ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Improving Energy Equity, Air Quality, and Comfort in a Low-Income Coastal Community

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

This project examines the impact of building weatherization, energy efficiency, electrification, and renewable generation in a low-income community. The analysis uses community scale building energy models and optimization tools to analyze these measures. The analysis accounts for the impacts of local electric distribution systems. Building measures are evaluated using total cost of energy, change in carbon and pollutant emission reductions, and improvement in interior comfort. The analysis shows that replacing gas appliances with electric appliances is the most effective way to reduce carbon and pollutant emissions. In particular, the heat pump water heater can reduce carbon and pollutant emissions by 40 percent to 50 percent. Ductless air-source heat pumps are required to decarbonize space heating, but also represent a huge increase in cost since buildings lack air conditioning. However, under current utility rates and equipment costs, electrification increases the total cost of energy for all residents. Utility rates must be reduced for low-income tenants beyond current levels and equipment must be subsidized to avoid doubling the energy burden. This analysis includes low-income assistance programs that reduce utility bills and support weatherization and energy efficiency. For low-income residents, utility rate reductions must increase from current levels of 33 percent to 40 percent for utility-bill parity during hot-water electrification, so subsidies for heat pump water heats must increase.

Keywords: Building decarbonization; electrification; low-income housing; disadvantaged community; urban building energy modeling; electric distribution infrastructure; AC power flow; low-income assistance; climate resilience

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Background

Over 27 percent of Californians qualify for low-income energy assistance; but if not remedied carefully, decarbonizing buildings across the state could substantially increase the energy burden for this population. Conversely, if done correctly, decarbonization could reduce the energy burden, reduce local air pollution, increase resiliency against extreme heat events and utility outages, and lead to an overall higher quality of life. The goal of this project was to analyze building-level measures to predict which steps lead to the best outcomes for residents, local utilities, and the state of California.

Project Purpose and Approach

The purpose of this project was to analyze the impacts of building weatherization, energy efficiency, electrification, photovoltaic solar, and battery energy storage in a low-income community. These measures were evaluated across total costs, carbon emissions, building-related pollutant emissions, interior comfort, and resilience during utility outages. The analysis used building energy models that capture the physics of energy use in buildings, coupled with electric-grid performance and degradation models. Solar and storage systems were sized to minimize total costs, using optimization models. These tools were applied to the Oak View community located in Southern California. Residential buildings in this community lack air conditioning, so the analysis first examined measures supported by low-income energy-assistance programs, which exclude air conditioning unless the building already has space-cooling systems: then passive and active space cooling technologies are considered. Finally, optimal solar and battery energy systems were designed for the community with and without space cooling. During each analysis, the impacts on local energy infrastructure were examined.

Key Results

Regarding building level technologies that are supported by low-income assistance programs, key findings include:

- Traditional low-income energy assistance measures (weatherization, efficient appliances, lighting upgrades) have limited impacts on cost, carbon, and pollutant reductions in the community. These measures reduce costs and emissions by 10 percent to 20 percent in the current community, and are also influenced by the temperate climate and lack of building air conditioning.
- Of the various measures examined in this project, the heat pump water heater (HPWH) produced the largest reduction in carbon emissions and the second largest reduction in pollutant emissions. When used to electrify a gas tank domestic hot water, carbon emissions over the next 30 years are projected to drop by over 40 percent, on average, while pollutant emissions from buildings are projected to be cut in half. However, due to the relatively high cost of California retail electricity, the HPWH increases the total

cost of energy by 17 percent for low-income households, and 22 percent for all others in the community. Pairing HPWHs with light-emitting diode (LED) interior lighting achieved 80 percent of the carbon reduction potential estimated in this work. When used to replace an electric resistive water heater, HPWHs decreased costs nearly 30 percent and carbon emissions by nearly 35 percent.

- HPWH and appliance electrification had similar impacts on Oak View electric distribution systems, with transformer replacements and other upgrades increasing Oak View ratepayer energy costs by 1 percent to 2 percent. Interestingly, electric distribution transformer degradation remained the same when both HPWHs and appliance electrification were implemented simultaneously.
- Electric resistive water heaters also displayed significant time-dependent valuation energy-reduction potential, but nevertheless increased the cost of energy 70 percent to 100 percent when replacing a domestic gas tank hot water system. Widespread deployment resulted in immediate distribution transformer upgrades (and in one instance, a distribution cable upgrade), resulting in a projected 7.5 percent cost-of-energy increase for the community.
- Current low-income utility rate reduction programs that reduce the cost of electricity by about 30 percent are insufficient to support electrification in this community. Holding utility gas costs constant, utility electricity must be reduced by 35 to 45 percent for utility bill parity following building electrification.
- Incentives that offset 80 percent or more of total HPWH installation costs across Oak View could potentially eliminate any cost increases associated with electrifying residential buildings. However, incentives provided to property owners may not directly translate into savings for low-income renters.

Regarding building technologies that provide space cooling, key findings follow.

- Building energy models predict that interior temperatures rise to unhealthy levels without either cooling measures or natural ventilation. Natural ventilation is not desirable in areas with poor air quality, however, creating the need for both passive and active space cooling.
- Of the passive measures examined, cool coatings (specifically, white paint), window film, and HPWHs pulling heat from the interior of the building are the most effective measures to reduce interior temperatures to acceptable levels. When the HPWH is used in combination with either the cool coating or window film, hazardous interior temperatures are almost eliminated and residential units are made comfortable for most of the year. The combination, however, does overcool buildings, resulting in space heater operation that reduces the positive environmental impact made by the HPWH.
- Of the active cooling measures examined, ductless air source heat pumps are the lowest cost measure for introducing space cooling since these systems avoid the installation of costly air ducts. However, any air conditioning system increases the cost of energy 70 percent to 120 percent due to higher utility bills and equipment costs.

- Integrating cool coatings and window films with a ductless air source heat pump reduced overall costs by reducing cooling loads. Additionally, if a HPWH is installed, integrating the system with the air source heat pump to provide space cooling could further reduce costs by reducing active space cooling.

Regarding solar generation and storage, the results heavily depend on access to low-cost solar and storage. If low-cost systems are available (specifically, if a property owner can access programs like the state's Solar on Multifamily Affordable Housing program), the overall cost increase from electrification can be reduced to more reasonable levels. Additionally, the availability of low-cost storage at low-income housing provides a critical resiliency backbone for a community if load controls across all homes on a distribution circuit are implemented and proper switching systems are installed across the utility distribution circuit. However, if low-cost solar is not available, solar provides minimal cost reductions. In general, electrification is responsible for the deep reduction in carbon emissions but solar plays a much smaller role in reducing building-related carbon emissions.

Knowledge Transfer and Next Steps

Knowledge transfer was organized into the following three levels.

- Research papers were developed, submitted, and published in high-impact, open-source academic journals and conferences. This process serves three purposes: 1) publishing journal articles communicates the new knowledge to the general scientific, engineering, and academic communities, 2) the work is improved through the peer-review process, and 3) publishing with co-authors belonging to national laboratories raises awareness of the work within the national laboratory community and with the United States Department of Energy.
- The team has and will continue to present the outcome of this work to non-profit low-income housing providers and organizations that locally manage and implement low-income energy-efficiency and weatherization programs. This stage of knowledge transfer is critical to informing and discussing project results with organizations that provide direct benefits to low-income communities, and that have an opportunity to pursue clean-energy technologies.
- The project team maintained education and outreach efforts to the Oak View community through the development of educational programs. This resulted in creation of the annual Oak View Summer Science Club, where researchers from the University of California (UC), Irvine, work with local librarians to put on a science club during the summer for local children. Examples of this effort are shown in Figure ES-1. This effort built rapport with the Oak View community and opened lines of communication for researchers to better understand the energy needs of community members, and also updated families about research efforts in the community.

Figure ES-1: Images From the Oak View Summer Science Club

Source: UC Irvine, 2023

Additional knowledge transfer activities are planned after completion of the project. These activities are aimed at communicating project outcomes to policymakers and low-income-assistance program providers.

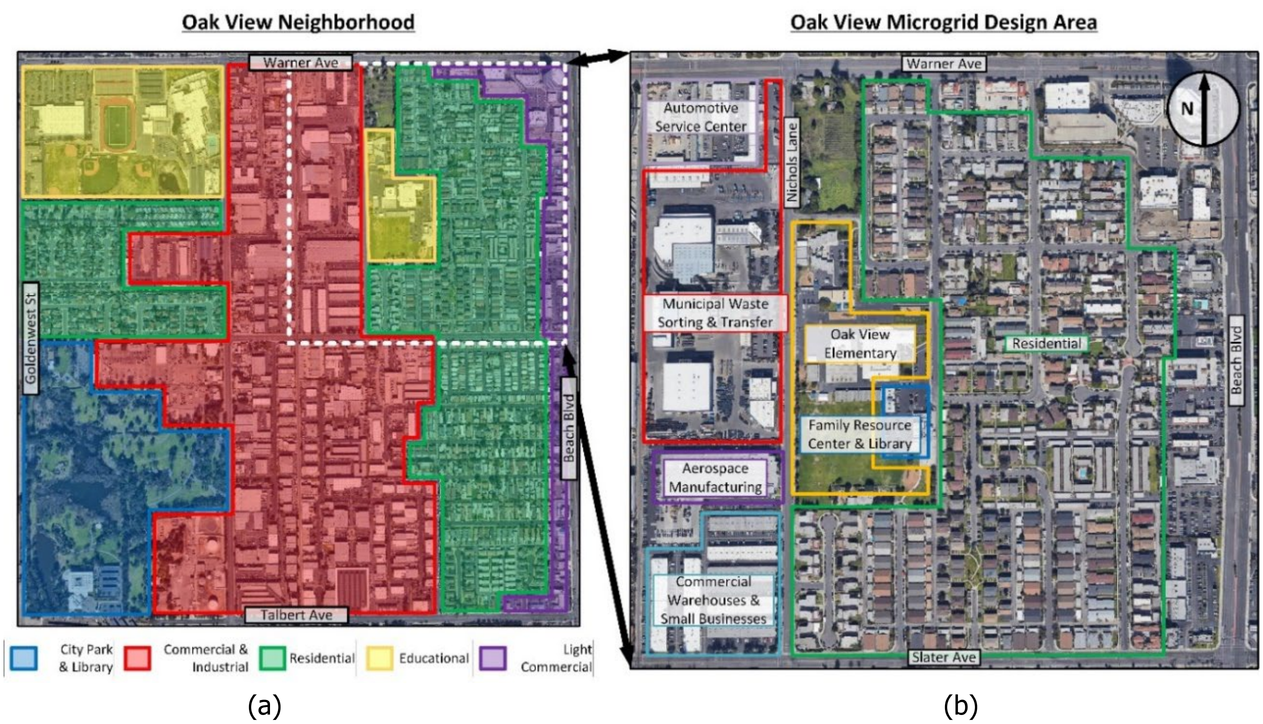
Next steps in this research include:

