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Examining the impact of energy efficiency retrofits and vegetation on energy performance of institutional buildings: An equity-driven analysis

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ABSTRACT

Inequities in the built environment have long persisted in communities around the world. Prior studies have exposed that energy retrofit programs invest inequitably in residential buildings, leaving racial minorities with disproportionately less energy inefficient homes, regardless of income level. This inequity in energy performance and retrofit investments has yet to be studied for commercial and institutional buildings. Further research has shown that tree canopy coverage and vegetation is less dense in historically disadvantaged communities, contributing to a greater urban heat island effect and corresponding higher energy consumption for cooling compared to historically advantaged communities. Moreover, there is limited albeit emerging research that utilizes granular socioeconomic data with fine temporal scale energy consumption data to help identify energy inequalities among race and income groups. This paper examines the differential impact of energy efficiency retrofit installation on energy performance between advantaged vs. disadvantaged groups using data from U.S. public school buildings. Additionally, it studies how the effect of retrofits is compounded by the presence of vegetation surrounding the building. Utilizing hourly interval smart meter data from primary and secondary school buildings in California, the impact of retrofits are quantified using three energy metrics. Then the disparities in retrofit impact for advantaged vs. disadvantaged groups (as defined by three equity metrics) are evaluated using school-level demographic data. Lastly, regression on the percent change in monthly energy consumption from the pre-retrofit to post-retrofit period is used to quantify the incremental benefits of retrofits compounded by vegetation. Findings show that energy efficiency retrofits can improve energy performance and reduce energy inequities. Specifically, retrofits significantly increase energy efficiency and reduce the energy efficiency equity gap by up to 198%. Evidence shows that vegetation surrounding a building has a synergistic effect with mechanical retrofits for reducing energy consumption in respect to reduced cooling loads, even in cases where mechanical retrofits alone resulted in significant increases in energy consumption. Dense vegetation provides around 6% energy savings, similar in magnitude to savings from mechanical retrofit installation. This validates the effectiveness of retrofits for reducing energy consumption and improving energy equity, and demonstrates the ability of vegetation to provide additional energy savings beyond mechanical interventions.

1. Introduction

Energy consumption from commercial buildings accounts for up to 27% of GHG emissions [1]. Therefore, reducing energy consumption in this sector presents a significant opportunity for reducing emissions and achieving climate goals. Energy efficiency (EE) retrofits are often deployed as an effective solution to decrease energy use and emissions from existing commercial and institutional buildings such as offices and schools. Rather than tearing down existing buildings, EE retrofits have been installed to update building systems while maintaining functioning infrastructure. An estimated 54% of public school districts in the U.S. need to update or replace multiple building systems, with a majority of necessary updates being to HVAC, lighting, and roofing systems [2]. Liang et al. showed that EE retrofits can reduce energy consumption by 12% in commercial buildings, and installing bundled HVAC and heat pump retrofits have the potential to reduce electricity consumption by 73% [3].

Energy performance in school buildings has been shown to affect student performance, making it even more imperative to update building systems. Temperature and ventilation in classrooms has a demonstrated effect on student learning, and hot school days with improper air conditioning were found to account for roughly 5% of the racial academic achievement gap [4]. Beyond mechanical EE measures,

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vegetation has been shown to reduce the urban heat island effect and thus reduce energy demand for cooling loads [5]. Vegetation provides learning benefits as well – connecting with nature in educational settings (i.e. green playgrounds, walks in nature, nature views from classroom windows, etc.) has been shown to substantially improve attention and memory, as well as enhanced wellbeing, cognitive restoration, and stress reduction [6].

Despite the benefits of both mechanical and vegetative EE retrofits, the decision to install them is influenced by several factors. Installation decisions for EE retrofits varies between building owners, but main considerations cited are financial (payback period, life-cycle cost, funding) or external (gas prices, climate initiatives, etc.) [7–9]. Cost prohibits schools in low-income communities from installing retrofits without the aid of external funding programs due to the fact that schools in the U.S. rely on local taxpayer funding [10]. School districts that are unable to pass a bond for property tax increases need to rely on federal or state funding to improve building systems. The California Proposition 39 K-12 program provided more than $1.7 billion of funding over five years to primary and secondary schools to install EE retrofits [11]. Retrofit funding was granted to schools that submitted a project plan with a savings-to-investment ratio greater than one. In this study, the effects of the California Proposition 39 program are examined.

Energy inequities have been demonstrated in the residential building sector, where low-income and racial minority communities have lower EE and less access to efficiency technologies than their high-income and White counterparts [12–16]. In this paper, inequities are defined as an unfair and disproportionate energy burden due to demographic traits (i.e. race and income). Both racial and income inequities in residential building energy performance are well documented in the literature, yet there is a lack of studies into social inequities of institutional building energy performance.

The extended use of cities open data portals, satellite data, and Geographic Information Systems has fostered extensive research in urban morphology and inequities in the physical built environment. One facet of this research has revealed that on average tree coverage is 15.2% less dense in low-income areas, where summer land surface temperature is 1.5 °C hotter than high-income areas [5]. In urban areas this inequity is exacerbated: low-income areas have 30% less tree coverage and are 4.0 °C hotter than high-income areas. The hotter urban environment requires more energy to cool buildings lest the residents face greater heat stress.

The goal of this research is to further the understanding of how EE retrofits and the surrounding vegetation impacts equity in public primary and secondary schools in Northern California, U.S. A data-driven approach is developed and employed to evaluate energy performance for advantaged and disadvantaged school subsets defined by three equity metrics: Median Household Income, Diversity Index (DI), and the percentage of students eligible for the Free and Reduced-Price Lunch (FRPL) program. Energy performance is quantified using the percentage of load shed during a Demand Response (DR) event (%), total annual energy consumption (kWh/year), and energy consumption per enrolled student (kWh/student). Vegetation is quantified using the Normalized Difference Vegetation Index (NDVI) of the area surrounding the school. Note that this study builds on previously presented research by significantly expanding the literature review and analysis to include the synergistic effects of vegetation and mechanical retrofits.[1]

[1] The short version of the paper was presented at ICAE2022, Bochum, Germany, Aug 8–11, 2022. This paper is substantial extension of the short version of the conference paper.

2. Background

2.1. Equity gap in energy efficiency

Among residential buildings, there exists an energy efficiency performance gap for both race and income. White and high-income homes have been shown to be more efficient than non-white and low-income homes [12]. Lower median household incomes and higher percentages of African American or Hispanic households are more likely to have higher heating energy use intensities (therefore less efficient homes) [12]. Energy use intensity disparities by income range from 27 to 167%, and racial disparities range from 40 to 156% [16]. This means that low-income households and Black, Hispanic and Native American households pay proportionally more than the average household for their energy [17,18]. Despite low-income households being less efficient (using more energy per square foot), high income areas actually use more energy per building [19]. This results in an emissions paradox in the U.S., where the most efficient homes emit the most carbon dioxide [13]. White households emit more carbon dioxide per capita despite having more efficient homes than Black households [18].

