. Wilson, "ResStock—Targeting energy and cost savings for U.S. homes," 2017.

[21] Earle L, Maguire J, Munankarmi P, Roberts D. The impact of energy-efficiency upgrades and other distributed energy resources on a residential neighborhood-scale electrification retrofit. Appl Energy 2023;329(August 2022):120256. https://doi.org/10.1016/j.apenergy.2022.120256.

[22] White PR, Rhodes JD, Wilson EJH, Webber ME. Quantifying the impact of residential space heating electrification on the Texas electric grid. Appl Energy 2021;298(June):117113. https://doi.org/10.1016/j.apenergy.2021.117113.

[23] Nutkiewicz A, Mastrucci A, Rao ND, Jain RK. Cool roofs can mitigate cooling energy demand for informal settlement dwellers. Renew Sustain Energy Rev 2022;159(February):112183. https://doi.org/10.1016/j.rser.2022.112183.

[24] Nutkiewicz A, Jain RK, Bardhan R. Energy modeling of urban informal settlement redevelopment: exploring design parameters for optimal thermal comfort in Dharavi, Mumbai, India. Appl Energy 2018;231(August):433–45. https://doi.org/10.1016/j.apenergy.2018.09.002.

[25] Ramos A, Gago A, Labandeira X, Linares P. The role of information for energy efficiency in the residential sector. Energy Econ 2015;52:S17–29. https://doi.org/10.1016/j.eneco.2015.08.022.

[26] Heinen S, Turner W, Cradden L, McDermott F, O'Malley M. Electrification of residential space heating considering coincidental weather events and building thermal inertia: a system-wide planning analysis. Energy 2017;127:136–54. https://doi.org/10.1016/j.energy.2017.03.102.

[27] Lahimer AA, Alghoul MA, Yousif F, Razykov TM, Amin N, Sopian K. Research and development aspects on decentralized electrification options for rural household. Renew Sustain Energy Rev 2013;24:314–24. https://doi.org/10.1016/j.rser.2013.03.057.

[28] Ang YQ, Berzolla ZM, Reinhart CF. From concept to application: a review of use cases in urban building energy modeling. Appl Energy 2020;279:115738. https://doi.org/10.1016/j.apenergy.2020.115738.

[29] Dong B, Li Z, Taha A, Gatsis N. Occupancy-based buildings-to-grid integration framework for smart and connected communities. Appl Energy 2018;219 (November 2017):123–37. https://doi.org/10.1016/j.apenergy.2018.03.007.

[30] Fonseca JA, Nguyen TA, Schlueter A, Marechal F. City energy analyst (CEA): integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. Energy Build 2016;113:202–26. https://doi.org/10.1016/j.enbuild.2015.11.055.

[31] Fonseca JA, Schlueter A. Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts. Appl Energy 2015;142:247–65. https://doi.org/10.1016/j.apenergy.2014.12.068.

[32] Crawley DB, et al. EnergyPlus: creating a new-generation building energy simulation program. Energy Build 2001;33(4):319–31. https://doi.org/10.1016/S0378-7788(00)00114-6.

[33] Mendon VV, Taylor ZT. Development of residential prototype building models and analysis system for large-scale energy efficiency studies using energyplus. Richland, WA (United States): Pacific Northwest National Lab. (PNNL); 2014.

[34] Deru M, et al. Commercial reference building models of the national building stock. US Department of Energy National Renewable Energy Laboratory; 2011.

[35] Sokol J, Davila CC, Reinhart CF. Validation of a Bayesian-based method for defining residential archetypes in urban building energy models. Energy Build 2017;134:11–24. https://doi.org/10.1016/j.enbuild.2016.10.050.

[36] Cerezo C, Sokol J, AlKhaled S, Reinhart C, Al-Mumin A, Hajiah A. Comparison of four building archetype characterization methods in urban building energy modeling (UBEM): a residential case study in Kuwait City. Energy Build 2017; 154:321–34. https://doi.org/10.1016/j.enbuild.2017.08.029.

[37] Buckley N, Mills G, Reinhart C, Berzolla ZM. Using urban building energy modelling (UBEM) to support the new European Union's Green Deal: case study of Dublin Ireland. Energy Build 2021;247:111115. https://doi.org/10.1016/j.enbuild.2021.111115.

