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RESEARCH ARTICLE

On energy sufficiency and the need for new policies to combat growing inequities in the residential energy sector

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The decreasing cost and increasing availability of new technologies capable of improving household energy efficiency, generating and storing renewable energy, and decarbonizing major end use appliances have begun to significantly transform many residential communities across the U.S. Despite these positive developments however, the degree to which disadvantaged communities (DACs) have been able to participate in and benefit from these transformations remains far from equal. Using historical time series data at the zipcode level within Los Angeles County, we document the scale and extent to which DACs continue to be left behind. These data show per-capita levels of electricity and natural gas consumption within DACs that are, on average, about half of those seen within their more affluent counterparts. We argue that the magnitude of these differences reflect a fundamental departure in the use of energy from purposes of sufficiency to those of excess. We introduce a set of forecasts that show the extent to which current inequities in per-capita energy consumption, rates of vehicle electrification, and adoption of rooftop solar PV are likely to persist under the status quo. In conclusion, we suggest that the redistributive investment of public funds for the purpose of accelerating DAC participation in energy system transformations constitutes a socially optimal investment strategy – one which reflects the dramatically higher marginal utility of units of energy consumed at levels of sufficiency rather than excess.

Keywords: Energy sufficiency; Residential electricity; Energy efficiency; Income; Housing size; Equity

Introduction

Residential Energy Systems in Transition

Energy systems are highly complex. Within them, technologies and policies interact with economics and social histories in unexpected ways. Some of these interactions combine to produce large scale systemic transformations while others do not (Grubler, 2012; Rutter and Keirstead, 2012; Cherp et al., 2018). Energy systems are also highly embedded. This statement applies not only to their physical manifestations but also to popular consumer expectations regarding the price-performance role of energy services (Goldthau and Sovacool, 2012; Stefes and Laird, 2012; Wilson, 2014; Edelstein and Kilian, 2009). People, often subconsciously, structure their lives around the expectation that the energy services they use will not change, and will continue to be available more or less indefinitely (DiCicco et al., 2015). These embedded expectations are evident in the layout of our cities, the design of our homes, the types of energy appliances that we own, and the frequency and intensity with which we use them (Banister et al., 1997; Kahn, 2000; Ewing and Rong, 2008). In this way, the impacts of major energy system transformations have the potential to reverberate through every aspect of society.

The suite of end-use energy demands supplied within residential buildings have historically been limited to: space heating and cooling, refrigeration, water heating, ventilation, cooking, lighting, laundry, computing and entertainment equipment, and other miscellaneous plug loads (Hirst and Jackson, 1977; Schipper et al., 1982). Over the past several decades, numerous incremental improvements have been made to the efficiency with which many of these services can be rendered (Meyers et al., 2003; Brown et al., 2008). Working in opposition to these trends however, have been other, troubling, developments. These include growth in the size of new residential structures and the penetration levels of the most energy intensive appliances (Isaac and van Vuuren, 2009; Zhou et al., 2014; Fournier et al., 2019). In addition to the changing dynamics within these traditional categories of residential energy end-use, a rapidly expanding market for electric vehicles is causing residential buildings to increasingly function as conduits for the supply of an entirely new sector of energy demand: transportation (Needell et al., 2016; Bunsen

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et al., 2018). In other instances, the rapid growth in the adoption of distributed renewable energy generation and storage resources, is even causing some residential buildings to intermittently switch from being net consumers to net-suppliers of energy to the electric power grid (Li and Yi, 2014; Janko et al., 2016; Kurdgelashvili et al., 2019).

In an effort to combat the destabilizing influence of highly uneven or bi-directional power flows resulting from these changes, utilities and rate-setting bodies are working to develop new default energy tariffs which would more aggressively disincentivize consumption on the basis of time-of-use (TOU) (Alexander, 2007). The equity impacts of these new default TOU rate structures are still not well understood within the U.S. context (Youn and Jin, 2016; George and Bell, 2018; Ozaki, 2018). However, it is likely that residents of low-income DACs will be inherently more limited in terms of their ability to either reduce or shift the timing of their consumption. Consequently, these communities may be more adversely impacted by these new energy pricing schemes.

Wealth is a prominent driver of demand for residential energy. Worldwide, wealthier groups lead more materially and energetically intensive lives than the less affluent, consuming in excess of what they require to meet their essential needs (Meyers et al., 2003; Creutzig et al., 2015; Fournier et al., 2019). In the state of California, this relationship between income and the demand for residential energy services has been previously studied – with higher-income groups being found to consume more electricity and gas than lower-income groups (California Energy Commission, 2018). These lower levels of consumption, in many cases, are also paired with a lower standard of energy services due to the inferior thermal performance among the older, lower-quality housing stock, and less efficient household appliances which are common in DACs (Barbose et al., 2018).

The Energy Sufficiency Paradigm

Domestic energy consumption may be thought to consist of three regimes. The first is the "insufficiency regime" which reflects a state of energy poverty. The second is the "sufficiency regime" which consists of the energy consumed to meet essential needs. Finally, the third is the "regime of excess" which reflects consumption above and beyond what is required to sustain an individual or household in a particular location (Peet, 1992, Princen, 2005). Depending on the operative definition of "essential needs," many possible thresholds between sufficiency and excess are possible, thus the sufficiency-excess threshold will naturally vary by climate zone and other features of the local geographic context.

