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Energy Research and Development Division

FINAL PROJECT REPORT

A Holistic Assessment of Building Energy System Transition Pathways in Under-resourced Communities

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This work was the result of a collaborative effort among university researchers from different disciplines, as well as a community-based organization whose mission is to support sustainability and equity within our project study area, and a nonprofit organization that works to implement energy programs. Only together, and with the participating households, were we able to achieve these results. We hope such collaborations will help provide a model for future research.

PREFACE

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

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC 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 CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

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

Using Big Data to Holistically Assess Benefits from Building Energy System Transition Pathways in Under-resourced Communities is the final report for the Using Big Data to Holistically Assess Benefits from Building Energy System Transition Pathways in Under-resourced Communities project (Contract Number: EPC-17-050) conducted by the California Center for Sustainable Communities at UCLA. 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 (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

This study is the first-of-its-kind integration of advanced community-level energy system modeling with on-the-ground public outreach and indoor air quality monitoring in an under-served community in eastern Los Angeles County. This novel integration of data and methods has enabled the holistic, quantitative assessment of indoor and ambient air quality benefits of residential building electrification. Results support prioritizing stove and oven electrification to improve indoor air quality and highlight tradeoffs between indoor and ambient air quality improvements. Participant households do not conform to regionwide averages for appliance types, fuel sources, or cooling behaviors. Energy modeling that informs State planning needs to reflect the diversity of local and household level characteristics to appropriately represent and address equity issues. Electrification strategies must also recognize the logistical challenges and costs of electric service panel upgrades and installation of new 240V circuits in underserved communities. Analysis of account-level hourly gas use within the community reveals that peak gas use throughout the day largely coincides with peak times of electricity use. This suggests that aggressive residential electrification will produce new winter season peaks and may amplify current summer peaks. Residential electrification is expected to substantially improve local air quality in communities that implement it, providing considerable reductions in adverse health impacts and their associated costs. The magnitude of these local benefits exceeds the health impacts from increased grid emissions near fossil-fueled generation by a significant margin. However, benefits and impacts may accrue to different populations. Electrification policies and planning for the retirements of fossil-fueled generation facilities must account for the possibility of creating new air pollution hot spots or exacerbating existing hot spots. Consideration should be given to policies that directly fund upgrades and electrification for homes in these hot spots to provide households with the best possible indoor air quality and reduce air pollutant emissions to the ambient environment.

Keywords: Building Electrification, Energy Transition, Natural Gas, Indoor Air Quality, Nitrogen Dioxide, Particulate Matter, Emission Factors, Building Energy Modelling, Energy System Modelling, Distributed Energy Resources, Energy Transition Forecasting

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EXECUTIVE SUMMARY

Background

California is moving aggressively with a multi-pronged agenda to decarbonize its energy system. Four primary pathways for residential buildings are: electrification of natural gas appliances, retrofits for energy efficiency, electrification of vehicles, and deployment of distributed generation and storage. More work is required, however, to understand energy system transformations within under-resourced communities, to quantify the health co-benefits from those transformations, and to anticipate potential unintended interactions between various initiatives.

Project Purpose

This project sought to:

(1) Improve current understanding of indoor air quality within under-resourced households in a community in eastern Los Angeles County and the extent to which household and appliance attributes and occupants' energy behaviors relate to pollutant concentrations.

(2) Illuminate the degree to which different energy transition pathways are likely to be pursued naturally within under-resourced communities.

(3) Enhance current understanding of interactions between electricity and natural gas systems.

Project Approach

This project was led by the California Center for Sustainable Communities within the University of California, Los Angeles (UCLA) Institute of the Environment and Sustainability, in partnership with the Center for Occupational and Environmental Health within the UCLA School of Public Health; Active San Gabriel Valley, a community-based organization; and The Energy Coalition, a non-profit organization.

The project contract period was from July 2018 to December 2021.

The project team engaged with a technical advisory committee (TAC) that included representatives from the California Air Resources Board, Lawrence Berkeley National Labs, California Department of Public Health, Natural Resources Defense Council, Sacramento Municipal Utility District, South Coast Air Quality Management District (SCAQMD), United States Department of Energy (USDOE), Grid Alternatives, LA County Chief Sustainability Office, and Earthjustice, among others.

The project study area consisted of two adjacent ZIP codes in Los Angeles County: 91746 within the unincorporated communities of Avocado Heights and Bassett, and 91732 within the City of El Monte.

The project components and approximate timeline are as follows:

- Community outreach and surveys (2018-2019).
- Enrollment of participant households; participants included renters and owners as well as both single-family (SF) and multi-family (MF) homes (2019).

- Air quality monitoring and data analysis of nitrogen dioxide (NO_2) and particulate matter, both indoors and outdoors, with separate winter and summer monitoring periods (2019).
- Analysis of hourly residential gas consumption data (2020).
- Building-scale prototype and scenario modeling for the four primary building decarbonization pathways (2020).
- Energy transition forecasting (2020).
- Energy system transformation pathway simulations (2020).
- Community-scale numerical modeling and load profile generation (2020-2021).
- A holistic assessment of residential electrification including calculation of emission changes, locally and by the grid, and calculation of public health benefits and impacts (2021).
- Communication of findings back to the community (2021).

Project Results

Air Quality Monitoring

Indoor air quality monitoring of 64 households in the study community revealed indoor pollutant levels that exceeded ambient air quality standards. More than 20 percent of the homes monitored during the winter sampling time frame experienced average NO_2 concentrations above the health-based standard of 30 parts per billion on an annual average basis (California ambient air quality standard). Approximately 11 percent of the homes sampled during the winter 2-week sampling period had average $PM_{2.5}$ concentrations above the 24-hour average air quality standard of 35 micrograms per cubic meter (national ambient air quality standard). Multiple lines of evidence point to gas stoves and ovens as a primary source of indoor NO_2. Homes that reported cooking more than 50 percent of their meals at home with gas cooking appliances had significantly higher NO_2 concentrations compared with homes that cooked less than 50 percent of their meals at home with gas cooking appliances. Nearly 10 percent of homes sampled reported using ovens as heating sources.

Recommendations from this work include a focus on the electrification of gas cooking appliances in under-resourced communities, additional research in similar communities to compare all-electric households to those using gas appliances, and development of indoor air quality standards to properly contextualize exposure risks.

