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FINAL PROJECT REPORT

Distributional Impacts of Climate Change from California's Electricity Sector

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PREFACE

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

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

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

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

Distributional Impacts of Climate Change from California’s Electricity Sector is the final report for the Distributional Electricity Impacts of Climate Change on California's Residential Communities project (Contract Number EPC-17-027) conducted by the University of California Berkeley. The information from this project contributes to the Energy Research and Development Division’s EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC’s research website at ERDD@energy.ca.gov

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ABSTRACT

This study analyzed the impacts of climate change driving the demand for electricity and its consequent air quality impacts on segments of California's population and economy. The study investigated the energy effects of climate change on disadvantaged and non-disadvantaged communities as defined in Senate Bill 535 (De León, Chapter 830, Statutes of 2012). The impact estimates were obtained by applying econometric estimators to billing data from California's investor-owned utilities, which allow for impact simulations under future climate with and without adaptation. Senate Bill 535 communities are projected to see larger percentage increases in electricity consumption and smaller decreases in natural gas consumption than their non-Senate Bill 535 counterparts.

An additional analysis explored the distributional consequences of changes in air pollution due to increases in electricity load. Higher demand for electricity, especially at peak times, would result in higher emissions of local air pollutants from fossil plants, which translate to higher ambient concentrations downwind. The researchers simulated the impact of a 20 percent change in aggregate electricity demand and translated these associated increases in emissions into changes in ambient concentrations of oxides of nitrogen (NO_x), sulfur oxide (SO_x), and particulate matter ($PM_{2.5}$). Results indicate that disadvantaged communities could experience twice the increase in ambient concentrations compared to non-disadvantaged communities. Communities with larger incomes, more Caucasians and populations of young and old people have lower increases in ambient concentrations. The researchers also found that the additional increases in ambient concentrations from a 20 percent increase in demand are relatively small. This suggests that addressing the local air pollution challenge by focusing on peak electricity alone will likely not cause dramatic air quality improvements. This study, however, can be used to examine the air pollution driven benefits and costs of emissions reductions from decreases and increases in load to different groups of ratepayers across the state.

Keywords: Electricity Consumption, Air Pollution, Environmental Justice, Disadvantaged Communities

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EXECUTIVE SUMMARY

Background

Climate change is anticipated to have many potential effects on the electricity system and its associated stakeholders. One anticipated effect is that hotter temperatures will cause households and businesses to use air conditioning more frequently or to install air conditioning units if they reside in climates that do not currently require it. Peak electricity demand, therefore, is expected to increase. California's electricity grid relies on a fleet of peaker plants that operate as needed to accommodate spikes or peaks in demand. Peaker plants, which are used when demand is high and mostly fueled by natural gas, typically generate more air pollutants than baseload generating facilities that operate most of the time. To meet higher demand from higher temperatures, peaker plants would operate more often and for longer periods than they currently are and consequently emit greater levels of air pollutants that have known human health impacts.

California is a diverse state with numerous climate zones, demographics, socio-economic conditions, existing pollution levels, and an uneven geographic distribution of peaker plants. This diversity suggests the dual impacts of greater electricity demand with associated costs and air pollution that might not be uniformly distributed across the state. Are some communities disproportionately impacted relative to others, especially disadvantaged communities? Studies about climate change impacts are relatively common, but few address this distributional question about who bears the health and financial costs of climate change.

The state has many policies designed to revitalize disadvantaged communities, including climate and energy policies to ensure that these communities are not unfairly burdened by policy impacts and that they share in the benefits of the clean energy economy. Senate Bill 535 (De León, Chapter 830, Statutes of 2012) formally defined disadvantaged communities as the 25 percent highest scoring census tracts in CalEnviroScreen 3.0, where scores are based on two components representing exposure to pollutants and their effects and two components representing population characteristics (sensitive populations in terms of health status and age) and socioeconomic factors. This information provides an opportunity to fill this gap in knowledge about the potential impacts of climate change on disadvantaged and non-disadvantaged communities.

Project Purpose

This project provides decision makers and researchers with insights into the degree of potential impacts of climate change at the community level that had not been achieved before. This project followed the projection of climate change (temperature) over the century to:

- Estimate the effects of climate change on the residential energy demand, using household electricity and natural gas usage data.
- Estimate the air pollution effects of increased electricity load.
- Characterize the relative impacts on disadvantaged and non-disadvantaged communities of these projected changes.

Although the researchers acknowledge that California's electricity system is rapidly evolving, for this study, they assumed that the 2015/2016 electricity system would continue to operate through the end of this century. It is anticipated that improvements in efficiency in cooling systems will likely offset the rise in demand as temperature increases, and greater use of clean energy sources will reduce or eliminate the need for dirtier peaker plants. Various policy studies have explored what that future California energy system might look like to achieve the state's ambitious climate and clean energy goals. This project provides a baseline to allow energy planners to estimate the benefits of those policies and new technologies and how those might be distributed among disadvantaged and non-disadvantaged communities. This study offers projections of the variation in concentrations of air pollutants across the state. The next step, one beyond the scope of the project, would be to estimate the impacts of those pollutant concentrations on public health in the various community types.

Project Approach

The project consisted of two components. The first component estimated the relative effects on energy use on communities due to projected changes in climate. The second explored the implications of increased electricity demand on exposure of communities to air pollutants. Both components were evaluated through an environmental justice lens to see if disadvantaged communities might experience greater consequences than non-disadvantaged communities.

A technical advisory committee was formed with a mix of perspectives and expertise. The committee consisted of experts in consumer energy behavior, demand forecasting, energy equity, and climate adaptation policy with members from Lawrence Berkeley National Laboratory, the California Public Utilities Commission, the California Energy Commission, and the California Environmental Justice Alliance. Among other suggestions, the committee weighed in on which model of how pollutants would disperse (a fate and transport model) would be most useful at the best geographic resolution for estimating impacts (such as utility service territory, climate zone, or county).

Residential Energy Demand Under Climate Change

The researchers used a four-step process to estimate the energy use response of California ratepayers to rising temperatures associated with climate change. First the researchers used household-level billing data from nearly a billion each of electricity and natural gas bills from California's investor owned utilities, identified at the ZIP code level for privacy concerns. The researchers used this data to estimate customer response of how electricity use increases with temperature, primarily for air conditioning, and how natural gas use increases at cooler winter temperatures for space heating. This provided an average response for each ZIP code in California, while attempting to account for factors that are associated with people's energy use, such as household level income and housing density.

Next, the researchers used a statistical regression to develop relationships between energy responsiveness and climate across ZIP codes, which allows accounting for adaptation later (that is, the increased adoption of air conditioners). To see how energy use might change with warming temperatures, the researchers used climate change projections scaled to the ZIP code level, considering the likely purchase of more air conditioners. An easy way to think about this is that if San Francisco inherits Bakersfield's warmer climate, the method assigns Bakersfield's response function to San Francisco, while correcting for the differences in income and population density. These projected increases in electricity consumption are compared to reductions in natural gas consumption to look at the net effects. In the final step, the researchers analyzed the results according to the status of each ZIP code as either disadvantaged or non-disadvantaged community to determine if the effects are equitably distributed across ratepayers.

Variable Exposure to Air Pollutants Emitted by Peaker Plants from Increased Load

With no changes in energy infrastructure, increased peak load from climate change or other factors would require more frequent and longer operation of peaker plants and therefore, in the summer, higher emissions of air pollutants. Health impacts ultimately depend on where high levels of pollution concentrations are experienced by residents, not by where emissions are produced. To study these potential changes in pollutants and their concentrations across California, the researchers simulated the impact of a 20 percent overall electricity load increase in the Western Interconnection of which California is a part. This larger geographic scope accounts for the imports of electricity to California from out of state.

Emissions of oxides of nitrogen (NO_x), sulfur dioxide (SO_2), and secondary particulate matter ($PM_{2.5}$) were modeled by statistical regression for three types of fossil fuel power plants using two years of data from public sources. The researchers then applied a fate and transport air quality model called, Intervention Model for Air Pollution (InMAP) that disperses the emissions across the landscape according to physical and chemical processes. InMAP generates a high-resolution grid map of annual average increases in ambient concentrations of the pollutants across the landscape. These concentrations were then aggregated from grid cells to census tracts across California so that results could be broken down by income, race, age and disadvantaged community status.

Project Results

Residential Energy Demand Under Climate Change

Using an approach the researchers had previously developed, they successfully projected future energy demand by ZIP code areas and evaluated the distribution of effects between disadvantaged and non-disadvantaged communities. ZIP codes in the Central Valley and non-coastal Southern California were projected to experience the largest increases in household electricity consumption. Disadvantaged communities were projected to experience higher percentage increases in electricity consumption and smaller percentage decreases in natural gas consumption due to climate change than their nondisadvantaged counterparts. Climate change will further exacerbate existing inequalities in energy consumption. Moreover, the inequities become wider over time. Easy solutions to address these issues are hard to come by. One avenue may be via rate design, which may offset the increases in expenditures via lower rates. One must be mindful that lower prices lead to increases in quantity demanded, however, making it harder to achieve the state’s energy and climate goals. Another avenue may be to increase programs that improve the efficiency of building envelopes to reduce future demand rather than increasing energy consumption to mitigate hotter temperatures.

Variable Exposure to Air Pollutants Emitted by Peaker Plants From Increased Load

Areas with already challenged air quality are shown to experience the larger increases in ambient concentrations of all three pollutants, with the greater Los Angeles area, Sacramento and the Central Valley showing the largest increases. The distribution of increases in ambient concentrations across the state differ by pollutant, which depends on the location of emissions as well as pollution dispersion and transformation through physical and chemical atmospheric processes. Finally, and maybe most importantly, the increases in pollution are extremely small; if one looks at averages, the increases are well below one percent.

The simulation projected that communities that are poorer and have a higher fraction of non-White populations will experience higher increases in ambient concentrations of the three air pollutants. The simulation also showed that disadvantaged communities, as defined by SB 535, will experience higher increases in ambient concentrations. This points to an environmental justice issue related to possible increases of electrification of end uses — absent matching increases in renewable generation capacity.

While these results show significant distributional effects from increase in load, it is of utmost importance to put the magnitudes into perspective. A 20 percent increase in aggregate load is massive. The corresponding increases in ambient concentrations are on average significantly less than 1 percent. This is likely because many of the dirtier power plants supplying electricity to Californians are located outside the state. Further, plants located inside California have pollution control equipment installed that removes a significant share of the pollutants from the smokestacks. Significant further investments in cleaning up fossil electricity generation in California may not be the most effective strategy to improve air quality. The transport sector, which is responsible for a significant share of the same pollutants and toxics may be worth studying more closely.

Knowledge Transfer

The knowledge from this project was targeted to two critical audiences. The first audience is state and local policy makers tasked with development of electricity demand forecasts and climate adaptation and resilience plans. For this audience, the researchers are offering briefings to commissioners, advisors, and staff at the state energy agencies. They also intend to prepare a policy blog summarizing the policy implications of the study.

The second audience is academic researchers engaged in research on energy and climate change. The researchers intended to make presentations of the project for seminars at different universities in 2020, but this was postponed because of the coronavirus pandemic. The project will issue working papers describing the research question, methods used, and results, which will be posted on the Energy Institute's web site with an email notification to their large subscriber base.

Benefits to California

Environmental justice is an important dimension of state policy, including fighting climate change and adapting to it. An important knowledge gap to help inform policy making is about how climate change may increase inequities for disadvantaged communities. In addition to forecasting future energy demand under climate change, this project reveals the equity implications in terms of increased demand in disadvantaged communities and on the corresponding changes in air quality. This information provides a baseline against which policy makers and energy planners can estimate the equity benefits of alternative policies. It also forms the foundation of future analysis of the potential health impacts of criteria pollutants associated with greater peak electricity demand and how those impacts might be distributed among disadvantaged and non-disadvantaged communities.

CHAPTER 1: Introduction

Background

California is a global leader in addressing the impacts and sources of climate change. It continues to be aggressive in its policies to reduce the emissions of greenhouse gases (GHG) and local pollutants. While there are numerous national or statewide studies of the economic and physical impacts of climate change, there are few rigorous studies identifying how communities of different types are affected by climate change - using empirically calibrated dose response functions at a high level of spatial resolution. This is especially true when thinking about the distributional direct and indirect effects of climate change. In California, SB 535 (De León, Chapter 830, Statutes of 2012) categorizes communities as disadvantaged or not disadvantaged. The designation is based on whether a community suffers from a combination of economic, health, and environmental burdens. In this study the researchers test whether communities will be affected uniformly or not via two channels: climate change driven electricity consumption (demand) and air quality (supply/generation). Decision makers need this information to plan policy options on the demand (such as demand side management programs) and supply (such as power plant construction) side of the electricity market, as well as to inform California's current and future climate policy.

Specifically, this project's first part studied the effects of rising temperatures on the electricity demand side. The researchers used an empirically calibrated statistical model (Auffhammer 2018) using household level data to estimate household temperature response of electricity demand and estimate the adaptive response to climate change and its cost. In the second part, the supply side, the study built a model to estimate the implications of increased electricity through increased emissions of local pollutants, all by community.

Objectives and Organization of the Report

The goal of this project was to provide a partial estimate of the distributional impacts of climate change on California's electricity demand from residential communities and the consequential impacts on emissions of air pollutants. The project was designed to generate new and precise estimates of the forecasted damages to California's residential communities due to climate change.

The objectives of this project were to:

- Use granular electricity data to estimate the effects of climate change on the residential demand side of the electricity system.
- Estimate the effects of increased load, possibly due to but not limited to climate change, in terms of air pollutants from the supply side of the electricity system operating to meet this increased demand.
- Characterize the differences in impacts between disadvantaged and non-disadvantaged communities.