These disparities come from inequitable access to EE technologies. Not only are EE technologies less available in high poverty areas, but they are also more expensive: Reames et al. found lighting upgrade costs to be more expensive in high poverty areas [15]. It is also more difficult for lower income households to secure loans to afford these upgrades – low-income households need higher credit scores to get loans for EE technologies [20]. Regardless of potential energy savings, financial barriers are the most cited reason for not adopting energy efficiency measures among households [21]. Self-referential programs are not effectively targeting low-income communities because these programs do not recognize participation barriers or facilitate alternative opportunities for participation. The most energy burdened groups (low-income, elderly, and renters) experience the greatest barriers to retrofitting, such as high capital costs, lack of control during the process, disruption of daily life, and "presentism" thinking [22].

Energy efficiency programs that specifically target low-income homeowners have substantially lower investments; there are substantial disparities in household energy savings when comparing high vs low income programs, in some cases 22:1 [23]. This disparity in energy efficiency exists beyond residential buildings as well. Institutional buildings in the U.S. rely on funding from taxpayers to keep buildings up-to-date, and if taxpayers do not vote for a bond to invest in building renovations it is unlikely for them to happen. This structure means that low-income areas face more difficulties funding necessary building upgrades. Energy efficiency disparities are found even in privately owned buildings, where LEED certifications for commercial buildings are more likely to be adopted in urban, white, and highly educated areas [24].

Disadvantaged communities (DACs) have been left behind in the energy transition and often consume below the level of sufficiency. DACs consume less energy per capita, have less efficient buildings, drive fewer electric vehicles, and adopt rooftop solar at lower rates [25, 26]. With current investments of public funds, these disparities are likely to persist. This demonstrates the need for specific investment in DACs to promote their participation in the energy transition. Fournier et al. suggests a "socially optimal investment strategy" in which much higher marginal utility is placed on energy consumed at sufficient levels rather than excessive ones [25]. This would promote investment in low-income and minority communities that currently consume less energy at a less efficient level, thereby "bringing them up to speed" on current technological advances.

Typical equity metrics quantify personal information such as income, wealth, race, gender, education, and employment status. These must be adapted to the context in which they are used to capture the true differences that people of these groups are faced with [27]. For non-residential building types, which may draw occupants from disparate geographic areas, it is more difficult to collect demographic information through survey due to privacy laws. This leads to many studies being performed using data collected by government agencies (e.g., the U.S. Census) that aggregate data at larger geographic scales to preserve anonymity (e.g., census block group, tract, or state level).

Beyond higher electricity bills, equitable energy efficiency matters because of the effect the built environment has on people's lives. The energy performance of the buildings in which people work and learn have been shown to influence productivity. Indoor environmental quality, resulting from HVAC and lighting systems, has a strong influence on occupant comfort, productivity, and health [28]. With improper cooling and ventilation, hot classrooms have been shown to inhibit learning; proper thermal comfort in classrooms can mitigate this effect [4,29,30]. Most classrooms, even with updated HVAC, are not operated properly [30]; not only does this make the building less efficient, it means the classrooms are still not thermally comfortable. When the energy performance of buildings is inequitable across income and race, this disproportionately disadvantages those populations when working and learning.

Green space has manifold benefits, including energy savings, health, and wellbeing. Research in public health and urban planning has demonstrated inequities in access to green space. They found that U.S. minority communities lack access to green space, due to gentrification; this inequitable access has an impact on health outcomes in these communities [31,32]. Unequal tree coverage in low-income communities compared to high-income areas makes the summer land surface temperature 1.5 °C hotter, exposing these residents to higher likelihood of heat stress [5]. Energy efficiency and equity are tied to land use, transportation, walkability, urban green space [33].

2.2. Measuring energy performance

Existing studies on equity in buildings often take a modeling approach to estimating energy performance, with few using data-driven methods for evaluating energy consumption [16]. Data-driven approaches are very useful in real-world applications due to their accuracy and ease of implementation. They allow utilities to predict demand, municipalities to enforce energy efficiency laws or distribute retrofit funding, and policymakers to benchmark energy performance or evaluate policies. Data-driven analyses require large amounts of historical electricity consumption for the buildings they study. With improvements in smart meter technology and machine learning, new methods and metrics have been developed to describe the various aspects of building performance. Typically, energy metrics such as energy use intensity or energy per capita are calculated at yearly or monthly time scales. However, smart meters have enabled the creation of new metrics that can capture the time-varying energy behavior on hourly to sub-hourly time intervals [34–36]. These metrics can capture efficiency, flexibility, and volatility aspects of loads that are more relevant to daily operations.

Regression methods that quantify performance are often used to evaluate policy effectiveness, benchmark buildings against peers, or understand physical relationships. The difference-in-difference regression has been used to quantify the effectiveness of retrofit installation or policy intervention [37,38]. Difference-in-difference assumes a parallel trend in energy performance among similar buildings over time and attributes additional changes in energy consumption to an intervention received by a subset of buildings.

2.3. Improving energy performance through retrofits

Energy efficiency retrofits are used to improve energy performance in a building; natural solutions, such as installing green space and urban greening, also have demonstrated cooling and energy saving benefits for buildings. Urban heat island has a significant impact on electricity and gas consumption [39]; therefore, reducing urban heat island in a community through additional green space leads to energy savings in buildings. It is important to consider how to retrofit existing buildings to improve energy performance; most lifecycle greenhouse gas emissions are embodied rather than operational, meaning retrofitting can save more emissions than new construction [40].

Typically, an energy auditor evaluates a building through a series of on-site tests to determine which retrofits are necessary to keep the building up-to-date and improve efficiency. Deep retrofits consist of replacing entire building systems, such as HVAC, electrical, plumbing, and insulation. Light retrofits are easier to change out, such as new light fixtures, new windows, and sealing leaks.

Deep HVAC and envelope retrofits, while the most expensive and disruptive to install, lead to the greatest energy savings and greatest reduction in heat stress among occupants compared to other building retrofits. Liang et al. [3] empirically estimated the energy savings from energy savings measures installed in commercial and residential buildings in Phoenix, AZ; they found that HVAC and pump retrofits had the greatest potential for savings, which could reduce energy consumption by 73%. Through the EnergyStar program, HVAC retrofits in homes led to 41% source energy savings on average, and envelope retrofits alone led to 29% savings [41]. Nutkiewicz et al. found that up to 98% of annual heat stress exposure can be mitigated by improving the building envelope [42]; cool roofs reduce up to 91% of annual heat stress exposure.

Urban green space has been shown to reduce the urban heat island effect and provide cooling benefits to the surrounding area [5]. Vegetation cools through shading and evapotranspiration, which reduces cooling energy demand [43–45]. Green spaces do not trap heat like asphalt and concrete, thus lowering urban heat island. Greening systems can be applied directly to a building (e.g. green roofs, garden balconies, vertical greening, indoor gardens), and have been shown to reduce energy consumption [46].

Urban green space has been shown to reduce the urban heat island effect and provide cooling benefits to the surrounding area [5]. Kong et al. found that the presence of green space led to a 0.5 °C lower mean air temperature and creates a "cooling island" effect that provides vertical cooling within the mean building height, resulting in a mean 14.4 °C cumulative reduction in temperature from the ground to 30 meters [44]. Tree cover also reduces urban heat island – on a summer day, tree coverage can reduce land surface temperature by 10–20 °C [47].