- **Space Cooling HPWH Systems:** Simulation results suggest that HPWHs could play a critical role in decarbonizing California buildings while providing space cooling for residents without air conditioning. However, the full potential of space cooling HPWHs remains unexplored, and current building practices do not support using HPWHs for both hot water and space cooling. Further research is required to validate the use of HPWHs for space cooling proposed in this study. If successful, subsequent research should focus on integrating these systems into buildings both with and without existing space-cooling solutions.
- **Extension to Different Climate Zones:** The current simulation results are specific to the Oak View community in California Energy Commission Climate Zone (Zone) 6. Extending this research to other California climate zones, such as Zone 14 and Zone 15, is likely to yield similar outcomes. However, the climatic diversity in Zone 1 and Zone 16 requires additional work to determine the most suitable technologies for other regions in California.
- **Low-Income Support Programs:** The project team's findings indicate that traditional energy efficiency and weatherization measures, often funded by federal, state, and local utility programs, may not significantly benefit low-income families. Redirecting funds to support newer, more effective technologies could better address the energy, safety, and comfort needs of this population while aligning with state greenhouse-gas and air-pollution reduction goals. However, these advanced technologies are more capital intensive, potentially limiting the number of low-income households able to benefit from them. Additional research is needed to explore the potential for reallocating funds within low-income support programs to back these cleaner, more efficient technologies, and to assess the overall impact of such a shift.

CHAPTER 1: Introduction

The goal of this work was to analyze the impact of clean energy technologies on the Oak View community in Southern California. The community of 8,000 residents has a per-capita income nearly 50 percent lower than the county average (United States Census Bureau, 2015). Residential buildings were built before establishment of the California Title 24 energy code, and residents primarily use natural gas for space and water heating and lack air conditioning (Flores et al., 2023) at higher rates than the rest of California (U.S. EIA, 2022). Less than 1 percent of residential buildings have rooftop solar. A map of the community is provided in Figure 1, where (a) shows the entire Oak View census tract, and (b) shows the portion of the community considered in this research. These subsets capture almost exclusively multi-family residential buildings, and include all residential units owned by non-profit low-income housing providers in Oak View. This community 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. Social factors that also contribute to this ranking include low education levels, high housing burden, and high poverty rates. Residential buildings predominantly use natural gas for heating and domestic hot water. Only six residential buildings had central air conditioning.

Figure 1: The Oak View Community and Microgrid Design



Aerial images and building cluster information for the Oak View neighborhood, and additional building details for the Oak View Microgrid design area. North runs top to bottom in the image.

Source: UC Irvine, 2023; Flores et al., 2023

Low-Income Buildings and State Environmental Goals

Low-income families are more likely to live in less energy-efficient buildings (Brown et al., 2020), are less likely to have energy-efficient appliances (Cluett et al., 2016; Xu and Chen, 2019), and experience an energy burden[1] that is two to three times higher than average (Drehobl et al., 2022). Low-income energy assistance programs designed to address these challenges through utility bill support, building weatherization, and energy efficiency have existed for decades. These programs, which typically do not yet support building electrification, operate amid a backdrop of aggressive environmental goals and shifting building performance standards (for example, the regularly updated Title 24 building energy efficiency standards). There is a gap in understanding between how different weatherization, energy efficiency, and electrification measures will affect cost, carbon emissions, and low-income assistance programs.

Reducing Exposure to Extreme Heat and Air Pollution

Oak View residents have long faced a difficult decision during heat waves: open their homes to increase natural ventilation at the risk of exposure to elevated pollution levels or endure unhealthy building temperatures. Residents have grappled with elevated pollution levels due to the presence of a waste transfer station that processes up to 4,000 tons of garbage per day (Arellano, 2015) less than 500 feet from the local elementary school and the closest apartment buildings. The community is also exposed to high levels of diesel particulate matter and is in close proximity to other toxic releases. Extreme heat events are becoming more severe and are occurring more frequently, forcing residents to face either uncomfortable and/or dangerous indoor temperatures, or increased exposure to high levels of air pollution. These challenges are not unique to Oak View. California residents are less likely to have air conditioning than residents in other states, and low-income families are even less likely to have space cooling (U.S. EIA, 2022). There is a gap in knowledge in how cooling can be added to low-income buildings so that occupant comfort and health are improved, while also supporting the state's environmental mandates.

Onsite Generation and Energy Infrastructure

Incentive and support programs targeted at low-income families offset the cost of solar photovoltaics and electric battery storage. However, the adoption of onsite generation does not occur in a vacuum since building improvements can affect electricity demand. There is a gap in knowledge of understanding how solar and storage should be used in low-income communities to support these building improvements, primarily through support of building electrification. This gap includes the overall benefit of onsite generation with and without these incentives and support programs. There is an additional knowledge gap on how new onsite generation and building electrification will affect local electric infrastructure.

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

Research Questions

Analyzing the impact of clean energy technologies required that the following questions be answered:

1. What suite of weatherization, energy efficiency, and electrification measures leads to the lowest cost of energy, carbon emissions, and pollutant emissions?
2. What measures most effectively cool a building without air conditioning?
3. What are the costs and environmental impacts of solar and storage in low-income buildings?
4. To what extent do current low-income energy assistance programs support clean energy technologies?
5. How do clean energy technologies affect local energy infrastructure?

This report is a detailed engineering analysis. However, the intended audience includes low-income housing tenants and providers, low-income-assistance program administrators, and the engineers and researchers developing next generation low-income housing developments.

CHAPTER 2: Approach and Methods

The project team's approach to modeling clean energy technologies applied to the Oak View community follows.

1. Develop a community-scale energy model that captures how electricity and natural gas are used throughout the community (Flores et al., 2023).
2. Modify the community-scale energy models to consider different weatherization, energy efficiency, and electrification measures (Flores et al., 2024).
3. Evaluate the different measures to predict changes in cost, carbon emissions, pollutant emissions, and interior-building comfort. Assemble combinations of measures to form urban energy scenarios (UES).
4. For each design, develop the lowest-cost combination of rooftop-solar energy and battery-energy storage for each building (Novoa et al., 2019, 2021).
5. Evaluate the impact of the different measures on the electric distribution system (Wang et al., 2023).

Each step in this process was documented in peer-reviewed research articles. Please refer to these articles for complete technical details on project approach and methods. Additional information is provided on the community-scale energy model since the work in this project directly contributed to development of the fundamental tool.

The evaluation criteria used for evaluating any building measure are:

- **Change in Total Cost:** the net present value of change in total cost due to changes in utility bills and equipment costs. All analyses assume that new equipment is adopted after failure of existing building systems or components (or replacement following burnout).
- **Change in Carbon Emissions:** this is taken as the change in the time dependent value of energy (TDV energy), which is the metric used by the California Energy Commission to examine different building energy efficiency measures.
- **Change in Pollutant Emissions:** taken as the change in oxides of nitrogen, or NOx.
- **Change in Heat Index Hazard Hours (HIHH):** HIHH considers the ability of the human body to safely reject heat through perspiration. A heat index over 80 degrees Fahrenheit (°F) (27 degrees Celsius [°C]) is uncomfortable and unsafe for strenuous activity, and a heat index over 90°F (32°C) leads to increased risk of heat stroke. The units of HIHH are degrees Fahrenheit * ·number of hours.

These models were developed with support from project partners. National Renewable Energy Laboratory (NREL) developed the URBANopt tool and provided support for the REopt tool, Altura Associates developed building measure cost predictions and performed targeted building energy audits, and the City of Huntington Beach facilitated contact with community members and led outreach efforts to survey the community.

Community Scale Energy Models

The URBANopt software development kit was used to build the Oak View community-scale energy model. URBANopt generates physics based OpenStudio® and EnergyPlus models (Charan et al., 2021; Houssainy et al., 2020; El Kontar et al., 2020; Macumber et al., 2016) using simplified building geometry and end-use information. These models were used to simulate the application of weatherization, energy efficiency, electrification, and other building-improvement measures.

The application of building measures was split between upgrading and replacing existing building components and appliances and introducing active and passive cooling measures. This distinction was made since most low-income assistance programs focus on upgrading existing building components and appliances but do not provide new space-cooling measures. Energy reduction measures are listed in Table 1. Measures designed to provide space-cooling are listed in Table 2. There is overlap between "passive" cooling measures in Table 2 and envelope upgrades in Table 1 to clarify which measures were included in each set of analysis. One novel cooling technology was the use of heat pump water heaters (HPWH) to provide space cooling (in addition to hot water).

Table 1: Summary of Clean Energy Technologies Considered for Each of the Building Classifications for Analyzing Clean Energy Technologies That are Partially or Fully Supported by Low-Income Assistance Programs

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/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/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/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
Domestic hot water (DHW)	• Upgrade to a condensing gas water heater • Electrification of DHW with an electric resistive water heater (ERWH)[2] • 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)

[2] 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.

Measure Category	Residential	Already Electrified Residential	Nonresidential
Envelope[3]	• 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 percent • Apply a novel cool coating to the building exterior

Source: UC Irvine, 2023

[3] 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 (Sun et al., 2021; Wei et al., 2021). As a result, effort was directed elsewhere.