The basic behavioral mechanism underlying these effects relies on the fact that people generally rely on increased indoor cooling in hotter summers and decreased indoor heating in milder winters. This response is thought to increase electricity consumption in the summer due to the increased operation of air conditioners. In the wintertime, the response is thought to decrease the consumption of multiple energy sources - heating oil, natural gas and electricity as all of them are widely used as sources for heating. Chapter 2 describes statistical models of household energy consumption for summer and winter, how they vary across California, and the changes in consumption in disadvantaged and non-disadvantaged communities in response to projected warming from climate change.

Increases in peak summer load from climate change would require greater use of peaker plants, which typically generate more air pollutants than baseload generating facilities. Chapter 3 presents a series of models that use increased electricity demand from an increase in load, allocate that excess demand to specific plants in California, predict emissions of several air pollutants of interest, and then project pollutant concentrations across the state in relation to disadvantaged and non-disadvantaged communities and other demographic groups.

The remaining chapters describe how the researchers transferred the knowledge gained in this study to various stakeholder audiences, the overall conclusions and recommendations from the study, and how the study benefits California's electricity ratepayers.

CHAPTER 2: Environmental Justice in Energy Consumption: The Relative Impact of Climate Change on Senate Bill 535 Communities

Introduction

Climate change can be detected in the historical record in physical systems across the planet (Bindoff et al., 2013). Further there have been detectable and attributable impacts on human and natural systems (Cramer at al. 2014). Going forward, the Intergovernmental Panel on Climate Change (IPCC) projects that the average surface temperature on earth will rise by between 1 and 3.7°C (1.8 - 6.7°F) by 2100. Humans, where possible, will adapt to this change in climate in a variety of ways. Maybe the most straightforward adaptation mechanism to hotter summers and milder winters is the increased reliance on indoor cooling and decreased reliance on indoor heating. This response will happen in the residential setting to increase comfort in the home as well as workplace settings, as it has been shown that higher temperatures lead to negative impacts on physical and cognitive performance of workers (Carleton and Hsiang, 2016). Since currently available technologies for cooling the indoor environment primarily rely on electricity (such as air conditioners and heat pumps) this response is thought to increase electricity consumption in the summer due to the increased operation of air conditioners. In the wintertime, the response is thought to decrease the consumption of multiple energy sources - heating oil, natural gas and electricity as all of them are widely used as sources for heating. Using these technologies will help humans prevent the negative health consequences from extreme heat days, which include increased morbidity and mortality, as well as the aforementioned negative productivity effects (Carleton et al., 2019).

This adaptation is not without costs. Increasing the consumption of cooling services may result in expenses as installation and operating costs of air conditioners, while the benefits accrue in the form of better health and increased comfort. Quantifying the overall magnitude of these responses in terms of electricity consumption is important to understand the overall costs of climate change on an economy. What is maybe just as important is *who* bears these costs. The literature studying empirically who suffers bigger impacts is woefully small. This chapter provides estimates for California policymakers of who would bear the biggest burden from climate change in terms of future electricity consumption.

The study used a method that allows one to econometrically estimate the response of households' electricity consumption to hotter climates at a fine degree of spatial resolution (Auffhammer, 2018). The variation in short run electricity consumption and weather is exploited to estimate dose response functions between temperature and electricity/natural gas consumption. The shape of these dose response functions, which varies across space, is used to simulate the hypothetical response of electricity consumption in locations with a changed climate. An easier way to think about this is that if San Francisco inherits Bakersfield's warmer climate, the method assigns Bakersfield's response function to San Francisco, while empirically correcting for the differences in income and population density.

To do this, in a first step, using household-level billing data, the causal temperature response function of household electricity consumption is estimated at a fine level of spatial aggregation — the five-digit ZIP code level. These response functions allow one to examine the increased use of existing equipment across 1,165 ZIP codes in California. In a second step, regression is used to explain cross-sectional variation in these "first-step" estimated slopes of each ZIP code's temperature response function as a function of long-run average weather ("climate") and other confounders (such as income, population density) varying across ZIP codes. Downscaled climate projections are used from 18 of the IPCC's most recent climate models to simulate future household electricity consumption at the ZIP code level under climate change, taking into account adaptation — the adoption of more air conditioners. The projected increases in electricity consumption are compared to climate-driven reductions in natural gas consumption, which is estimated and projected separately. For California's residential sector, the overall natural gas savings are greater than the increases in electricity consumption in end consumption British thermal unit terms.

This supplement to the Auffhammer (2018) paper, which was part of California's Fourth Climate Change Assessment, examines the distributional impact of climate change on residential electricity and natural gas consumption for disadvantaged communities as defined by SB 535 relative to non-disadvantaged communities for the ZIP codes in the sample. It uses the projections provided by Auffhammer (2018) and breaks them out by SB 535 status as provided by CalEnviroScreen 3.0.[1] It shows that disadvantaged communities are projected to have larger percentage increases in electricity consumption and lower percentage decreases in natural gas consumption relative to nondisadvantaged communities. The differences are statistically significant, especially so for periods later in the century.

Data

Residential Billing Data

This study employs an extensive history of bills for all households serviced by California's investor-owned utilities (IOU) obtained as part of a confidential data sharing agreement with Pacific Gas and Electric (PG&E), Southern California Edison (SCE), Southern California Gas Company (SoCalGas), and San Diego Gas and Electric (SDG&E). SDG&E and PG&E are gas and electric utilities, while SoCalGas only provides gas and SCE only provides electricity. The billing frequency is approximately monthly for each household, but the length and beginning and end days vary across households. Table (1) provides an overview of the temporal data coverage for the four utilities by energy source (electricity and natural gas) as well as the number of bills by energy source.

[1] https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-30

Table 1: Electricity and Natural Gas Bills by Utility

Utility	Electricity Years	# of Bills	Gas Years	# of Bills
PG&E	2003-2009	342 Million	2004-2014	587 Million
SDG&E	2000-2009	153 Million	2008-2015	74 Million
SCE	1999-2008	469 Million		
SoCalGas			2010-2015	267 Million
Total		964 Million		928 Million

This table displays the total number of bills in the dataset. Electricity bills with average daily consumption less than 2 kilowatt-hours as well as solar homes were dropped. Further, the estimated models only include ZIP codes for which the dataset contains more than 1,000 bills.

Source: UC Berkeley

The dataset contains the complete bill-level consumption and expenditure information for the population of single metered residential customers during the years available in the database. Specifically, the data have an ID number for the physical location (such as residence), a service account number (such as customer), bill start date, bill end date, total electricity or natural gas consumption (in kilowatt-hours, kWh, or therms for gas), and the total amount of the bill (in $) for each billing cycle, as well as the five-digit ZIP code of the premise metered. Only customers who were individually metered are included in the dataset - multi-unit buildings with a shared meter are not included. Households that have moved cannot be reliably identified and are not included as a source of econometric identification. In this chapter, a customer is defined as a unique combination of premise and service account number. The researchers used this data base to identify whether a customer receives a low-income subsidy on electricity pricing through a state program or which homes are all-electric, meaning that they heat and cool using electricity and have their own electric water heaters.

Each billing cycle does not follow the calendar month, as the beginning date and the length of the billing cycle vary across households, with the vast majority of households being billed on a 25-35 day cycle. The analysis drops any bill with average daily consumption less than 2 kWh from the sample, because there is concern that these outliers are not regular residential homes, but rather vacant vacation homes. It also removes homes on solar tariffs from the data, since total consumption is not observed for these homes, but only what they take from the grid, rendering these data useless for the purpose of this exercise. This dataset is referred to as "billing data."

For electricity, the data contain a total of 964 million bills; for gas they contain 928 million bills. Of those, 658 million electric bills are for "normal" households, which are neither on the subsidized California Alternate Rates for Energy (CARE) tariff nor all-electric homes. In addition, the data identify 92 million bills for all-electric homes in the PG&E and SCE territories. The remaining bills are for households on the subsidized CARE tariff in all four utility territories. It is important to note the electricity and gas data cannot be matched below the ZIP code level because a customer's address and the account numbers were excluded for privacy reasons by the utility.

There is significant variation in bill-level consumption across and within households. Because across-household variation may be driven by unobservable characteristics at the household level (such as income, physical building characteristics, and installed capital), one can control for unobservable confounders at the household level using fixed effects, and use bill-to-bill within-household variation at the household level as the source of identifying variation. To proceed with estimation at the ZIP code level, this report identifies all ZIP codes across the four utilities' territories for which there are at least 1,000 bills. The data cover 1,165 ZIP codes for which one observes such billing data. The ZIP codes in the chapter represent approximately 80 percent of California's population.

Weather Data

The daily weather observations to be matched with household consumption data have been provided by the 2018 "Parameter-elevation Regressions on Independent Slopes Model" (PRISM) project at Oregon State University. This dataset contains daily gridded maximum and minimum temperature for the continental United States at a grid cell resolution of roughly 2.5 miles. These data are daily for California from 1980-2015. To match the weather grids to ZIP codes, this report uses a geographic information system layer of ZIP codes from ESRI, which is based on the U.S. Postal Service delivery routes for 2013. For small ZIP codes not identified by the shape file, it uses geographic information purchased from a private vendor (zip-codes.com). The PRISM grids are matched to the ZIP code shapes from the census and the daily temperature data are averaged across the multiple grids within each ZIP code for each day. For ZIP codes identified as a point, the daily weather observation in the grid at that point is used. This results in a complete daily record of minimum and maximum temperature as well as precipitation at the ZIP code level from 1980 to 2015, which matches the period of the billing data coverage.

Disadvantaged Communities Data (Senate Bill 535)

California has designated a set of communities as "disadvantaged communities." These are targeted for investment of revenues from the state's greenhouse gas emissions trading program. This recycled revenue represents investments targeted at "improving public health, quality of life and economic opportunity in California's most burdened communities at the same time reducing pollution that causes climate change" (CalEnviroScreen 3.0). SB 535 mandated CalEPA to identify those communities. This project used the CalEnviroScreen 3.0 data to identify ZIP codes that are characterized as disadvantaged by SB 535.[2] It then matches the ZIP codes identified in the tool to the billing and weather data. There are 327 ZIP codes with complete data on observable characteristics that are identified as disadvantaged. The number of the remaining ZIP codes with data, not currently identified as disadvantaged, is 838.

Other Data

Unfortunately, the dataset is missing any sociodemographic observables at the household level, only the five-digit ZIP code in which each household is located. The data were amended with socio-demographics at the ZIP code level from a firm aggregating this information from census estimates (zip-codes.com). These data are only for a single year snapshot (2016).

[2] CalEnviroscreen identifies disadvantaged communities both by ZIP code and Census Tract. As the electricity data in this chapter are identified by ZIP code of the household, the mapping the authors use is to the five-digit zip code provided by https://oehha.ca.gov/media/downloads/calenviroscreen/document/ces3results.xlsx.

Table 2 shows summary statistics for the ZIP codes for disadvantaged communities and non-disadvantaged communities. For these ZIP codes the data contain weather from the PRISM Project as well as billing and socioeconomic characteristics data. The disadvantaged ZIP codes in the sample are more populous, younger, have lower home values and household incomes, are at lower elevations, have a higher share of African Americans and Latinx populations and have higher summer and winter temperatures and get less winter rainfall. Population density is more than double in these disadvantaged communities, and electricity consumption is slightly lower.

Table 2: Summary Statistics for ZIP Codes by Disadvantaged Community Status

Variables	Non-SB 535 [N =838]	SB 535 [N=332]	Difference
Population (in thousands)	19.78	38.56	-18.78***
% White	76.79	52.87	23.92***
% Black	3.670	8.840	-5.17***
% Hispanic	21.56	55.02	-33.47***
% Asian	10.48	11.88	-1.400
% Male	50.09	50.26	-0.170
Median Age (Years)	41.61	31.95	9.66***
Persons per Household	2.640	3.390	-0.75***
Average Home Value (in 100k US$)	4.660	2.810	1.85***
Income per Household (in 10k US$)	7.110	5.010	2.10***
Elevation (in feet)	415.2	333.0	82.18**
Mean Summer Temperature (°F)	71.10	74.39	-3.29***
Mean Winter Temperature (°F)	49.93	52.81	-2.88***
Mean Summer Precipitation (mm/day)	0.120	0.0500	0.07***
Mean Winter Precipitation (mm/day)	3.690	2.140	1.55***
Population Density (# of residents/Mile^2)	2154	5242	-3088.68***
Electricity Consumption (kWh/day)	19.87	18.09	1.78***

This table displays the mean observable characteristics of the ZIP codes in the sample and ZIP codes not in the sample with positive population. The t-test assumes unequal variances. The observable characteristics were purchased from zip-codes.com. Statistical significance is indicated by stars with * = 10%, ** = 5% and * 1% level of significance.**