[38] Nagpal S, Hanson J, Reinhart C. A framework for using calibrated campus-wide building energy models for continuous planning and greenhouse gas emissions reduction tracking. Appl Energy 2019;241(February):82–97. https://doi.org/10.1016/j.apenergy.2019.03.010.

[39] Ang YQ, Berzolla ZM, Letellier-Duchesne S, Jusiega V, Reinhart C. UBEM.io: a web-based framework to rapidly generate urban building energy models for carbon reduction technology pathways. Sustain Cities Soc 2022;77(November 2021). https://doi.org/10.1016/j.scs.2021.103534.

[40] Reyna JL, Chester MV. Energy efficiency to reduce residential electricity and natural gas use under climate change. Nat Commun 2017;8(May 2017):1–12. https://doi.org/10.1038/ncomms14916.

[41] Ang YQ, Berzolla ZM, Letellier-Duchesne S, Reinhart CF. Carbon reduction technology pathways for existing buildings in eight cities. Nat Commun 2023;14 (1). https://doi.org/10.1038/s41467-023-37131-6.

[42] Nutkiewicz A, Yang Z, Jain RK. Data-driven urban energy simulation (DUE-S): a framework for integrating engineering simulation and machine learning methods in a multi-scale urban energy modeling workflow. Appl Energy 2018;225(May): 1176–89. https://doi.org/10.1016/j.apenergy.2018.05.023.

[43] Nutkiewicz A, Choi B, Jain RK. Exploring the influence of urban context on building energy retrofit performance: a hybrid simulation and data-driven approach. Adv Appl Energy 2021;3(May):100038. https://doi.org/10.1016/j.adapen.2021.100038.

[44] Roth J, Martin A, Miller C, Jain RK. SynCity: using open data to create a synthetic city of hourly building energy estimates by integrating data-driven and physics-based methods. Appl Energy 2020;280(May):115981. https://doi.org/10.1016/j.apenergy.2020.115981.

[45] Vazquez-Canteli J, Dilsiz Demir A, Brown J, Nagy Z. Deep neural networks as surrogate models for urban energy simulations. J Phys Conf Ser 2019;1343(1). https://doi.org/10.1088/1742-6596/1343/1/012002.

[46] Hong T, Chen Y, Lee SH, Piette MA. CityBES: a web-based platform to support city-scale building energy efficiency. Urban Comput 2016;14:2016.

[47] Chen Y, Hong T, Piette MA. Automatic generation and simulation of urban building energy models based on city datasets for city-scale building retrofit analysis. Appl Energy 2017;205(April):323–35. https://doi.org/10.1016/j.apenergy.2017.07.128.

[48] Teso L, et al. Large scale energy analysis and renovation strategies for social housing in the historic city of Venice. Sustain Energy Technol Assess 2022;52 (PA):102041. https://doi.org/10.1016/j.seta.2022.102041.

[49] Sun K, Zhang W, Zeng Z, Levinson R, Wei M, Hong T. Passive cooling designs to improve heat resilience of homes in underserved and vulnerable communities. Energy Build 2021;252:111383. https://doi.org/10.1016/j.enbuild.2021.111383.

[50] El Kontar R, Polly B, Charan T. URBANopt: an open-source software development kit for community and urban district energy modeling. In: 2020 building performance analysis conference and SimBuild; 2020. p. 293–301.

[51] Houssainy S, Faramarzi R, Farahmand F, Pande A, Griesser J. Community-scale energy efficiency assessment for zero net energy using the URBANopt simulation platform. Golden, CO (United States): National Renewable Energy Lab.(NREL); 2020.

[52] Charan T, et al. Integration of open-source urbanopt and dragonfly energy modeling capabilities into practitioner workflows for district-scale planning and design. Energies (Basel) 2021;14(18):1–28. https://doi.org/10.3390/en14185931.

[53] Fallahi Z, Houssainy S, Ling J, Leach M, Klun L, Slovensky M. Designing for zero energy and zero carbon on a multi-building scale using URBANopt. Golden, CO (United States): National Renewable Energy Lab. (NREL); 2022.

[54] Long N, et al. Modeling district heating and cooling systems with URBANopt, Geojson to modelica translator, and the modelica buildings library. Berkeley, CA (United States): Lawrence Berkeley National Lab. (LBNL); 2021.