Table 2: Passive and Active Cooling Measures Applied to the Baseline Oak View Model

Measure Category	Measure Details	
Passive Cooling	• Upgrade wall insulation to T24 (Title 24) mandatory levels (R13) • Upgrade roof insulation to T24 mandatory levels (R22) • Upgrade windows to T24 mandatory levels (U-value: 0.55, solar heat gain coefficient: 0.65, visual light transmittance: 0.66) • Apply a window film (solar heat gain coefficient: 0.45, visual light transmittance: 0.66) (Sun et al., 2021) • HPWH sourcing heat from the building interior. Uniform energy factor (UEF): 3.75 (Rheem Manufacturing Company, n.d.)	• Upgrade wall insulation to T24 recommended levels (R21) • Upgrade roof insulation to T24 recommended levels (R30) • Upgrade windows to Energy Star ratings (U-value: 0.3, solar heat gain coefficient: 0.25, visual light transmittance: 0.25) (U.S. EPA, 2015) • Apply a cool coating to the building exterior opaque surfaces (Solar absorptance: 0.07, thermal absorptance: 0.9) (Nie et al., 2020)
Active Cooling	• Install a ducted central alternating current (AC) system that meets T24 minimum efficiency standards (Seasonal Energy Efficiency Ratio [SEER] 14), includes new ductwork • Install a ductless[4] ASHP that meets T24 minimum efficiency standards (SEER 14, HSPF 8)	• Install a high efficiency ducted central AC system (SEER 21), includes new ductwork • Install a high efficiency ductless ASHP (SEER 21, Heating Seasonal Performance Factor [HSPF] 10)
Energy Efficiency	• Replacement of baseline lighting (55 lumens/watt) with LED lighting (80 lumens per watt) (Feit Electric, 2020) • Upgrade appliances to ENERGY STAR® or high efficiency models (refrigerators, dishwashers, clothes washers & dryers, smart power strips) • Upgrade natural gas appliances to higher efficiency models • Electrification of gas appliances • Electrification of gas appliances using ENERGY STAR® appliances	

Source: UC Irvine, 2023

[4] Ducted ASHP systems were considered initially but ultimately disqualified for this community since total cost, including cost of new ducts, were estimated to be higher than a ductless system.

CHAPTER 3: Results

This section summarizes results from this project. Detailed results were published in peer-reviewed publications (Flores et al., 2023, 2024; Wang et al., 2023).

Lowest Cost, Carbon, and Pollution Building Improvements

This section presents analysis of building energy measures that are supported by low-income assistance programs.

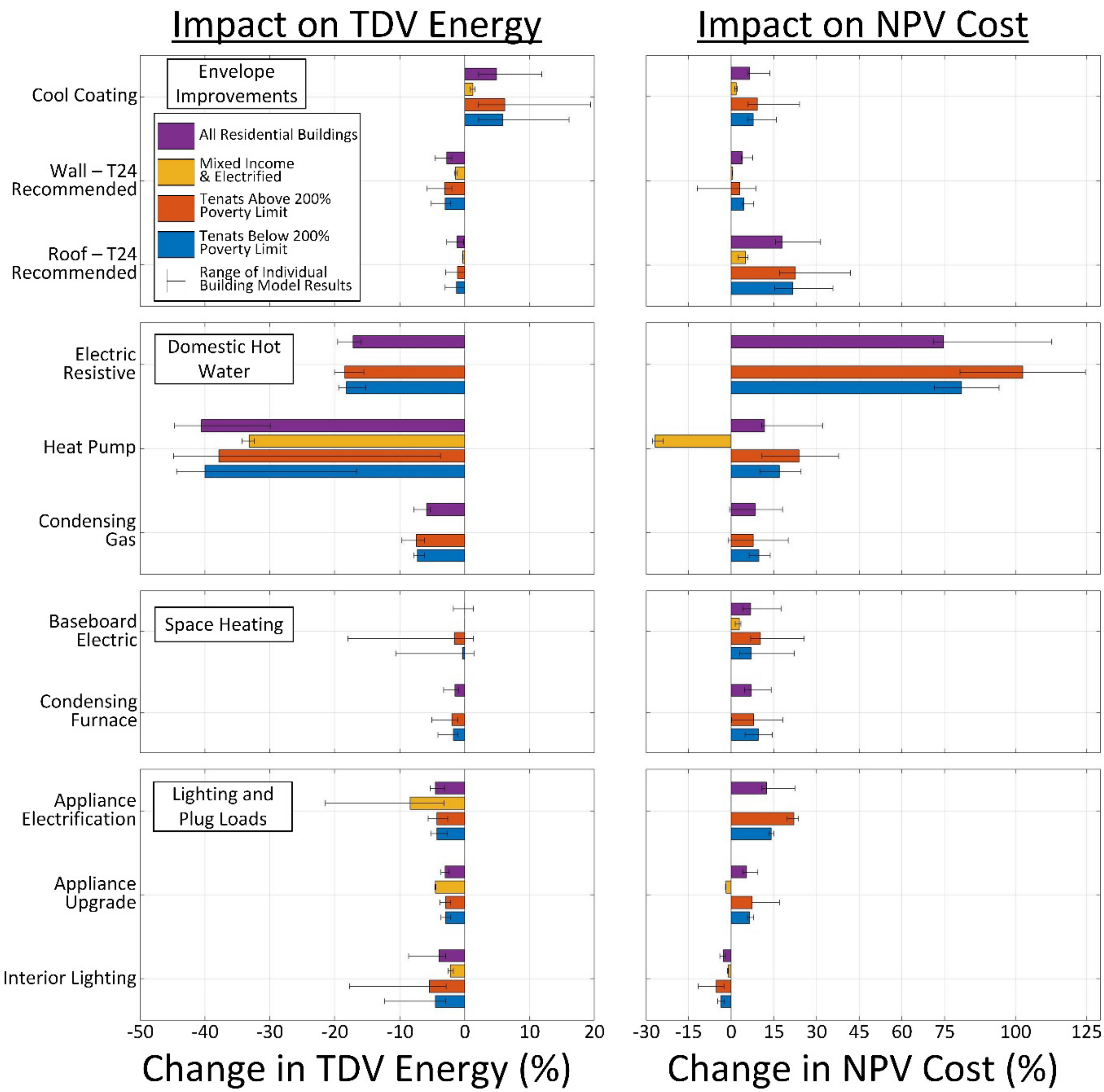
Residential – Individual Measures

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

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

Change in TDV energy and net present value (NPV) cost for select measures applied to the Oak View community are shown in Figure 2. Bars show the average change per group of buildings. Whiskers, or the "error bars," show the span of results produced by individual building energy models (BEM). Complete results for every measure are provided in the supplemental material and include mandatory wall and roof insulation. Both measures produce modest cost savings and have similar impacts on TDV energy as recommended for insulation levels. Window results are also absent from Figure 2, 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).

Figure 2: Change in TDV Energy and NPV Cost for Select Residential Measures



Source: UC Irvine, 2023

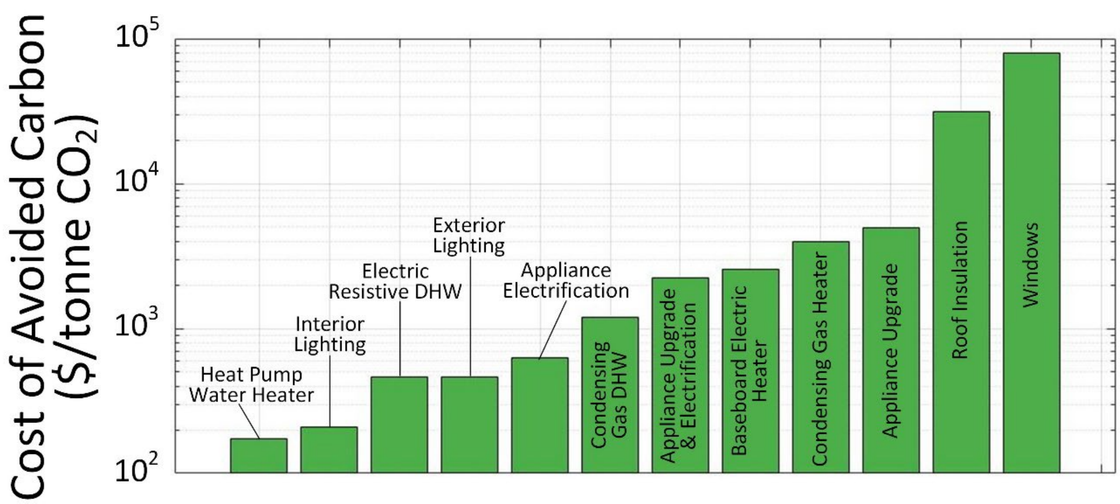
The primary conclusions from this figure are that envelope and space heating improvements have a small impact on cost and energy use, appliance upgrades and electrification decrease total energy use but increase cost, and the HPWH can decrease TDV energy use by up to 40 percent. The HPWH measure does this through the efficient electrification of domestic hot water (DHW) loads previously met with natural gas. This is highlighted by the deep energy savings generated by the electric resistive water heater, which decreases energy by nearly 20 percent but at the expense of nearly doubling energy costs. Despite the energy savings benefit, the HPWH increases costs in part due to higher equipment capital and utility costs.

Since HPWHs increase utility bills, these systems are not eligible for support under conventional low-income support programs. With passive measures, the cool coating increases cost and energy use, but also makes buildings more comfortable.

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.

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; the cost of avoided carbon due to investment from low-income energy assistance programs is presented in Figure 3. 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 (for example, 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 plotted using a logarithmic scale.

Figure 3: Costs of Avoided Carbon for Low-Income Assistance Programs



Source: UC Irvine, 2023

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 percent of the HPWH cost. For appliance electrification, the basic appliance option achieves the lowest cost of avoided carbon at a cost of slightly over \$1,000 per one tonne of carbon dioxide (CO_2).