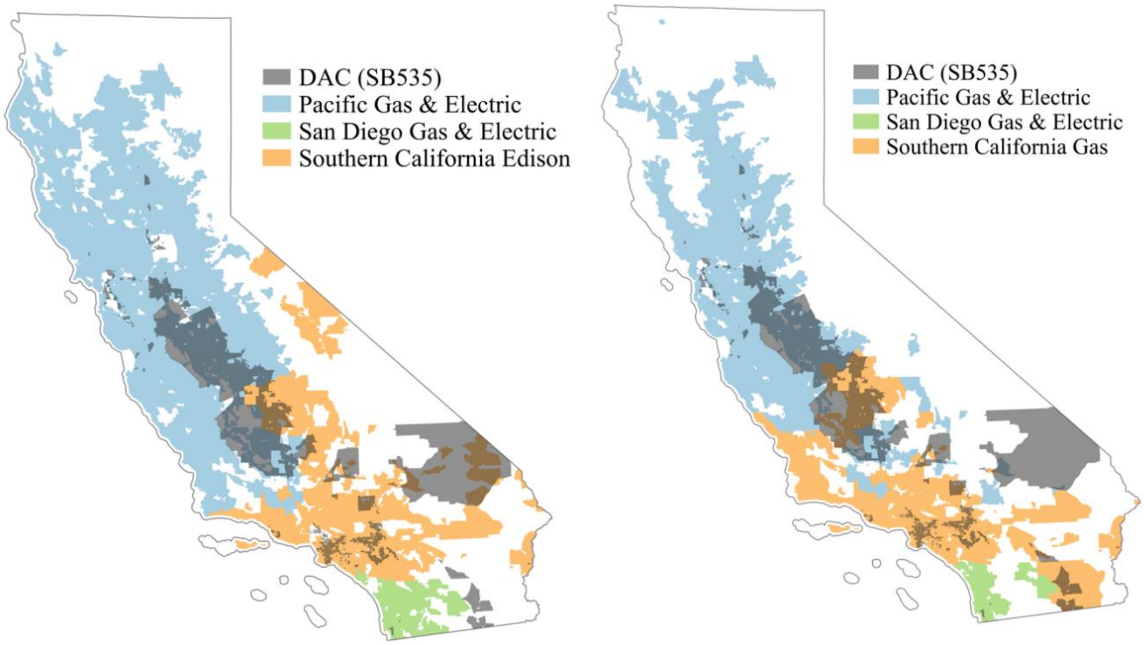
Source: UC Berkeley

It is important to keep in mind that the disadvantaged and non-disadvantaged groups are very different in composition as households choose their home location based on a variety of characteristics of the home and community, one of which is air quality.[3] There are plenty of observable and unobservable differences in the characteristics of these communities that have a causal impact on energy consumption. However, this chapter examines the anticipated trajectories for these two types of communities as they currently are, which is valid under a "no re-sorting" assumption. If there is climate driven resorting across these two types of communities, one would expect that the simulated impacts would differ from what is

[3] Other examples of important dimensions are school quality and availability of employment.

presented here. Figure 1 maps the ZIP codes included in the estimation sample by disadvantaged community status.

Figure 1: Electric Billing Data, Natural Gas Billing Data and Disadvantaged Community Location



This figure displays the coverage of the electric billing data by investor owned utility used in the estimation (left panel), the coverage of the natural gas billing data by investor owned utility used in the estimation (right panel), overlapped with the location of the disadvantaged ZIP codes (grey) in the sample. Areas with no data are blank. Also note that not all ZIP codes in the data are identified as a polygon as some ZIP codes are points and hence not plotted here.

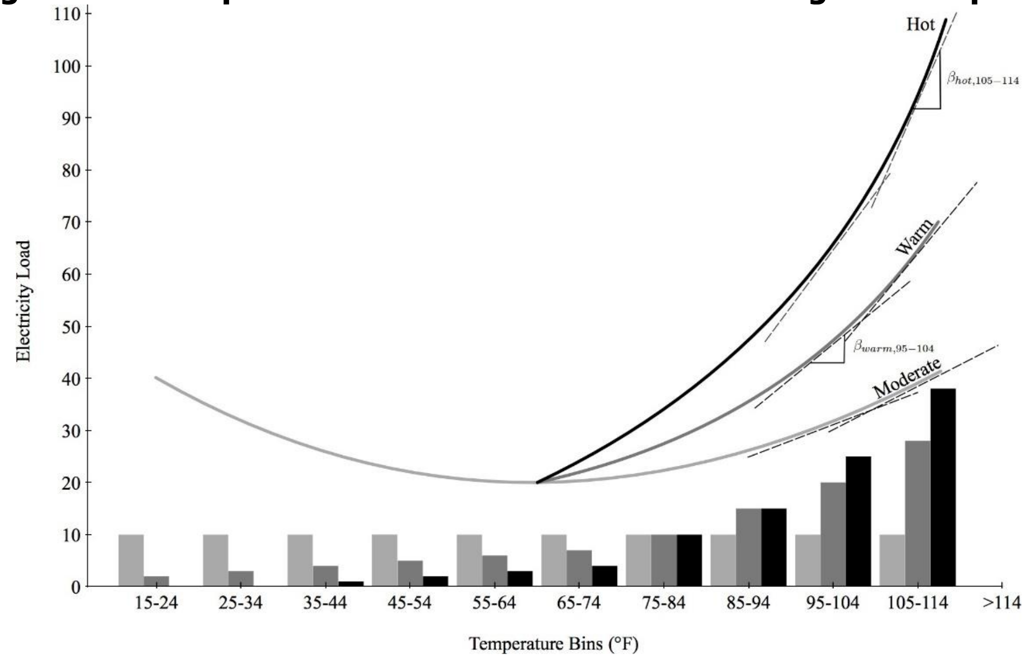
Source: CalEnviroScreen 3.0 and UC Berkeley

Estimation Strategy

Short Run Response to Temperature

For the simulation exercise, the study used the output of the estimation and simulation results in Auffhammer (2018), which contains a detailed description of the statistical method. Figure 2 visualizes the econometric estimation strategy.

Figure 2: Conceptual Identification of Short and Long Run Response



This figure displays the temperature response function of electricity consumption on an arbitrary stylized scale (measured in kWh) in three fictional ZIP codes with differing fictional climates - moderate, warm and hot. The bars at the bottom display the daily average temperature (weather) distribution for the three ZIP codes in degree Fahrenheit. The figure displays that the hot ZIP code has a steeper temperature response at higher temperatures than the warm and moderate ZIP codes. The first step in the estimation identifies the ZIP code specific temperature response curves using household level data. The second estimation step estimates the effect of climate (average time spent in a portion of the temperature spectrum) on the slope of the response curves across ZIP codes for the air conditioning relevant portion of the temperature spectrum.

Source: UC Berkeley

The figure displays stylized current intensive margin dose response functions between an arbitrary weather distribution and hypothetical electricity consumption for a moderate, a warm and a hot ZIP code. The horizontal axis displays the proportion of days mean daily temperature falls into discrete temperature bins in a year. The width of the bins displayed here is arbitrarily chosen, but in the analysis the researchers choose resolution of the bins which accounts for the share of data at each level of temperature. The moderate ZIP codes have more days in the bin spanning 15-24 degrees and fewer days in the 105-114 degree bin. Using billing data for a group of households in the moderate ZIP codes, one can econometrically recover an estimate of its response function by regressing billed consumption on the temperature controls, other observed confounders, and a suite of fixed effects.

For each bin, one estimates a ZIP code-specific slope of the temperature response curve. One can do this for each ZIP code and recover a set of slope coefficients across the observed temperature spectrum for each ZIP code. One would expect that the slope of the temperature response in the warm ZIP codes (such as Fresno) for the bin 95-104 degrees would be steeper than the slope of the cold ZIP codes (such as San Francisco), yet flatter than the slope of the hot ZIP codes (such as El Centro), as air conditioning penetration is thought to be increasing with temperature. The second estimation step takes these β estimates for each bin and ZIP code in the upper portion of the temperature spectrum and regresses their cross section on long-run historical averages of observed temperature (climate). The estimated second-step coefficients can then be used to change the slope of each ZIP code's response curve as future climate changes.

Equation 1 shows the main estimating equation, which is a simple log-linear equation estimated separately for each of the 1,165 ZIP codes indexed by j. This estimating equation has been commonly employed in climate change impacts estimation (such as Deschenes and Greenstone 2011, Davis and Gertler, 2015)

$$\log(q_{it}) = \sum_{p=1}^{14} \beta_{jp} D_{pit} + \gamma Z_{it} + \alpha_i + \phi_m + \psi_y + \varepsilon_{it} \qquad (1)$$

where $\log(q_{it})$ is the natural logarithm of household i's daily average electricity (natural gas) consumed in kilowatt-hours (therms) during billing period t. D_{pit} are the binned measures of temperature into 14 bins indexed by *p*, which is discussed. Z_{it} are observed confounders at the household level, α_i are time-invariant household fixed effects, ϕ_m are month of year fixed effects, and ψ_y are year fixed effects. ε_{it} is a stochastic error term. Because bills do not overlap perfectly with calendar months and years, ϕ_m and ψ_y are assigned as shares to individual bills according to the share of days in a bill for each month and year.

The key novelty of this approach is that one can causally estimate Equation 1 separately for each of the ZIP codes in the data. The motivation for doing this is that one would expect the relationship between consumption and temperature to vary across these ZIP codes according to the penetration of air conditioners and the resident population's propensity to use these.

Z_{it} is a vector of observable confounding variables, which vary across billing periods and households. In this setting, that is precipitation in the form of rainfall. The regression controls for rainfall using a second-order polynomial. Fixed effects control for time invariant differences across households such as location and its associated characteristics (for example school districts, shade, soils, proximity to traffic routes) as well as seasonal and year to year shocks common to all households in a given ZIP code.

Equation 1 is estimated separately for electricity and natural gas for each of the ZIP codes with data, using a least-squares fitting criterion and a household-level clustered variance covariance matrix. This approach is the first estimation step in the overall method and is equivalent to estimating the individual curves in Figure 2 empirically.

Long Run Response to Temperature

In a warmer world, existing air conditioners will be run for more hours, which Auffhammer (2018) refers to as the intensive margin adjustment. The second margin of adaptation is the installation of additional air conditioners in existing homes and new construction. One can easily imagine that if San Francisco's future climate resembles that of current Fresno during the summer, the wealthy and no longer cool residents of San Francisco will install (additional) cooling equipment in their homes.

To be clear, the interest is in the climate change-driven response, not an income- or price-driven response. This study attempts to quantify the magnitude of this response shown in Equation 2

$$\beta_{jp} = \delta_1 + \delta_2 C_{pj} + \boldsymbol{\delta_3 Z_j} + \eta_{jp} \tag{2}$$

where β_{jp} is a measure of ZIP code j's temperature responsiveness in bin p $\in$ [10; 14] as estimated in Equation 1. The authors essentially break up the temperature spectrum and allow for the temperature response to vary depending how hot or cold it is. It fundamentally allows for a very flexible response allowing for a variety of nonlinearities. Another advantage of this approach is that it does not require the response function to be symmetric, which a quadratic would. A response would only be expected in the upper portion of the temperature response curve, where building cooling occurs, which is why the estimation of Equation 2 is limited to the top four bins. A common threshold for the uptick in the temperature response curve, which is valid for these data, is 65 degrees Fahrenheit. It is also a commonly used base temperature for calculating cooling degree days.

The variable C_{pj} in Equation 2 is the share of days that ZIP code j experienced in temperature bin p during the sample years 1981-2000 from the ZIP code-level weather data produced from the PRISM data. C_{pj} is bounded by 0 and 1 and adds to one when summed across all temperature bins from 1-14. The variable(s) Z_j are other factors that may affect the temperature response of the population in ZIP code j. One confounder considered is income, as higher-income households can more easily afford the capital expenditure of an air conditioner and its associated operating expense (Rapson 2011). The regression also includes population density to proxy for the level of urbanization. Controlling for these confounders ensures that one does not confound the climate adjustment by income. Equation 2 is estimated via Ordinary Least Squares with heteroskedasticity robust standard errors, as the dependent variables are estimated coefficients and do not have constant variance. Running weighted least squares does not significantly change the results, yet the least squares estimates are more stable.

Results

Overall Impacts on Household Consumption

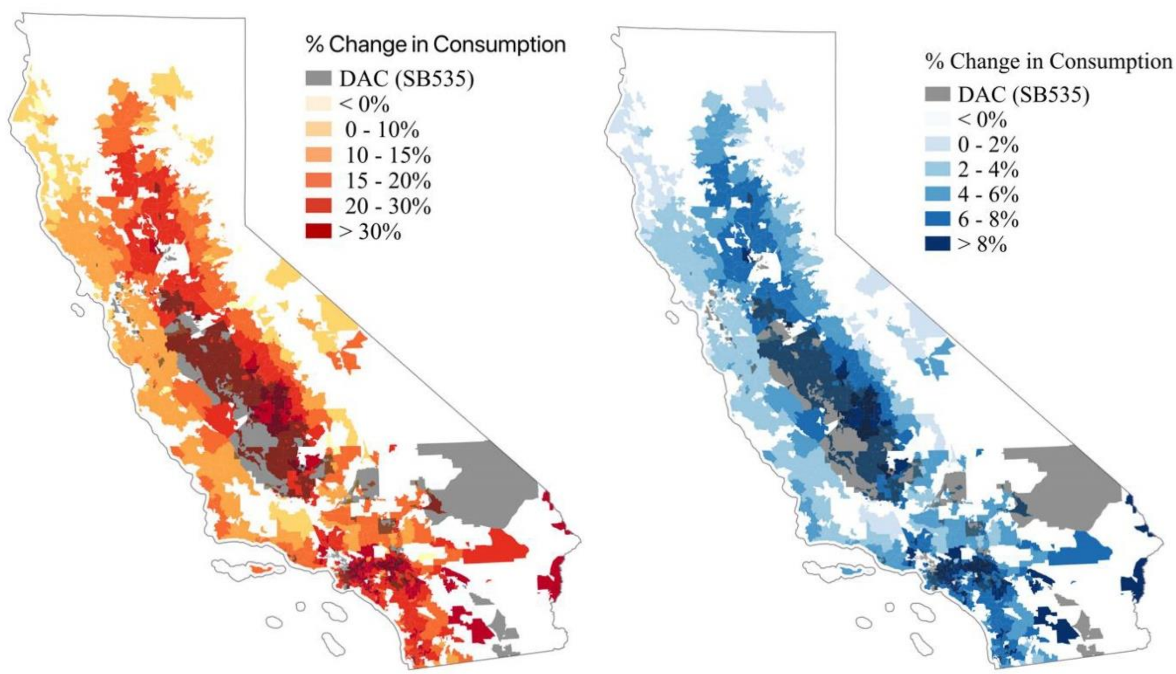
This section presents the results from estimating equations (1) and (2) to simulate the impacts of climate change on electricity and natural gas consumption. It uses counterfactual climate futures from 18 General Circulation Models (GCM, the technical term for climate models) and two different scenarios of emissions from the IPCC's Coupled Model Intercomparison Project Phase 5 (CMIP5) database, downscaled by the Multivariate Adaptive Constructed Analogs approach. It uses these ZIP code-level climate futures to simulate future consumption at the ZIP code level with and without adaptation. For the technical description, consult Auffhammer (2018).