[55] Doubleday K, et al. Toward a subhourly net zero energy district design through integrated building and distribution system modeling. J Renew Sustain Energy 2019;11(3). https://doi.org/10.1063/1.5093917.

[56] Buonocore JJ, Salimifard P, Magavi Z, Allen JG. Inefficient building electrification will require massive buildout of renewable energy and seasonal energy storage. Sci Rep 2022;12(1):1–9. https://doi.org/10.1038/s41598-022-15628-2.

[57] Tarroja B, et al. Translating climate change and heating system electrification impacts on building energy use to future greenhouse gas emissions and electric grid capacity requirements in California. Appl Energy 2018;225(April):522–34. https://doi.org/10.1016/j.apenergy.2018.05.003.

[58] Blonsky M, Nagarajan A, Ghosh S, McKenna K, Veda S, Kroposki B. Potential impacts of transportation and building electrification on the grid: a review of electrification projections and their effects on grid infrastructure, operation, and planning. Curr Sustain/Renew Energy Rep 2019;6(4):169–76. https://doi.org/10.1007/s40518-019-00140-5.

[59] Fowlie M, Greenstone M, Wolfram C. Do energy efficiency investments deliver? Evidence from the weatherization assistance program. Q J Econ 2018;133(3): 1597–644. https://doi.org/10.1093/qje/qjy005.Advance.

[60] Hernández D, Bird S. Energy burden and the need for integrated low-income housing and energy policy. Poverty Public Policy 2010;2(4):5–25. https://doi.org/10.2202/1944-2858.1091.

[61] Murray AG, Mills BF. The impact of low-income home energy assistance program participation on household energy insecurity. Contemp Econ Policy 2014;32(4): 811–25. https://doi.org/10.1111/coep.12050.

[62] Heleno M, et al. Optimizing equity in energy policy interventions: a quantitative decision-support framework for energy justice. Appl Energy 2022;325(April): 119771. https://doi.org/10.1016/j.apenergy.2022.119771.

[63] Bradshaw JL, Bou-Zeid E, Harris RH. Comparing the effectiveness of weatherization treatments for low-income, American, urban housing stocks in different climates. Energy Build 2014;69:535–43. https://doi.org/10.1016/j.enbuild.2013.11.035.

[64] Bradshaw JL, Bou-Zeid E, Harris RH. Greenhouse gas mitigation benefits and cost-effectiveness of weatherization treatments for low-income, American, urban

housing stocks. Energy Build 2016;128:911–20. https://doi.org/10.1016/j.enbuild.2016.07.020.

[65] "2010 census tract reference maps." Accessed: Sep. 28, 2021. Available: https://www.census.gov/geographies/reference-maps/2010/geo/2010-census-tract-maps.html.

[66] L. August et al., "CalEnviroScreen 4.0," 2021.

[67] United States Census Bureau, "American community survey." Accessed: Dec. 31, 2017. Available: https://www.census.gov/programs-surveys/acs/.

[68] Southern California Edison, "Rates & Pricing Choices | SCE Tariff Books | Regulatory Information | Home - SCE." Accessed: Apr. 05, 2023. Available: https://www.sce.com/regulatory/tariff-books/rates-pricing-choices.

[69] Southern California Gas Company, "SoCalGas - Rate Schedules." Accessed: Apr. 05, 2023. Available: https://tariff.socalgas.com/regulatory/tariffs/tariffs-rates.shtml.

[70] Flores R, et al. Developing and tuning a community scale energy model for a disadvantaged community. Energy Build 2023;285:112861.

[71] Wang W, Flores RJ, Razeghi G, Brouwer J. Quantifying transformer and cable degradation in highly renewable electric distribution circuits. In: IEEE PES grid edge technologies conference & exposition; 2023.

[72] Polly B, Kutscher C, Macumber D, Schott M. From zero energy buildings to zero energy districts. In: 2016 ACEEE summer study on energy efficiency in buildings; 2016. p. 1–16. https://www.researchgate.net/publication/307955877_From_Zero_Energy_Buildings_to_Zero_Energy_Districts.

[73] Chen J, et al. Stochastic simulation of occupant-driven energy use in a bottom-up residential building stock model. Appl Energy 2022;325(August):119890. https://doi.org/10.1016/j.apenergy.2022.119890.