Building-Scale Modeling and Impacts of Electrification in Under-resourced Communities

Appliance profiles within participant households do not conform to regionwide averages; participants had a higher number of natural gas appliances and far fewer central forced-air systems. Modeled load impacts of electrification varied widely across typical houses, and there was a high level of sensitivity to various levels of electrification. Depending on the baseline appliance profile, a wide range of bill changes could result from the same electrification scenario. Electrification of water-heating technologies was found to be the main source of modeled bill increases. Electric vehicle charging, even assuming Level 1, nearly doubled customer bills. Adding solar photovoltaic generation lowered energy bills, as expected. It will be critical to couple solar (and properly sequence it) with appliance electrification and electric vehicle charging.

To shed light on the impacts of electrification on under-resourced communities, it is critical to account for their unique circumstances and attributes. However, the variability and distributions of household and community circumstances and attributes are not traditionally captured in energy modeling, including assumptions about appliance types, occupancy levels, and cooling set points. Modeling conducted to inform state or local policies and programs should be required to demonstrate how under-resourced communities are represented in the model and to describe how model assumptions might impact results in these communities.

Implications of the Timing of Natural Gas Use for Building Electrification

Over the course of a day, peak rates of household gas use appear to largely coincide with peak rates of electricity use. Hourly patterns in the intensity of residential gas use present important challenges to widespread appliance electrification, both from the perspective of grid operators and utilities as well as from consumers. Aggressive electrification of existing buildings will significantly alter the average load profile of residential customers, producing new winter system peaks and, very likely, amplifying current summer peaks as well. In California, electricity costs more on average per unit than natural gas; these cost premiums also increase during peak electricity demand periods. Time-of-use electricity rates could additionally make the electrification of certain gas appliances more financially burdensome, wherein peak residential electricity demands would coincide with peak electricity rates.

A statewide electrification strategy must account for multiple aspects of residential appliance electrification, including: indoor air quality, total percentage of household energy use from different appliances, load shifting for given end uses, replacement and installation costs of different appliances, and the need for electric service-panel upgrades.

Building Electrification Benefits and Impacts

Residential building electrification measures can significantly improve local air quality for residents of the communities in which they are implemented. Air quality improvements would also reduce health costs including costs associated with hospital visits, asthma, lost workdays, and many other health effects. The overall magnitude of local public health benefits associated with residential electrification exceeded the estimated value of ambient public health impacts (due to increased grid emissions) by a significant margin.

However, impacts associated with increased grid emissions tend to be geographically concentrated within communities situated near existing fossil-fueled electricity generating units and these populations may be different from those directly benefiting from electrification. The present capabilities of common distributed energy resources (for example solar photovoltaics and batteries) are not yet sufficient to completely offset ambient emission increases from full-house electrification. However, a more targeted electrification strategy could possibly minimize, if not nullify, ambient emissions growth.

Distributed energy resources also mitigate increases in electricity bills resulting from electrification. However, given current net-energy metering rules and the many solar installations that will be installed before buildings become fully electrified, it is likely that solar installations could be significantly undersized when compared with what is required to offset even targeted appliance electrification. This study also found that the present capabilities of avoided emission and impact quantification tools are insufficient to properly analyze statewide electrification initiatives.

One of the most important findings of this study is that electrification policies and planning for fossil-fueled generator retirements need to consider the possibility of creating new air pollution hot spots or exacerbating existing ones. Consideration should be given to policies that directly fund upgrades to homes in these hot-spot communities, including for air conditioning and filtration, full appliance electrification, proper ventilation of cooking appliances, and building shell upgrades, to both provide households with the best possible indoor air quality and reduce ambient emissions. A related tariff should also be considered to further extend California Alternative Rates for Energy (CARE)-type rates to a broader population of middle-to-low-income households within proximity of these generator units.

Expansion of the United States Environmental Protection Agency's (EPA) CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)[1] modeling framework to account for changes in indoor emissions exposure pathways as well as changes in concentrations of NO_2 and other pollutants is important to understanding health-related economic benefits. This will require the establishment of indoor air quality standards and improvements in residential appliance emissions factors, especially for stoves and ovens.

Finally, more research is required to fully understand the complexity of indoor environments and human health responses to gas combustion co-product emissions exposures. Overall, the electrification of gas end-uses which involve the heating of water and air has the largest potential to reduce net CO_2, NOx, and $PM_{2.5}$ emissions. However, this study indicates that electrifying gas cooking appliances would also be a source of significant health benefits for affected households. Different gas appliances have different seasonal and diurnal usage patterns. Thus, an electrification effort which may be focused on one appliance category, say for example - water heaters, is likely to have a very different overall net impact profile than another one focused on stoves. This holds true even if the two programs show similar annual net increases in total electricity loads.

Knowledge Transfer

Knowledge transfer included technical advisory committee meetings, presentations to community members, and a final project presentation in September 2021. Project information is documented in ten detailed reports, as well as this Final Project Report, journal articles and conference presentations. Links to documentation are maintained on the UCLA California Center for Sustainable Communities (CCSC) website, UCLA Box shared folder, and Active San Gabriel Valley's website.

Benefits to California

This study was one of the first indoor air quality studies of under-resourced households, to monitor particulate matter and to conduct seasonally specific monitoring to allow comparisons between winter and summer. Findings demonstrated the importance of seasons when

[1] COBRA is EPA's CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool.

assessing the influence of appliance usage and ventilation practices. Research and policy needs were identified as they related to indoor air quality standards, appliance emission factors, and quantification of benefits from cooking appliance electrification.

This work produced an introductory, plain-language guide to household electrification including an appliance-by-appliance discussion of benefits and potential costs. While the utility incentive program information is specific to Southern California Edison's service territory and the South Coast Air Basin, this section could be easily revised by a university or non-profit serving other areas of the state.

Project analyses determined that residential appliance electrification results in significant local air quality improvements (a major benefit to communities with high CalEnviroScreen pollution burden scores) and made recommendations for investments and tariff designs that mitigate the upfront and ongoing costs of electrification for under-resourced households.

The potential for air quality "hot spots" near fossil-fuel electricity generation units was identified, and recommendations made for investments and tariff designs that mitigate air quality impacts through 2045.

This study also identified considerations that could increase costs for under-resourced households, namely the coincidence of peak gas use with peak electricity use, which may result in higher time-of-use rates during those peak hours.