The simulation provides impacts of climate change on electricity and then natural gas consumption under two different emissions scenarios using 18 different climate models from the latest round of the IPCC assessments (CMIP5) in their downscaled form. It first simulates electricity consumption per household using the estimates from Equation 1, which do not allow for changes in the adoption of air conditioners. It then incorporates the extensive margin adjustments from Equation 2. For each simulation, it provides the trajectory of household electricity consumption from the residential sector until the year 2099, which is standard in the climate change literature. It provides simulated impacts for the periods 2020-2039, 2040-2059, 2060-2079 and 2080-2099.

The simulation is based on one key assumption. For natural gas, it only uses Equation 1, because one would not expect households to install more efficient or fewer heaters in response to climate change. One would expect existing equipment to be operated less frequently. Simply put, one would not install a more efficient and costly heater that is going to be used less due to climate change.

To display the spatial variability in intensive margin impacts for the average household across ZIP codes, the simulation generates a map of average household-level impacts by ZIP code. Panel (a) in Figure 3 plots the predicted impact for the average household by end of century using the ensemble average prediction across all 18 GCMs for Representative Concentration Pathway (RCP) 8.5.

Figure 3: Intensive and Extensive Margin Adjustment — Projected Percent Increases in Average Household Electricity Consumption 2080-2099 over 2000-2015 for RCP8.5



(a) Intensive Margin **(b) Extensive Margin Delta**

This figure plots the average per household percentage increase across all 18 GCMs for RCP8.5 for the last two decades of this century relative to the years 2000-2015. Panel (a) holds the temperature response curve fixed at the values estimated in-sample. Panel (b) allows for the empirically guided extensive margin adjustment (that is, the adoption of new air conditioning). The gray polygons indicate the DACs according to SB535.

Source: UC Berkeley

This graph shows that the ZIP codes in the Central Valley and non-coastal Southern California are projected to experience the largest increases in household electricity consumption. The location of the disadvantaged communities (shaded in grey) this shows significant overlap. A casual glance would suggest that the higher increases are concentrated in disadvantaged communities. The reason for the higher impacts, technically speaking, is a combination of the slope of the temperature response function and projected warming from the GCMs. These projections ignore potential extensive margin impacts, which are discussed in the next section.

Panel (b) in Figure 3 displays the impacts on the average household in a ZIP code using the ensemble average of GCMs and RCP8.5 by end of century across the state for the extensive margin adaptation. It is important to note that this figure plots the "delta" from the intensive margin results. It indicates a noticeable increase in consumption across the state relative to the intensive margin only, shown in Panel (a). The right panel shows that these extensive margin impacts will be felt most strongly in the Central Valley and non-coastal areas of Southern California, which tend to have a higher concentration of disadvantaged communities.

Relative Impacts on Disadvantaged Communities

This section breaks out the increases in average household electricity and natural gas consumption for disadvantaged and non-disadvantaged communities. Table 3 displays the relative impacts for household electricity consumption for the two types of communities in percent terms.

Table 3: Projected Change in Household Level Electricity Consumption by Disadvantaged Community Status

Variables	Non-SB 535 [N= 838]	SB 535 [N=327]	Difference
RCP 4.5 2020-39	0.730	1.190	-0.46***
RCP 4.5 2040-59	2.070	3.220	-1.15***
RCP 4.5 2060-79	3.090	4.720	-1.63***
RCP 4.5 2080-99	3.610	5.500	-1.89***
RCP 8.5 2020-39	1.020	1.630	-0.60***
RCP 8.5 2040-59	3.110	4.790	-1.68***
RCP 8.5 2060-79	6.740	10.08	-3.34***
RCP 8.5 2080-99	11.06	16.19	-5.13***

"Variables" refers to the emissions scenario and the future time period. RCP8.5 refers to a high GHG emissions case associated with business-as-usual. RCP4.5 refers to a lower emissions case, which represents a stabilization scenario.

Source: UC Berkeley

Across the two emissions scenarios and any time period considered, disadvantaged communities are projected to experience higher increases in electricity consumption in percentage terms relative to non-disadvantaged communities. The difference becomes uniformly bigger the further out in this century one goes. For the period from 2020-2039 the difference ranges from 0.49-0.60 percent. For the end of the century the difference is 1.80 percent for the low emissions scenario and 5.13 percent for the high emissions scenario. It is important to note that these are percentage increases over baseline consumption, which makes the end of the century number an economically meaningful difference. Disadvantaged communities are projected to experience an increase in consumption of 16.19 percent compared to the non-disadvantaged communities, which are projected to see an increase of 11.06 percent by 2099. When looking at this in terms of energy units, a similar picture emerges, where the predicted rise in daily consumption for disadvantaged communities is 2.89 kwh/day while the rise in non-SB 535 communities is 2.19 kWh/day.

Table 4 displays the same statistics, but for household natural gas consumption. A similar picture emerges.

Table 4: Projected Change in Household Level Natural Gas Consumption by Disadvantaged Community Status

Variables	Non-SB 535 [N=616]	SB 535 [N=309]	Difference
RCP 4.5 2020-39	-3.320	-2.830	-0.49***
RCP 4.5 2040-59	-7.700	-6.570	-1.13***
RCP 4.5 2060-79	-10.420	-8.820	-1.60***
RCP 4.5 2080-99	-11.580	-9.850	-1.73***
RCP 8.5 2020-39	-4.430	-3.750	-0.68***
RCP 8.5 2040-59	-10.460	-9.000	-1.46***
RCP 8.5 2060-79	-16.900	-14.61	-2.29***
RCP 8.5 2080-99	-21.820	-18.91	-2.91***

"Variables" refers to the emissions scenario and the future time period. RCP8.5 refers to a high GHG emissions case associated with business-as-usual. RCP4.5 refers to a lower emissions case, which represents a stabilization scenario.

Source: UC Berkeley

Disadvantaged communities are projected to experience smaller drops in natural gas consumption than non-disadvantaged communities across emissions scenarios and time periods. The difference is statistically different from zero for all eight simulations. For the low emissions scenario, the drops in natural gas consumption by end of century are 21.82 percent versus 18.91 percent for non-disadvantaged versus disadvantaged communities, respectively.

These results suggest that SB 535 communities are expected to experience lower beneficial decreases in natural gas consumption and higher increases in electricity consumption, which again is disadvantageous to these communities. This suggests that, absent policy intervention, a higher burden is placed on these SB 535 communities relative to the rest of California, exacerbating already significant inequalities in environmental equity across these two types of communities.

Chapter Conclusions

This chapter is an extension of Auffhammer (2018) and examines the breakdown of projected climate change driven changes in electricity and natural gas consumption by community type. It shows that disadvantaged communities, as defined by SB 535, are projected to experience higher percentage increases in electricity consumption and smaller percentage decreases in natural gas consumption due to climate change. While Auffhammer (2018) argued that the overall impacts of climate change on California's residential energy consumption may be slightly beneficial, the distribution of these benefits is likely not distributed equally across California's communities. Climate change will further exacerbate already significant inequalities along a new dimension - energy consumption. Easy solutions to address these issues are hard to come by. One avenue may be to increase programs that improve the efficiency of building envelopes and air conditioning equipment. It is important to be mindful of possible rebound behavior as replacing broken, less efficient equipment with new more efficient equipment may lead to increases in the amount of time equipment is operated. Another avenue may be via rate design, which may offset the increases in expenditures via lower rates. Once again, it is important to be mindful of the fact that lower prices lead to increases in quantity demanded (Ito, 2014).

CHAPTER 3: Whose Lungs? The Disparities in Exposure to Local Air Pollution from Power Plants

Ambient air pollutants are responsible for 4.2 million premature deaths per year worldwide (WHO, 2020). The morbidity effects, while much less studied than the mortality effects, are also economically significant. Due to aggressive implementation of environmental policies at the federal and local level, as well as a significant shift in the sectoral composition of the economy, emissions of local air pollutants from the power and other important sectors in the United States have dropped significantly (Shapiro and Walker, 2018). For example, annual emissions of SO_2 from power plants fell by 94 percent and those of NO_X by 86 percent between 1990-2019, which is a staggering drop (EPA, 2020). The aggregate health benefits from improvements in ambient air quality due to these emission reductions are significant.

Massive reductions in emissions have happened despite an almost 20 percent increase in end use consumption of electricity for California (EIA, 2020). Aggregate electricity consumption is expected to continue to grow due to California's growing population and increased, often policy driven, electrification of end uses in the residential and transportation sectors (such as electric vehicles, electric water heaters). As the previous chapter pointed out, another new driver of electricity demand may be from cooling demand due to climate change. Much of the economic literature has focused on studying the costs of increasing electricity demand as well as the overall changes in damages from increased emissions.

What has not been well studied, however, are the distributional consequences from changes in emissions from the power sector specifically. Specifically, will already disadvantaged communities experience more significant increases in air pollution compared to California's other communities? This chapter studies the consequences of changes in California's air quality via local pollutant emissions from electricity generation due to changes in aggregate electricity load.

The intuition behind what the authors are trying to do is relatively simple, yet the mechanics are complex. If aggregate load in the system increases, the next plant to come online is the one with the lowest marginal cost. That plant is not necessarily located near where that demand is coming from. For example, if it is hot in the city, peaker plants in the system get ramped up. Peaker plants are largely located outside of the urban core. So, when it is hot in heavily populated areas, demand for cooling increases electricity use, thereby increasing emissions in other communities. The model described below, allows the researchers to estimate at which level of system load individual power plants are likely to come online and how much NO_X, SO_2 and particulate matter they emit. Although this model can be applied to almost all power plants in the United States, this study focuses on California's generating units only and system load in the West, which is the grid system to which California belongs. It simulates emissions from all power plants in California from a 20 percent uniform increase in peak load and studies what this does to emissions in different parts of California. The simulated change is slightly larger than just climate change driven increases in load to be conservative. The projected impacts for this significant increase in load are very small, and smaller increases in load would result in even smaller increases in ambient air pollution concentrations. To translate the increased emissions from these plants into ambient concentrations of pollutants, the InMAP model (Intervention Model for Air Pollution) was used. As the model provides fairly high-resolution output of ambient pollution concentrations, estimates of changes in pollution concentrations by community can be provided.[4] This chapter breaks down changes in emissions by three factors:

1. Disadvantaged community status according to SB 535
2. Average Household Income
3. Percent of Non-White Population
4. Percent below age 5 and above age 65 Population

The results are interesting. The simulation results suggest that disadvantaged communities are predicted to experience proportionally higher increase in ambient concentrations of NOx, SO_X and secondary $PM_{2.5}$. The results also suggest that poorer communities and communities with higher shares of non-white populations are projected to experience higher increases in ambient concentrations of these pollutants from increases in load. Yet the overall increases in ambient concentrations from increases in peak electricity load are extremely small, almost negligible in most areas. This is due to the fact that most of California's power plants are powered by natural gas with pollution control equipment installed.

The remainder of the chapter describes the data and the modeling framework before turning to a discussion of the results and policy recommendations.

Data

Load and Emissions Data

The dataset contains hourly emissions for all fossil fuel powered generating unit in the continental United States and the corresponding load in the relevant interconnection at an hourly frequency. This study only employs load for the Western Interconnection and emissions from all fossil fueled power plants (peakers and baseload) for California, although future work will likely repeat this exercise for the entire country. The empirical model discussed requires hourly measures of generation in megawatt-hours (MWh) for each power plant and emissions (CO_2, SO_2, NO_X) from all power plants in the system. The database built for this project contains these data for the years 2015 and 2016, which are the most recent years with complete data available. These data come from the US EPA's Continuous Emissions Monitoring System (CEMS) database. CEMS does not include primary $PM_{2.5}$ and volatile organic compounds, so the study was limited to emissions of NO_X, SO_2 and secondary particulate matter. CEMS data are matched to aggregate demand data at the interconnection level from the Federal Energy Regulatory Commission Form 714 for the same time period. In addition to emissions from each power plant and aggregate system load, the researchers observe detailed characteristics of each individual generating unit, such as age, capacity, and technology. The

[4] The grid-cell size in InMAP varies from 1 km × 1 km (typically in urban areas) to 48 km × 48 km (typically in rural areas), depending on the gradient in the population density and pollutant concentrations.

researchers sum up emissions for the year to generate average emissions to feed into InMap, which provides an annual resolution.

Sociodemographic Data

To determine characteristics of the population near power plants and changes in ambient exposure, the researchers collected data on the characteristics of the population from the Census Bureau. Table 5 shows demographic summary statistics near different types of power plants. Relative to the rest of California, the populations near combined cycle plants and combustion turbine plants are quite similar in terms of age structure, gender, race, education, veteran status, income, health insurance, poverty status, and the unemployment rate. In contrast, some differences in demographic characteristics can be seen near steam boilers: the surrounding community tends to be somewhat older, more White, more educated, higher income, and less likely to be below the poverty line.