[74] Macumber D, et al. City scale modeling with openstudio. In: Proceedings of SimBuild. 6; 2016.

[75] E. Wilson, C.E. Metzger, S. Horowitz, and R. Hendron, "2014 building America house simulation protocols," National Renewable Energy Laboratory, no. NREL/TP-5500-60988, p. 91, 2014, Available: http://energy.gov/sites/prod/files/2014/03/f13/house_simulation_protocols_2014.pdf.

[76] U.S. Energy Information Administration, "2015 residential energy consumption survey (RECS)—Energy information administration." Accessed: Feb. 08, 2021. Available: https://www.eia.gov/consumption/residential/index.php.

[77] U.S. Energy Information Administration, "2012 energy information administration (EIA)—Commercial buildings energy consumption survey (CBECS)." Accessed: Feb. 08, 2021. Available: https://www.eia.gov/consumption/commercial/.

[78] I. KEMA, "2009 California residential appliance saturation study," 2010. Available: https://www.energy.ca.gov/2010publications/CEC-200-2010-004/CEC-200-2010-004-V1.PDF.

[79] Nie X, Yoo Y, Hewakuruppu H, Sullivan J, Krishna A, Lee J. Cool white polymer coatings based on glass bubbles for buildings. Sci Rep 2020;10(1):1–10. https://doi.org/10.1038/s41598-020-63027-2.

[80] Dugan R. The open distribution system simulator(OpenDSS). Sourceforge 2020;(June):1–218.

[81] Novoa L, Flores R, Brouwer J. Optimal renewable generation and battery storage sizing and siting considering local transformer limits. Appl Energy 2019;256(October):113926. https://doi.org/10.1016/j.apenergy.2019.113926.

[82] Southern California Edison, "Southern California Edison DRPEP.".

[83] IEEE C57.91™-2011, *IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators - Redline*, vol. 2011, no. March. 2012.

[84] Bartos M, et al. Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States. Environ Res Lett 2016;11(11). https://doi.org/10.1088/1748-9326/11/11/114008.

[85] R.K.D. Abdulsalam S. Alghamdim, "A study of expected lifetime of XLPE insulation cables working at elevated temperatures by applying accelerated thermal ageing," 2020, https://doi.org/10.1016/j.heliyon.2019.e03120.

[86] Southern California Gas Company, "California alternate rates for energy CARE | SoCalGas." Available: https://www.socalgas.com/save-money-and-energy/assistance-programs/california-alternate-rates-for-energy.

[87] Southern California Edison, "FERA & CARE Discounted Rates." Accessed: Jan. 16, 2023. Available: https://www.sce.com/residential/assistance/fera-care.

[88] Southern California Edison, "Appliance Replacement Assistance | Help Paying Your Bill | Your Home | Home - SCE." Accessed: Jan. 16, 2023. Available: https://www.sce.com/residential/assistance/energy-saving-program.

[89] California Department of Community Services & Development, "Low-income weatherization program guidelines multi-family (MF) energy efficiency and renewables." Available: https://www.csd.ca.gov/SharedDocuments/LIWP-2022-Multi-Family-2.0-Draft-Program-Guidelines.pdf.

[90] G. Sadhasivan and S. Chang, "2019 California Low-Income Needs Assessment Final Report: volume 1 of 3: summary of Key Findings," 2019. Available: https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/energy-efficiency/iqap/2019linavol1.pdf.

[91] E. Chac, A. Dominguez, L. Froess, M.-A. Jones, and T. Mateo, "Building initiative for low- emissions development program," 2021.

[92] TECH Clean California, "Support : contractor support center." Accessed: Jan. 18, 2023. Available: https://tech.freshdesk.com/support/home.

[93] E. Chac et al., "Building initiative for low- emissions development (BUILD) program, First Edition," 2022.

[94] TECH Clean California, "TECH Public Reporting Incentives." Accessed: Apr. 05, 2023. Available: https://techcleanca.com/incentives/.

[95] "H.R.5376—Inflation Reduction Act of 2022." Accessed: Jun. 03, 2023. Available: https://www.congress.gov/bill/117th-congress/house-bill/5376#:~:text=5376-117thCongress(2021-,Congress.gov%7CLibraryofCongress.