This project included one of the first analyses of hourly natural gas data, which revealed the coincidence of peak gas use with peak electricity use and flagged it as a potential concern for grid managers.

This study demonstrated the potential for geographic dislocation between areas of local air quality improvement from appliance electrification versus areas of ambient air quality deterioration from grid emissions due to added electricity loads. It also showed the potential for annual net reductions in grid emissions to be associated with net increases in annual health impacts--such an outcome can happen if the timing of electricity consumption causes generating units located closer to larger population centers to operate more frequently.

CHAPTER 1: Introduction and Project Approach

1.1 California's Residential Building-Related Initiatives

California is moving forward aggressively with a multi-pronged agenda to decarbonize its energy system. However, more work is needed to understand rates of energy system transformations within under-resourced communities, the resulting health co-benefits of these transformations, and the potential for unintended interactions between various initiatives, with resulting impacts to these communities.

The state is currently pursuing initiatives along multiple pathways to accelerate reductions in energy consumption and greenhouse gas (GHG) emissions and transition to renewable energy. Four primary pathways identified for residential buildings are: electrification of natural gas appliances, retrofits for energy efficiency, electrification of vehicles, and deployment of distributed generation and storage.

Beyond the mitigation of carbon dioxide (CO_2) emissions, these initiatives are expected to provide enormous health benefits through reductions in exposure to natural gas combustion by-products including particulate matter, carbon monoxide (CO), nitrogen oxides (NO_x) and sulfur oxides, (SO_x), both from residential appliances and from grid-scale generator stations.

Greenhouse gas emission reductions associated with reduced fossil gas consumption are equally beneficial whether reduced consumption is from power plant generation or from gas appliances in homes. Health benefits from reduced pollutant emissions are geographic; the number of persons who benefit, and the degree to which health impacts differ, depend upon proximity to combustion sources. Those relationships are also pollutant-specific. It is essential to understand the unequal distribution of benefits associated with different energy transition pathways, particularly as they may accrue unequally to residents who have the resources to reduce their exposure to air pollutants and those who do not.

1.2 Project Goals and Objectives

This project sought to:

- Expand current understanding of indoor air quality within under-resourced households and the extent to which household appliances and occupants' energy behaviors relate to pollutant concentrations.
- Better understand the degree to which different energy transition pathways are likely to be naturally pursued within under-resourced communities.
- Enhance current understanding of interactions between electricity and natural gas systems.

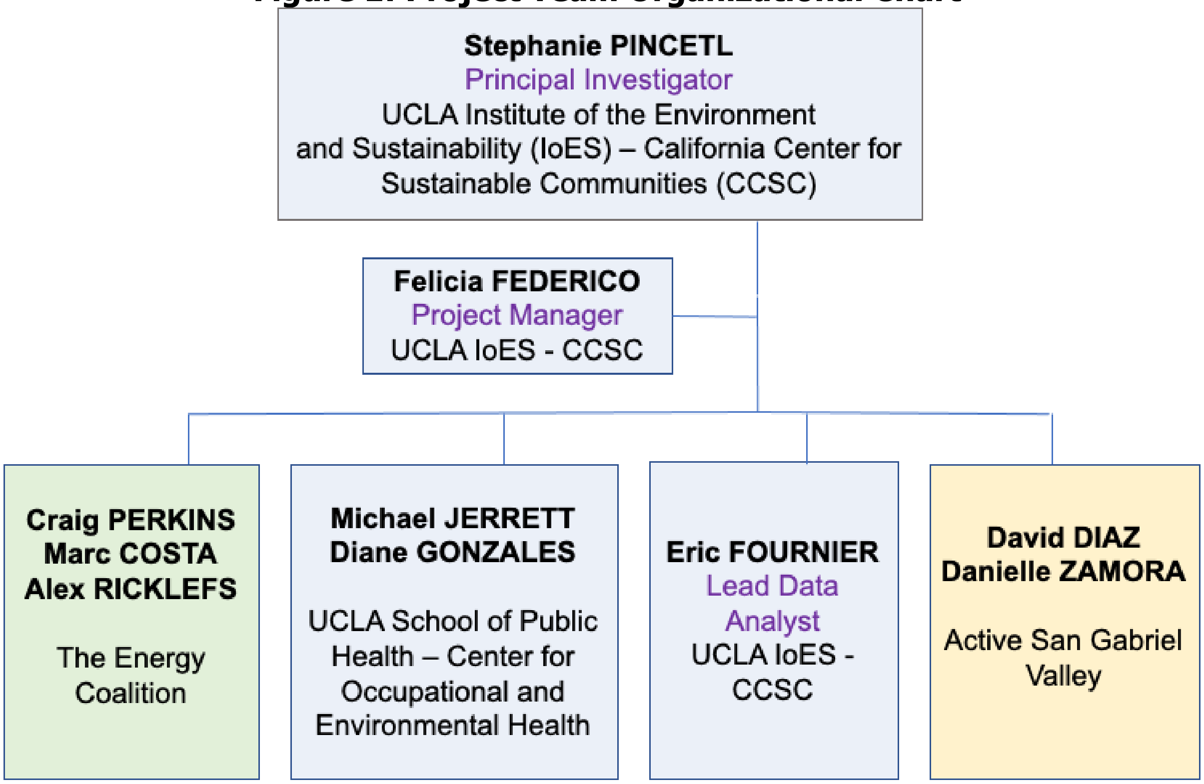
1.3 Project Team

This project was a collaboration between the University of California, Los Angeles (UCLA), Active San Gabriel Valley, and The Energy Coalition. The team was led by the California Center for Sustainable Communities (CCSC), within the UCLA Institute of the Environment and

Sustainability, in partnership with the Center for Occupational and Environmental Health (COEH), within the UCLA School of Public Health. Active San Gabriel Valley (Active SGV) is a community-based organization with 10 years of deep civic engagement in supporting a more sustainable, equitable, and livable San Gabriel Valley. The Energy Coalition (TEC) is a nonprofit established over 45 years ago that is dedicated to creating an equitable, clean-energy future.

Figure 1 shows the project team participants and organizational chart.