Table 5: Demographics of Communities with Power Plants

	1 mile from steam boiler	1 mile from combined cycle	1 mile from combustion turbine	California
Percent under the age of 5	0.0546	0.0705	0.0642	0.0645
	(0.0380)	(0.0377)	(0.0360)	(0.0372)
Percent over the age of 65	0.165	0.127	0.130	0.135
	(0.143)	(0.110)	(0.106)	(0.115)
Percent female	0.509	0.497	0.494	0.497
	(0.0684)	(0.0868)	(0.0864)	(0.0838)
Percent non-white	0.306	0.414	0.356	0.365
	(0.182)	(0.211)	(0.168)	(0.188)
Percent no high school diploma	0.131	0.229	0.244	0.220
	(0.145)	(0.169)	(0.165)	(0.168)
Percent veterans	0.0570	0.0561	0.0567	0.0566
	(0.0479)	(0.0420)	(0.0473)	(0.0458)
Avg. median household income	79773.3	66549.2	60796.1	65840.4
	(37046.5)	(35611.7)	(26140.2)	(32063.6)
Percent without health insurance	0.100	0.134	0.148	0.135
	(0.0773)	(0.0882)	(0.0827)	(0.0852)
Percent below poverty line	0.117	0.183	0.169	0.165
	(0.0997)	(0.133)	(0.115)	(0.120)
Unemployment rate	0.0834	0.100	0.0994	0.0969
	(0.0593)	(0.0669)	(0.0620)	(0.0634)

Estimates are population weighted means across census block groups. Numbers in brackets are standard errors.

Source: UC Berkeley

Statistical Modelling of Emissions Load Relationship

To analyze how power plants would behave under various counterfactual scenarios, the authors generated regression-based models that describe power plant behavior as a function of several exogenous observables. For each generation unit in Western Electricity Coordinating Council (WECC), the empirical specification used is the following time series regression:

$$y_t = \alpha + \sum_b \gamma_b B_b + X_t \Theta + \varepsilon_t \tag{3}$$

where y is generation (or CO_2 or SO_2 or NO_x emissions) from generator i at time t; B is an indicator variable for system-wide demand falling in bin b, and X_t could include a vector of fixed effects to account for seasonality and other temporal fluctuations. The model allows system-wide demand to enter the equation in a continuous piecewise linear fashion, in which the data follows different linear trends over different regions of the data. This chapter refers to this throughout as a spline but note that it is piecewise linear. The variables in Greek letters are the estimated coefficients in the model.

The most basic specification drops all covariates — in this specification, it assumes that generating units are dispatched from least-cost to highest-cost, and so their behavior can be entirely explained by the level of system-wide load. The model is based on two primary assumptions: (1) that generator behavior is not additionally determined by unobserved behaviors that are correlated with system-wide demand; and (2) that system-wide demand is not impacted by the behavior of individual generators. Assumption 1 is relaxed, incorporating additional control variables. Assumption 2 is widely used in the related literature, which justifies the assumption by pointing to the inelastic nature of electricity demand: most consumers do not face real-time prices, and thus are not sensitive to hourly fluctuations in the wholesale price.

The specification is very similar to that in Davis and Hausman (2016), but it allows for a slope coefficient within each bin, rather than simply an intercept coefficient. This specification allows for simple and transparent counterfactual construction: to predict generator behavior under higher or lower levels of load, the model simply uses the y_b coefficients.

An alternative specification incorporates additional control variables: days of week effects, hour of day effects, the ratio of coal to natural gas prices, as well as separate spline functions for solar, wind, hydropower, and nuclear generation in the Western Interconnection. This specification allows for the possibility that generator behavior is additionally determined by these other observables, which may be correlated with system-wide demand. In practice, the results are similar when including these control variables. When constructing counterfactuals using these regressions, the model varies the bin in which system-wide demand falls, while holding constant the day of week, hour of day, and non-fossil generation levels.[5]

Fate and Transport Model

To translate the additional emissions from the power plants due to the simulated increases in load, the fate and transport of the increased emissions must be modeled. This study employed the InMAP model (Tessum, Hill and Marshall, 2017). InMAP is an alternative to computationally intensive air quality models, which cannot run at this scale in a reasonable timeframe. InMAP provides estimates of annual-average changes in primary and secondary

[5] The results with the additional controls are available upon request.

fine particle ($PM_{2.5}$) concentrations. InMAP uses pre-processed physical and chemical information from another chemical transport model and a variable spatial resolution computational grid. It uses a baseline level of emissions and then the modeler adds increases in emissions, in this case NO_X and SO_2 which are the only pollutants measured by CEMS, from whatever change one studies. The model then delivers a grid of annual average increases in ambient concentrations of the pollutants across space.[6] The researchers used the default baseline emissions in InMAP and then added the simulated emissions increases from a 20 percent increase in load.

Results

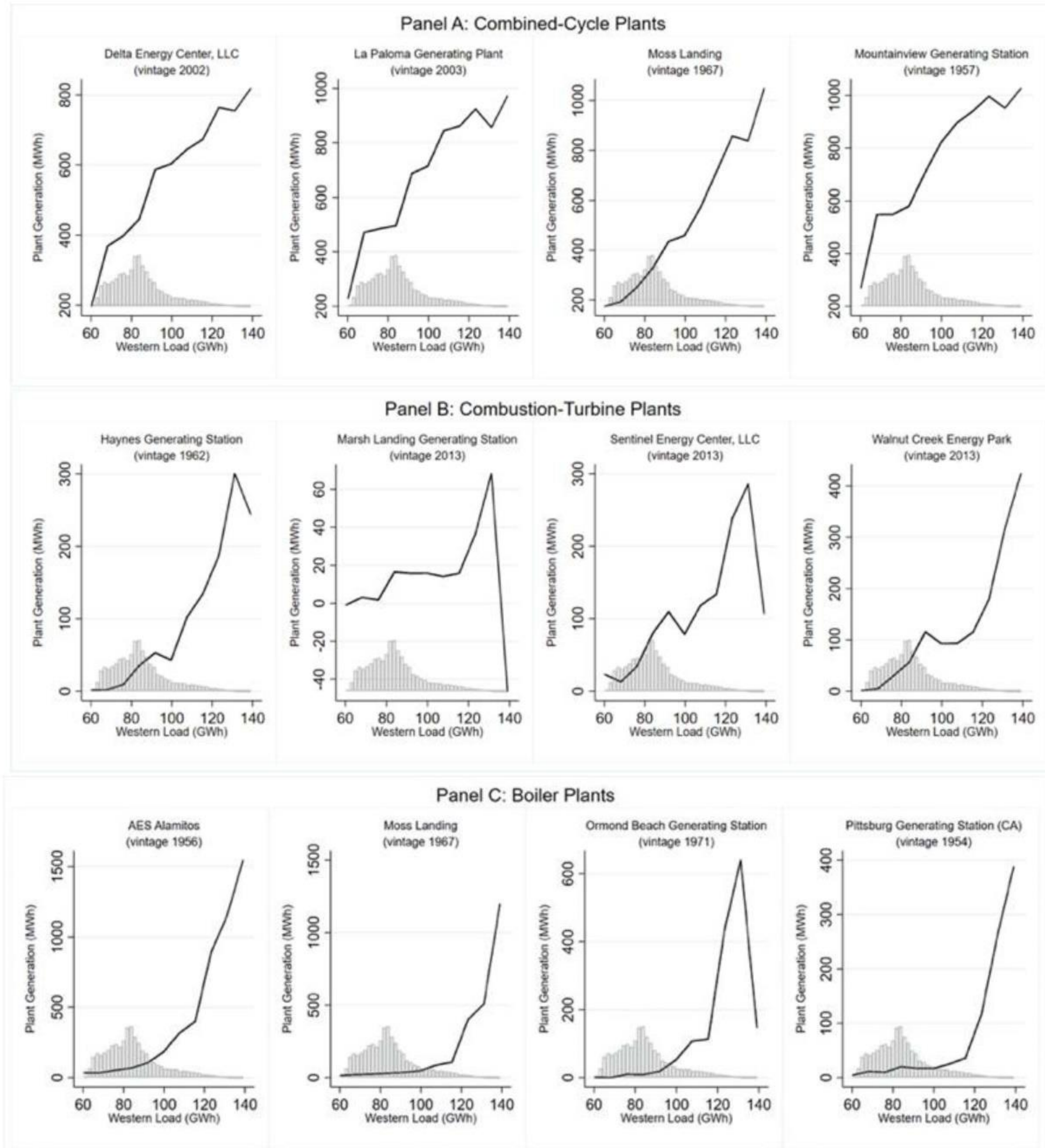
Generation/Emissions Load Relationship

To understand how these generation regressions behave, Figure 4 plots the estimated coefficients for twelve large plants in California (the four largest for each of three fuel and technology type combinations). Specifically, the figure shows how generation at each of the plants varies (along the y-axis) with changes in total demand (along the x-axis). The figure also shows a histogram along the x-axis, which makes clear that WECC-level demand tends to fall within 60-90 GWh, but occasionally gets as high as almost 140 GWh. This figure uses the specification with no additional controls.

The four combined-cycle plants tend to be dispatched even at low levels of demand. The combustion turbine and boiler plants, in contrast, are dispatched only at much higher levels of demand. This is intuitive since combustion turbine and boiler units tend to have much higher cost. Reassuringly, the overall appearance of the twelve figures roughly matches what is found in Davis and Hausman (2016). The combustion turbine and boiler plants have somewhat puzzling coefficients at very high levels of demand, but note that these represent only a tiny percentage of hours, and that the standard errors are very large – one cannot rule out that generation remains steady (rather than dropping, as some figures appear to show) at high levels of WECC-level demand.

[6] The grid-cell size in InMAP varies from 1 km × 1 km (typically in urban areas) to 48 km × 48 km (typically in rural areas), depending on the gradient in the population density and pollutant concentrations. This study used a GIS to overlay the INMAP grids with a layer of census block groups and used area weights to go from INMAP grid impacts to impacts at the block group level.

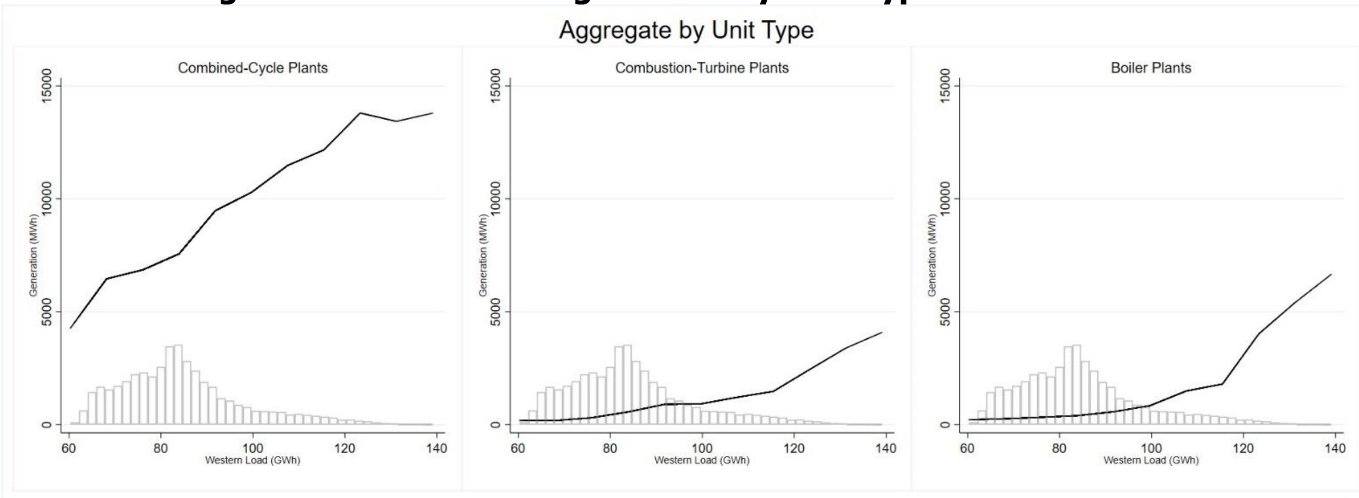
Figure 4: Generation Regressions By Individual Plant



Source: UC Berkeley

The next step aggregates these regressions to the unit-type level. The same regressions as before are run, but with all unit types of type I located in California (combined cycle; combustion turbine; or natural gas boiler) collapsed to a single time series. Results are similar to those of the four largest units for each type: again, combined cycle plants are dispatched at low levels of demand, whereas combustion turbines and boilers are dispatched only at much higher levels. Results are similar when controls are included.