[96] United States Environmental Protection Agency, "ENERGY STAR Multifamily New Construction, California Program Requirements, Version 1.3." Available: https://www.energystar.gov/sites/default/files/asset/document/ENERGYSTARMFNCCAProgramRequirementsVersion1.3_Rev03.pdf.

[97] M. Sontag et al., "Time Dependent Valuation of Energy for Developing Building Efficiency Standards," 2020. Available: http://www.energy.ca.gov/title24/2013standards/prerulemaking/documents/general_cec_documents/Title24_2013_TDV_Methodology_Report_23Feb2011.pdf.

[98] California Energy Commission, *2019 Building Energy Efficiency Standards for Residential and Nonresidential Buildings - Title 24*. 2019.

[99] United States Environmental Protection Agency (EPA), "Emissions & generation resource integrated database (eGRID), 2020." Accessed: Oct. 31, 2023. Available: https://www.epa.gov/egrid.

[100] Zhao Y, McDonell V, Samuelsen S. Influence of hydrogen addition to pipeline natural gas on the combustion performance of a cooktop burner. Int J Hydrogen Energy 2019;44(23):12239–53. https://doi.org/10.1016/j.ijhydene.2019.03.100.

[101] V. McDonell, Y. Zhao, and S. Choudhory, "Implications of increased renewable natural gas on appliance emissions and stability California energy commission," 2020.

[102] Zhao Y, McDonell V, Samuelsen S. Experimental assessment of the combustion performance of an oven burner operated on pipeline natural gas mixed with hydrogen. Int J Hydrogen Energy 2019;44(47):26049–62. https://doi.org/10.1016/j.ijhydene.2019.08.011.

[103] Choudhury S, Zhao Y, Mcdonell VG. Combustion performance of storage water heaters operated on mixtures of natural and renewable gas. Int J Hydrogen Energy 2019;45(3):1–8. https://doi.org/10.1016/j.ijhydene.2019.11.043.

[104] Choudhury S, McDonell VG, Samuelsen S. Combustion performance of low-NOx and conventional storage water heaters operated on hydrogen enriched natural gas. Int J Hydrogen Energy 2020;45(3):2405–17. https://doi.org/10.1016/j.ijhydene.2019.11.043.

[105] Choudhury S, McDonell VG, Samuelsen S. Performance of low-nox and conventional storage water heaters operated on biogas and natural gas. In: ASME international mechanical engineering congress and exposition. American Society of Mechanical Engineers; 2021. V011T11A071.

[106] Zhao Y, Morales D, McDonell V. Influence of blending hydrogen and biogas into natural gas on the combustion performance of a tankless water heater. In: ASME international mechanical engineering congress and exposition, proceedings (IMECE). 8; 2019. https://doi.org/10.1115/IMECE2019-10792.

[107] U.S. Energy Information Administration, "Table 6: residential Sector - Electric Sales, Revenue, and Average Price - Energy Information Administration." Accessed: Apr. 10, 2023. Available: https://www.eia.gov/electricity/sales_revenue_price/.

[108] Environmental Protection Agency, "eGRID2012 Version 1.1 Year 2009 Summary Tables." Available: http://www.epa.gov/cleanenergy/documents/egridzips/eGRID2012V1_0_year09_SummaryTables.pdf.

[109] EPA. eGRID2016 summary tables. Clean Air Markets Division, Office of Atmospheric Programs U.S. Environmental Protection Agency; 2015. p. 3–8. https://doi.org/10.1073/pnas.0703993104.

[110] Li X, Li B, Zhang L. Molding the impact of all-electric suburbs on power grids using probabilistic load flow. In: 2021 IEEE 3rd international conference on power data science, ICPDS 2021; 2021. p. 33–9. https://doi.org/10.1109/ICPDS54746.2021.9689925.

[111] TRC Energy Services, "Palo Alto Electrification Final Report." Available: https://www.cityofpaloalto.org/civicax/filebank/documents/55069.

[112] U.S. Energy Information Administration, "2020 RECS Survey Data - Table HC9.2 Household demographics of U.S. homes, by owner or renter status, 2020," 2022.

[113] Bird S, Hernández D. Policy options for the split incentive: increasing energy efficiency for low-income renters. Energy Policy 2012;48:506–14. https://doi.org/10.1016/j.enpol.2012.05.053.