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Exploring Decarbonization and Clean Energy Pathways for Disadvantaged Communities in California

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SUMMARY

California has a state-wide goal of carbon neutrality by 2045. Decarbonization for disadvantaged communities (DACs) poses extra challenges due to financial, informational, language, and other barriers. This paper presents the methodology, results, and analysis of energy efficiency measures (EEMs) to save energy, reduce CO_2 emission, and promote clean energy access at the district scale for two DACs in Fresno, California. The methods are broadly applicable to other neighborhoods across the U.S. 22 EEMs were identified and modelled for all residential buildings in the two DACs both individually and as packages. Results show that for energy and CO_2 reduction purposes, the top performing EEM package can decrease energy use and CO_2 emissions by an average of 60%. For electrification, heat pump water heaters are a viable solution, coupled with air source or mini-split heat pumps. Replacing gasoline vehicles with electric vehicles is another important measure in electrification and reducing GHG emissions.

INTRODUCTION

California has a state-wide target of 40% GHG reductions by 2030 compared to the level of 1990 and a 100% zero-carbon electricity target (for retail sales) by 2045 [1]. In 2018, then Governor Jerry Brown issued an Executive Order for the state to achieve carbon neutrality by 2045 [2]. Access to clean technology options (e.g. solar PV, storage, microgrids, major energy efficiency upgrades, electric heat pumps, and electric vehicles) is essential to reach the GHG reduction target, but constrained in disadvantaged communities (DACs) by many structural barriers [3]. Getting to the decarbonization targets for DACs in California poses extra challenges due to the limited financial resources, information and transactional barriers, lack of contractor training, and other constraints such as not increasing residents' utility bills [4].

Extensive research on building electrification have shown promising results in contributing towards California's GHG emissions reduction target. For instance, research by Brockway and Delforge has revealed that the electrification of water heating and space heating of households in California can result in an annual reduction of 50-70% and 46-54% of GHG emissions, respectively

[5]. Similarly, Hopkins et al. also explained that if the space and water heating in 1/3 of California's buildings are electrified by 2030, it would annually reduce 7 million metric tons of GHG emissions, which is equivalent to eliminating emissions from 1.5 million cars annually [6]. Ultimately, both research outcomes have highlighted the importance of adopting electrification technologies such as heat pumps for HVAC and water heating for building decarbonization. However, neither of them target specifically at DACs. As Hopkins et al. have stated in their research, despite the utility cost reduction benefit, such retrofits have high investment costs [6], which remains a challenge for practical application in DACs. In the research reports by Mahone et al. and Choi et al., they have explained the benefits of electrifying residential buildings in California along with the need for rebates for low-income households to reduce the cost of electrification retrofits [7], [8]. However, these research have only discussed DAC cases qualitatively, and quantitative analysis on the effectiveness of potential measures is still missing. Similarly, while the California building code (Title 24) is evolving to encourage more electrification [9], building codes applies to new construction and major retrofits, and there is very little new construction or major retrofit activity (e.g., major additions) for homes in DACs, and there is the need for more modelling and analysis of electrification of existing buildings in DACs to support further policy development.

To address the gaps, we developed the methodology and workflow to quantitatively evaluate the effectiveness of energy efficiency measures (EEMs) on improving energy efficiency, reducing carbon emission, and promoting clean energy access, i.e., building electrification, in underserved areas. Two DAC neighbourhoods in the City of Fresno, California, were selected to demonstrate the methodology. Fresno is a good candidate because it has many DACs in the San Joaquin Valley and is home to several related activities and initiatives that can be leveraged. Fresno is a very high scoring area in CalEnviroScreen 4.0 [10] as a community disproportionately burdened by low incomes, high unemployment, and multiple sources of pollution.

OVERALL MODELING AND ANALYSIS APPROACH

Figure 1 illustrates the overall workflow of the modeling and analysis approach. First, input data for the model is collected from multiple sources, including Title 24 codes and standards, site surveys and stakeholder interviews, tax assessor data, and building characteristics compiled from city's public data sources for the DAC buildings into a CityBES dataset. Second, the baseline models of the DAC buildings were created in CityBES based on the model inputs. Third, energy efficiency measures for buildings and electric vehicles for transportation, were applied to the baseline models to evaluate their effectiveness in improving energy efficiency, reducing carbon emission, and facilitating clean energy access. They were first evaluated individually, then compiled as packages based on their performance. Each part will be described in detail in the following sections.