Greening systems on buildings have demonstrated cost benefits over their lifecycle; it is possible the same could be true for urban green space and green infrastructure. While green roofs are more expensive than cool or conventional roofs, they provide significantly higher relative benefits per square foot over a 50-year lifecycle [48]. The EPA has aggregated a list green infrastructure cost–benefit resources [49]; many of the benefits listed in these resources are environmental impacts that do not have a quantifiable cost to include in a cost–benefit analysis. Additionally, none of the resources account for the energy savings of surrounding buildings from green infrastructure.

Although research has studied the cost–benefit tradeoff of greening and traditional building systems, this research has not extended to comparing the energy savings of natural and mechanical retrofits or analyzing the potential synergies of combining the two. Additionally, there is a lack of research that compares communal green infrastructure and individual building retrofits. Previous studies have compared energy and cost savings of greening systems and mechanical systems on a single building [48], or they have compared types of mechanical systems on a single building [3]. The potential synergies between green infrastructure and mechanical building retrofits have not yet been quantified.

Table 1
Summary of school characteristics. Statistics given as: median (25th percentile, 75th percentile).

	Control school ($n = 386$)	Prop 39 school ($n = 139$)
Age (years)	53 (24, 66)	57 (30, 69)
Average NDVI	0.16 (0.13, 0.18)	0.17 (0.14, 0.20)
Annual median income (USD)	$67,992 ($45,311, $99,002)	$54,205 ($41,628, $87,376)
Poverty index	0.70 (0.41, 0.86)	0.67 (0.53, 0.87)
Diversity index	0.49 (0.30, 0.58)	0.47 (0.17, 0.54)

3. Materials and methods

A data-driven approach is developed and employed to evaluate energy performance for advantaged and disadvantaged school subsets defined by three equity metrics: Median Household Income, Diversity Index (DI), and the percentage of students eligible for the Free and Reduced-Price Lunch (FRPL) program. Energy performance is quantified using the percentage of load shed during a Demand Response (DR) event (%), total annual energy consumption (kWh/year), and energy consumption per enrolled student (kWh/student). Vegetation is quantified using the Normalized Difference Vegetation Index (NDVI) of the area surrounding the school. First a description of the dataset and metrics employed in the analysis is given in Section 3.1 and then the four-step methodology to quantify the differential impact of retrofits and vegetation on advantaged versus disadvantaged groups is outlined in Section 3.2.

3.1. Dataset

The dataset for this study combines 2013–2014 and 2016–2017 hourly interval electricity meter readings made publicly available through the Proposition 39 program, school-level student demographic information from the Stanford Education Data Archive (SEDA), census tract-level median household income data from the 2016–2020 American Community Survey (ACS) 5-year data release, and California Proposition 39 K-12 Program retrofit information accessed through the California Energy Commission (CEC). These datasets are assembled for 525 out of 10,558 total primary and secondary schools in California; the schools in the study are located throughout Northern California.

For each school year, the SEDA dataset includes the proportion of the student population belonging to each race and ethnicity, the proportion of students eligible for the FRPL program, and the total enrollment [50].

The CEC provides information on EE retrofits that were funded through the California Proposition 39 K-12 program (Prop 39) [51]. The Prop 39 program provided funding for K-12 schools to improve their energy efficiency through retrofit installation. The Prop 39 data from the CEC is used to determine (a) whether a school received funding through Prop 39 for an EE retrofit and (b) whether the retrofit installation occurred during our time period of study. If a school received Prop 39 funding, it is referred to as a Prop 39 school; if it did not, it is referred to as a control school.

Monthly average Normalized Difference Vegetation Index (NDVI) values were collected for 2013–2014 and 2016–2017 from the Landsat 8 satellite data released through the U.S. Geological Survey. A summary of the building age, NDVI, and equity metrics for the control and Prop 39 schools can be seen in Table 1. A table of students t-test results testing a difference in means between the control and Prop 39 group for each variable in Table 1 can be found in the supplementary materials.

3.1.1. Equity metrics

As previously mentioned, this study considers inequities to be an unfair and disproportionate energy burden due to demographic traits (i.e. race and income). Three equity metrics were constructed from the SEDA and ACS datasets: income, Diversity Index, and % of students eligible for FRPL. These metrics are used to subset the population into advantaged (high-income, low-diversity, low % FRPL) and disadvantaged schools (low-income, high-diversity, high % FRPL). A high-diversity metric is used, rather than percentage of racial minority, to account for the unique nature of the California population having high percentages of several race groups. Some racial minorities in California have equally high incomes as racial majorities, therefore the DI is intended to capture historically or currently segregated communities.

The first metric, income, is the Median Household Income of the census tract in which the school is located. School districts are a geographically defined area that typically do not correspond to census areas; however, it is common that a school district is comprised of several census block groups and sometimes several census tracts. Therefore, the census tract is used to capture an area that is similar in size to the school district and a close approximation of a school district's median household income [52], as school district-level information was not available. While the census tract is not the exact same geographic area as the school district, it provides an approximation of the income in the surrounding community, and thus helps approximate the taxpayer funding provided to the school. The low-income subset is constructed based on the California Department of Housing and Community Development (HCD) definition of a low-income community having a Median Household Income at or below 80% of the statewide median household income [53]. According to the ACS, for 2016–2020 California's median household income was $78,672. Therefore, the cutoff for a school in a low-income community is a Median Household Income at or below $62,937. A high-income community is defined as having a median income at or above 150% of the statewide Median Household Income, or $118,008. HCD defines a moderate income community as having a Median Household Income between 80% and 120% of the statewide Median Household Income; therefore, to capture the most advantaged communities in a state with high income inequality, the high income cutoff is set at 150%.

The second metric used is the Diversity Index of the student population. The Diversity Index is a measure (bounded between 0 and 1) of the probability that two people randomly chosen from the population will belong to different race and ethnicity groups. The U.S. Census defines the Diversity Index (DI) as [54]:

$$DI = I - (H^2 + W^2 + B^2 + AIAN^2 + Asian^2) \tag{1}$$

where H is the proportion of the population who are Hispanic or Latino, W is the proportion of the population who are White alone, B is the proportion of the population who are Black or African American alone, $AIAN$ is the proportion of the population who are American Indian or Alaska Native alone, and $Asian$ is the proportion of the population who are Asian alone. The DI of each school is calculated using the SEDA dataset; if SEDA data was unavailable for the school, ACS census data was used to compute the DI. Then the quintiles of the DI are calculated for the population to set cutoffs for high- and low-diversity schools. High-diversity schools fall in the top quintile (DI $\geq$ 0.58) and low-diversity schools fall in the bottom quintile (DI $\leq$ 0.21).