Figure 1: Project Team Organizational Chart



Source: UCLA

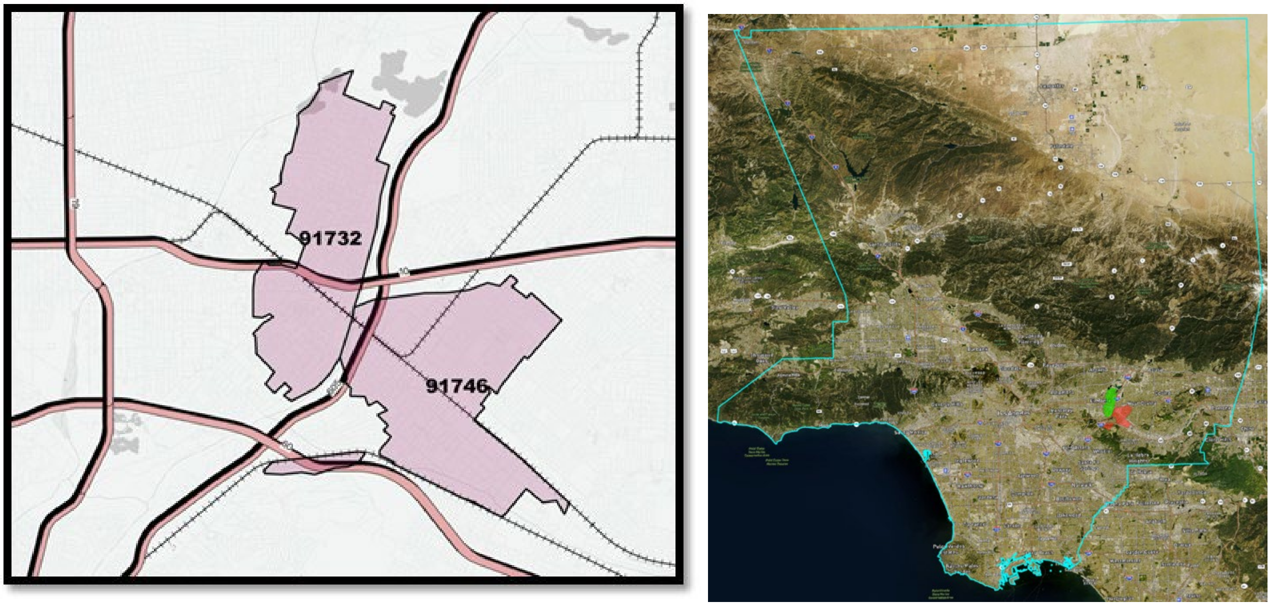
1.4 Study Area

The project study area consisted of two adjacent ZIP codes, shown in Figure 2:

- 91746–within the LA County unincorporated communities of Avocado Heights and Bassett
- 91732–within the City of El Monte

Demographic data on the two target areas are provided in Appendix Section A.1 - Table A-1.

Figure 2: Study Area



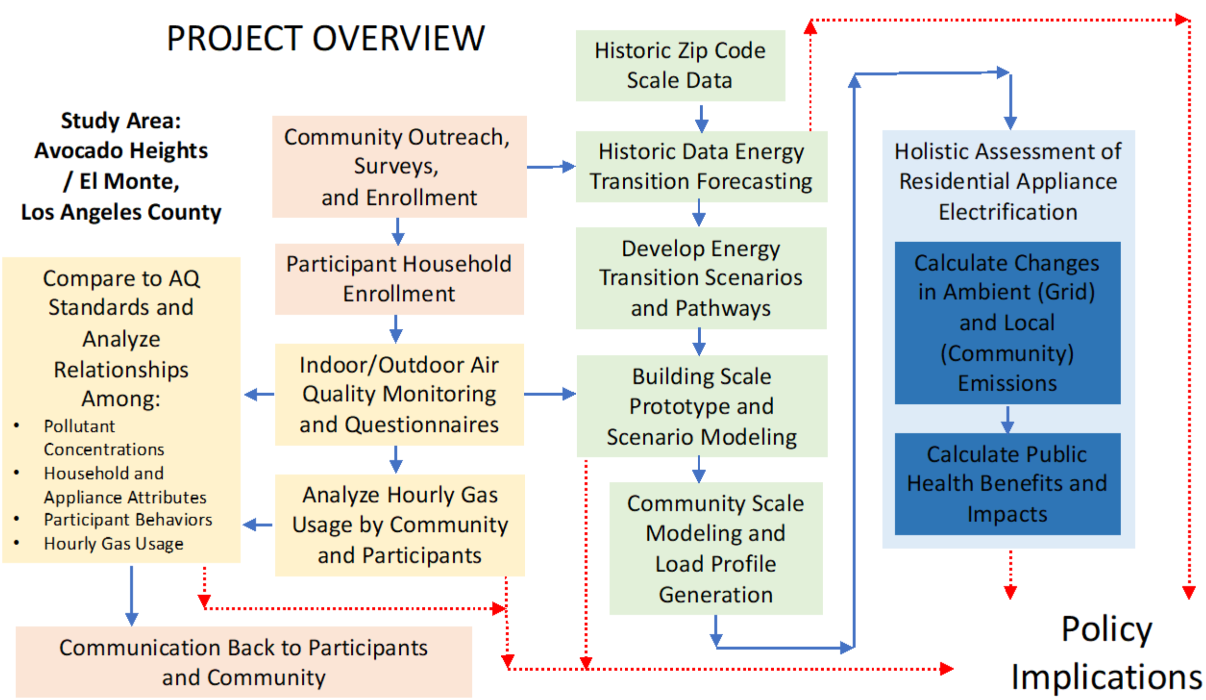
(Left) Study Area ZIP Codes; (Right) Study Area Location within the Context of Los Angeles County – green is 91732, red is 91746

Source: UCLA

1.5 Project Components and Schedule

The project consisted of various components, each briefly introduced here and more fully described in subsequent sections of this report. Figure 3 shows the overall relationships between project components.

Figure 3: Overview of Project Components and Relationships



Source: UCLA

- **Community Outreach and Surveys:** A brief survey of energy-related behaviors and household conditions was designed and distributed to residents in the study area. Outreach was conducted through public events, presentations to community groups, and social media, as well as through partnerships with school districts and other community organizations. Survey responses were used to solicit and screen households willing to participate in the indoor air quality monitoring and were also used to more fully understand the types of appliances in residents' homes, as well as the degree of, or the interest in, adoption of the energy transition pathways studied in this project: electric vehicles, rooftop solar, appliance electrification, and energy efficiency retrofits. Surveys were administered in both English and Spanish.