Lowest Cost and Lowest Emission Community Designs

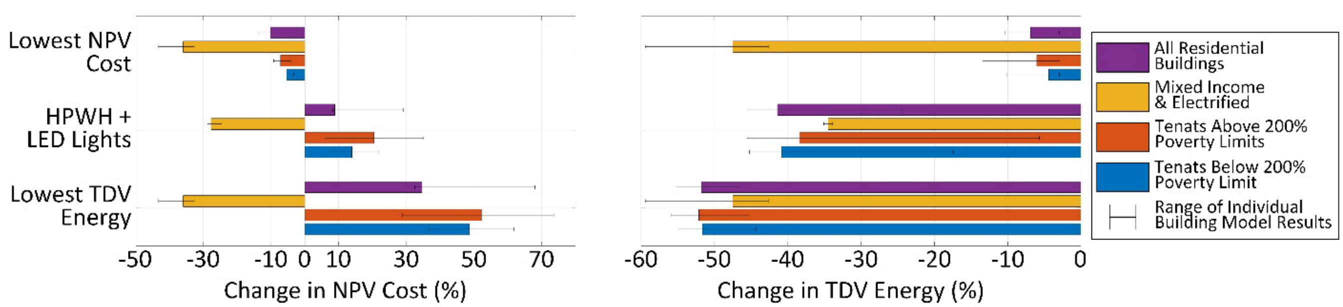
Individual measure results were used to create optimal combinations of clean energy technologies and weatherization measures that minimize total cost, pollutant emissions, and TDV energy. Various combinations of measures applied to the Oak View Urban Building Energy Model were tested to identify the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

The lowest total cost design for all buildings included interior lighting and mandatory Title 24 envelope measures. Designs for buildings with electric resistive heating were also included in HPWHs and high-efficiency electric appliances.

Lowest TDV energy and pollutant emission designs included hot water and appliance electrification, energy efficiency, and building-envelope upgrades. 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 included only HPWH and LED lighting upgrades.

Figure 4 illustrates the change in total cost and TDV energy for these two design goals. 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 percent. The intermediate lowest TDV energy scenario reduces TDV energy by over 40 percent but increases cost by 15 to 20 percent. The lowest TDV energy scenario reduces energy by approximately 50 percent but increases cost more than 50 percent. For already-electrified buildings, the lowest cost and lowest TDV energy scenarios match, both reducing cost and energy by 35 percent and 45 percent, respectively.

Figure 4: The Cost and Energy Results for Different Measure Combinations



Designs are for lowest cost or lowest TDV energy. An intermediate HPWH+LED Lights design is included as an intermediate scenario between lowest NPV and lowest TDV energy designs.

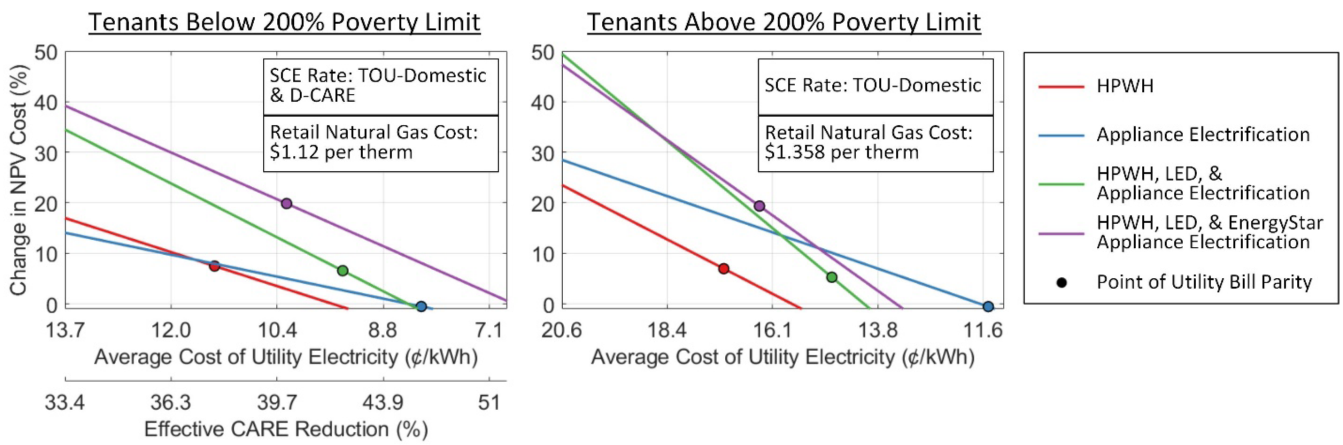
Source: UC Irvine, 2023

Expansion of Low-Income Support Programs

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

Figure 5 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 percent federal poverty limit. Natural gas rates also depend on income level and are $1.12 per therm for low-income residents, and $1.36 per therm for all else. Since some electrification measures have a higher cost of installation, the point at which utility bill parity occurs is indicated with a dot. Under current California Alternative Rate for Energy (CARE) rates, the average actual discount applied to low-income ratepayers is 33.4 percent.

Figure 5: The Financial Effect of Reducing the Cost of Utility Electricity on Residential Oak View Buildings That Undergo Electrification



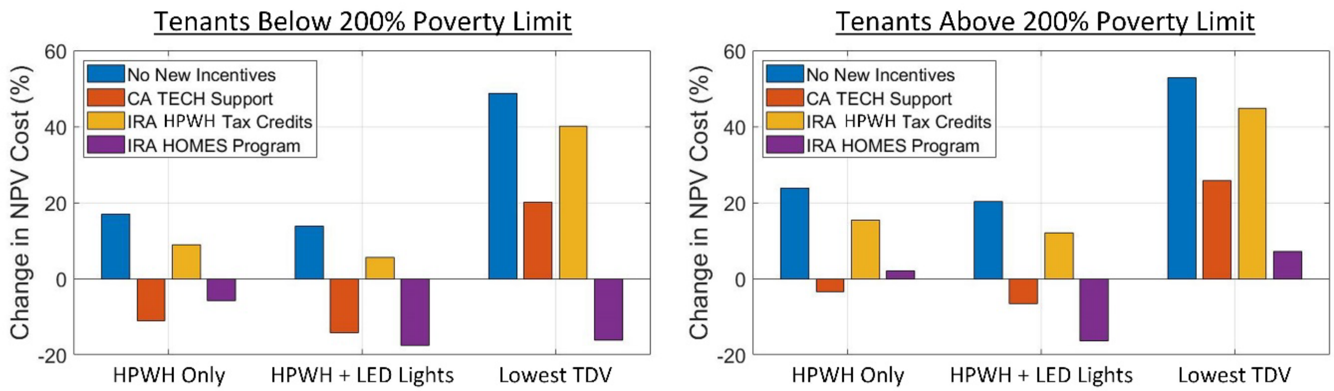
The figure on the left focuses on families below the 200 percent poverty limit and provides the effective CARE rate reduction. The figure on the right focuses on families above this poverty limit. Dots indicate the point at which electrification does not increase total utility bill cost (electricity + gas). Results are based on current Southern California Edison retail residential rates. According to simulation results, Oak View tenants below the 200 percent poverty limit pay $13.7 per kilowatt-hour (kWh) electricity and $1.12 per therm natural gas. Tenants above the 200 percent poverty limit pay $20.6 per kWh electricity and $1.358 per therm natural gas.

Source: UC Irvine, 2023

For the HPWH, utility bill parity occurs when average utility electricity is reduced by $0.025 per kWh for ratepayers below the 200 percent poverty limit (or a 38 percent 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. Federal and state programs described in Chapter 3 such as the TECH Clean California (TECH) program, the HOME Investment Partnerships (HOMES) program, and the Inflation Reduction Act tax credits 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 Figure 6. 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 (with electrified homes excluded).

Figure 6: Change in Total Cost for HPWH-Based Measures After Applying New Assistance Programs



Results are shown for Oak View families above and below the 200 percent household income poverty limit.

Source: UC Irvine, 2023

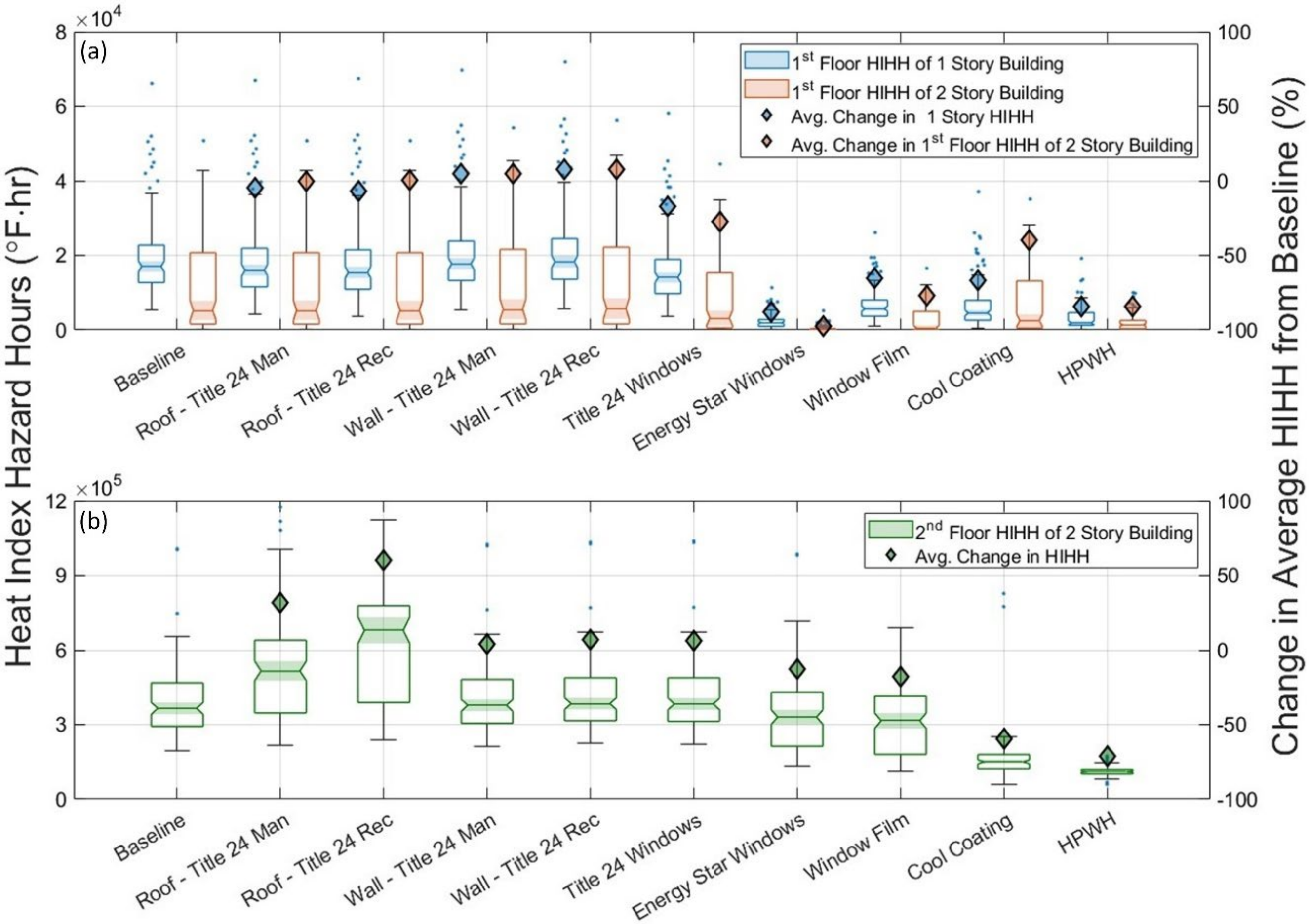
These results indicate that the new and emerging clean energy technology support programs provide significant cost savings to Oak View tenants and property owners. In the case of the TECH program, funding the purchase of a HPWH offsets both the HPWH installation premium and higher utility bills. This 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 percent, despite only supporting HPWHs.