The third equity metric is the proportion of students eligible for FRPL in the school, which is used as a proxy for poverty levels in the school. Households apply to the FRPL program by providing household size and income information to the Local Education Agency [55]; ultimately, eligibility is determined by a local official. Cutoffs are established for this metric using quintiles calculated for the population. Schools with a high proportion of FRPL eligibility have $\geq$ 91% of

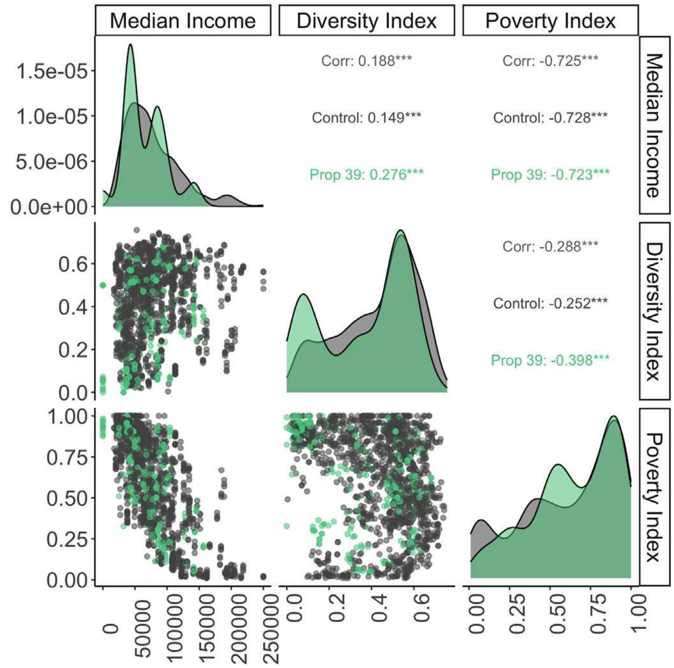

Fig. 1. Correlation coefficients matrix of equity metrics.

students eligible for FRPL and fall into the high poverty subset. Schools with a low proportion of FRPL eligibility have ≤ 35% of students eligible for FRPL and fall into the low poverty subset.

Additionally, exploratory data analysis was used to verify that the Prop 39 schools are a representative sample of the population. The Prop 39 schools are distributed throughout the equity metrics, as seen in Fig. 1.

3.1.2. Energy metrics

Three energy metrics are used to evaluate the impact of Prop 39 retrofits on the energy performance of the school building: the percentage of load shed during a demand response (DR) event (%), the annual energy consumption (kWh/year), and the energy consumption per enrolled student (kWh/student).

All of the schools in the population participated in the Pacific Gas and Electric Peak Day Pricing DR program; this program calls nine to 15 DR event days per year, and customers can elect to participate in them [56]. A DR event is a period of several hours in which the utility projects abnormally high demand on the grid and asks customers to reduce their consumption during that period. Customers determine the degree to which they reduce their consumption during the DR event. The percentage of load shed during a DR event is calculated by subtracting the actual energy consumption during a DR event from the estimated consumption in the absence of a DR event (calculated using a baselining model). The baseline electricity usage is calculated by a regression model using hour-of-week terms and hour-of-day cooling degree response terms as follows:

$$kWh_{baseline} = \sum_{HOW} \alpha_{HOW}\delta(HOW) + \sum_{HOD} \beta_{HOD}\delta(HOD)CDH_{65} + \epsilon \quad (2)$$

Hour-of-week (HOW) is a categorical variable for each of the 24 × 7 h of the week, hour-of-day (HOD) is a categorical variable for each hour of the day, α_{HOW} terms are HOW fixed effects, and the β_{HOD} terms are 24 HOD cooling degree response (CDH65) [57]. The percentage of load shed during a DR event is then calculated as:

$$kWh_{\%loadshed} = \frac{kWh_{baseline} - kWh_{actual}}{kWh_{baseline}} \quad (3)$$

The load shed is a percentage of the baseline load. The annual energy consumption (kWh/year) is calculated by summing all interval meter readings for a calendar year. The energy consumption per enrolled student (kWh/student) is calculated by dividing the annual energy consumption by the number of enrolled students in the school year beginning in the fall of that year.

This study does not use the Energy Use Intensity (EUI) metric, which calculates the kWh consumed per square foot, although this is commonly used to benchmark energy performance in buildings. An accurate source for the square footage of each building was not available for every building in the study – square footage information for the schools that received retrofits was available, but not for the control group of schools. Although methods exist to approximate square footage using the building footprint area obtained from satellite images, these are not precise and accurate representations of square footage that are needed for this analysis. Additionally, the EUI metric has been criticized for having issues capturing efficiency. The traditional EUI metric does not reflect the occupant density or services provided by a building, which may cause different energy use patterns in buildings of a similar size [58,59]. Estrella Guillén et al. found that EUI is a poor proxy for more meaningful metrics such as thermal comfort and indoor environmental quality and proposes using an "EUI per person" [60]. This study uses kWh per student as a proxy of efficiency because it represents the amount of energy a building needs to fulfill its ultimate end use of educating students and it reflects the amount of energy resources used by each occupant.

3.1.3. Vegetation metric

The vegetation surrounding a given school is quantified using the Normalized Difference Vegetation Index (NDVI), which was calculated using Band 4 and Band 5 data collected by Landsat 8 according to the methodology outlined by Doughtery and Jain [61]. The surrounding area for each school was defined as a 200-meter buffer zone around the building centroid [62]. A shapefile of these areas was then provided to Google Earth Engine to gather the monthly average NDVI value for that area. Monthly average values are collected for January 2013 through January 2018; seasonal trends in NDVI are seen throughout the year, but on average NDVI stays constant from year-to-year for the schools in the study (see supplementary materials).

In the regression model, the NDVI value is centered and standardized for each equity subset to maintain the interpretation that the effect of increased vegetation is from a one standard deviation increase in NDVI relative to similar building types. Measured (non-standardized) NDVI values throughout the study period for each equity subset can be found in Fig. 2.

Through a students t-test, NDVI values are shown to be significantly correlated with whether schools received retrofits through Prop 39; the distributions of NDVI for Prop 39 and control schools can be seen in the supplementary materials. Therefore, NDVI is included as an interaction term with retrofit installation in the regression analysis. Within equity subsets, Prop 39 and control schools appear to have similar NDVI values. Generally, advantaged schools have higher NDVI values for the area surrounding the building. It is possible that the relationship between energy consumption and NDVI varies between equity groups, thus this relationship is explored using separate regressions for each equity subset.

3.1.4. Year built

Data on the year of construction for each school building was collected through an exhaustive search of each school's website and/or openly accessible real estate listings and construction documentation. The year of construction was used to calculate an age for each building. Data on year of construction is missing for 16% of the schools (n = 71); 28 of the schools missing this data had retrofits done through the Proposition 39 program. As seen in 3, Prop 39 schools were slightly older than control schools, which was expected given they required building system updates. A student's t-test showed no significant difference in mean age between the Prop 39 and control schools. Therefore, the age of the building is controlled for as a fixed term in the regression.