Consumption within the sufficiency regime can be though to encompass all energy end-uses required to maintain a safe, healthful, and decent standard of living in a particular place (Fawcett and Darby, 2018). It therefore includes not only the energy required to meet biological needs, such as food preparation and the maintenance of a safe, thermally comfortable home, but also the energy required to maintain health and participate in a productive economic and social life. The energy consumed for transportation, or to power personal computers and consumer electronics also counts towards the quantity that is considered sufficient. Thus, the quantity of energy sufficient to live decently within a given community is therefore a function of the predominant modes of life in that community, the infrastructural systems that make these modes possible, and the energy intensity of the infrastructure systems (Princen, 2005).

Energy sufficiency is not defined with respect to personage; it is independent of wealth and notions of socio-economic status (Fawcett and Darby, 2018). This is because the quantity of energy required for a productive social and economic life is locationally determined. As such, the quantity of energy required for an individual or household to sustain a decent existence in a particular place is unrelated to whether or not one can consume energy in excess of that quantity. The differences between these regimes can be illustrated graphically by the plots contained in **Figure 1**. **Figure 1a.** provides a conceptual view of how these regimes of consumption map to a model frequency distribution of per-capita consumption intensities. **Figures 1b.** and **1c.** illustrate how these regimes might

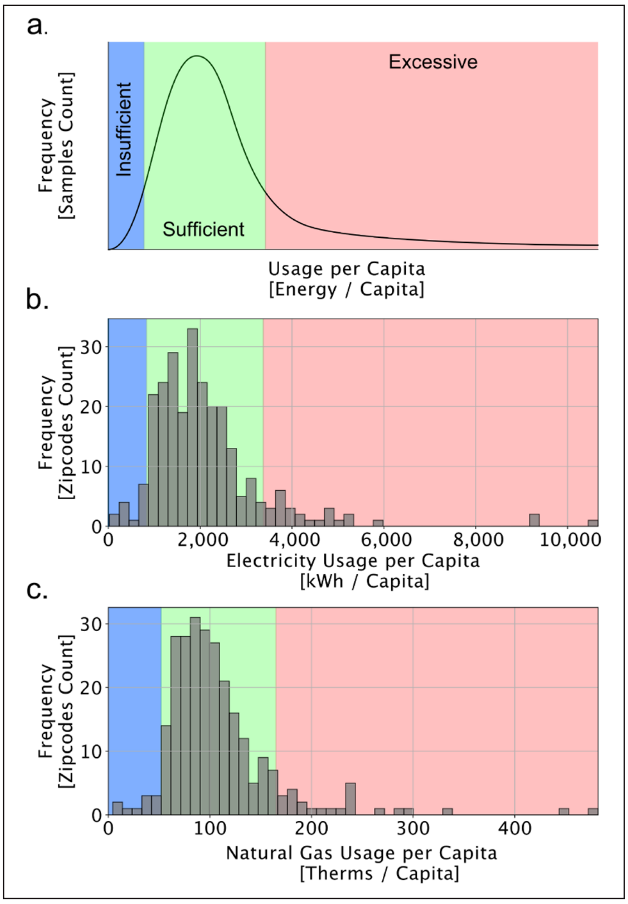

Figure 1: Conceptual illustration depicting the relationship between **(a.)** regimes of energy insufficiency (blue), sufficiency (green), and excess (red) with empirical data on **(b.)** residential per capita electricity usage [*kWh/Capita*] and **(c.)** residential per capita natural gas usage [*Therms/Capita*] among zipcodes within Los Angeles County as of 2017. DOI: https://doi.org/10.1525/elementa.419.f1

be more rigorously defined using empirical data on per capita residential electricity and natural gas usage among zipcodes within Los Angeles County (LAC). Here the sufficiency ranges have been specified, somewhat arbitrarily, as ±1 standard deviation from the mean.

Excess consumption has many causes, but often arises from individuals choosing to meet their needs by inherently more energy intensive means, such as purchasing large, single-family homes, or by overconsumption of energy services, such as leaving the air conditioning on while the home is unoccupied. Distinguishing between consumption regimes is necessary in order to analyze the equity effects of residential electrification, renewable energy, and efficiency programs, and estimate cumulative value society derives from them. DACs and non-DACs differ greatly with respect to socio-demographic characteristics, most significantly income and the age and condition of their housing stock (Hernández et al., 2016). These factors determine the relative burden of energy costs, the proportion of a household's total budget devoted to energy, and the value extracted per unit energy consumed (USDOE, 2018). Thus, the value of the benefits received by program participants depends to a large extent on the exigencies of their individual situations.

Current Policy Approaches to the Redress of Energy Inequities

Faced with need to reduce the greenhouse gas emissions (GHGs) of their energy consumption, many states, including California, have embarked on courses of market-based ecological modernization (Mol et al., 2009). In the past 20 years, market-based electrification and energy efficiency (EE) initiatives, primarily subsidies and tax credits, have become preferred tools for encouraging adoption of domestic renewable energy systems, electric vehicles, and newer, more efficient appliances (Reames and Stacey, 2019). Rather than curtailing the demand for energy, states have instead sought to reduce the GHG intensity of energy services by increasing the efficiency of residential housing stock and electrifying end-uses currently powered by fossil fuels. Increases in residential efficiency and distributed generation, it is hoped, will decrease demand for energy, with gradual fuel-switching for heating and transportation enabling further de-carbonization (Reames and Stacey, 2019).

California has taken steps to reduce the energy intensity of new housing stock, passed measures that require new homes be built to accommodate rooftop PV panels, and implemented building codes requiring continuous improvements in the energy efficiency of building materials and systems. However, by and large, improving energy efficiency and promoting the deployment of renewable generation systems have been the preferred to pursuing actual reductions in residential demand (California Energy Commission, 2018). In parallel, the state has also been working to promote the electrification of fossil fuel dominated end-uses. This included providing rebates for EVs, heat pumps, and various types of household appliances. If successful, these efforts are likely to greatly increase future electricity demand. It is presumed that the environmental impacts of this consumption will be mitigated by transitioning the grid to be powered by 100% renewable sources. However, the timely success of this transition is not guaranteed.