Reducing Interior Temperatures

All results reported in this section are for the application of individual measures only. Measures are compared with a baseline scenario where no measures are implemented. Results are split between "active" and "passive" measures. Extreme heat is a more challenging of a problem for 2-story buildings, so the project team's summary of results focuses on these buildings.

Figure 7 shows the extent to which individual passive measures reduce interior heat index hazard hours (HIHHs). Results are split between the first and second floors. Central air conditioning and air-source heat pump (ASHP) systems are excluded since these measures eliminate all HIHHs. Figure 7 shows box plots that summarize all individual BEM results. The middle line in each box plot shows the median number of HIHHs experienced in the first or second floor of a building. The top and bottom of each box captures the upper and lower quartile of HIHH results, and the whiskers indicate "non-outlier" minimum and maximum HIHH results. Outliers are indicated with dots above the maximum whisker. Each box plot has a corresponding diamond marker that shows the average reduction in HIHH, versus baseline.

Figure 7: Boxplots That Show the Median and Range of HIHH Results for all Passive Measures



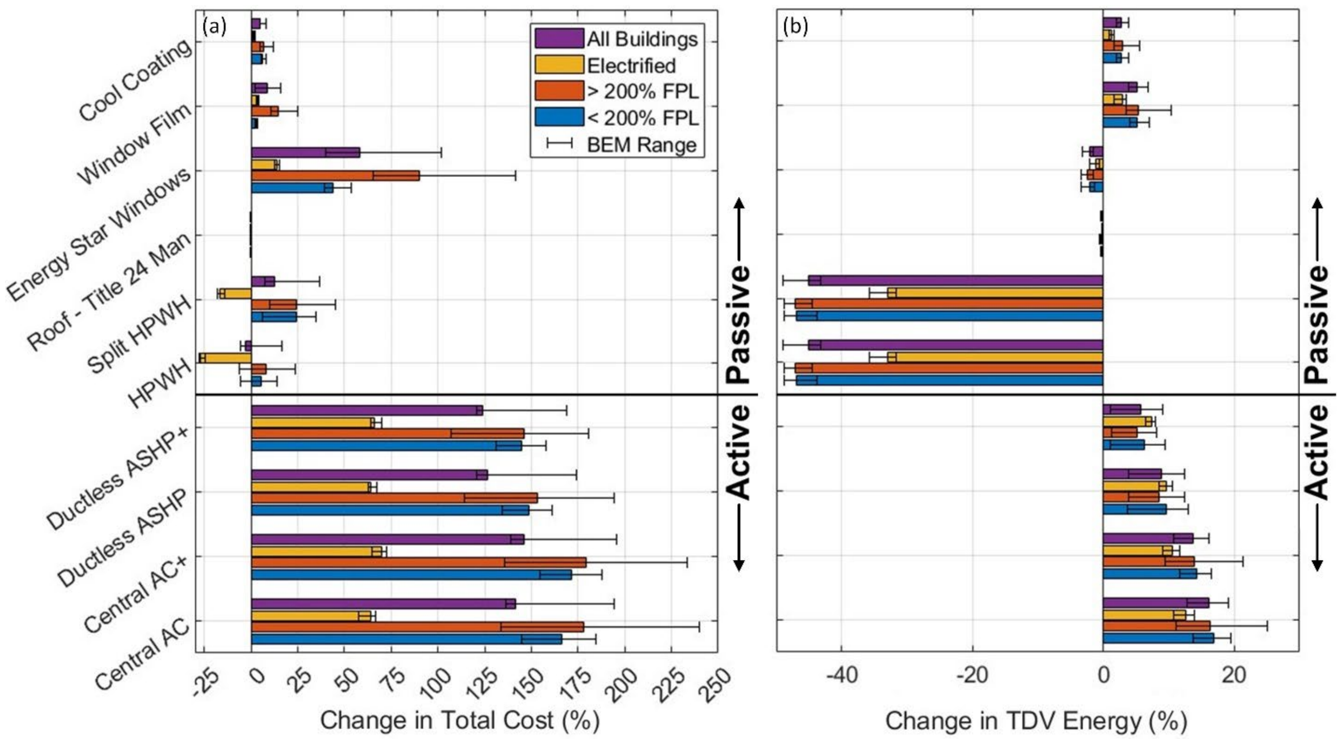
Source: UC Irvine, 2023

Prior to examining any measure, BEM results predict that residential units on the 2nd floor experience over 10 times more HIHHs than units on the 1st floor. This result is consistent with prior work. The models also predict that the most comfortable residential units are found on the 1st floor of 2-story buildings.

The HPWH and whole building cool coating are the only measures that achieve deep HIHH reductions (over 40 percent) across 1st and 2nd floors. HPWHs shrink HIHHs by 75 to 85 percent, while the cool coating reduces HIHHs by 40 to 67 percent. The performance of window upgrades depends on the floor. For example, ENERGY STAR windows virtually eliminate HIHHs for 1st floor units, but reduce HIHHs only 12 percent for 2nd floor units. Conversely, Title 24 windows have a small to negative effect, indicating that the primary value of the ENERGY Star windows is the lower solar heat gain coefficient. This is supported by window film results, which reduced 1st floor HIHHs 65 to 77 percent, but only by 12 percent for 2nd floor units. These results also show that roof and wall insulation improvements have a small to deleterious impact on HIHHs.

Changes to cost and energy results for 2-story residential buildings are shown in Figure 8. BEM results suggest that cool coating window film and HPWH measures are more cost and energy effective when applied to 2-story residential buildings, and ENERGY STAR windows and roof insulation improvements are less effective. Active cooling solutions are more expensive to implement at 2-story locations due to the larger cooling demand, but ASHP+ systems are consistently estimated to be the lowest-cost whole-building cooling solution. Since 2-story building cooling loads are larger and heating loads are smaller than in 1-story buildings, the use of ASHPs did not result in net reductions of TDV energy.

Figure 8: Average Change in (a) Total Cost and (b) TDV Energy for 2-Story Residential Buildings



Central AC and Ductless ASHP systems meet minimum Title 24 performance standards, and Central AC+ and Ductless ASHP+ systems exceed these standards. The only difference between the HPWH and Split HPWH is the assumption that the split system uses an evaporator that is separate from other HPWH components – performance characteristics are assumed to be the same.

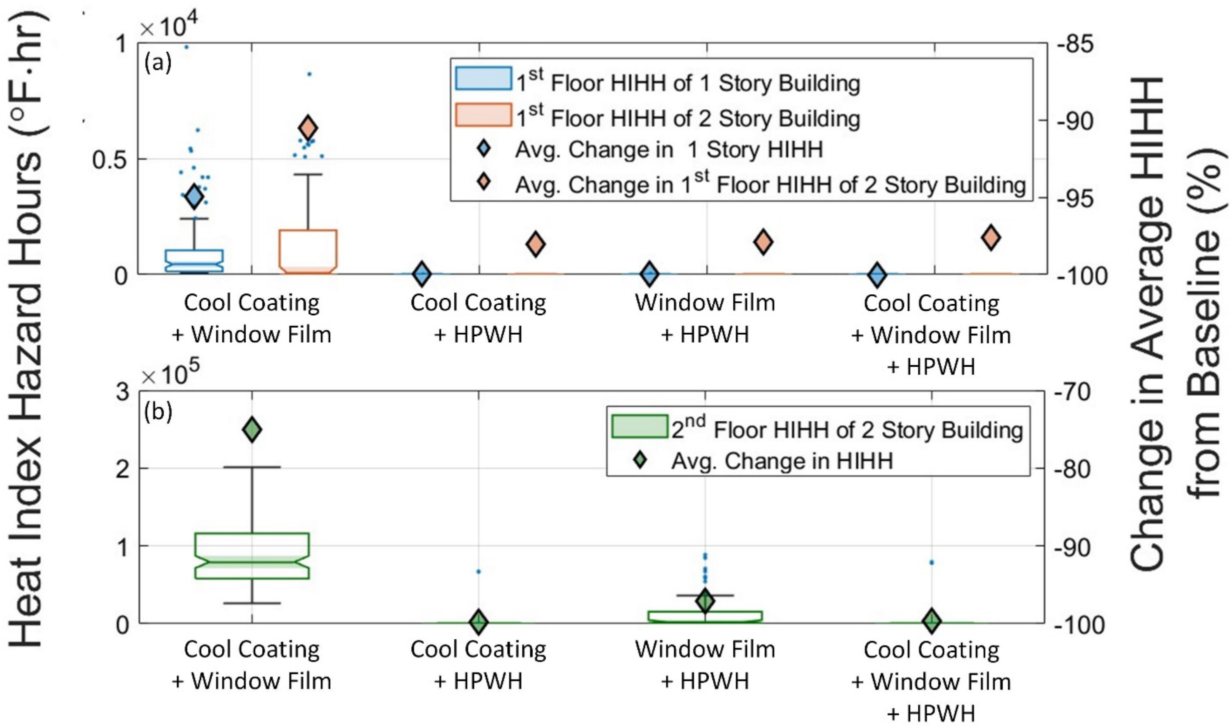
Source: UC Irvine, 2023

Performance of Passive Measure Combinations

Results for individual measures suggest that the cool-coating window film and HPWH measures are the only passive building modifications that consistently reduce HIHHs. This section analyzes the impact of combinations of these three measures on interior building comfort, cost, and energy use. ENERGY STAR windows virtually eliminate HIHH in 1-story buildings. However, this measure is more expensive than other passive measures and is not directly included in this section. HPWH results in this section are based on standard HPWH costs. Using a split HPWH would increase cost by between 15 and 20 percent more than a standard HPWH.