- **Enrollment of Participant Households:** Recruitment of participants followed from the outreach and survey work, although direct canvassing of homes was also required to enroll participants. A total of 64 unique homes were enrolled for air quality monitoring across two time periods: Winter 2019 and Summer 2019, with a subset of homes monitored in both time periods. Selection criteria included non-smoking households and a fairly even distribution between the two ZIP codes. Participants included both renters and owners, as well as SF and MF homes.

- **Air Quality Monitoring:** Air quality monitoring was conducted over a 2-week period in both winter and summer and involved contacts with participating households over three consecutive weekends. Homes were monitored using passive nitrogen dioxide ($NO_{2)}$ samplers for the first week and time-resolved PM measurement devices for the full two weeks. PM measurements were taken using paired indoor and outdoor monitors at each home; outdoor NO_2 sampling was conducted at selected homes, and three ambient weather stations were deployed. Monitoring equipment was installed in the homes over the first weekend, along with administration of Questionnaire #1 (which collected extensive information about home characteristics and appliances). NO_2 samplers were collected during the second weekend, along with administration of Questionnaire #2, which collected information about household behaviors during the first week. PM monitors were collected on the third weekend, along with administration of Questionnaire #3, which collected information about household behaviors during the second week. Questionnaires were written in both English and Spanish, and Spanish speakers were among the trained field research assistants.

- **Air Quality Data Analysis:** Summary tables, quality assurance/quality control (QA/QC) evaluations, analyses, and statistical tests were produced from the field data. Correlations were examined between measured pollutant concentrations and the presence and locations of natural gas appliances and ventilation equipment, along with the reported use frequency of natural gas appliances and ventilation equipment, among other variables. Results were then compared with monitoring seasons, between indoor and outdoor measurements, and with external data (such as American Community Survey data), previous indoor air quality monitoring studies, and national and state air quality standards.

- **Hourly Natural Gas Data Analysis:** Hourly natural gas consumption data for the two study ZIP codes, obtained from Southern California Gas Company (SoCalGas), were analyzed for annual, weekly, and hourly patterns to better understand implications for the electrification of gas appliances. In addition, hourly gas consumption data for program participants were analyzed for relationships to measured indoor pollutant concentrations.

- **Building-Scale Prototype and Scenario Modeling:** To characterize current and potential future household-scale energy use, a set of prototype building energy models was developed to reflect the study community's most common energy consumption and residential building stock characteristics. These prototype models were informed by data collected from study participants. For each prototype, modeling was conducted for baseline conditions and for a series of future scenarios related to residential building energy transitions. The term "scenario" refers to a set of discrete measures or new technologies that can be applied to the energy transition categories examined in this project: distributed energy resource (DER) adoption, light-duty electric vehicle (EV) adoption, energy efficiency (EE) improvements, and natural gas appliance electrification. For purposes of building-scale modeling scenarios (and subsequent community-scale modeling), EE measures were combined with appliance electrification measures. Model outputs included: total annual consumption and hourly load profiles for electricity and natural gas, GHG emissions, and utility bill cost estimates.

- **Energy Transition Forecasting:** The goal of this component of the project was to understand the current trajectory of the two study area ZIP codes with regard to residential building energy transitions within the scope of this project. First, historical empirical data around each transition were collected and analyzed by ZIP code. Next, population-growth forecasts were obtained from the responsible regional agency. Finally, appropriate mathematical growth-rate models were applied to the previous two data sets to create the forecasts. These forecasts reflect anticipated future changes in aggregate residential building energy demand, by ZIP code, in the absence of supplemental incentives; they inform the "baseline" conditions when developing transformation pathways in the next step of the project.

- **Energy System Transformation Pathway Simulation:** The term "pathway" corresponds to a specific rate and extent of future scenario adoption related to the three categories of residential building energy transitions just described: DER adoption, EV adoption, and appliance electrification. The team developed a set of pathways based on building-scale modeling scenarios evaluated through subsequent steps in the project analysis. For each category of transition, a set of low, medium, and high growth rates for each scenario was evaluated. For example, a total of 10 different pathways were evaluated for the building electrification transition. These consisted of a baseline plus three scenarios, each at three different growth rates, for a total of nine alternative pathways.

- **Community-Scale Modeling and Load Profile Generation:** This step of the analysis built on annual hourly kWh load profiles (8,760 hours) generated through building prototype modeling. These load profiles reflect the average baseline performance of a range of buildings representative of the current community building stock, as well as the modeled performance of these buildings under possible future energy system transformation scenarios. Community-scale load profiles were generated by aggregating and scaling building load profiles based on the number of buildings assigned to each model scenario. Future changes in hourly loads can be composed into an aggregate community-scale hourly load profile. Each pathway simulation run generated a 25-year hourly composite load profile (219,000 hours) that reflects the future electricity demand of all the households in the study area, from 2020 to 2045.

- **Holistic Assessment of Residential Electrification:** This portion of the analysis focused on residential building electrification to better understand if future electrification efforts could potentially cause unanticipated net-increases in overall emissions. It has been hypothesized that such an unintended outcome may be possible when accounting for ambient emissions from the grid's fossil fueled generators. Therefore, only on the highest growth rate pathways were assessed, as a reflection of the maximum speed of electrification within the study community.

    - **Calculation of Emissions Changes:** Two categories of pollution emissions estimates were generated: one for reductions in local emissions due to appliance electrification, based on residential natural gas appliance emissions factors; and the second for marginal grid emission increases associated with increased electricity demand, using the United States Environmental Protection Agency's (EPA) "AVoided Emissions and geneRation Tool" (AVERT). AVERT allows users to estimate spatial and temporal changes in marginal emissions from three major categories of air pollutants (CO_2, NO_X, $PM_{2.5}$) from anticipated grid output changes required to meet electricity demand. AVERT incorporates a database of historical electricity generator unit (EGU) operational performance and emissions data that describes the likelihood that an EGU will be turned either on or off when faced with the decision to supply a marginal unit of electricity demand. Using a set of probability distributions computed for all of the generator units within a specific geographic region, marginal grid emissions associated with different aggregate load changes can then be derived using a Monte-Carlo sampling procedure. Projections from Grubert el al. 2020 on future fossil EGU retirement dates were incorporated into the AVERT model.