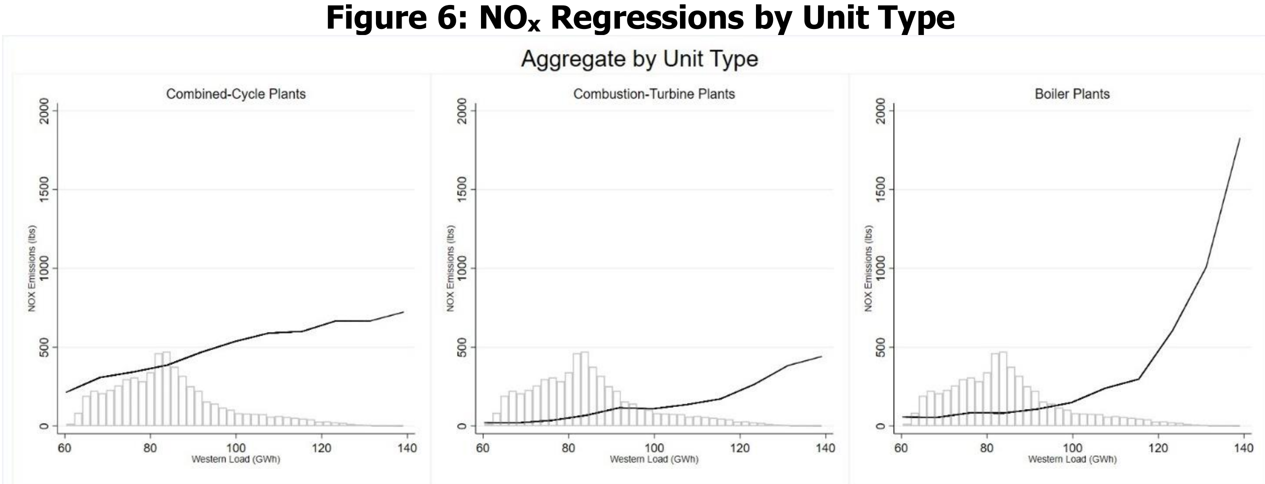
Figure 5: Generation Regressions By Unit Type for California



Source: UC Berkeley

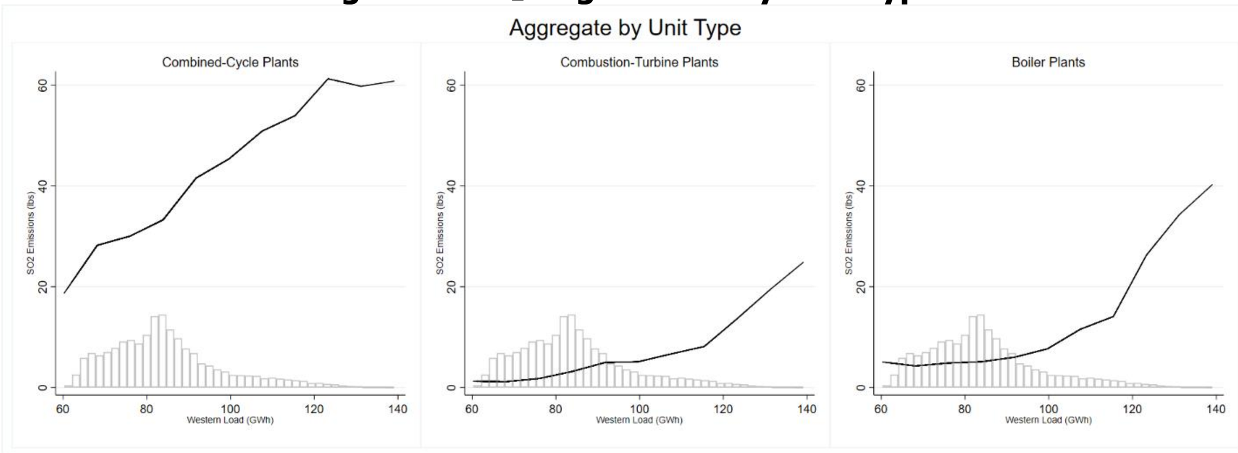
For the counterfactuals, what matters is not the impact of changes in demand on *generation*, but rather on *emissions*. The same regressions as in Equation 3 are run, but with emissions (NO_x or SO_2, in pounds) as the dependent variable, rather than generation. As expected, NO_x and SO_2 emissions are generally higher when generation is higher (Figures 6 and 7), and the figures look qualitatively similar to the generation regressions. At higher levels of demand, both NO_x and SO_2 emissions are significantly higher, and *which* plants are contributing to these emissions changes as demand increases. At low levels of demand, combined cycle plants are the primary contributors, whereas at higher levels, combustion turbines and boiler units are the primary contributors. The magnitude of the contribution across unit types depends on multiple factors: combined-cycle plants tend to contribute the most *generation*, but the median *emissions rates* at boiler units are much higher.

Figure 6: NO_x Regressions by Unit Type



Source: UC Berkeley

Figure 7: SO_2 Regressions by Unit Type



Source: UC Berkeley

Because different unit types have different emissions profiles, the impact of changes in demand varies across communities. These patterns show that communities that are nearer to combined-cycle units are more likely impacted at low levels of demand, whereas communities that are located nearer to boiler units are impacted by high levels of demand. The first step is to analyze where different unit types are located in California. If emissions simply settled close to plants, this would suggest which types of communities are impacted by changes in generation. Of course, it is not that simple. Changes in local ambient concentrations depend crucially on local and regional meteorological conditions as well as complex air chemistry. In a second analysis, the InMAP model was applied, since which communities are ultimately impacted by changes in emissions depends on how pollutants spread and transform in the atmosphere.

Emissions/Load Relationship and Community Characteristics

Some recent literature studying the environmental justice concerns related to flexibility inherent in some environmental regulations has focused on emissions in communities, so the model is used to produce some results looking at emissions from power plants.

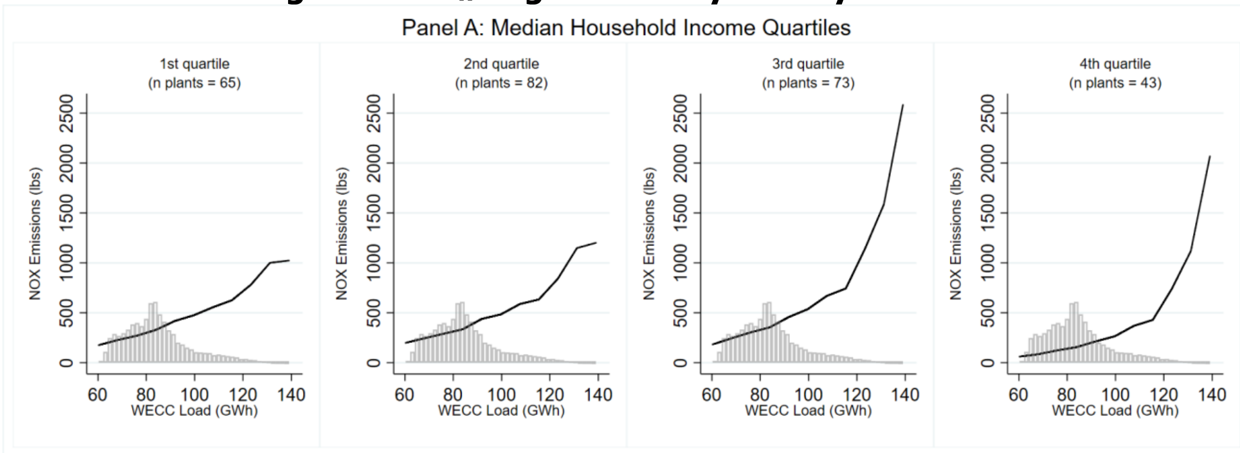
As a ”naive” first step, how emissions change with system-wide demand can be evaluated across power plants located in different types of communities. Specifically, the output aggregates the emissions regressions above into time-series regressions for four types of communities, separated by their median income level. The regression equation is thus:

$$y_t = \alpha + \sum_b \gamma_b B_b + X_t \Theta + \varepsilon_t \tag{4}$$

where y is generation (or CO_2 or SO_2 or NO_x emissions) from generators in community type i at time t; B is an indicator variable for system-wide demand falling in bin b, and X_t is a vector of covariates.

Figure 8 shows that across income levels, very few differences in either the *level* or the *slope* of the emissions function can be seen. Low-income and high-income communities tend to have similar levels of nearby NO_x emissions, and this is generally true across the levels of demand. This is intuitive, given the similarity in income levels across unit types.

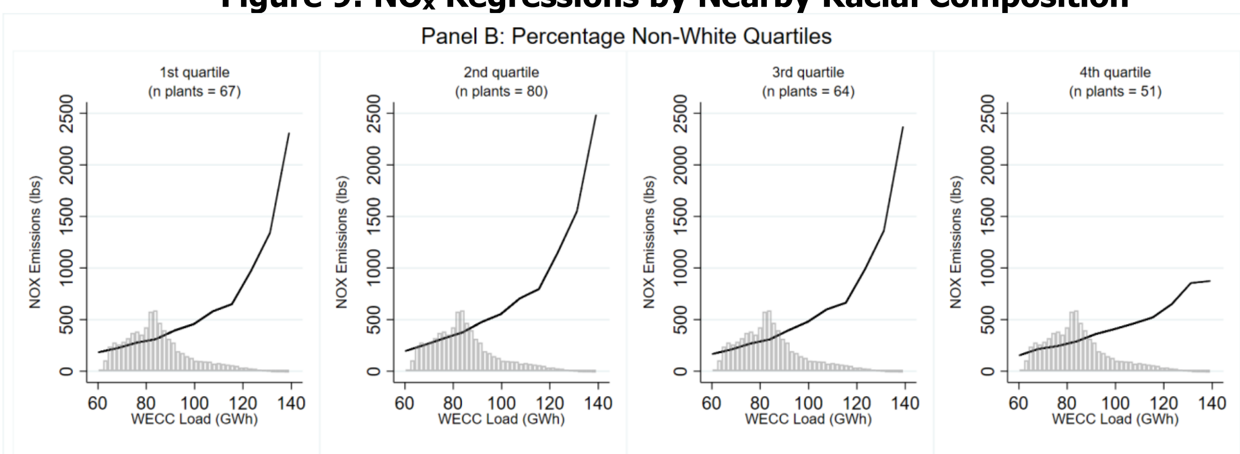
Figure 8: NO_x Regressions By Nearby Income Levels



Source: UC Berkeley

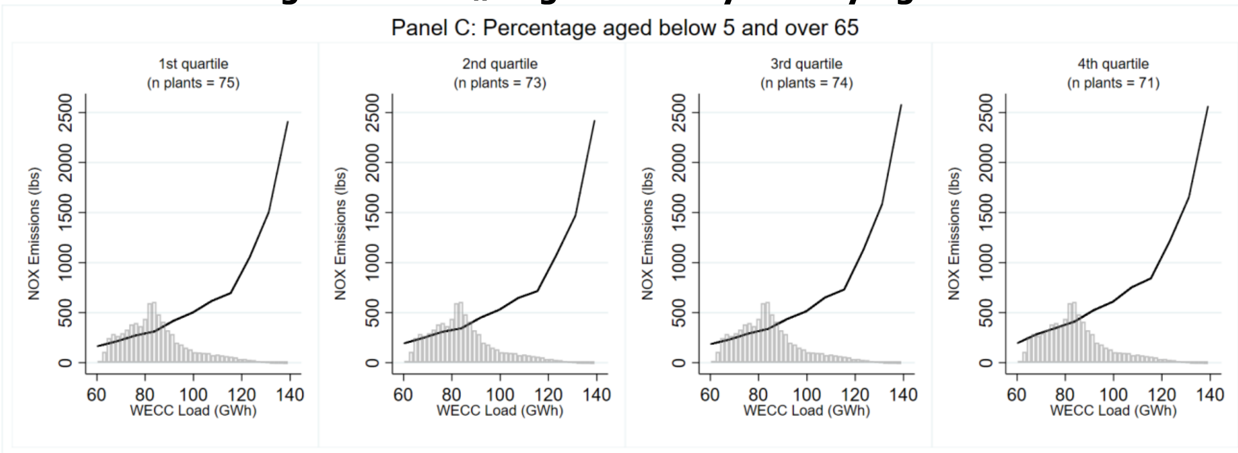
Other demographic characteristics can be analyzed, and Figures 9 and 10 show the emissions functions across quartiles of non-White percentages and percentages of the population at vulnerable ages (below 5 years and over 65 years). Some heterogeneity across racial composition is apparent in Figure 9 although it does not appear to be statistically significant. Very little heterogeneity across age composition is apparent in Figure 10. Of course, health impacts ultimately depend on where high levels of pollution concentrations are experienced by residents, *not by where emissions are produced*. The model is augmented by employing a fate and transport model next.

Figure 9: NO_x Regressions by Nearby Racial Composition



Source: UC Berkeley

Figure 10: NO_x Regressions by Nearby Age Structure



Source: UC Berkeley

Fate and Transport Modeling Results

This section analyzes the results of a 20 percent increase in aggregate load in the Western Region on the emissions from fossil fuel powered generation units.[7] The researchers are indifferent to what is behind the simulated increases in load. The sources could be increases in economic activity, electrification, climate change driven demand to name the most commonly noted drivers of demand.