Governments and utilities have enthusiastically embraced market-based approaches to incentivizing these transitions because they are simple to implement, do not complicate utility operations, and do not otherwise limit absolute levels of consumption (Tonn and Peretz, 2007). Overall spending on such programs provide a good indication of their popularity – in 2016 at least $2.5 billion dollars on residential EE initiatives, based upon data available from twenty-nine states (Reames and Stacey, 2019). While their ease of implementation and politically inoffensive nature are attractive to policymakers, many of these programs have been found to disproportionately benefit wealthier individuals (Galli-Robertson et al., 2019). Incentive programs, even those that offer more generous payments to applicants that meet low-income requirements, are consistently under-utilized by lower-income and minority cohorts due to financial barriers, limited awareness of such programs, and lower rates of property ownership (Bird and Hernández, 2012; Scavo et al., 2016; Parsons et al., 2018).

California has previously experimented with more redistributive policy measures designed to enhance DAC participation in energy transitions (Lukanov and Krieger, 2019). Unfortunately, the scope of the impacts from these programs have thus far been small due to their limited budgets and restrictive eligibility requirements. For example, the California solar initiatives single family affordable solar home (SASH) program, established in 2006 by state assembly bill 2723, has provided qualified low-income homeowners fixed, up-front, capacity-based incentives to help offset the upfront cost of a solar electric system – currently, $3 per watt (California State Assembly, 2006). In order to be eligible for this incentive however, applicants must (1) own and live in their home, (2) have a household income that is 80% or below the area median income, and (3) live in a home defined as "affordable housing" by California Public Utilities Code 2852. Due to these restrictions on eligibility, over its entire lifetime the program has spent $124 million on the construction of 8,228 PV systems representing a total combined capacity of just 26 MW statewide.

In addition to SASH there was also a Multi-Family Solar Housing (MASH) program. First initiated in 2008, MASH provides fixed, up front, capacity-based incentives for qualifying solar energy systems (California State Assembly, 2013). The amount of the incentive depends on the chosen application tract. Different tracts reflect different characteristics of the loads intended to be offset by the system. Under the program participating tenant units receive benefits through a virtual net metering scheme which offset a portion of their energy consumption with a portion of the output from the installed system. Despite the potentially transformative power of this virtual net metering concept for renters, the program's reach has been limited. Since its inception just 480 projects have been completed statewide, representing 41.9

MW of installed capacity. Furthermore, at present, the MASH program is closed and is no longer accepting new applications.

Assessing Current Status and Future Progress

In order to assess the current and likely future effectiveness of the existing suite of policies for promoting equity within the residential energy sector, we analyzed set of historical time series data documenting per-capita levels of energy consumption and energy system transformation engagement. The first component of this analysis focuses on quantifying the current magnitude of the inequities which exist between DACs and non-DACs within LAC, a diverse area home to some 10.2 million people. The second component of this analysis uses recent historical trends observable within these data to develop forecasts of expected future changes. These forecasts are then used to assess whether or not existing levels of inequality are likely to be diminished in the future as a result of currently implemented policy measures.

Materials and Methods

Data on Community Disadvantage

The California Office of Environmental Health Hazard Assessment (OEHHA), on behalf of the California Environmental Protection Agency (CalEPA), has developed a quantitative methodology which assigns numerical scores to local geographies based upon their aggregate burden of and vulnerability to various sources of environmental pollutants. This effort is known as the CalEnviroScreen program and is currently on its third iteration. CalEnviroScreen 3.0 (CES) scores are issued at the census tract level for the entire state. Census tracts whose combined CES scores place them above the 75th percentile statewide are technically classified by the California Energy Commission (CEC) as environmentally disadvantaged communities (DACs). This designation qualifies these communities for priority consideration under various state level funding programs and initiatives.

The CES program's use of census tract boundaries as a reference geography presents a challenge for this analysis as zipcode geographies are the most common geographic unit for the spatially disaggregated reporting for energy system transformation metrics. In order to reconcile the incongruence between census tract and zipcode geographies we developed a methodology to assign each zipcode with the average scores of all of the census tracts that it spatially intersects. According to this methodology, zipcodes whose mean CES composite scores are still above the 75th percentile DAC threshold were assigned the label *majority-DAC zipcodes*. A more detailed discussion of this spatial aggregation as well as a map visualization of the spatial correspondence between DAC census tracts and majority-DAC zipcodes are provided in the supplementary material.

Data on Residential Electricity and Natural Gas Usage

Our research group at the California Center for Sustainable Communities (CCSC), which operates within UCLA's Institute of the Environment and Sustainability, has developed a unique multi-year time series database of electricity consumption data for customers served by the major investor owned utilities (IOUs) and municipally owned utilities (MOUs) operating within LAC (Porse et al., 2016). For the purposes of this analysis, these utilities include Southern California Edison (SCE), the Los Angeles Department of Water and Power (LADWP) and the Southern California Gas Company (SCG). This dataset, which we refer to as the UCLA Energy Atlas, is based upon raw monthly account level billing data obtained under non-disclosure agreements with either the individual utilities themselves, or with the California Public Utilities Commission (CPUC). The full temporal coverage of this dataset spans from 2011 to 2016.