Box plots capturing HIHHs for all BEMs, and average reductions from a baseline of "no new measures" are shown in Figure 9. These results show that the application of 2 or more of these passive measures reduce HIHHs by over 90 percent for 1-story buildings and 75 percent for 2-story buildings. Passive measure combinations that included a HPWH pulling heat from the building interior reduced HIHH by 97 to 99 percent.

Figure 9: Box Plots That Show the Median and Range of HIHH Results for Combinations of the Cool Coating, Window Film, and HPWH Measures

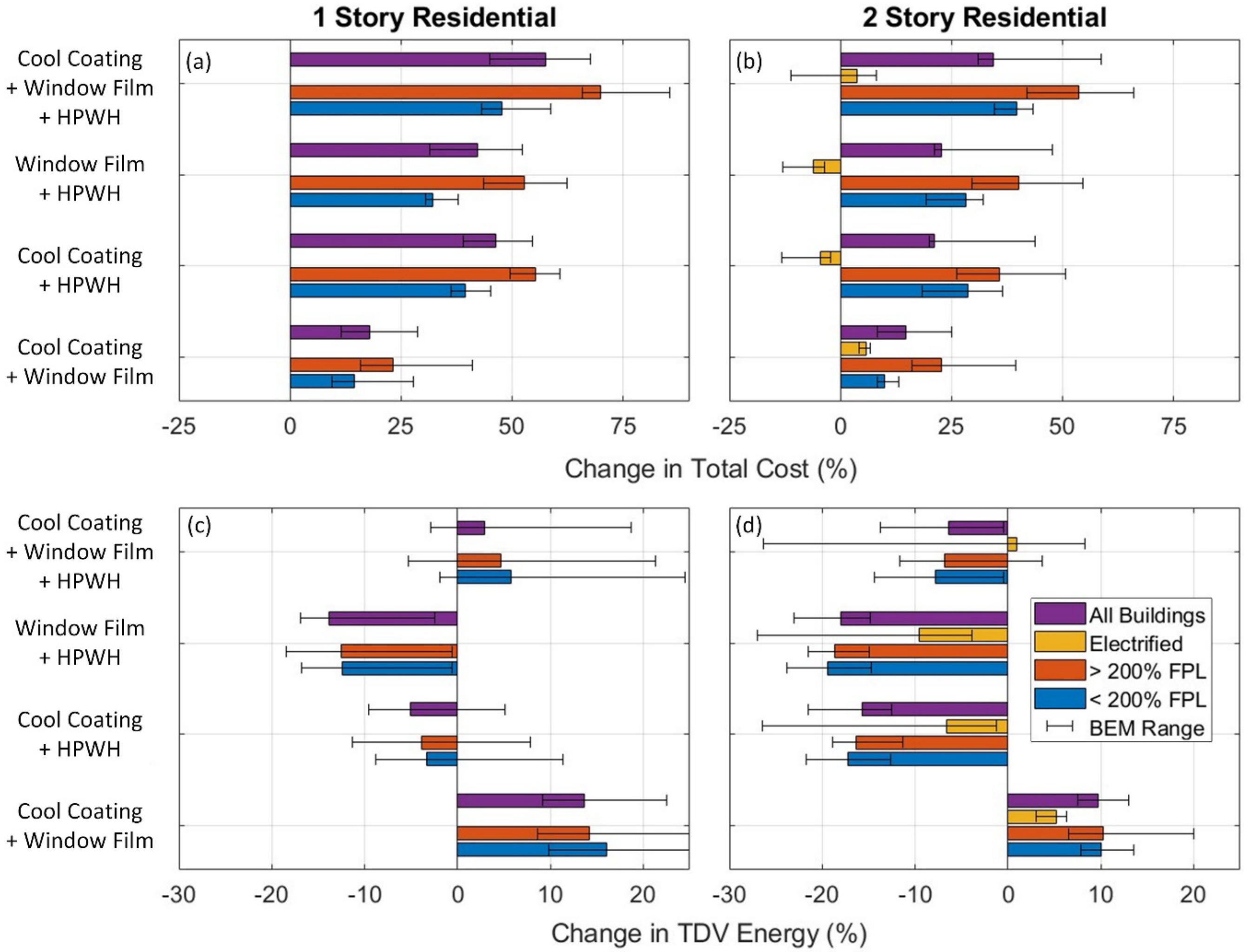


Diamond markers show the average reduction in HIHH versus the baseline of implementing no new measures. Results are split between (a) the 1st floor of all buildings, and (b) the 2nd floor of any 2-story buildings. The baseline HIHH box plot shown in Figure 8 is excluded since the combination of the three passive measures reduce HIHH by 90 percent or more in (a), and 75 percent or more in (b).

Source: UC Irvine, 2023

Change in total cost and TDV energy for the four combinations of passive measures is shown in Figure 10. Results are split by number of building stories. Although not shown, the initial point of comparison are the Energy Star window upgrade results versus the combination of passive measures shown in Figure 10. For 1 story buildings, the combined cool coating and window film measures generate an equivalent HIHH reduction as Energy Star windows, but at half the cost. The cost of the combined cool coating, window film, and HPWH is similar to ENERGY STAR windows. However, the combined set of measures virtually eliminates HIHHs for 1- and 2-story buildings.

Figure 10: Change in Total Cost (a) and (b); and Change in TDV Energy (c) and (d) for the Four Sets of Passive Measures



Source: UC Irvine, 2023

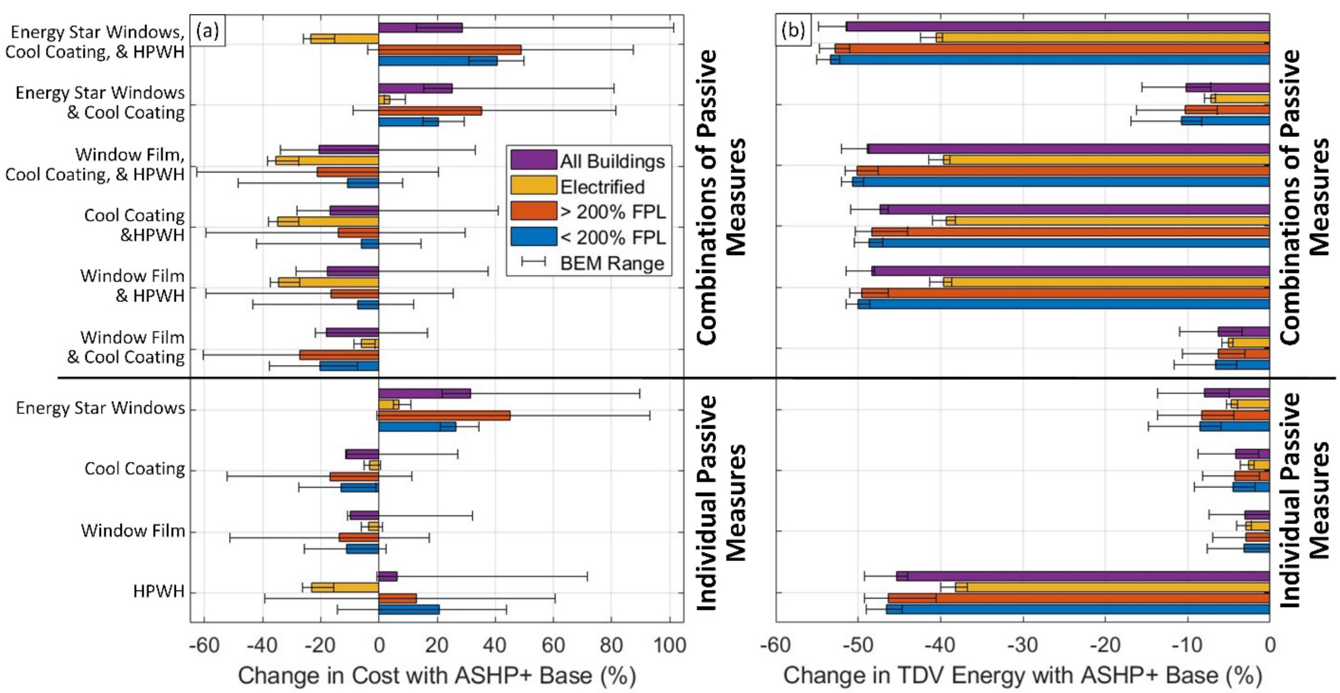
Many results shown in Figure 10 can be inferred from examining the performance of individual measures. One notable departure from individual results is the HPWH TDV energy results. Results from prior sections show that a HPWH has the potential to reduce TDV energy by 30 to 40 percent. When the HPWH measure is combined with either the cool coating or window film, TDV energy savings are cut in half or eliminated. When all three measures are implemented, TDV energy increases for single-story buildings. In all instances, the benefits of gas DHW electrification evaporate when a HPWH is implemented with other passive measures.

ASHP+ and Passive Measure Performance

High performance ASHP (ASHP+) are the lowest cost and lowest TDV energy system that provides active whole building cooling. This section explores the integration of ASHP+ systems with passive cooling measures in order to further reduce cost and energy use. Complete results for ASHP+ with all passive measures is provided in the Supplemental Results. Passive cooling measures in this section are limited to the whole building cool coating, window film, HPWH, and Energy Star windows.

Changes in total cost and TDV energy for individual and combinations of passive cooling measures on top of the ASHP+ to two story buildings are shown in Figure 11. Unlike one story buildings, the combination of cool coating and window film measures are complimentary, leading to deeper cost and energy reductions than the individual measures. These savings are sufficient to offset the cost of the HPWH, resulting in a net reduction in total cost when the cool coating, window film, and HPWH are implemented in parallel to the ASHP+. The lowest cost solution for two story buildings with gas space and water heating are either the ASHP+ combined with both the window film and cool coating (83 percent) or with these measures plus the HPWH (17 percent). The lowest TDV energy solution for these buildings are the ASHP+ combined with the cool coating, window film, and HPWH. The lowest cost and TDV energy solution for buildings with electric resistive space and water heating is the ASHP+ combined with the cool coating, window film, and HPWH.