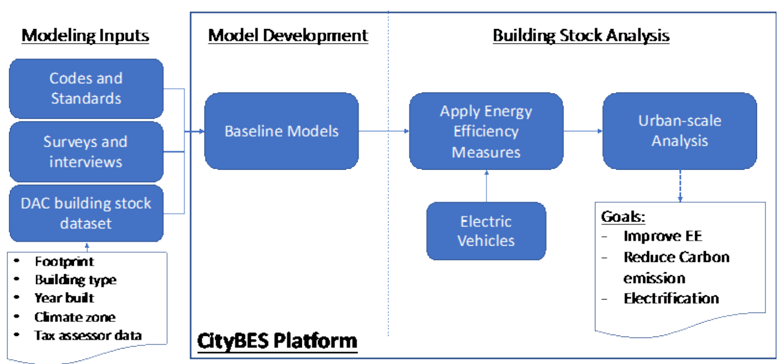


Figure 1. Overall workflow of modeling and analysis.

CityBES is used for district-scale modeling and analysis. CityBES is a web-based data and computing platform developed by Lawrence Berkeley National Laboratory [11] and is freely available at CityBES.lbl.gov. It focuses on energy modeling and analysis of a city's building stock to support district or city-scale efficiency programs. CityBES employs EnergyPlus [12] to simulate building energy use and savings from energy efficient retrofits.

Baseline model characterization

In the selected DAC neighborhoods, more than 95% of the buildings are single-family homes (SFH) and low-rise multi-family homes (MFH). Therefore, we focus mainly on the modeling of residential buildings in this study. Three types of prototype models are designed to represent existing buildings, including one-story SFH, two (or more) story SFH, and low-rise MFH. They were calibrated in terms of energy usage based on CBECC-RES (California compliance software for the residential buildings) and IECC (International Energy Conservation Code) prototype models. For the district scale modeling, the prototype models were modified to reflect the actual floor area of each building in the building stock and our best estimates of in-place equipment.

The envelope properties, internal loads, and HVAC efficiencies are derived from Title 24 minimum efficiency requirements. Buildings constructed in different years are assumed to comply with Title 24 energy efficiency standards of the corresponding vintages (Title 24 is updated every three years) [9]. According to the Fresno Economic Opportunities Commission (EOC), which conducts energy audits and weatherization in Fresno, the most commonly used types of HVAC systems in the Fresno DACs are 1) evaporative coolers with gas wall heater, 2) window air conditioners with gas wall heater, and 3) central air conditioners with gas furnace. In homes constructed before 1978 in the Fresno DACs, we assume that the three system types account for 25%, 50%, and 25% respectively for SFH, and 25%, 25%, and 50% respectively for MFH. Nearly all buildings constructed after 1978 are equipped with central air conditioners and gas furnaces. Per Fresno EOC, the overwhelming majority of homes use natural gas storage water heaters for domestic hot water as with most of the state's homes and because natural gas is less expensive than electricity in California at about five times less cost per unit of energy. Each SFH and each unit in the MFH is equipped with its own water heater.

Buildings dataset development

The Columbia and Winchell neighborhoods in the southwest Fresno are selected as the example DAC districts in this study with 1679 buildings and 1433 buildings, respectively. Building properties are collected from several sources for creating the dataset to be used in CityBES, and include the building footprints, use type, height, number of stories, and the year of built. The building footprints are extracted from the Microsoft Building Footprint database with the boundaries of the neighborhoods, and year of built, use type, and number of stories are mainly from query results using the Atom API. The median floor area of SFH and MFH for the two neighborhoods are 134 and 385 m^2 (Columbia), and 122 and 229 m^2 (Winchell).

Evaluation of energy efficiency measures

A total of 22 EEMs were selected and modeled in this study, which cover the following categories: (a) space cooling and heating improvement, such as fuel-switching to an air-source heat pump (ASHP) system or mini-split heat pump (MSHP) system from gas-based heating; (b) domestic hot water system improvement, such as efficiency upgrade of gas storage water heater, improving water tank insulation, or fuel switching (and efficiency upgrade) to an electric storage heat pump water heater (HPWH); (c) envelope performance improvement, such as adding wall insulation, adding air sealing, or adding solar-control window film; (d) increasing air circulation, such as adding ceiling fan, adding portable fan, or adding attic fan; (e) lighting system improvement, such as replacing existing lighting with LED fixtures; (f) improving operation and maintenance, such as reducing duct leakage; and (g) replacing gasoline vehicles with electric vehicles (EVs).