Data on Residential Electrification

Our approach to quantifying residential electrification involved normalizing total electricity and natural gas consumption data derived from the UCLA Energy Atlas into standardized units [*MBtu*]. Following from this, for each zipcode, we calculated the fraction of the total volume energy consumed within each zipcode and for each each year that was delivered in the form of electricity. Changes in this fraction over time provide insights into the cumulative effects of of electricity load growth, natural gas usage efficiency improvement, and natural gas appliance electrification between the various zipcode geographies.

Data on Alternative Fuel Vehicle Adoption

The National Renewable Energy Laboratory (NREL) has developed a time series database of residential light-duty vehicle registrations, disaggregated by vehicle fuel type, for the entire United States. Access to records from this dataset, known as the Alternative Fuel Vehicles Database (AFVD), was obtained for zipcodes within LAC through a representative at the Southern California Association of Governments (SCAG). Records within the AFVD are sourced from state level vehicle registration reporting data. The full temporal coverage of this dataset spans from 1990 to 2017.

For this analysis, these records were aggregated to generate annual counts of the total number of vehicles registered within each zipcode, separated by fuel category. These categories include: Conventional Fuel Vehicles (CFVs) – gasoline, gasoline-hybrid, diesel, and diesel-hybrid; Alternative Fuel Vehicles (AFVs) – ethanol, hydrogen fuel-cell, butane, compressed natural gas, methane, and propane; Plug-In Electric Vehicles (PEVs) – battery electric and plug-in hybrid. For the purposes of this analysis we focus only on the PEV category, and disaggregate its entries into EVs and PHEVs subgroups. A more detailed overview of relative proportions of vehicles of different fuel types that are registered within each zipcode is provided in the supplementary material.

In urbanized areas such as LAC, active and public transit options can function as important alternatives to personal vehicle ownership. This is particularly true with respect to DAC residents, for whom the costs of personal vehicle ownership are often prohibitively high (Giuliano, 2005). The availability and usage of public transit options (buses, light-rail, subways, etc.) throughout the LAC region is highly uneven. This uneven distribution, to a large extent, reflects the distribution of population density throughout the region. Recent analyses have shown that, despite substantial investments in the expansion and upgrading of the LAC's public transit infrastructure over the past decade, ridership rates have actually declined (Manville et al., 2018). A more detailed discussion of the region's available public transit options and patterns of use is provided in the supplementary material for additional context.

Data on Residential Rooftop Solar PV Adoption

The CPUC coordinates a statewide, multi-agency effort, to collect and standardize historical data about the location and design characteristics of installed solar generation assets. This database is known as the Distributed Generation Statistics (DG-Stats) database. Records within the DG-Stats database are sourced from a variety of sources including participating IOUs, MOUs, and independent solar installation and development firms. For the purpose of this analysis, records within the DG-Stats database were first filtered on the basis of their rated nameplate capacity to reflect net-metered systems deemed to be of residential scale (<25 *kW-AC*). They were then aggregated on an annual basis to the zipcode level. The full temporal coverage of this dataset spans from 1990 to 2017.

Methods of Forecasting Energy Consumption

Developing an understanding of the extent to which current inequities within the energy system are likely to persist, or even grow, in the future is of critical importance. This requires the development of forecasts for future energy system consumption and transformation metrics. Our approach to forecasting future per-capita electricity and natural gas consumption levels is based upon the application of a parametric model of exponential decay to recent historical rates of change observed within the individual zipcode level time series data. This approach reflects the perpetuation of existing policies in a "business as usual" context. According to this model formulation, the growth rate at some future time $f(t)$ can be expressed mathematically as in Equation 1.

$$\begin{gathered} f(t) = Ce^{-kt}, \mathit{where}: k > 0 \\ f(t) = C\left(1 - e^{-kt}\right), \mathit{where}: k < 0 \end{gathered} \tag{1}$$

Using a set of numerical libraries written in the Python programming language, estimates for the model parameters (C,k) were generated for each zipcode using a least squares based procedure to statistically fit the model's functional form to its historical per-capita consumption time series. These parameter estimates were then used to generate individualized forecasts, with corresponding escalating uncertainty bounds (0–10%), for each zipcode and for each future year, through the end of a 2030 forecast time horizon. Median values for the groups of majority-DAC and majority non-DAC zipcodes were then computed from the individual zipcode level forecasts. For electricity consumption, the increasing form of the model ($k > 0$) was used. For natural gas, the decreasing form of the model ($k < 0$) was used.

Methods of Forecasting Energy Transformation Participation

Our approach to the problem of forecasting future per-capita EV, PHEV, and rooftop solar PV adoption levels involved a broadly similar process; however, here we made use of a fundamentally different parametric growth model. In order to realistically forecast energy transformation participation, the growth model used must be able to accurately depict the non-linear, saturating growth behavior characterized by consumer adoption decisions that occur as a new product passes through phases from initial release on to full market penetration. For this reason, we chose to use the Bass Diffusion Model. The Bass diffusion model can be expressed mathematically as in Equation 2. A more detailed discussion of the conceptual ideas behind the Bass model's formulation and our justification for its use in this application is provided in the supplementary material.

$$f(t) = \left(p + qF(t)\right)\left(1 - F(t)\right) \tag{2}$$

According to the Bass diffusion model the growth rate at some future point in time $f(t)$ can be expressed as a differential equation comprised of two fixed parameters (p, q) and the current level of adoption at that time $F(t)$. When estimating parameters for any individual Bass diffusion model fit, it is necessary to provide a fixed value which corresponds to the boundary condition of the market's full saturation potential. For the EV and PHEV forecasts, these boundary conditions were chosen to be the total number of vehicles registered within the zipcode in the most recent year in the time series; this assumes static vehicle ownership levels throughout the forecast period. Competition between EVs and PHEVs for a market share was addressed by iteratively constraining the combined adoption levels between the two categories within each successive forecast year. For the rooftop solar PV forecasts, full market saturation potentials were computed for each zipcode using a database of individual building level rooftop solar capacity potentials generated for all structures larger than 400 ft^2 within Los Angeles County (Jakubiec and Reinhart, 2012). Similar to the historic analysis, only systems with residential scale solar potential values (<25*kW-AC*) were included.