    - **Calculation of Public Health Benefits and Impacts**–The United States Environmental Protection Agency's (EPA) CO-Benefits Risk Assessment (COBRA) model was used to estimate human health benefits and impacts associated with changes in $PM_{2.5}$ emissions, as calculated by the AVERT model. COBRA is comprised of three core modules: (1) a fate-transport module, based upon simplified regional atmospheric dynamics; (2) a human-health-impact module that translates ambient air pollutant concentrations into estimates of human health incidents; and (3) a monetization module that converts human health incidents into dollar values of public health costs.

- **Communication of Findings Back to the Community:** Findings were communicated back to the study community using multiple methods throughout the project period. Following the air quality monitoring, a summary of individualized results was provided to each participating household, using a reader-friendly format, including: a wind-rose diagram that showed average indoor concentrations of $PM_{2.5}$ during each hour of the day, the percent of time that indoor $PM_{2.5}$ levels exceeded health benchmarks, and a categorical designation (for example, slightly lower) for levels of indoor NO_2 compared with California's ambient air quality standard. Additional communications were designed to reach a broader audience beyond the participant households; however, activities taking place from March 2020 onwards were impacted by the COVID-19 pandemic, which precluded in-person meetings. A virtual social event was held in June 2020 via Zoom to present preliminary findings from the project and answer questions. A series of post-event materials was shared in multiple languages on the project webpage, Active SGV's monthly email newsletter, social media accounts, and via direct mail. A final virtual community event took place on July 22, 2021.

The project contract period was July 2018–Dec 2021. The project schedule is shown in Appendix Section A.2-Table A-2.

CHAPTER 2: Methods

2.1 Community Outreach and Participant Enrollment

2.1.1 Overview

This initial step of the project included development of a survey within the project area, followed by enrollment of participants in the indoor air quality monitoring program. Administration of the survey was part of a broad effort to connect with various community groups and use social media to develop awareness of and an interest in the project to attract participants.

2.1.2 Survey Design

To identify and recruit volunteer residents for in-home air quality monitoring, an informal survey was developed to collect basic data from a broad set of residents in the study community. Survey data also informed assumptions about the rate of transformation pathways within the communities and identified potential volunteers to screen for suitability.

The survey was designed to meet the following criteria:

- No more than two pages (one page, front and back), to avoid questionnaire "fatigue" and the possibility that recipients might not complete it.
- Pre-printed answer options wherever possible, for ease of completion and for consistency in tabulation and analysis.
- Questions about contact information were marked as optional, to protect privacy.
- Included a question about household smoking because smoking was the most critical screening criteria for potential volunteers for air quality monitoring.

A copy of the final survey appears in Appendix Section B.1 - Figure B-1. It was also translated into Spanish due to the large number of Spanish-speaking households in the target areas.

2.1.3 Outreach

An extensive, multimodal, multilingual outreach effort was developed and implemented to engage a broad cross section of project area residents to administer surveys and recruit volunteers. The goals were to:

- Form partnerships with school districts and community-based organizations in the target areas.
- Raise project visibility via social media, tabling at events, and presentations.
- Collect at least 250 surveys through outreach activities.
- Identify, screen, and engage 70 households to participate in indoor air quality monitoring.

Between December 2018 and April 2019, the following outreach activities were completed:

- Developed a recruitment flyer and website - http://www.activesgv.org/healthy-home-study.html.
- Developed vibrant social media content using Facebook.
- Translated all materials into Spanish.
- Attended 36 events:
  - Hosted interactive outreach booths at community events (for example El Monte – South El Monte Christmas Basket Giveaway, Parks After Dark community event series).
  - Presenting to existing community groups (such as school districts, Parent Teacher Student Associations (PTSA), neighborhood watches).
- Collected 449 surveys. Although not all survey respondents included their addresses, the following totals were identified in the two project ZIP codes:
  - 134 Survey respondents from 91732.
  - 69 Survey respondents from 91746.
- Conducted labor intensive direct canvassing of homes in the two study ZIP codes to meet targets for the total number of participant households (while also screening for smoking) and achieved a balanced distribution both within and across the two ZIP codes and between SF and MF buildings.
- Recruited 64 households to participate in the air quality monitoring program. This included 35 homes in ZIP code 91732 and 29 homes in ZIP code 91746. Participants were both renters and owners.

2.2 Air Quality Monitoring and Data Analysis

2.2.1 Overview

Monitoring was conducted from February 9-24, 2019 (winter) and July 13-28, 2019 (summer) in accordance with the protocol summarized here. Discussion of university review for "human subjects research" is included in Appendix Section B.2.1.

Air quality data was collected both inside and outside volunteer participant homes using passive NO_2 samplers and time-resolved PM monitors. All air quality measurement devices were set up, monitored, and collected by trained field research assistants who also administered three sets of questionnaires with each participant household.

2.2.2 Sampling Rationale

Gas combustion from residential appliances is a source of criteria air pollutants including NO_2. In 2016, Lawrence Berkeley National Laboratory (LBNL) published the California Health Homes Indoor Air Quality study (Mullen et al., 2016). This large-scale study investigated the impact of gas appliances on indoor air quality in 352 California homes. Air pollutants measured included carbon monoxide (CO), nitrogen oxides (NO_X), NO_2, formaldehyde, and acetaldehyde. That study guided development of the air quality and meteorological-data collection methodologies for this project.

To utilize project funds most effectively, collection and analysis of nitrogen-oxide compounds were restricted to only NO_2 because most data for oxides of nitrogen (e.g., distribution in air, human exposure and dose, health effects) are for NO_2, as it is the most prevalent form of NOx in the atmosphere. Furthermore, NO_2 is an air pollutant covered by California ambient air quality standards, and there is ample research correlating NO_2 with residential gas appliance use.

Few studies examining indoor air quality and gas appliance use have concentrated on PM, so this current research offers new insights into these appliances. A study by Dennekamp et al. (2001) used low-cost PM monitors to collect speciated particle sizes (0.3-10 µm in diameter) which are within the range of emissions from gas cooking (0.15 – 0.40 µm). Given this unique opportunity to examine particles in indoor environments, PM and NO_2 were prioritized for the current study.

Due to limited funds and the number of homes in the study, field data collection did not include CO monitoring. Furthermore, Mullen et al. (2016) showed approximately three times as many homes exceeding the annual average air quality standard for NO_2 than for CO, which supports the prioritization of NO_2 monitoring.