Figure 11: Change in Total Cost and TDV Energy (Subplots a and b Respectively) for Two-Story Buildings



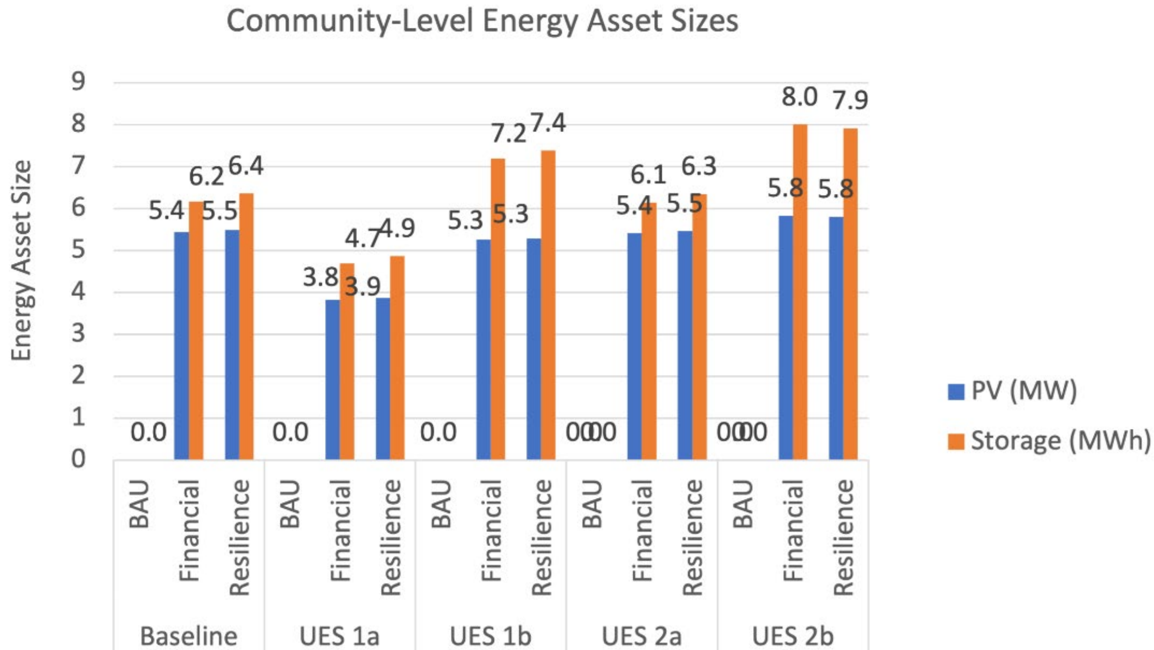
Results are presented relative to the ASHP+ results shown in Figure 8. Total change in cost and TDV energy is equal to the sum of results in Figure 8 with the results in this figure. For reference, the ASHP+ change in cost was approximately 140 percent to 150 percent increase, and a 66 percent increase for previously electrified buildings. ASHP+ change in TDV energy ranged between 5 percent and 7 percent for all 2 story buildings.

Source: UC Irvine, 2023

Optimized Solar and Storage

Figure 12 summarizes the REopt determined, cost-optimal, aggregate, energy assets sizes for each URBANopt-modeled UES of the Oak View community. The financial and resilience scenario results are also included in Figure 12. As noted in Figure 12, a moderate increase in the optimal photovoltaic (PV) and battery size is needed between the financial and resilience scenarios across all UES' to ensure a cost-optimal survival of the pre-defined, 50-hour, summer outage. In addition, an increase in both PV and battery capacity is required with both added electrification measures as well as increases in UES-1a to UES-1b, and UES-2a to UES-2b.

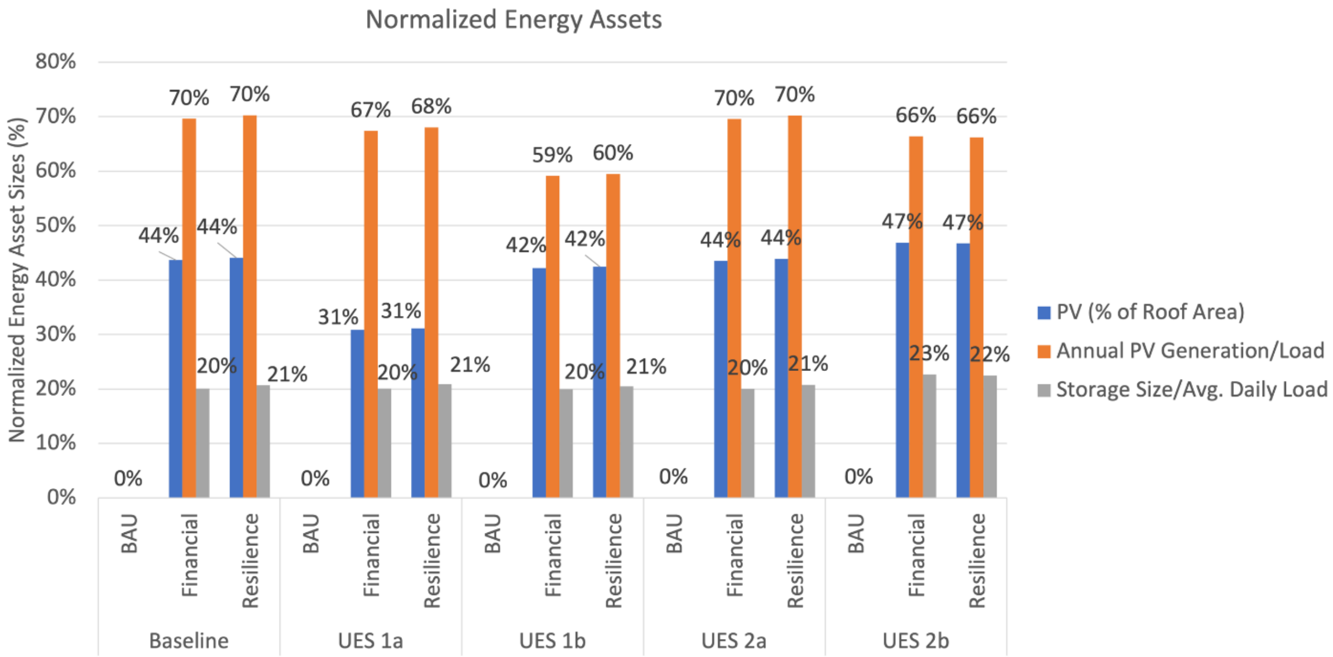
Figure 12: REopt Results for Cost-Optimal, Aggregate, Energy Asset Sizes for Each UES of the Oak View Community



Source: NREL, 2023

The normalized, cost-optimal, community-level energy asset sizes, determined by REopt, for each UES is shown in Figure 13. In Figure 13, the PV size is expressed as the percentage of rooftop area covered by PV, across the entire community. The PV size is expressed in terms of its annual generation divided by its annual electric load. The cumulative storage size (in kWh) is normalized by the average daily electricity load (in kWh) on a community level. The results in Figure 13 indicate that 59 percent to 70 percent of renewable energy penetrations reflect the optimal financial solution across all UES's. Moreover, rooftop area is available to achieve the target. Throughout all UES's, the optimal battery capacity reflects 20 percent to 23 percent of the average daily load, and the percent of rooftops covered by PV increases from the non-electrified 'a' subgroup to the electrified 'b' subgroups given the increased community-level electric load. Due to Oak View's mild coastal climate, the added cooling load in the 'b' subgroup does not require a significant increase in the required PV, compared with 'a' UES subgroup.

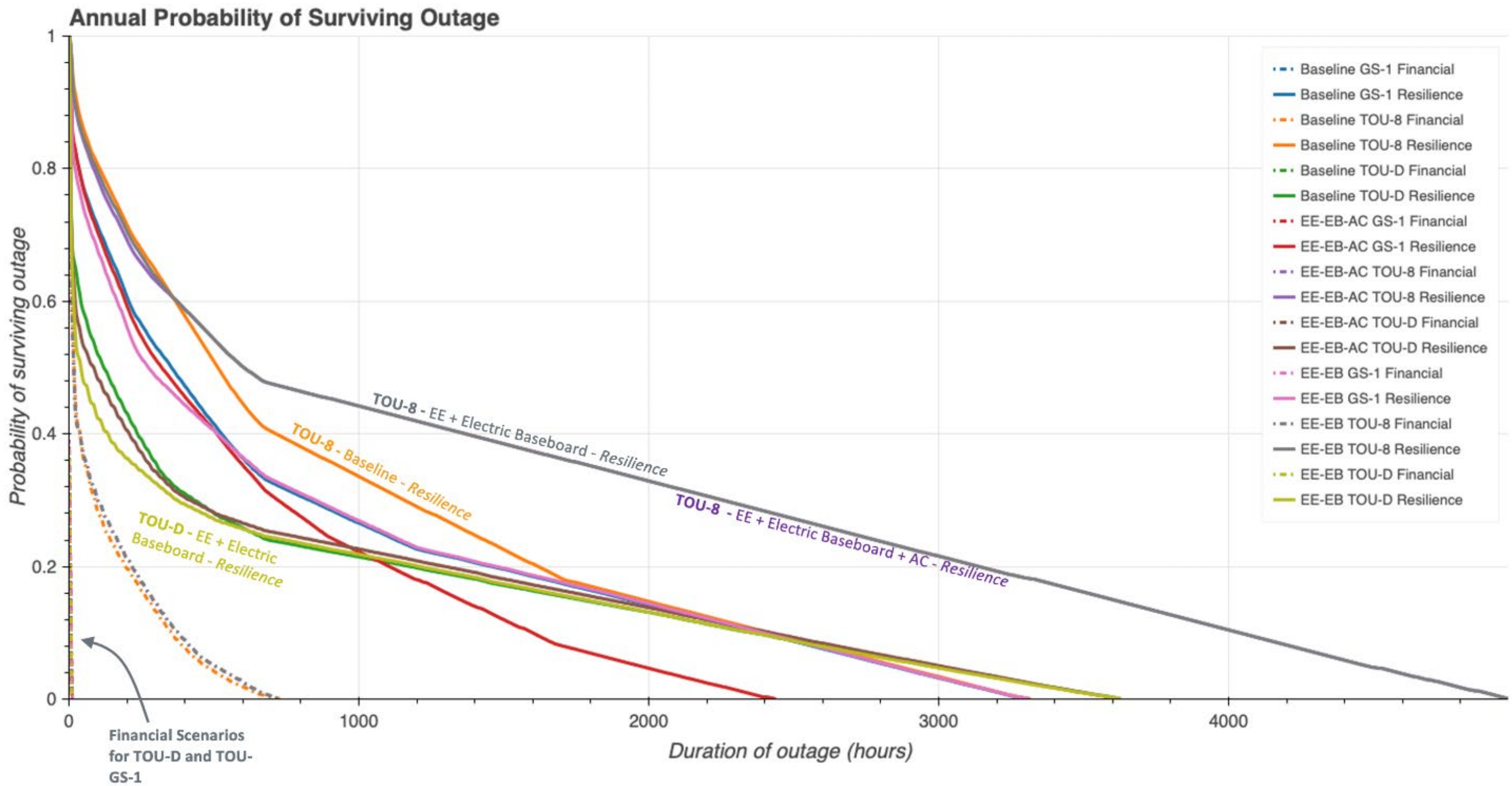
Figure 13: Normalized, Cost-Optimal, Energy Asset Sizes as Determined by REopt for Each UES of the Oak View Community