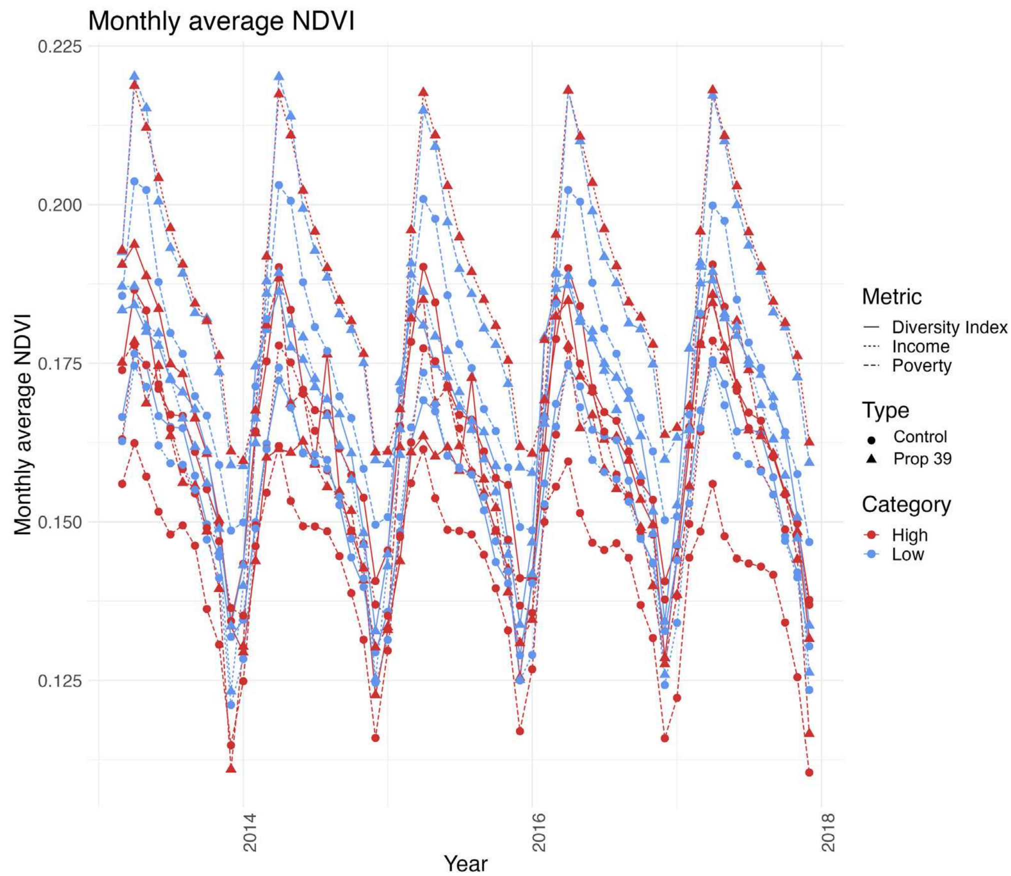

Fig. 2. Measured monthly average NDVI over time.

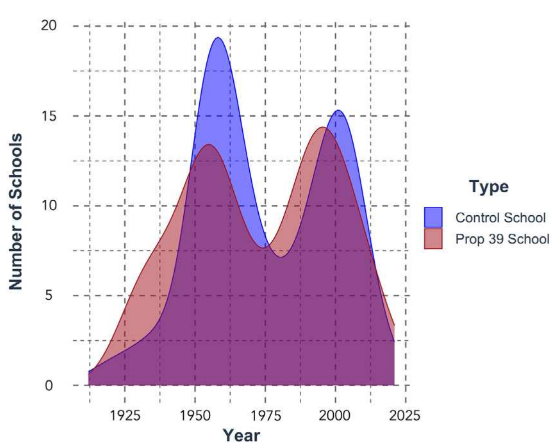

Fig. 3. Year of construction. Schools that received funding through Proposition 39 were generally older.

3.2. Four-step methodology

The first step is to quantify the impact of retrofits on energy performance using the difference-in-differences method. The second step is to assess the statistical significance of the effect of retrofits on energy performance using the Mann–Whitney U test. In the third step, the differential impact of retrofits is evaluated on advantaged versus disadvantaged schools. Lastly, the fourth step is to quantify the additional compounding effect of vegetation context on retrofitted schools in each equity subset (see Fig. 4).

3.2.1. Quantifying retrofit impact using difference-in-differences

Drawing on prior research that employs the difference-in-differences method to evaluate retrofit effectiveness in residential buildings [37], a difference-in-differences regression model is used to evaluate the impact of energy efficiency retrofits in school buildings. For each subset of advantaged and disadvantaged schools, the treatment effect of retrofits on each energy metric is calculated using the difference-in-differences method. This analysis is conducted on schools within equity subsets (three advantaged and three disadvantaged) to meet the parallel trends assumption of the difference-in-differences method. The difference-in-differences method compares the energy metric for treatment (here, Prop 39) and control groups before and after an intervention (Prop 39 retrofit installation). The treatment effect of the retrofit is the additional change in the energy metric of the Prop 39 group compared to the change in the control group. The difference-in-differences is calculated by regression:

$$y = \beta_0 + \beta_1 t + \beta_2 R + \beta_3 t R + \epsilon \tag{4}$$

where y is the energy metric, t is time, R is a binary retrofit installation variable, β_0 is the baseline average, β_1 is the time trend in the control group, β_2 is the difference between Prop 39 and control schools pre-retrofit, and β_3 is the retrofit treatment effect. A visual representation of the difference-in-difference method can be seen in Fig. 5.

3.2.2. Assessing statistical significance of retrofit impact using Mann–Whitney U test

When comparing two independent samples where the outcome is not normally distributed and the samples are small, a non-parametric test is appropriate. The Mann–Whitney U test is a non-parametric test used to compare outcomes between two independent groups and to test whether two randomly selected samples are likely to derive from

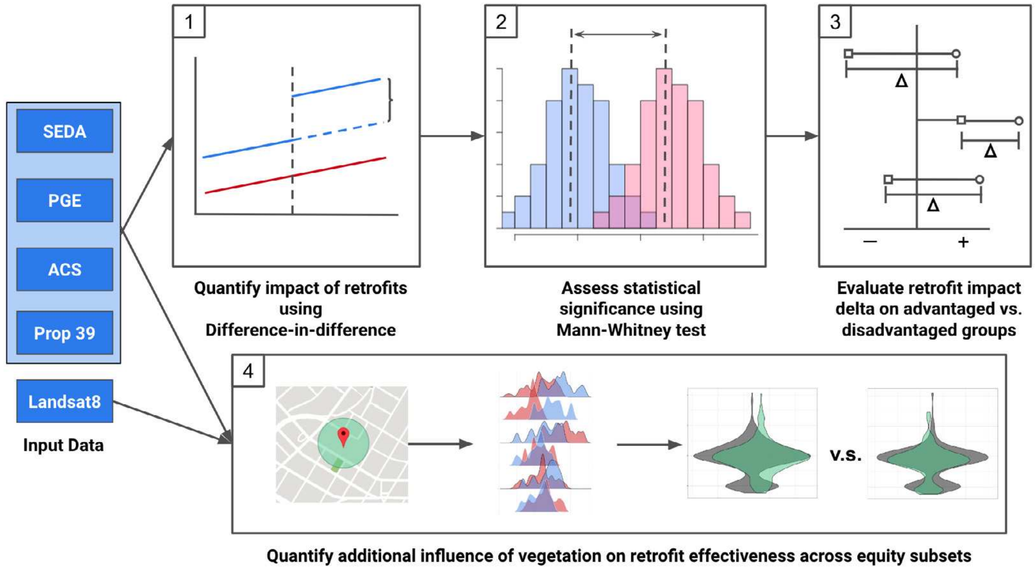

Fig. 4. Methodology. A four-step approach to quantifying the differential impact of retrofits and vegetation on advantaged vs. disadvantaged groups.