Results

Current Consumption Status

Figure 2 depicts the current status of three key metrics of residential energy system performance at the zipcode level within LAC. These metrics include: (a.) annual total electricity usage per-capita, (b.) annual total natural-gas usage per-capita, and (c.) the ratio of per-capita total electricity to total natural gas usage. Data for of these metrics are shown in map form – with majority-DAC zipcodes outlined in red – as well as in scatterplots – with each zipcode being sorted along the horizontal axis on the basis of its mean CES score and the majority-DAC zipcodes plotted in red. Within each scatterplot, a simple linear trend line has been fit to illustrate the directionality and consistency of the relationships. Zipcodes for which consumption data was not available from the UCLA Energy Atlas or for which

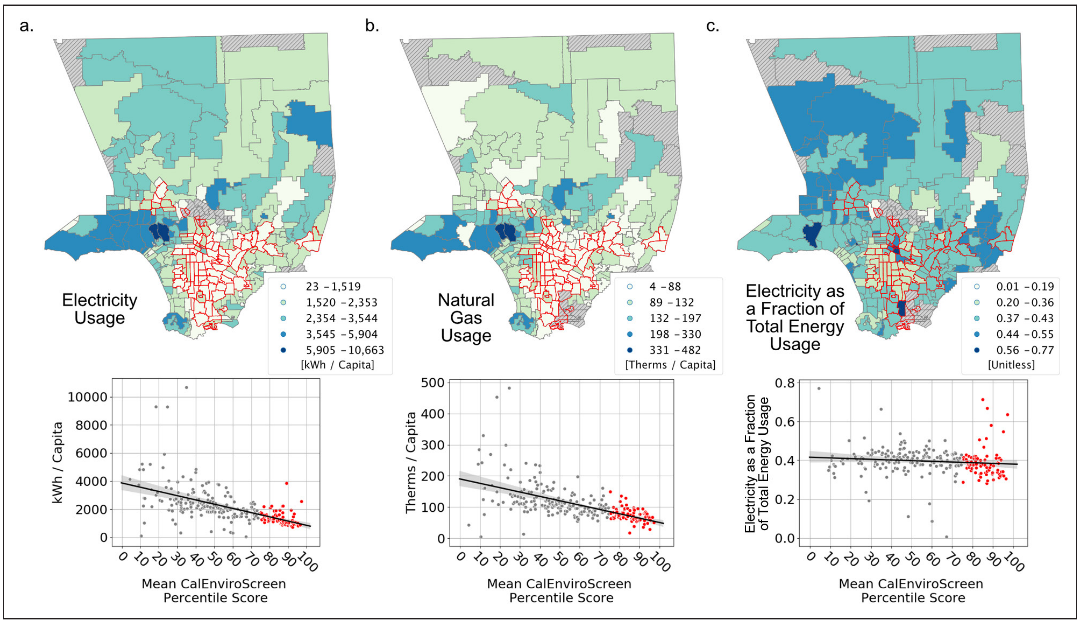

Figure 2: Paired maps and scatterplots depicting **(a.)** residential electricity usage intensities per-capita [*kWh/Capita*], **(b.)** residential natural gas usage intensities per capita [*Therms/Capita*], and **(c.)** the fraction of total combined energy use delivered as electricity [*Unitless*] among Los Angeles County zipcodes as of 2017. Majority-DAC zipcodes are colored in red in both the maps and the plots. DOI: https://doi.org/10.1525/elementa.419.f2

CES scores were not generated due to low population densities have been colored in gray within the maps and excluded from the scatterplots.

As **Figure 2a.** and **2b.** illustrate, the relationship between community disadvantage status and per-capita energy consumption levels are striking, with a significant degree of separation between the majority-DAC and majority non-DAC groups. The average resident within the majority-DAC zip codes consumes 1,383 *kWh/Capita*Year*. This is 55% of the 2,487 *kWh/Capita*Year* consumed, on average, by the residents of the majority non-DAC zip codes. In terms of natural gas usage the differences are similarly stark. The average per capita consumption among the majority DAC zipcodes is 76 *Therms/Capita*Year*. This amounts to 60% of the 126 *Therms/Capita*Year* consumed, on average, by residents of the majority non-DAC zipcodes.

Results for the computed fractions of total per-capita residential energy use that are being delivered in the form of electricity are depicted in **Figure 2**. The strength of the correlation between these fractions and each zipcode's mean CES score is significantly weaker than for the previous two metrics and thus, does not provide sufficient evidence for any meaningful conclusions to be drawn.

Current Transformation Participation Status

Figure 3 depicts the current status of three key metrics of residential energy system transformation participation at the same zipcode level as was used previously. These metrics include: (a.) cumulative total battery electric vehicle registrations (b.) cumulative total plug-in hybrid electric vehicle registrations, (c.) cumulative total installed capacity of residential scale rooftop solar PV systems. Here again, zipcodes for which adoption data was not available or for which CES scores were not generated due to low population densities have been colored in gray within the maps and excluded from the scatterplots.