Source: NREL, 2023

Based on the cost-optimal technology asset selections and associated sizing determined by REopt, the added resilience benefits for each URBANopt-modeled UES and REopt scenario were investigated through a statistical resiliency analysis. In REopt, a statistical resiliency analysis was performed by conducting a large set of runs in which outages were randomly injected into the model. These outages were random in both occurrence and duration, with each variable sampled independently from a uniform distribution. Outage survivability is then calculated from the results of the large set of runs. In the context of this analysis, survivability is defined as the probability that the community can supply energy to its critical loads for "X" hours given a certain set of energy outages. The annual probability of surviving an outage for each modeled UES and REopt scenario, per Southern California Edison Company's (SCE) tariff group in the Oak View community, is shown in Figure 14. Figure 14 illustrates that resilience scenarios (solid curves) had a higher probability of surviving an outage when compared with the financial scenarios (dotted curves) due to their larger distributed energy resource asset sizes. Moreover, the commercial Time-of-Use (TOU)-8 group had the highest probability of surviving an outage given its larger battery, which was induced by avoiding its demand charges. In addition, the energy efficiency measures increased the resiliency of the TOU-8 group by increasing the overlap of hourly PV generation with its electric loads. Figure 14 also illustrates that the financial scenarios for the residential TOU-D group, and non-residential TOU-GS-1 group, had the lowest resiliency, which is due to a lack of batteries selected in its cost-optimal solution. Lastly, it is noted that the electrification of heating misaligns the load and generation in the TOU-D group, which reduced its survivability when compared with its baseline UES.

Figure 14: Annual Probability of Surviving an Outage for Each Modeled UES and REopt Scenario per SCE Tariff Group of the Oak View Community



Source: NREL, 2023

CHAPTER 4: Conclusion

This project developed a process for a series of models that were applied to a low-income community to understand the impact of building weatherization, energy efficiency, electrification, and onsite generation on energy cost, emissions, comfort, and resiliency. The five major contributions of this work follow.

1. Development of a community scale energy model (or urban-building energy model) for a low-income community
2. Analyses of various building measures considering low-income assistance and emerging clean-energy technology-support programs
3. Analysis of cooling methods to enhance community resilience against extreme heat events
4. Analysis of solar and storage technologies to reduce cost, enable electrification, and improve energy-system resiliency and reliability
5. Consideration of impacts on electric distribution systems during all steps of the analyses.

Regarding the development of an urban-building energy model for a low-income community, important outcomes from this work emerged.

- This work demonstrates the development of an accurate low-income community-based energy model using publicly available data and with support from local governments. While results are specific to the case study presented in this work, necessary data inputs are widely available, and the approach is replicable in different cities and climate zones.
- Special care must be taken when simulating a disadvantaged and low-income community. For the community in this study, the application of a prototype of energy model standards yielded an aggregated residential electricity demand 54 percent higher and natural gas use 28 percent lower than actual use. This error was reduced through the development of a bottom-up load construction approach based on site information and visits, energy-survey data, and building-energy modeling standards. The combination of the approach with community interaction led to critical model fine tuning such as the modification of miscellaneous plug loads and DHW demand.
- At the community level, the proposed modeling approach captured the dynamics of monthly energy use across the residential sector. This was accomplished through the annual tuning of loads. Typical monthly errors between aggregate BEM and actual residential building energy use were less than 10 percent.
- The individual BEM tuning method can readily incorporate real building energy-use data. This creates the potential to improve BEM accuracy as higher-quality data becomes available.

- The resulting model captures both the physics of building-energy use and interaction with the local electric-distribution system. The model is ready to examine the impacts of energy efficiency, electrification, and renewable distributed energy resource systems. The model is also suitable for integration with transportation models that capture the introduction of electric vehicles into the local energy system.

Regarding low-income assistance programs and the adoption of clean building energy technologies, important outcomes included the following.

- 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 percent to 20 percent, and were 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 percent, 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 percent for low-income households, and 22 percent for all others in the community. Pairing HPWHs with LED interior lighting achieves 80 percent of the carbon reduction potential estimated in this work. When used to replace an ERWH, HPWHs decrease costs by nearly 30 percent, and carbon emissions by nearly 35 percent.
- 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 percent to 2 percent. Interestingly, electric distribution transformer degradation remains the same when HPWHs and appliance electrification are implemented simultaneously.
- ERWHs also display significant TDV energy reduction potential but increase the cost of energy 70 percent to 100 percent when replacing a gas tank DHW. Widespread deployment results in immediate distribution transformer upgrades, and in one instance, a distribution cable upgrade resulted in a projected 7.5 percent cost of energy increase for the community.
- Current low-income utility rate reduction programs, which reduce the cost of electricity by about 30 percent, are insufficient for supporting electrification in this community. Holding utility gas costs constant, utility electricity must be reduced by 35 percent to 45 percent to achieve utility-bill parity after building electrification.
- Incentives that offset 80 percent or more of total HPWH installation costs across Oak View could potentially eliminate any cost increases associated with electrifying residential buildings. However, incentives provided to property owners may not directly translate into savings for low-income renters.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AC	alternating current
ASHP	air-source heat pump
BEM	building energy model
°C	degrees Celsius
CARE	California Alternative Rate for Energy
CO_2	carbon dioxide
DHW	domestic hot water
EPIC	Electric Program Investment Charge
ERWH	electric resistive water heater
°F	degrees Fahrenheit
HIHH	heat index hazard hours
HOMES	HOME Investment Partnership Program
HPWH	heat pump water heater
HSPF	Heating Seasonal Performance Factor
kWh	kilowatt-hours
LED	light-emitting diode
NOx	oxides of nitrogen, including nitric oxide (NO) and nitrogen dioxide (NO_2)
NPV	net present value
NREL	National Renewable Energy Laboratory
PV	photovoltaic
SCE	Southern California Edison Company
SEER	Seasonal Energy Efficiency Ratio
T24	Title 24
TDV	time-dependent valuation
TECH	TECH Clean California Program
TOU	Time-of-Use
UC	University of California
UEF	uniform energy factor
UES	urban energy scenario
U.S. DOE	United States Department of Energy
U.S. EPA	United States Environmental Protection Agency
Zone	California Energy Commission Climate Zone

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Project Deliverables

The following peer reviewed articles were published thanks to the research performed under this grant:

1. Flores, Robert, Sammy Houssainy, Weixi Wang, Joseph Robertson, Khanh Nguyen Cu, Ben Polly, Ramin Faramarzi, Jim Maclay, and Jack Brouwer. 2023. "Developing and Tuning a Community Scale Energy Model for a Disadvantaged Community." *Energy and Buildings*, 285, 112861. Available at https://doi.org/10.1016/j.enbuild.2023.112861.
2. Wang, Weixi, Robert Flores, Ghazal Razeghi, and Jack Brouwer. 2023. "Quantifying Transformer and Cable Degradation in Highly Renewable Electric Distribution Circuits." Institute of Electrical and Electronics Engineers Power and Energy Society. 2023 IEEE PES Grid Edge Technologies Conference and Exposition. San Diego, CA. April 10–13, 2023. Available at https://doi.org/10.1109/GridEdge54130.2023.10102733.
3. Nie, Xiao, Robert Flores, Jack Brouwer, and Jaeho Lee. 2024. "Energy and cost savings of cool coatings for multifamily buildings in US climate zones." Advances in Applied Energy, 13, 100159. Available at https://doi.org/10.1016/j.adapen.2023.100159.
4. Flores, Robert, Sammy Houssainy, Weixi Wang, Khanh Nguyen Cu, Xiao Nie, Noah Woolfolk, Ben Polly, Ramin Faramarzi, Jim Maclay, Jaeho Lee, and Jack Brouwer. 2024. "Addressing Building Related Energy Burden, Air Pollution, and Carbon Emissions of a Low-Income Community in Southern California." *Advances in Applied Energy*, 14, 100169. Available at https://doi.org/10.1016/j.adapen.2024.100169.
5. Wang, Weixi, Robert Floresi, and Jack Brouwer. "Optimal Topology Design in Radially Distributed Electrification Scenarios with Distributed Generation." Accepted to the IEEE GridEdge2025 Conference.
6. Novoa, Laura, Robert Flores, and Jack Brouwer. 2019. "Optimal renewable generation and battery storage sizing and siting considering local transformer limits." *Applied Energy*, 256, 113926. Available at https://doi.org/10.1016/j.apenergy.2019.113926.
7. Novoa, Laura, Robert Flores, and Jack Brouwer. "Optimal solar inverter sizing considering Volt-Var droop-control and PQ control for voltage regulation." Prepared for submission as a conference proceeding for IEEE.
8. Flores, Robert, Sammy Houssainy, Weixi Wang, Joseph Robertson, Khanh Nguyen Cu, Ben Polly, Ramin Faramarzi, Jim Maclay, and Jack Brouwer. "Adaptive Cooling Strategies for Vulnerable Communities in Southern California." Manuscript under internal review.

Additional interim project reports and deliverables are available upon request by submitting an email to pubs@energy.ca.gov.