The goal of EEM evaluation is to figure out the top performing EEMs and EEM packages that can maximize energy savings or minimize CO_2 emissions. The above developed DAC dataset was used to create baseline models for the building stock in CityBES. The baseline models were then applied with selected EEMs individually, and their effectiveness was evaluated and ranked according to the goals above. The EEMs were then combined as packages based on their categories and performance. The packages were further modeled and analysed. Typical meteorological year (TMY) weather data is used in EnergyPlus simulations for EEM evaluation. The CO_2 emission factor for electricity is 420.4 lbs CO_2/MWh in California, based on the Emissions & Generation Resource Integrated Database (eGRID) [13] and for natural gas is 399.5 lbs CO_2/MWh. With SB100 legislation, electricity emissions factors are decreasing with time so our CO_2 emissions savings are a lower bound on lifetime savings.

Electrification

We explored the viable pathways towards electrification by evaluating the performance of electrification measures. Out of the above 22 EEMs, four measures were selected and evaluated for the fuel switching purpose: (1) upgrade to an ASHP system; (2) upgrade to MSHP system; (3) upgrade to HPWH; (4) replace passenger gasoline vehicle with electric vehicle.

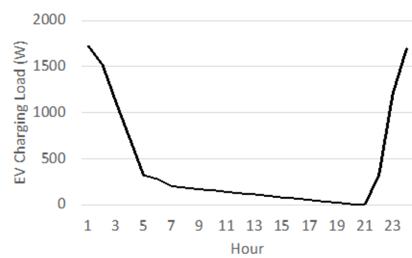


Figure 2. Typical daily EV charging profile under TOU rate.

Szinai et al. from Lawrence Berkeley National Lab modeled the added grid load under different EV adoption rates and charging scenarios [14]. We referred to the simulation results of their 2.5 million EV adoption scenario (median adoption rate assumption), and adopted the modeled EV charging profile under the time-of-use (TOU) scenario in our study, as shown in Figure 2. This is compatible with Fresno's local utility rates which are lower in the middle of the night and daytime and highest in the late afternoon and early evening (5 to 8 pm).

Other related assumptions include the annual mileage, fuel car efficiency (mile per gallon or MPG), and gasoline price. According to the statistical data of the U.S. Department of Transportation, the annual mileage per vehicle in the Fresno Columbia and Winchell districts is 9,000 [15]. The survey data in the Fresno local communities indicate that the median car age is 13 years. Based on an earlier study by Lawrence Berkeley National Lab, the realized fuel efficiency for 2007 new cars in California is 22.2 MPG [16]. We assume a 5% degradation in fuel efficiency over 13 years (since 2007) due to poor maintenance, and estimated 21 MPG as the fuel efficiency assumption for the existing gasoline vehicles. Considering that the vehicles tend to be older in DAC than other communities, this assumption is consistent with the statistical data from the U.S. Department of Transportation that the national average light duty vehicle fuel efficiency is 22.3 mpg in 2017 [17].

RESULTS

Optimal package for energy savings and CO_2 emission reduction

21 out of the 22 selected EEMs (excluding EV) were modeled in CityBES to explore potential solutions to reduce energy consumption and CO_2 emission from the previously described baseline homes. The performance of each EEM is evaluated and ranked towards maximizing site energy savings and CO_2 emission reduction. These EEMs are ranked by the median value of the results. Figure 3 reveals the ranking of these measures based on site energy use reduction and CO_2 emission reduction. The results of the Winchell neighbourhood are illustrated in this section as example.

After running a series of simulations with different measures combinations, the measure package with the most energy savings is selected, as illustrated in Figure 3. It includes eight high-performing measures: replacing existing lighting with LED (0.6 W/sf), applying ceiling insulation (R-38), upgrading to MSHP system (cooling and heating COP 3.66 and 3.7), upgrading to HPWH (COP 3.3), re-roofing and adding roof insulation (R-24.8), adding an interior storm window layer, applying wall insulation (R-21), and adding window film. In terms of maximizing CO_2 emission reduction, the selected optimal measure package turns out to be the same as the energy saving package. This is mainly due to the similar CO_2 emission factors for electricity and natural gas in California. For both energy savings and CO_2 emission reduction, the measure of upgrading to MSHP system outperforms others by a large margin. MSHP saves cooling energy from its high cooling efficiency, eliminates natural gas use for space heating, and consumes limited heating energy due to high heating efficiency. Another high-performing measure, upgrading to HPWH, is also effective for electrification purposes in addition to excellent energy and CO_2 reduction.