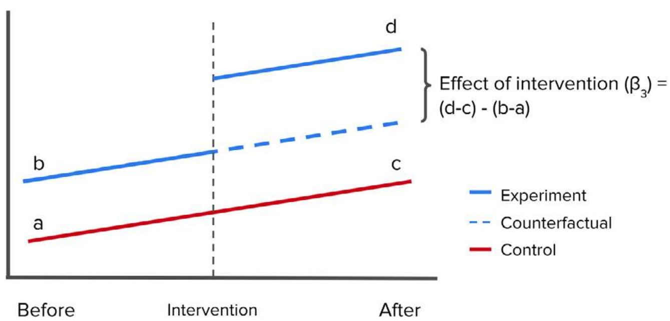

Fig. 5. The difference-in-difference method. This method estimates the effect of an intervention, β_3, on the experimental group.

the same population – it is commonly used in the epidemiology and medical fields to determine significant treatment effects in clinical trials [63]. The statistical significance of the retrofit impact (treatment effect) is assessed using a Mann–Whitney U test on the post-retrofit energy metrics for Prop 39 and control schools.

The retrofit treatment effect (β_3) is considered significant if the post-retrofit energy metric distributions for the Prop 39 and control schools are not equal ($p < 0.05$) and therefore the population means are different. This test is performed for each energy metric on each subset of advantaged and disadvantaged groups – a retrofit impact is significant if the retrofit treatment effect (β_3) is statistically significant for both the advantaged and disadvantaged groups.

3.2.3. *Evaluating differential retrofit impact between groups*

The differential retrofit impact is a normalized percent difference between the advantaged and disadvantaged groups' retrofit treatment effects that is used to understand disparity in retrofit impact. This metric is calculated as:

$$\Delta RI = 100 * \frac{|\beta_{3,advantaged} - \beta_{3,disadvantaged}|}{|\bar{y}|} \quad (5)$$

where ΔRI is the differential retrofit impact, β_3 is the retrofit treatment effect for the advantaged or disadvantaged group, and $\bar{y}$ is the mean value of the energy metric across all schools in the population.

This percent difference shows the magnitude of the difference between β_3 for the two groups and which group received a more favorable impact from retrofit installation.

3.2.4. *Quantifying additional influence of vegetation on retrofit effectiveness*

To further understand the interaction between vegetation and energy performance, and how this might be compounded through retrofits, a regression model is run with the percentage change in monthly energy consumption as the dependent variable. The percentage change in the total kWh consumed in a month and the kWh consumed per person in a month is calculated between a year before retrofit installation to a year after retrofit installation. The years 2014 and 2016 represent pre- and post-retrofit energy consumption, as most retrofits were installed in 2015 across the 525 schools. Where there are missing monthly kWh values in 2014, the monthly values from 2013 are imputed; similarly for 2016 and 2017, respectively. A separate regression is run for each equity subset in order to compare the differential impacts of vegetation. The form of the regression is as follows:

$$y = \beta_0 + \beta_1 m + \beta_2 R + \beta_3 RN + \beta_4 N + \beta_5 A + \epsilon \quad (6)$$

where y is the percent change in energy from a given month in 2014 to that same month in 2016 (i.e. December 2014 to December 2016), m is a factor variable representing the month, R is a binary retrofit installation variable, N is the average NDVI value for that school in that month of 2016, and A is the age of the building. The NDVI values were standardized within each equity subset. The m monthly fixed effects term is included to control for seasonal effects, and the age of the building and the surrounding NDVI are included to control for the effect of these characteristics on energy consumption. The regression coefficient β_2 is the additional percent change due to retrofits, and β_3 is the additional percent change due to one standard deviation increase in NDVI for retrofitted schools (i.e. the compounded effect of vegetation on top of retrofits).

Outliers were removed from the percent change independent variable by first log transforming the data and then removing values outside of 1.5x the interquartile range of the log-transformed variable. This was done to create a Gaussian distribution of the dependent variable.

4. Results

Fig. 6 gives a summary of the differential retrofit impact (ΔRI) on each energy metric for each subset of equity metric. The β_3 values for each regression can be found in the supplementary materials. There were significant impacts from retrofits on annual energy consumption

	Percentage of Load Shed during DR	Annual Energy	Energy per Enrolled Student
Income	526%	7.3%	**2.77%**
Diversity	243.3%	**10.9%**	**198%**
Poverty	2118%	**19.8%**	80.0%

Fig. 6. Differential retrofit impact (ΔRI) shows the percent difference in retrofit impact between advantaged and disadvantaged groups. Bold numbers indicate a statistically significant retrofit impact for both advantaged and disadvantaged subsets (both P-values < 0.05). Blue indicates greater benefit for disadvantaged schools; red indicates greater benefit for advantaged schools.

and energy consumption per enrolled student for both high- and low-diversity subsets. There were also significant impacts for both poverty subsets on annual energy consumption, and for both income subsets on energy consumption per enrolled student.

Retrofits led to larger energy equity gaps between high- and low-income schools for the energy per enrolled student metric, with a 2.77% difference in the retrofit impact. The energy equity gap shrank between high and low poverty schools for the annual energy consumption metric, where high poverty schools had a 19.8% larger treatment effect due to retrofits on reducing annual energy consumption. The diversity subsets show an increased energy equity gap for the annual energy consumption metric (10.9% difference in retrofit effect, favoring advantaged schools) yet a decreased energy equity gap for energy consumed per enrolled student (198% difference in retrofit effect, favoring disadvantaged schools).

4.1. Significant findings for diversity index subsets

After retrofits, the annual energy consumption increased over the baseline for both high- and low-diversity schools by a similar magnitude; high-diversity schools saw a marginally higher increase, 10.9% over the low-diversity schools. The marginal increase in annual energy consumption of high-diversity schools over low-diversity could be due to changes in enrollment during the study period that would cause an increase in overall energy consumption (see supplementary materials for enrollment data over time). Installing retrofits would improve building services and could lead to increases in enrollment as improvements in building infrastructure have been found to drive attendance rates [64]. Moreover, energy consumption per enrolled student decreased relative to baseline for both diversity subsets, but the more diverse schools had a much greater (198%) reduction in energy consumed per student. This indicates that school buildings with higher diversity reap significantly more efficiency benefits when normalized for enrollment effects. Additionally, the per student measurement of energy usage is likely more robust in measuring the efficiency impact of retrofit as it can capture some of the well-established school building size and occupancy effects on energy usage [65].

4.2. Measures of income and poverty

High-income schools had a greater reduction in energy consumption per enrolled student than low-income schools, but only slightly – both income groups had decreases in energy consumption per enrolled student. The marginal reduction in energy consumption per enrolled student for high-income over low-income schools of 2.77% is, while significant, nearly within the margin of measurement error for electricity meters of 2% [66]. The Median Household Income of the surrounding area does not show a great impact on the differential benefits to schools in high- vs. low-income areas in comparison to other measures of equity.