The output produced by the InMAP model is a grid of changes in ambient concentrations from point specific increases in emissions. The increased emissions from a 20 percent increase in load in the Western region is fed into InMAP. CEMS only allows the modeling of NO_x, SO_2 and secondary $PM_{2.5}$, which leaves out primary $PM_{2.5}$. It is also important to note that InMap includes all SO_x in its baseline, hence all results for ambient concentrations hereafter include baseline SO_x and the simulated increases in SO_2 as "SO_x". Figure 11 shows the distribution of the changes in ambient concentrations from a 20 percent increase in load for the three pollutants modeled at the Census tract level.[8]

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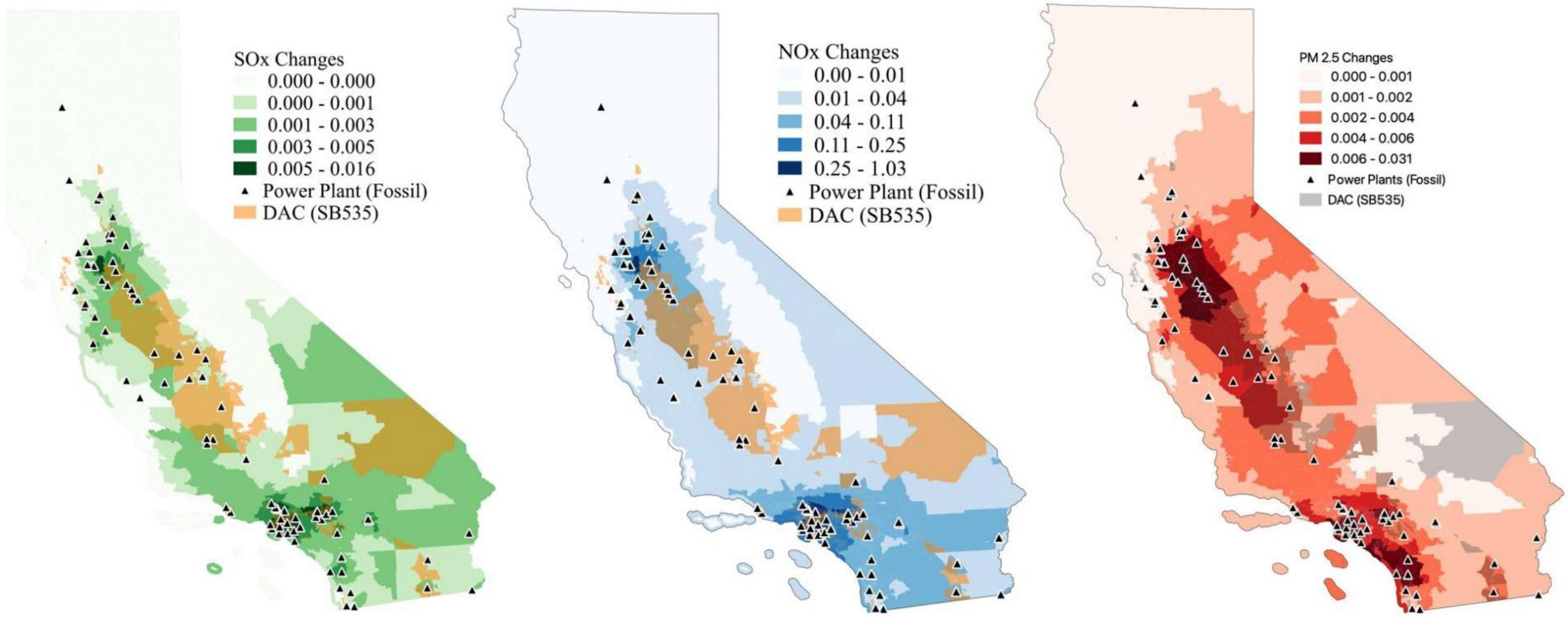
[7] Results are available for smaller increases of load (5, 10 and 15 percent), but given the small impacts for a 20 percent increase in load, the researchers do not present these here. They are available from the authors upon request.

[8] The spatial unit of analysis in this chapter is that of census tracts; sociodemographic data are available directly at this level of aggregation, without having to interpolate census data to ZIP codes, which are not polygons. SB 535 communities are identified by ZIP codes and Census Tracts in Enviroscreen 3.0.

Figure 11: Change in Average Annual Ambient Concentrations of SO_x, NO_x and Secondary $PM_{2.5}$ from a 20 Percent Load Increase



Units are in micrograms per cubic meter

Source: UC Berkeley econometric model / InMAP simulations.

A few things emerge from these pictures.

First, the distributions of changes in ambient concentrations are not uniform across California. Areas with already challenged air quality are shown to experience the larger increases in ambient concentrations of all three pollutants, with the greater Los Angeles area, Sacramento and the Central Valley showing the largest increases.

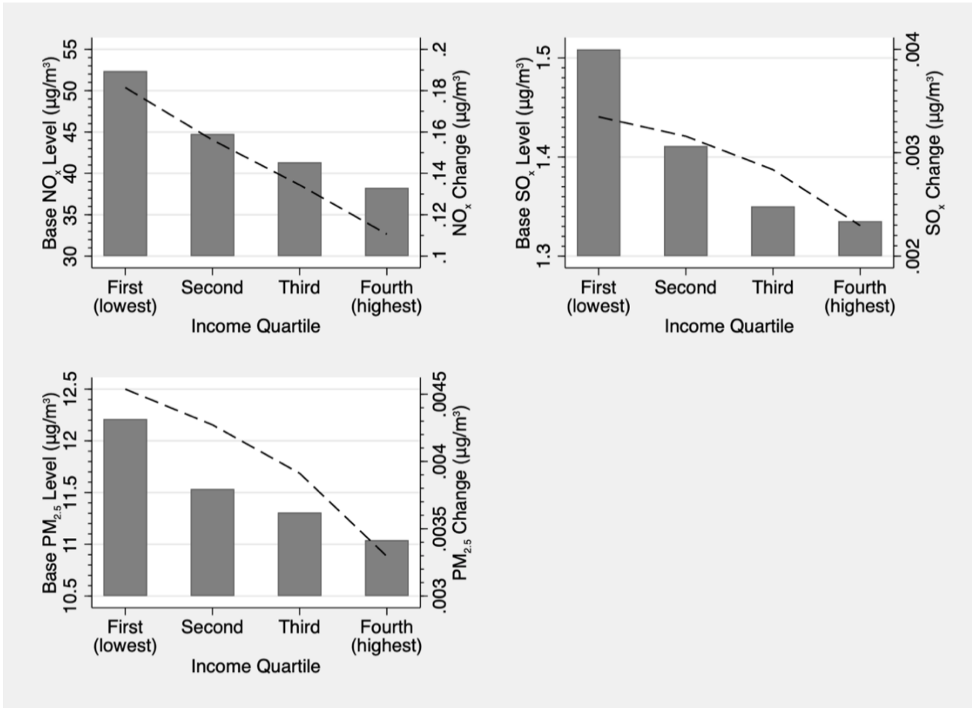
Second, the spatial distribution of ambient concentration increases differs by pollutants, which depends on the location of emissions as well as fate and transport plus air chemistry.

Finally, and maybe most importantly, *the increases in pollution are extremely small to the degree that they are almost negligible*, if one looks at averages. The average increase in NO_x across all census tracts in California is 0.32 percent. The average increase in SO_x across all census tracts in California is 0.20 percent. The average increase in $PM_{2.5}$ across all census tracts in California is 0.33 percent. *These are very small numbers* for a 20 percent increase in load. The 99th percentile of the percentage increase distribution of ambient pollution increases is less than a 1 percent increase in SO_x and $PM_{2.5}$ and 1.25 percent for NO_x.

The changes of ambient concentration in the spatial raster were assigned to individual census tracts using spatial weighting according to area via a geographic information system. The distribution of ambient concentration changes across communities by type can be studied, based on whether a census tract belongs to the set of disadvantaged communities as well as the share of different socio-economic groups in the census tracts.

Figure 12 shows the results from the first heterogeneity exercise. The model employs the average household income for each census tract and split census tracts by income quartile. The first quartile are census tracts with the lowest incomes and the fourth quartile are census tracts with the highest incomes. The 2005 baseline ambient concentrations can be calculated for each census tract from the baseline emissions raster in InMAP and generate a histogram. What is noteworthy, yet not surprising, is that ambient concentrations are decreasing almost linearly in income quantiles. There is almost a 15 micrograms per cubic meter difference in the concentrations of NO_x between the richest and poorest quartile of households. The simulation results can be used to plot the projected changes in ambient concentrations across the census tracts by income quartile. This is depicted by the dotted line. What is noteworthy, again, is that the line is decreasing with income, but that the difference is small – less than 0.1 micrograms per cubic meter. Yet this points at an albeit minuscule difference in projected increases in ambient concentrations between poorer and richer communities, with richer communities expected to experience smaller increases in concentrations based on lower baseline levels of all three pollutants – NO_x, SO_x and $PM_{2.5}$. The patterns could not be any clearer.

Figure 12: Baseline Level & Change in Ambient Concentrations of NO_x, SO_x and $PM_{2.5}$ by Income Quartile from 20 Percent Increase in Load

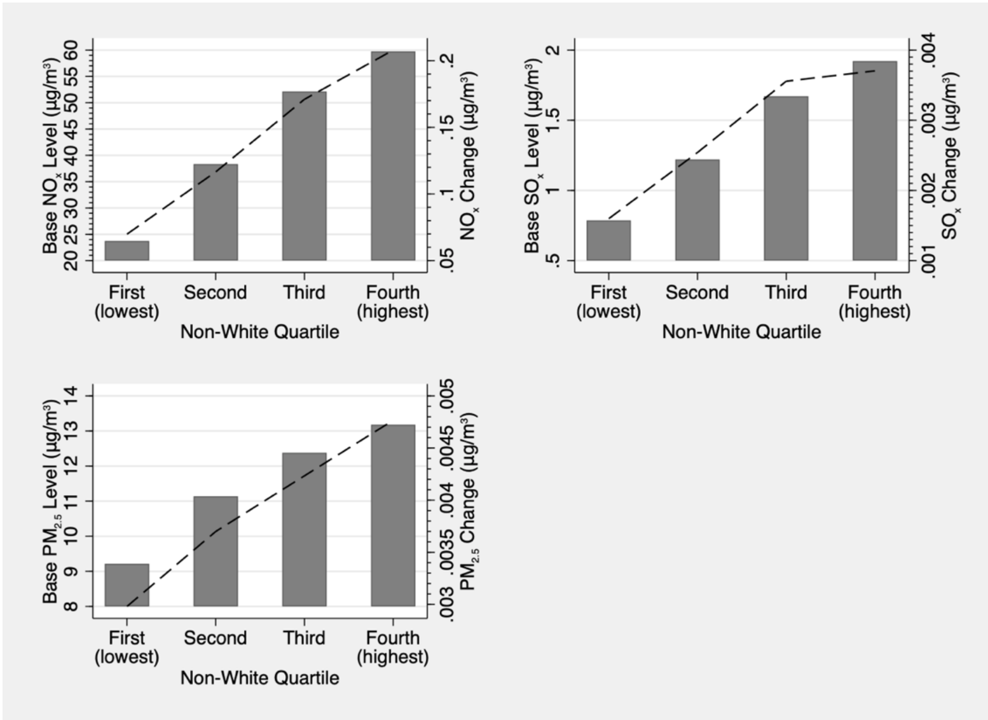


The bars indicate the average baseline level of the respective pollutant by income quartile based on average income across census tracts. The dotted line indicates the simulated change in ambient concentrations from a 20 percent increase in load in the Western Grid. All units are in micrograms per cubic meter.

Source: UC Berkeley

The next step is to look at another dimension of socioeconomic characteristics. Figure 13 replicates Figure 12, yet instead of income looks at the share of non-White population. What is stark in this figure is the difference in baseline concentrations – an almost 35 microgram difference between the first and fourth quartile. Communities with higher shares of non-White population have a much higher baseline concentration and again, are projected to experience larger increases in ambient concentrations from a 20 percent increase in load. Again, the level of the increase is minuscule, but the pattern is undeniable – for all three pollutants.

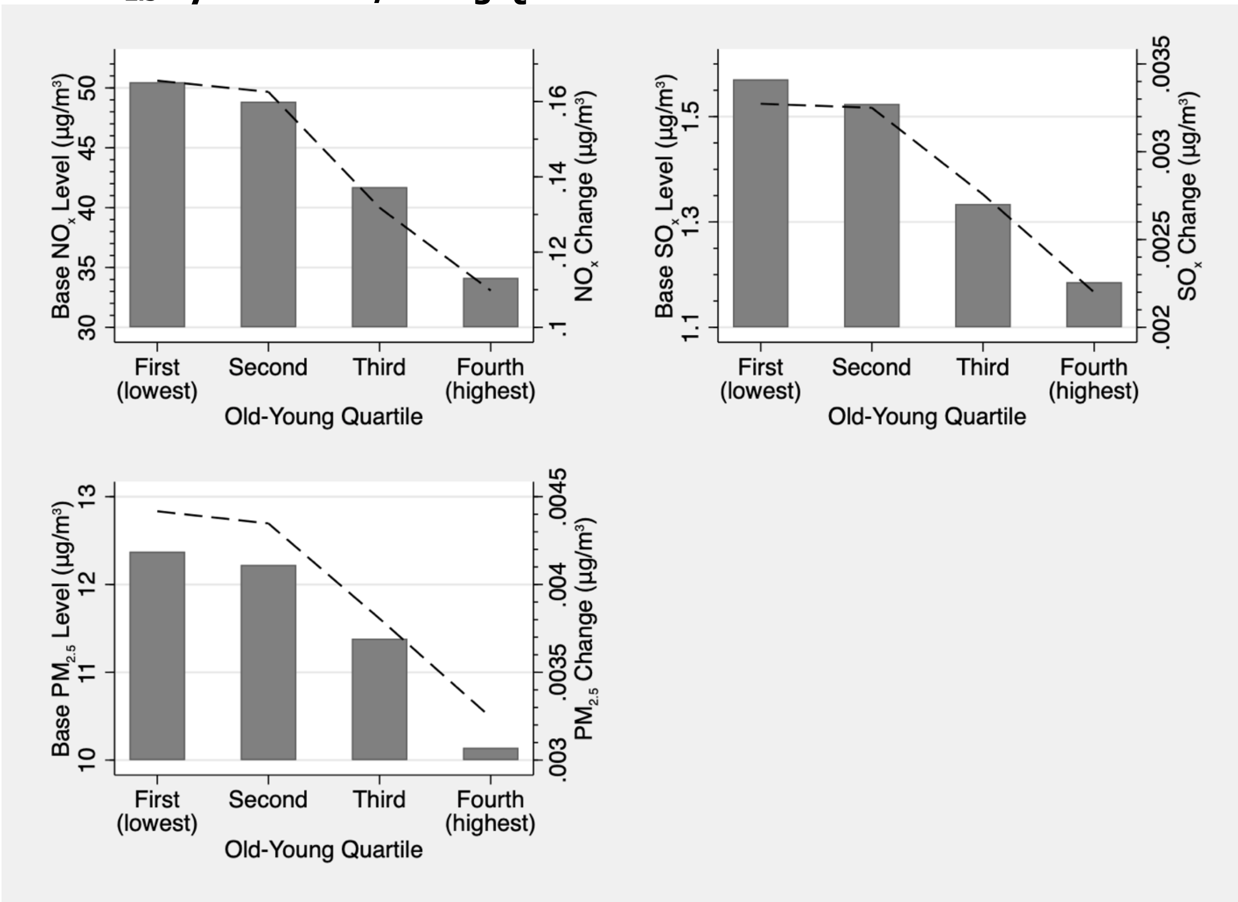
Figure 13: Baseline Level & Change in Ambient Concentrations of NO_x, SO_x and $PM_{2.5}$ by Non-White Quartile from a 20 Percent Increase in Load



The bars indicate the average baseline level of the respective pollutant by percent Non-White quartile based on average percent of non-White population across census tracts. The dotted line indicates the simulated change in ambient concentrations from a 20 percent increase in load in the Western Grid. All units are in micrograms per cubic meter.