As shown in Figure 4(a), the measure package can reduce the site energy consumption by a median of 63%, from the initial distribution of site energy consumption ranging between 75-275 kWh/m^2 annually to a new distribution ranging between 25-125 kWh/m^2. Moreover, the CO_2 emission was reduced from mostly 15-50 kg/m^2 to 5-25 kg/m^2, as shown in Figure 4(b), following the trend of a median of 63% reduction. These savings are due to the combination of active and passive measures in the package. For the active measures, the upgrade to LED reduces electricity consumption from interior lighting, while the MSHP and HPWH upgrades of the HVAC and domestic hot water system, respectively, eliminate natural gas usage from these two end-uses. Passive measures like roof insulation, wall insulation, ceiling insulation, and interior window storm layer are applied to reduce heat gain in summer and heat loss in winter through the envelope, which can reduce cooling and heating load. Window film is a passive cooling measure to decrease buildings' solar heat gains through the windows, which can further reduce cooling load in summer. However, an important caveat is that while the measure package can achieve large energy savings and CO_2 emission reduction, they may be associated with high initial investment cost and long payback period. Cost-effectiveness should be a key focus for future study.

Electrification analysis

The EV measure was evaluated independently, and also combined with HVAC and domestic hot water systems as two electrification packages: (1) EV + HPWH + ASHP (cooling and heating COP 3.22 and 3.3); (2) EV + HPWH + MSHP. As shown in Figure 5, when EV is added, the majority of electricity use increases from 60-80 to 85-110kWh /m² due to the additional EV charging load. This increase adds directly to the site energy use since the natural gas use stays unchanged. Note that site energy includes electricity and gas only, not gasoline consumption from vehicles.

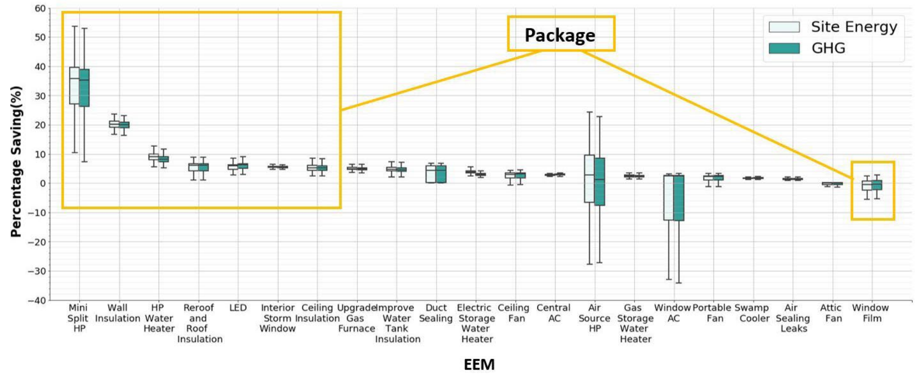
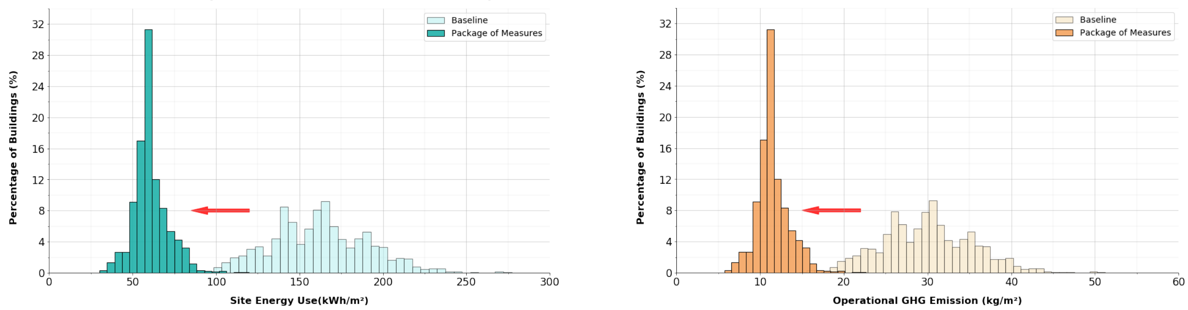


Figure 3. Selected measure package for maximizing site energy saving and GHG reduction for the residential buildings in the Winchell neighborhood.