Higher poverty schools (high % eligible for FRPL) show a reduction in annual energy consumption post-retrofit, whereas low poverty schools (low % eligible for FRPL) increased annual energy consumption over the baseline. This is a favorable outcome given that high poverty schools likely serve student populations that require more resources and aid – reducing the amount of school funding spent on energy bills could benefit student services.

Income and poverty had different directionalities of results, although they measure similar concepts. This calls into question which metric is better suited for assessing equity in energy performance when assessing institutional buildings with complex public funding mechanisms.

4.3. Significant benefit gained from increased vegetation

The installation of EE retrofits and increased vegetation surrounding the school site both significantly impacted energy consumption. The regression coefficients shown in Table 2 and visualized in Fig. 7 indicate that retrofits significantly reduced the percent change in monthly kWh consumption for high income and more diverse schools, while retrofits increased energy consumption in low income schools. Higher NDVI values, indicating more dense vegetation, contributed to an additional decrease in monthly kWh consumption post-retrofit, showing the synergistic effect of mechanical and natural energy efficiency interventions. The effect of increased vegetation was significant for low poverty, low diversity, and high diversity subsets, showing that vegetation benefits can be gained across all demographics. Within the diversity subset, more diverse schools received a greater benefit from increased vegetation than less diverse schools; this can also be seen in Fig. 7.

Retrofits significantly reduced kWh per person consumption for high poverty and high income schools (see Table 3). Increased vegetation on top of retrofit installation provided significant reductions in kWh per person for the low poverty and high diversity subsets. In this case, results show the benefits of mechanical retrofits and increased vegetation for both advantaged and disadvantaged communities. Note that the significant effects due to increased vegetation surrounding the school on top of retrofit installation all resulted in a significant reduction in annual energy consumption and in kWh per person, whereas significant effects due to retrofits alone resulted in either an increase or decrease in energy consumption. When considering the resources required for the activities in the building, in this case kWh per student

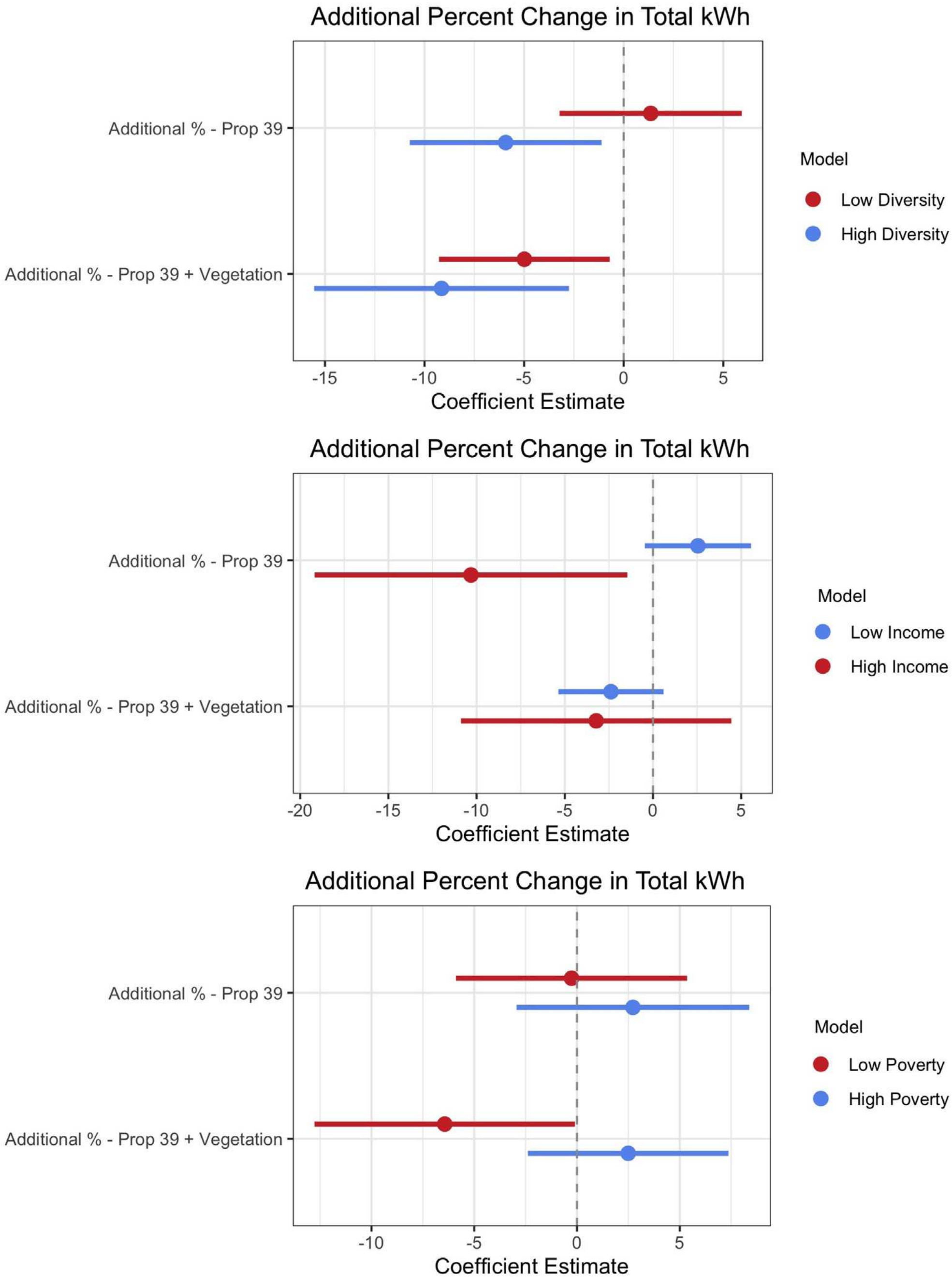

Fig. 7. Regression coefficient estimates for the percent change in total kWh consumed per month by equity subset.

being educated, the results show that retrofits and vegetation made schools more efficient at consuming resources for the ultimate end use of the building. The additional increase in vegetation density on top of retrofit installation was consistently shown to improve efficiency and reduce overall energy consumption beyond the savings provided by retrofits alone. In some cases, the savings provided by increased vegetation were similar in magnitude or greater than the savings provided by retrofits alone. For example, the low poverty schools saw 0.27% savings in energy consumption and a 2.49% increase in efficiency from retrofits, which, when compounded with increased vegetation, increased to 6.44% savings in energy consumption and a 7.39% increase in efficiency.

5. Discussion

Retrofits have a significant impact on annual energy consumption and energy consumption per enrolled student for both high- and low-diversity schools. While income subsets had significant impacts from retrofits on energy consumption per enrolled student, the marginal benefit to high-income over low-income schools was close to the margin of error. There was a significant reduction in annual energy consumption for high poverty schools compared to low poverty schools, which had a relative increase in annual energy consumption. This calls into question which measurement of income and poverty may be more beneficial for studying energy equity.