Both indoor NO_2 and PM concentrations can be influenced by ambient air quality depending on location, housing stock, and occupant behavior in each residence. Therefore, in the present study, three primary outdoor environments were selected to examine the effects of local sources on NO_2 and residential penetration factors specific to the study area. One home was selected for outdoor NO_2 sampling from each category: near major roadways, near industrial emissions, or removed from any identifiable competing source(s). These three distinct environments provided information about the impact of local NO_2 sources and penetration factors on adjacent homes. All sampled homes were assigned to one of the three environmental categories, and indoor NO_2 concentrations were adjusted accordingly. Furthermore, outdoor PM was measured at each home.

Additional discussion of controls for outdoor sources and weather are included in Appendix Section B.2.2.

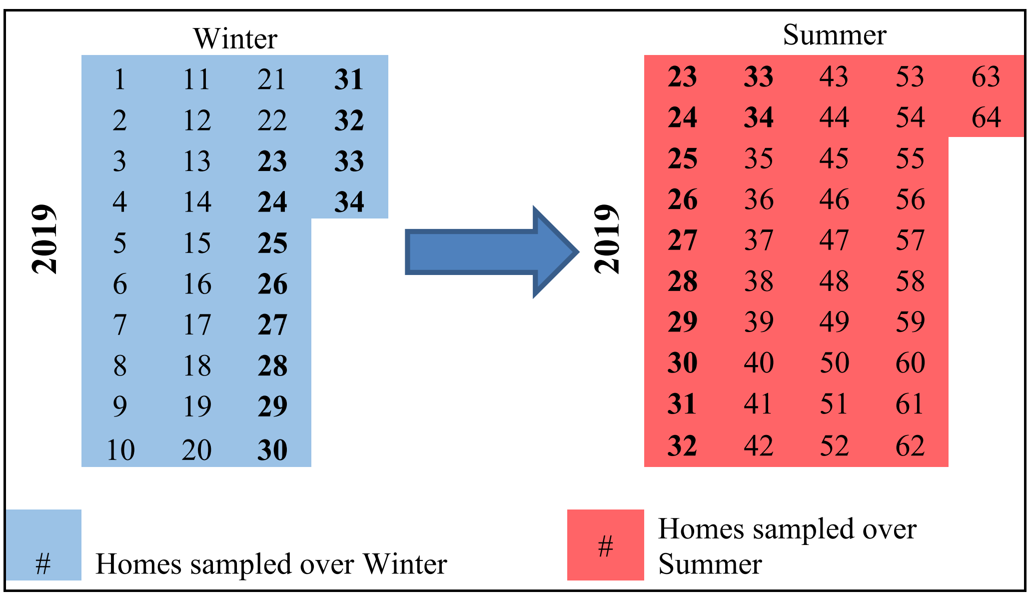
Mullen et al. (2016) reported that appliances were not associated with higher concentrations of formaldehyde or acetaldehyde, so these aldehydes were not included in this analysis. There were insufficient project funds to install continuous recording devices that monitor furnace and hot water heater operations. Detailed data were collected regarding home appliance use, however, and gas consumption data were obtained from SoCalGas. Both data sets were used in the interpretation of pollutant monitoring results.

2.2.3 Participant Households

A total of 76 homes was monitored over two sampling periods: 34 in winter and 42 in summer. Of these homes, 12 were sampled in winter and summer, resulting in a total of 64 unique homes sampled (Figure 4). Monitoring was conducted across the two ZIP codes of the study area in eastern Los Angeles County; 35 homes were located in ZIP code 91732, and 29 homes were in ZIP code 91746 (Figure 5). Summary demographic data for the study communities is included in Appendix A–Table A.1.

This total was four homes short of the target 80 homes per the Monitoring Design Plan, primarily due to difficulties in recruiting participants. Although Active SGV far exceeded targets for attending community events and conducting surveys (and even did some time-consuming door-to-door recruitment), the monitoring protocol was a big "ask" for households. It required a commitment of an hour or more on three consecutive weekends, as well as sharing appliance and activity information, having strangers inside the home, and hosting equipment for two weeks. Experience from this study, however, showed that these aspects of the protocol were essential to obtaining high-quality data and gaining insights that would have been impossible with other methods such as phone interviews or mailing participants monitoring equipment for self-installation.

Figure 4: Graphical Representation of Sampled Homes During Two Sampling Time Frames



Numbers represent unique household identifiers. Bolded numbers indicate homes sampled over both winter and summer.

Source: UCLA

Figure 5: Distribution of Homes in Project (black dots) During Both Sampling Time Frames

(n = 64 unique homes). Twelve (12) homes were included in both summer sampling time frames to identify potential seasonal variations.

Source: UCLA

2.2.4 Monitoring Locations and Equipment

Air quality data were collected inside and outside participant homes using passive (Ogawa NO_2 samplers) and time-resolved (PurpleAir PA-SD-II for particulate matter) measurement devices for 7 days and 14 days, respectively. The air quality monitoring instruments used are summarized in Table 1. Pollutant concentrations, temperature (T), and relative humidity (RH) were measured in the family room of each home and in select outdoor environments. Each participant also hosted a PM monitor outdoors with one exception, where one PM monitor was used to measure the outdoor air quality of two adjacent homes.

Table 1: Summary of Pollutant and Environmental Monitoring Instruments Used in Study

Parameter	Manufacturer and Model	Data Resolution	Monitoring Time Period	Location of Deployment
NO_2	Ogawa NO_2 passive sampler	Integrated over sample period	7 days	Family room, outdoors at a selected number of homes
PM	PurpleAir (PA-SD-II) with secure digital (SD) data storage. Particle sizes: 0.3, 0.5, 1.0, 2.5, 5.0 and 10um. Also measures T and RH.	80 - 120 seconds	2 weeks	Family room, outside home

Source: UCLA

2.2.5 Participant Questionnaires

Questionnaires related to household characteristics and occupant behaviors were conducted in person during the setup and collection of the monitoring equipment. The following three questionnaires were administered:

- Questionnaire #1: Collected extensive information about home attributes including building type, vintage, square footage, construction, and occupancy, as well as appliance types, numbers, and fuel sources. Administered the first weekend as monitoring devices were installed in the homes.
- Questionnaire #2: Collected information about behaviors during week 1 and was administered during the second weekend when the passive NO2 meters were collected.
- Questionnaire #3: Collected information about behaviors during week 2 and was administered during the second weekend when the time-resolved PM monitors were collected.