Across all three metrics plotted within **Figure 3** strong and consistent negative relationships between the mean CES score of the zipcode and their levels of transition participation are evident. The maps of EV and PHEV adoption levels, (**Figure 3a.** and **3b.**), show much higher levels in majority non-DAC coastal areas. These differences are also clearly evident in the statistics computed for the two groups, with the average for majority DAC zip codes is 2.52 *PHEVs/1k-Capita*, which is 65% lower the 7.34 *PHEVs/1k-Capita* for the majority non-DAC group.

The spatial distribution of rooftop solar adoption mapped in **Figure 3c.** shows the highest rates of adoption within the high desert communities that are located in the Northwestern portion of LAC. These adoption rates reflect the abundant solar resources that are available in this region as well as generous levels of financial compensation that are being provided to customers for their distributed solar generation output under the current feed-in-tariff. This new feed-in-tariff structure was implemented by the recently formed local Community Choice Aggregation (CCA), Lancaster Clean Energy, and differs substantially from the net-metering tariff that was previously available from SCE.

Forecasts of Future Energy Consumption

Figure 4 depicts the recent historical and projected future rates of change in levels of (a.) annual total electricity consumption per-capita and (b.) annual total natural gas consumption per-capita between majority-DAC and majority non-DAC zipcode groups. These values have been calculated as the median of all the zipcodes contained within each group for each time period. As **Figure 4a.** illustrates, future forecasts based upon recent historical

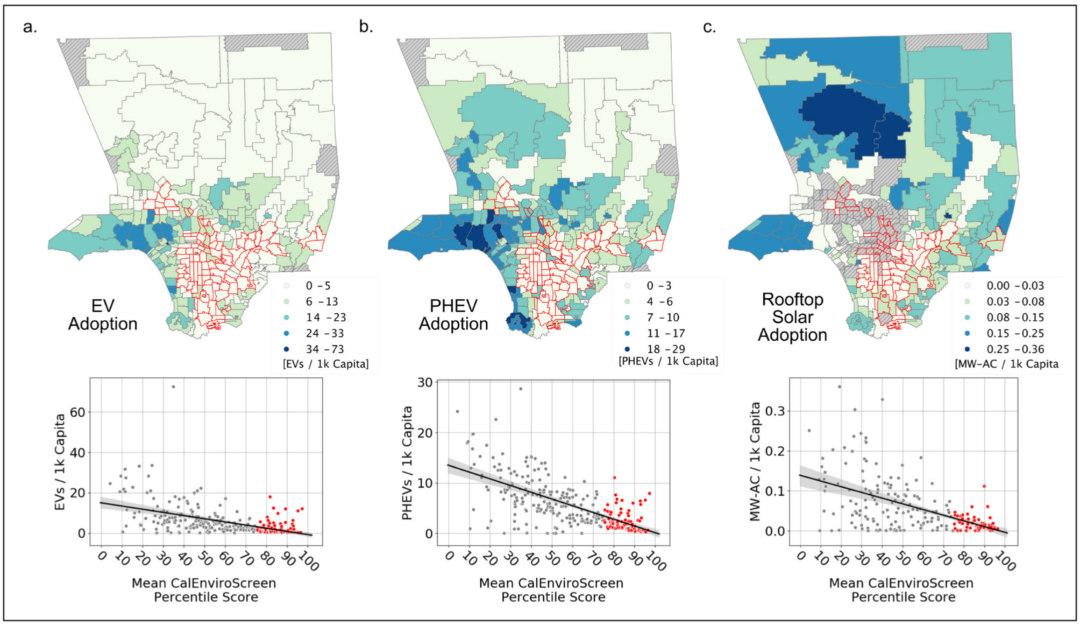

Figure 3: Paired maps and scatterplots depicting recent **(a.)** battery electric vehicle adoption levels [*EVs/1k-Capita*], **(b.)** plug-in hybrid vehicle adoption levels [*PHEVs/1k-Capita*], and **(c.)** residential scale distributed rooftop solar installed capacities [*MW-AC/1k-Capita* among Los Angeles County zipcodes as of 2017. Majority-DAC zipcodes are colored in red in both the maps and the plots. DOI: https://doi.org/10.1525/elementa.419.f3

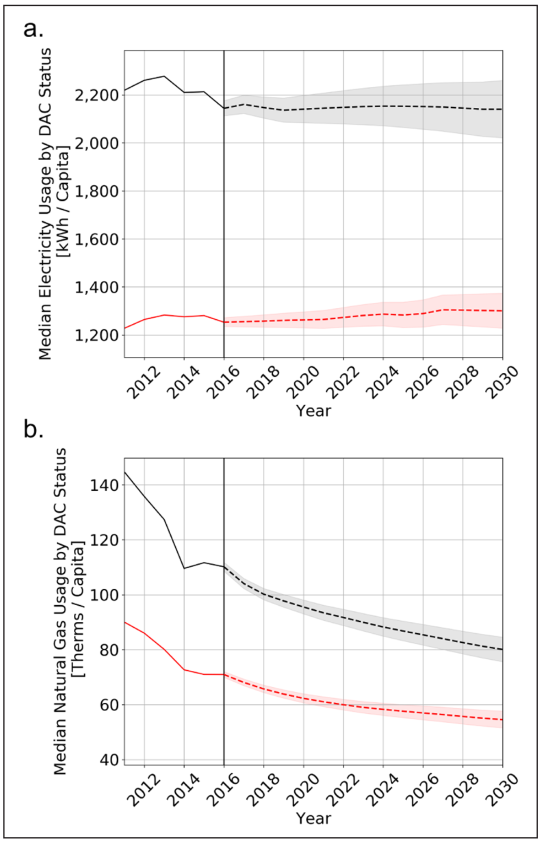

Figure 4: Time series plots depicting recent past (solid lines) and forecast future (broken lines) **(a.)** residential electricity usage intensities per capita [*kWh/Capita*] and **(b.)** residential natural gas usage intensities per capita [*Therms/Capita*] calculated as the median values for each group of majority-DAC and majority non-DAC zipcodes. DOI: https://doi.org/10.1525/elementa.419.f4

rates of change in per-capita electricity consumption levels indicate that the current significant differences (+81%) between the majority-DAC and majority non-DAC zipcode groups are likely to persist through the end of the forecast time horizon. This persistence is despite modest growth in median per-capita consumption levels within the majority-DAC group and correspondingly modest declines in the median per-capita consumption levels among majority non-DAC group.