In the U.S., tax-payer dollars are used to fund public schools, therefore the median income of an area is an approximation the relative

Table 2
Monthly percentage change in total kWh. Negative sign indicates a negative percent change, meaning reduced energy consumption and energy savings. The monthly percentage change in total kWh was significantly reduced by both retrofits and increased vegetation for high diversity, low diversity, and low poverty subsets. P-values: (***) ≤ 0.001, (**) ≤ 0.01, (*) ≤ 0.05.

	Additional percent change in total kWh due to retrofit installation	Additional percent change in total kWh due to 0.05 increase in NDVI and retrofit installation
High poverty	2.72%	2.49%
Low poverty	−0.27%	**−6.44% (*)**
High income	**−10.32% (*)**	−3.22%
Low income	2.55%	−2.38%
Low diversity	1.35%	**−4.99% (*)**
High diversity	**−5.93% (*)**	**−9.15% (**)**

Table 3
Monthly percentage change in kWh per person. Negative sign indicates a negative percent change, meaning reduced energy consumption and energy savings. Retrofit installation and increased vegetation led to significant reductions in kWh consumed per person across most equity subsets. P-values: (***) ≤ 0.001, (**) ≤ 0.01, (*) ≤ 0.05.

	Additional percent change in kWh per person due to retrofit installation	Additional percent change in kWh per person due to 0.05 increase in NDVI and retrofit installation
High poverty	**−8.00% (**)**	−0.26%
Low poverty	−2.49%	**−7.39% (*)**
High income	**−24.98% (***)**	−7.73%
Low income	−2.03%	−2.45%
Low diversity	−2.82%	−2.33%
High diversity	−0.97%	−10.26%

amount of funding available to a school. However, the median income of the census tract does not exactly measure the income of the school district, rather the area surrounding the school. The percentage of FRPL eligible students is a more robust, direct measure of student poverty within a school, whereas Median Household Income is an indirect measure of the tax-payer funding contributed to a school.

When studying energy equity, it is important to consider which metric is capturing the benefits that matter to the students that would be affected. The percentage of students eligible for FRPL could be more indicative of the benefit of reducing operating costs to schools with strained resources and a high-poverty student population. It should also be considered whether there is more benefit to reducing annual energy consumption or saving energy per student. The efficiency of energy used per occupant may be a more important consideration when considering the services that energy provides to the building and the impact of building performance on its occupants. It is important to note that the enrollment in schools changes over time, as can be seen in the supplementary materials. Yearly changes to enrollment can affect both annual energy consumption and energy per student metrics, as more energy may need to be service more occupants. Post-retrofit increases in annual energy consumption seen in Table 2 may have been influenced by changes in enrollment.

Current research in education is identifying the advantages and disadvantages to using income and % FRPL as measures of socioeconomic status in terms of their impact on students' educational outcomes [67]. New methods are being assessed that combine multiple metrics such as income, free lunch eligibility, and wealth to create a new measure for "at-risk" students that may be more indicative of schools that would require additional resources and aid [68].

All schools with a significant effect from vegetation and retrofits saw a reduction in energy consumption and increase in efficiency due to increased vegetation, whereas mechanical retrofits alone sometimes caused an increase in energy consumption. This demonstrates that vegetation serves as a separate intervention that can significantly reduce energy consumption apart from a mechanical retrofit program. In other words, both mechanical retrofit and vegetation installations can significantly reduce energy consumption by a similar magnitude. This is an important equity implication as increasing vegetation can have a lower cost than a deep mechanical retrofit, but because the energy implications are harder to directly quantify, vegetation is rarely considered as an energy efficiency measure. The results of this study have quantified the energy savings due to increased vegetation and demonstrated the benefits that vegetation can have on the energy efficiency of a building.

6. Limitations and future work

An important contribution of this work is understanding the additional energy savings from increasing density of vegetation surrounding a building. Here the density of vegetation is analyzed, and while this is not an exhaustive description of all relevant characteristics of vegetation, findings demonstrate the significant influence of vegetation on the effectiveness of retrofits. This is a first step in assessing the cooling benefits and energy savings of vegetation, and future work aims to explore specific characteristics of vegetation (i.e. latent heat fraction, albedo, etc.) that are most relevant for saving energy in various climate zones. All of the schools in the study are in the same climate zone, thus they have similar types of vegetation and seasonal trends in air temperature and vegetation density. Future work will be expanded to other climates that host different vegetation to explore the relationship between energy consumption and varied vegetation types.

The schools in this study received funding specifically targeted for energy efficiency retrofits provided that they exhibited a predicted savings-to-investment ratio greater than one, meaning that the project was projected to save electricity consumption. Although the type of mechanical retrofits installed in the schools were not specified in the study, findings show that energy efficiency retrofits can improve energy performance and reduce the energy equity gap. Future work aims to explore synergies between specific types of mechanical and natural retrofit types and evaluate which characteristics of each retrofit type provide the greatest energy savings. Additionally, future work will explore the financial and energy performance tradeoffs of mechanical and natural retrofits and the impact that these have on the energy equity gap.

This work demonstrates the importance of metric selection for evaluating equity outcomes. Metrics should be curated to describe the social phenomena they are representing, and researchers should ensure that these metrics are suited to evaluating desired outcomes. Future work aims to explore the measures of income and poverty and the equity implications of energy performance for those subsets of buildings and occupants.

7. Conclusions and implications

This work demonstrates that energy efficiency retrofits increase energy efficiency and reduce the energy efficiency equity gap by 198%. Findings show that vegetation has a synergistic effect with mechanical retrofit through reducing the cooling loads. Even in cases where mechanical retrofits increased energy consumption, potentially due to bringing old buildings up to code and improving services in the building, significant overall energy savings were still achieved due to dense vegetation surrounding the building. Dense vegetation provides around 6% energy savings, similar in magnitude to mechanical retrofits alone.

Vegetation should be considered a viable alternative among energy efficiency retrofits for significantly reducing energy consumption and enhancing energy equity in low income areas. Once mechanical retrofits have achieved all possible energy savings within a building, increasing the surrounding vegetation is a viable pathway for further reducing energy consumption. Deep decarbonization will require additional reductions in energy consumption beyond what mechanical retrofits can provide, and this work has demonstrated that increasing vegetation can provide further reductions in energy consumption similar in magnitude to mechanical retrofits.

Beyond this, the presence of vegetation in educational settings (i.e. green playgrounds, walks in nature, nature views from classroom windows, etc.) has been shown to substantially improve student learning, as well as providing overall health and wellness benefits [6]. Additionally, investing in green spaces can mitigate negative health impacts of pandemic restrictions, which is particularly important for marginalized groups [69].

Strategic investment from state and federal government programs can reduce the energy equity gap by funding retrofit installation in historically disadvantaged communities. Purposefully targeting investment in underfunded communities is necessary for reducing social inequities, achieving deep decarbonization, and meeting climate goals.

CRediT authorship contribution statement

Lauren E. Excell: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Rishee K. Jain:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rishee Jain reports financial support was provided by National Science Foundation. Lauren Excell reports financial support was provided by National Science Foundation.

Data availability

The authors do not have permission to share data

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.apenergy.2023.121722.

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