(a) (b)

Figure 4. The change of distributions from baseline to measure package for the residential buildings in the Winchell neighborhood: (a) site energy use, (b) operational GHG emission.

For electrification package 1, the electricity use more than doubles from the baseline due to the additional EV load along with the electrification of domestic hot water and HVAC systems to HPWH and ASHP. Though natural gas for HVAC and water heating are eliminated, the overall site energy use increases slightly from the baseline. On the other hand, for electrification package 2, the electricity use is only slightly higher than the EV individual scenario, and less than double of the baseline. Although this package contains the same EV and HPWH measures as electrification package 1, it upgrades the HVAC system to a MSHP, which is generally more efficient than an ASHP. Therefore, electrification package 2 can suppress its site energy use to approximately 110-130 kWh /m², which is even lower than the baseline.

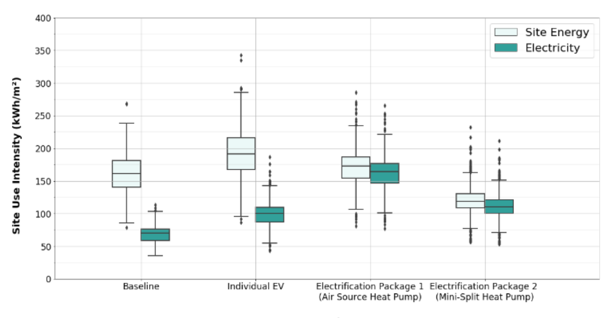


Figure 5. Annual site energy and electricity use of baseline and electrification scenario.

The electrification of vehicles eliminates gasoline consumption and replaces it with electricity as fuel source. This is an important contribution to the clean energy goal because gasoline emits 536 lbs CO_2/MWh, which is much higher than electricity at 420.4 lbs CO_2/MWh, which is much higher than electricity at 420.4 lbs CO_2/MWh, and electric-motors are more energy efficient than internal combustion engines. For this evaluation, CO_2 emission from both the building's operation and the vehicles are accounted for. Figure 6 shows that the EV individual scenario reduces CO_2 emission by an average of 40% via eliminating gasoline. For the first electrification package, it has an average of 47% CO_2 emission reduction by eliminating both gasoline and natural gas use. It is only slightly higher than the EV individual because the electricity consumption increases due to the electrification of the HVAC and domestic hot water systems. On the other hand, the second electrification package can reduce CO_2 emissions by an average of 60% and up to 67%. In this package, aside from gasoline and natural gas elimination, electricity is also greatly reduced due to the high efficiency of MSHP system.

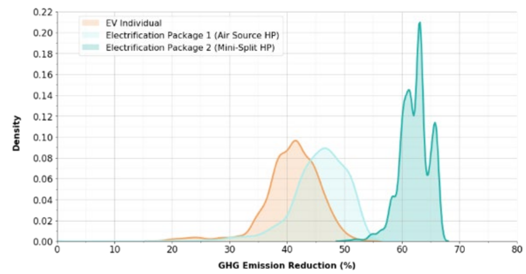


Figure 6. Annual GHG emission reduction for electrification scenarios.

CONCLUSIONS

This study presents the methodology, results, and analysis of EEMs to improve energy efficiency, reduce carbon emissions, and promote clean energy equity of the disadvantaged communities in Fresno. The developed methodology is applicable to other neighbourhoods and communities in California and across the U.S. through customization of related data and model inputs. A total of 22 EEMs were modeled for all residential buildings in the two DACs in Fresno. The most effective energy saving package can reduce total energy use by a median of 63% from 75-275 kWh/m² annually to 25-125 kWh/m², and reduce CO_2 emission by a median of 63% from mostly 15-50 kg/m^2 to 5-25 kg/m^2. For electrification purposes, both HVAC and domestic hot water systems are electrified in this study by upgrading to HPWH and ASHP or MSHP systems. In addition, gasoline vehicles are also replaced with electric vehicles. The EV measure by itself can reduce CO_2 emission by an average of 40% at the household level. EV is also combined with other electrification measures on HVAC and domestic hot water systems. The package of EV, HPWH, and MSHP together can reduce CO_2 emission by an average of 60% and up to 67%.

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