Figure 4b. shows how recent historical declines in per-capita gas consumption within both majority-DAC and majority non-DACs are expected to continue on into the future. With these ongoing reductions in per-capita gas usage, existing differences between the majority-DAC and majority non-DAC zipcode groups are forecasted to diminish, but not disappear (+65%), through the end of the forecast time horizon. This is due to the expectation that future reductions in consumption intensity will be proportionally higher within the majority non-DAC group.

Forecasts of Future Energy Transformation Participation

Figure 5 depicts the recent historical and project future rates of change in levels of (a.) battery electric vehicle adoption per 1k-capita (b.) plug-in-hybrid electric vehicle adoption per 1k-capita, and (c.) residential scale distributed rooftop solar PV adoption per 1k-capita. Across all three categories of energy system transformation, the plots clearly illustrate that we are currently approaching the period where rates of new adoptions are expected to reach their maxima.

As **Figure 5a.** and **5b.** show, within majority non-DAC communities, the numbers of EVs and PHEVs per 1k-capita are expected to more than double from their current levels by just 2022. By 2024, EV adoption levels within

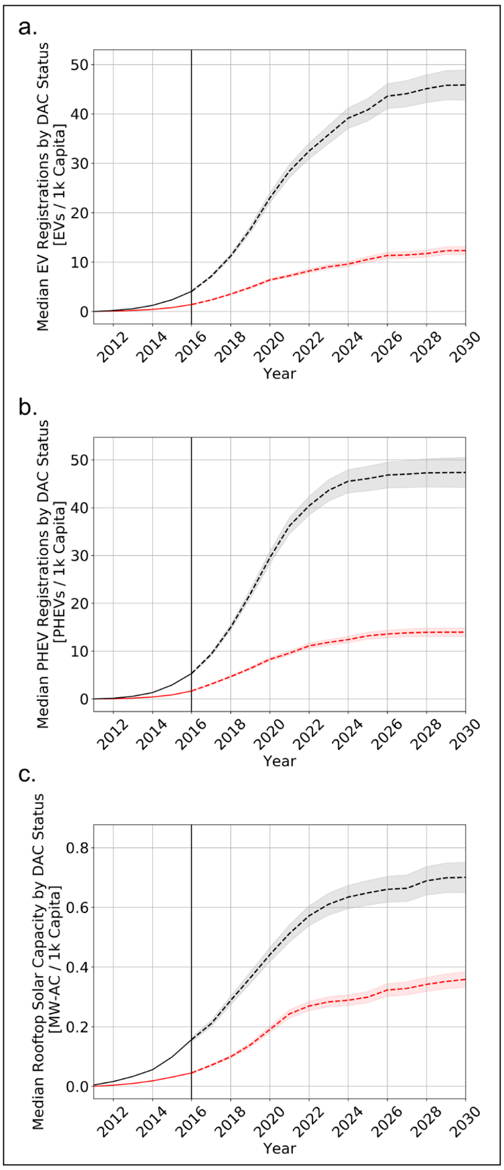

Figure 5: Time series plots depicting recent past (solid lines) and forecast future (broken lines) **(a.)** battery electric vehicle adoption levels [*EVs/1k-Capita*], **(b.)** plug-in hybrid vehicle adoption levels [*PHEVs/1k-Capita*], and **(c.)** residential scale distributed rooftop solar installed capacities [*MW-AC/1k-Capita*] calculated as the median values for each group of majority-DAC and majority non-DAC zipcodes. DOI: https://doi.org/10.1525/elementa.419.f5

majority non-DAC communities are expected to surpass those for PHEVs and continue climbing. The situation with the majority-DAC communities appears significantly less promising. For EVs, it will take until 2030 for per-capita penetration levels within majority-DAC zipcodes to reach levels already achieved in majority non-DAC areas. The situation is quite similar for the case of PHEVs with future growth in majority-DAC communities stagnating after 2024.

Looking at the expected future growth in the adoption of residential scale distributed rooftop PV systems, recent historical trends suggest that both majority-DAC and majority non-DAC groups will experience rapid growth through 2022, after which growth rates will begin to taper off through the end of the 2030. Despite these positive growth trends, the current, substantial, differences in per-capita installed capacities which currently exist between the two groups are expected to significantly increase, through the forecast time horizon.

Discussion

Shortcomings of Existing Market Based Programs

Mapping energy consumption and renewable technology adoption by DAC-status reveals stark differences between communities with respect to their participation in the energy transition so far, and the failure of market-based programs to adequately address the equity dimensions of the energy transition. Forecasts of EV/PHEV and rooftop solar adoption also indicate that unless redistributive measures are taken, existing inequities in access to zero-emission energy end-use technologies will persist long into the future.

By design, market-based approaches to residential EE, electrification, and renewable generation capacity expansion programs tend to prioritize volume – measured in units of either of estimated energy savings, sales, or installed capacity – over the equitable distribution of program benefits. The tendency of these programs to be over-utilized by the rich and under-utilized by the poor is well-documented. However, this tendency is not always perceived as problematic or even especially undesirable. If the primary objective of market-based incentive programs is GHG abatement, what does it matter if wealthy citizens are the ones who are participating, so long as demand for grid-supplied energy diminishes?