Source: UC Berkeley

Figure 14: Baseline Level & Change in Ambient Concentrations of NO_x, SO_x and $PM_{2.5}$ by Share Old/Young Quartile from 20 Percent Increase in Load



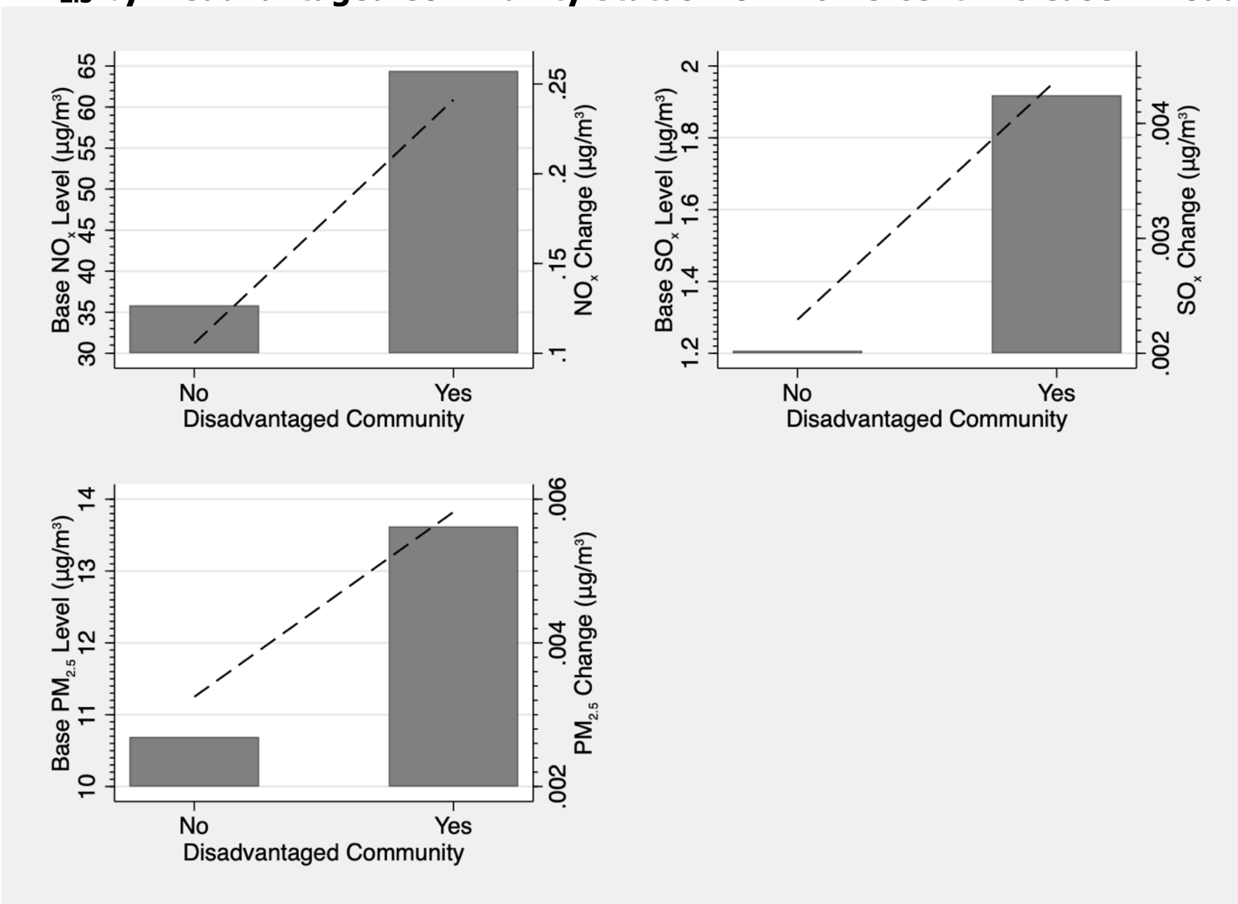
The bars indicate the average baseline level of the respective pollutant by percent younger than 5 and older than 65 quartile based on average percent of younger than 5 and older than 65 population across census tracts. The dotted line indicates the simulated change in ambient concentrations from a 20 percent increase in load in the Western Grid. All units are in micrograms per cubic meter.

Source: UC Berkeley

Next patterns in terms of the age of the population are investigated. It is often said that children younger than 5 and adults older than 65 are especially sensitive populations. The simulation suggests that census tracts with higher shares of these populations have lower baseline levels of ambient concentrations and are also projected to experience smaller increases for all three pollutants.

Finally, the model breaks out results between disadvantaged and non-disadvantaged communities, as defined above. Figure 15 displays these results. The results mirror those above, as disadvantaged communities are characterized by populations with lower incomes and a higher share of non-White population. The picture is stark, nonetheless. The baseline difference in ambient concentrations from the InMAP model are significant, with disadvantaged communities experiencing significantly higher ambient concentrations of all three pollutants, which is not surprising, as this is one of the dimensions used to define a disadvantaged community. The simulation results do show, however, an expectation of higher increases in ambient concentrations from a 20 percent increase in load. While the predicted increases, again, are extremely small, the relative magnitude is noteworthy. Disadvantaged communities are projected to experience almost double the increase in ambient concentrations relative to non-disadvantaged communities for all three pollutants. For NO_x increases are expected to be 129 percent higher and for $PM_{2.5}$ and SO_x 79 percent and 91 percent, relative to non-disadvantaged communities respectively. Simulations for smaller increases of load show smaller increases in ambient concentrations, but the distributional patterns are similar.

Figure 15: Baseline Level & Change in Ambient Concentrations of NO_x, SO_x and $PM_{2.5}$ by Disadvantaged Community Status from 20 Percent Increase in Load



The bars indicate the average baseline level of the respective pollutant by disadvantaged community status across census tracts. The dotted line indicates the simulated change in ambient concentrations from a 20 percent increase in load in the Western Grid. All units are in micrograms per cubic meter.

Source: UC Berkeley

Chapter Conclusions

This chapter builds an econometric model that relates aggregate system load to generation and emissions of NO_x and SO_2 at the generator level using two years of high-resolution data from public sources. It employs the InMAP model to simulate the impact of a 20 percent load increase in the Western Interconnection on ambient concentrations of NO_x, SO_x and $PM_{2.5}$ across California. The simulation results are broken down by income, race, age and disadvantaged community status. It projects that communities that are poorer and have a higher fraction of non-White populations will experience higher increases in ambient concentrations. The simulation also shows that disadvantaged communities, as defined by SB 535, will experience higher increases in ambient concentrations across the three pollutants studied. This points to an environmental justice issue related to possible increases of electrification of end uses - absent matching increases in renewable generation capacity.

While these results show significant distributional effects from increase in load, it is of utmost important to put the magnitudes into perspective. A 20 percent increase in aggregate load would be a massive increase in load. The corresponding increases in ambient concentrations are on average significantly less than 1 percent. This is due to the fact that many of the dirtier power plants supplying electricity to Californians are located outside of the state. Further, plants located inside California have pollution control equipment installed that removes a significant share of the pollutants from the smokestacks. Massive investments in cleaning up fossil generation in California may not be the most effective strategy to improve air quality. The transport sector, which is responsible for a significant share of the same pollutants and toxics may be worth studying more closely.

CHAPTER 4: Knowledge Transfer Activities

This project fills a knowledge gap in the impacts of climate change on the residential sector and the electricity system. The research provides the most comprehensive analysis of how climate change's impact on electricity supply and demand will affect California's disadvantaged and non-disadvantaged residential communities. It also provides crucial information to meet the goal of addressing equity considerations across sectors and regions in the development of a climate adaptation program (SB 246). It can also benefit cities and counties in their efforts to build resilience plans.

This knowledge needs to be shared with two critical audiences, requiring different methods of knowledge dissemination. The first audience is California energy planners and policy makers tasked with developing electricity demand forecasts and climate change policies, and the second audience is academic researchers engaged in research on energy and climate change.

The Energy Institute (EI) at UC Berkeley is offering presentations for the California Energy Commission (CEC) in Sacramento and the California Public Utilities Commission (CPUC) in San Francisco. The CEC briefings will focus on commissioners, advisors, and staff working on demand forecasting and climate change. At the CPUC, the focus is on commissioners, advisors, and Energy Division staff working on climate change and resource planning. These briefings will provide an opportunity for two-way dialogue about the project and its results. EI has experience in providing these briefings and has found them to be a very effective way to get research into the hands of policymakers and improve the quality and relevance of future research. EI will develop a policy blog summarizing the results and articulating the policy implications. They will share the policy brief with the policy makers and regulators with whom they meet.

For the academic audience, the researchers will prepare presentations of the project for seminars at different universities. The plan was to do this early in 2020, but the pandemic has put these plans on hold. These seminars will provide useful feedback on the research methods, which will be incorporated into the project. The researchers will present their findings at conferences. The project will culminate in papers describing the research question, methods used, and results. The papers will be issued as EI Working Papers and will be listed on the Energy Institute's web site[9]. The researchers will also send out an email notification of the release of each paper to their subscriber base of more than 8,000, including employees in state and federal government agencies, utilities, other businesses, and academia.

The project was advised by a technical advisory committee, which met in July 2019. The committee consisted of members from Lawrence Berkeley National Laboratory, the CPUC, the CEC, and the California Environmental Justice Alliance. Among other suggestions, the TAC weighed in on which pollutant dispersal model would be most useful at this scale and the best geographic resolution for estimating impacts (such as IOU territory, climate zone, or county).

[9] https://haas.berkeley.edu/energy-institute/research/working-papers/

CHAPTER 5: Conclusions/Recommendations

Findings

- Finding 1: Climate change will increase residential electricity consumption and decrease natural gas consumption for most of California.
- Finding 2: Changes in consumption vary greatly by location, with the highest increases in electricity consumption being concentrated in the Central Valley and Southern California.
- Finding 3: The impacts on consumption vary across sociodemographic groups, with consumers in SB 535 communities experiencing statistically significantly higher increases in electricity consumption and lower drops in natural gas consumption.
- Finding 4: Increases in electricity load in the Western grid lead to increased emissions of criteria pollutants from California power plants.
- Finding 5: A 20 percent increase in load in the Western grid, after accounting for the fate and transport of local pollutants, accounts for relatively higher increases in ambient concentrations for Californians living in disadvantaged, poorer, and more non-White communities.
- Finding 6: The relative increases in ambient concentrations of criteria pollutants from a hypothetical 20 percent increase in load are unequal yet minuscule, on average significantly less than 1 percent.

Recommendations

- Recommendation 1: As California's regulators, balancing authorities, and load-serving entities collaborate on ensuring grid reliability in the face of extreme events, they should develop new methods to incorporate climate change projections in demand forecasts, capacity and reserve margin planning, extending beyond methods based solely on observed historical data.
- Recommendation 2: Reductions in electricity generation are going to lead to minor improvements in air quality. The authors suggest studies of the relative cost in mitigation from other sectors such as transportation.
- Recommendation 3: Regulators must consider the impact of changes in broader energy consumption on disadvantaged communities and should encourage the development of methods and tools to measure these impacts.

CHAPTER 6: Benefits to Ratepayers

- Benefit 1: Estimates of climate change increases in electricity demand will allow for better demand forecasts, calculation of reserve margins and overall capacity planning.
- Benefit 2: Better demand forecasts, calculation of reserve margins and overall capacity planning will lower the risk of rolling blackouts on peak demand days.
- Benefit 3: Estimates of load increase driven changes in ambient concentrations of the studied criteria pollutants allow communities across California to estimate health impacts.
- Benefit 4: Findings suggest that decreasing electricity load results in negligible improvements in ambient concentrations of local air pollutants, which provides some guidance for the use of mitigation funds.

LIST OF ACRONYMS

Term	Definition
CARE	California Alternate Rates for Energy
CEC	California Energy Commission
CEMS	Continuous Emissions Monitoring System
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2	Carbon Dioxide
CPUC	California Public Utilities Commission
DAC	Disadvantaged Community
EI	Energy Institute [UC Berkeley]
EPIC	Electric Program Investment Charge
GCM	General Circulation Model
GHG	Greenhouse Gas
InMAP	Intervention Model for Air Pollution
IPCC	Intergovernmental Panel on Climate Change
IOU	Investor-Owned Utility
IPCC	Intergovernmental Panel on Climate Change
MWh	Megawatt Hours
NOx	Oxides of Nitrogen
PG&E	Pacific Gas & Electric Company
PM2.5	Particulate Matter with diameter less than 2.5 microns.
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RCP	Representative Concentration Pathway
SB	Senate Bill
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric Company
SoCalGas	Southern California Gas Company
SO_X	Sulfur Oxide
SO_2	Sulfur Dioxide
TAC	Technical Advisory Committee

Term	Definition
WECC	Western Electricity Coordinating Council

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