This simplistic approach ignores the fact that the marginal benefits enjoyed from the consumption of each additional kilowatt-hour or therm vary between individuals as well as at different levels of consumption. These marginal benefits decline substantially as the volume of consumption increases beyond the sufficiency range. Thus, the cumulative benefits generated from the expenditure of public funds are maximized when programs target households whose levels of consumption are within the sufficiency range.

The Need for a Fundamental Change in Approach

The time has come to reflect upon the reasons why the current slate of market-based incentive programs continue to produce such inequitable outcomes. We believe that, in many cases, program elements which were assumed to ensure equality of access or opportunity, may be inadvertently responsible for unequal rates of program utilization. This is because DAC members are known to be inherently more limited than their non-DAC counterparts in terms of their available time, attention, and capacity to take advantage of programs which are "generally" available (Scavo et al., 2016).

There are myriad examples of specific ways in which well intentioned program designs can produce unintended consequences. Consider, for example, which of the following alternative policy approaches would be more likely to produce equitable outcomes in the future:

Continuing to finance EE programs whose measures are most easily implemented during the processes of new construction or major renovations and thus, are disproportionally used by affluent, single family homeowners?	*OR*	*Creating new EE programs whose measures can be readily implemented in densely occupied, aging, or multi-family structures and which address the renter-owner split incentive barrier?*
Continuing to subsidize net-metering tariffs which pay the owners of affluent single family homes above market rates to install large PV systems capable of offsetting up to 100% of their total annual consumption?	*OR*	*Creating new virtual net-metering tariffs which allow for the output of community scale PV systems to be virtually allocated to several multi-family households, partially offsetting a fraction of their annual consumption?*
Continuing to provide tax rebates for the members of affluent households to purchase multiple, potentially redundant, EV/PHEVs for limited use in satisfying their personal transportation needs?	*OR*	*Restricting the availability of these rebates to low-income, single vehicle households and ride share fleet operators whose services can, potentially, satisfy the transportation needs of numerous households?*

The design of residential energy policies determines, in part, who is able to benefit from advances in energy technology. Current and future policy choices will also determine the depth and inclusivity of the energy transition as it progresses. If the renewable energy transition is to both significantly reduce emissions of locally impactful criteria pollutants and globally impactful GHGs as well as alleviate energy insecurity without enabling excessive consumption, current residential energy policies are inadequate. In order for these policies to maximize the social benefits of domestic renewable energy systems, electric vehicles, and energy efficiency programs, they must account for the higher marginal utility of units of energy consumed at or below the level of sufficiency.

DAC residents who currently experience energy poverty stand to benefit immensely from such redesign of energy efficiency and residential renewable energy incentives. Inequities in the energy transition are of concern not because DAC members should have EVs, PV systems, and efficient appliances as a matter of fairness in material allocations. Rather, they are of concern because adoption of these goods ensures that individuals and households are not deprived of the full suite of energy services in a renewable future and are not subjected to economic hardship or other indecencies as a result of the energy transition.

Conclusions

The results of this study have shown how public policies designed to reduce GHG emissions in California have resulted in a skewed distribution of benefits toward those who utilize the most energy. This is because these affluent consumers have a greater ability to access existing programs and incentives. This inequality of participation amounts to the implicit subsidization of excess consumption, which is being financed by the general energy utility rate payer. Program participation requires extra effort, knowledge and access. The underlying design assumption behind the majority of these policy programs – that equality of availability will necessarily produce equality of participation – is fundamentally flawed. This assumption reflects a modernist ideology that is evident in the design and layout of other major urban infrastructure systems.

Current policies do not address the absolute levels of energy consumption, per se, but rather tend to focus on increasing energy efficiency. However, increases in efficiency have largely only been realized at the highest levels of consumption. Low income DAC residents continue to live in less comfortable housing and pay a larger proportion of their income for that discomfort. This problem with efficiency has been known for over a century, and was first described by William Stanley Jevons when observing the introduction of coal in England (Alcott, 2005). He noted that though the efficiency of engines was improving, more and more coal was needed as there was an expansion of its use. It is critical today to understand that efficiency improvements alone are not likely to lead to absolute reductions in energy use.

The future need for additional generation capacity is likely to continue, whether it be from fossil or renewable sources. Renewably generated energy constitutes a dramatic improvement over the use of fossil fuels. However, it too has considerable environmental and social impacts – from the extraction of raw materials in production, to habitat loss in deployment, and the need to dispose of electronic waste at end of life. It is likely that the imposition of hard limits on total energy use will ultimately be necessary to mitigate all of the impacts incurred across the breadth of this life cycle. The inequities in the system as it exists today place a larger burden of cost on the least affluent, and, perversely, reward the high consumers with access to incentives. Policy aims need to get beyond efficiency to address absolute levels of consumption and to reflect reasonable need rather than excessive use. If not, efficiencies will continue to chase increased demand with limited effect, and DAC communities will be prevented from improving their well-being, though they use the least energy of all.

Data Accessibility Statement

All data files associated with the manuscript have been uploaded to FigShare and can be accessed here https://doi.org/10.6084/m9.figshare.12206366.

Supplemental file

The supplemental file for this article can be found as follows:

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Competing interests

The authors have no competing interests to declare.

Author contributions

Eric Daniel Fournier executed the quantitative analyses, generated the figures, and contributed to the development of the manuscript and its arguments. Robert Cudd, Felicia Federico, & Stephanie Pincetl contributed to the development of the manuscript and its arguments.

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