Data collected on activities in the home during the sampling period included frequency of appliance use, occupancy patterns, and other potential pollutant sources inside and outside of study homes. In addition, the questionnaires asked several open-ended questions regarding perceived sources of air pollutant emissions of concern near occupant homes.

2.2.6 Air Quality Data Analysis

Numerous summary tables, quality assurance/quality control (QA/QC) evaluations, analyses, and statistical tests were produced from the data collected. A discussion of QA/QC, data management, and privacy appears in Appendix Section B.2.3.

Statistical relationships were examined between measured pollutant concentrations and the presence and location of gas appliances, ventilation equipment, and the reported use frequency of gas appliances and ventilation equipment, among other variables. Results were compared between monitoring seasons, indoors and outdoors, and external data such as the

United States Census Bureau's American Community Survey (ACS)[2], American Housing Survey (AHS)[3], previous indoor air quality monitoring studies, and both National Ambient Air Quality Standards (NAAQS) and California Ambient Air Quality Standards (CAAQS).

2.2.7 Hourly Gas Data Analysis

Account level hourly gas usage data was obtained from SoCalGas for all residential customer accounts located within the project's study area. Data were provided for one year, from August 15, 2018 through August 15, 2019, which covered both summer and winter data collection periods. Billing account keys and meter badge numbers were associated with each household location using a precise address-matching procedure. Each address match was verified and manually cross-referenced with latitude/longitude coordinate data. Particulate matter measurements taken at 15-second intervals were aggregated to hourly average values for association with hourly gas metered data.

2.3 Energy System Modeling Methodology Overview

This section provides an overview of the methodology underlying the project's energy system modeling and co-benefit assessments.

2.3.1 Scope

The scope of the energy system modeling encompasses four major system components:

1. Energy flows (consumer hourly electricity and gas loads).
2. Economic flows (consumer retail expenditures on energy and equipment).
3. Emissions to ambient air of criteria air pollutants and greenhouse gases.
4. Emissions to local air (building emissions) of criteria air pollutants and greenhouse gases.

2.3.2 Assessment Framework

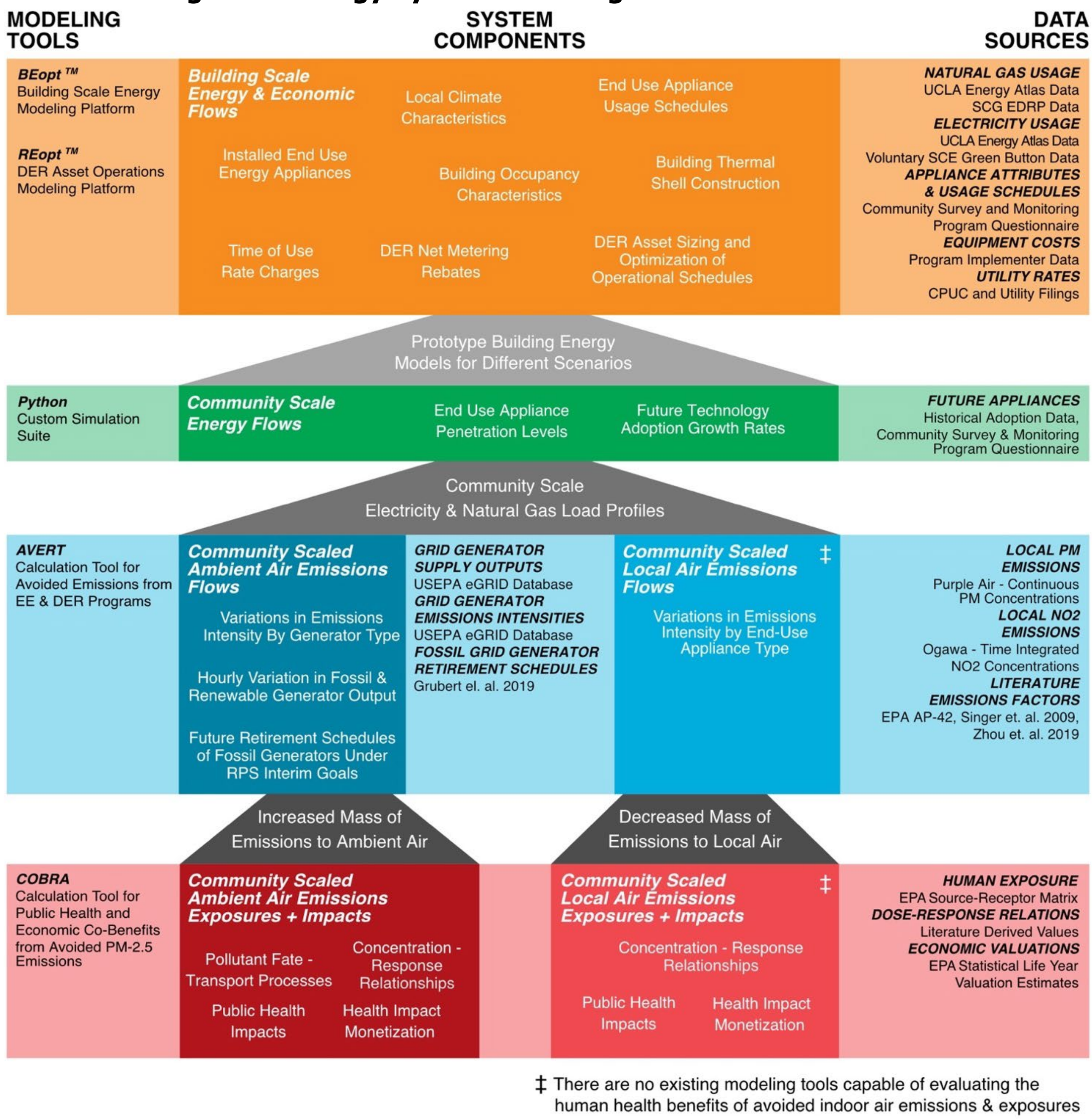
Figure 6 illustrates the flow of information through the assessment framework.

At the building level, the impact of different scenarios on hourly energy flows was modeled with customized building prototype models developed within the Building Energy Optimization Tool (BEopt) software. At the community scale, individual energy system transition pathways were simulated (through a set of custom python scripts) by specifying different rates of change, over time, in the combinations of household prototype models. Definitions and details of the scenarios and pathways modeled are provided in the next section.

[2] US Census Bureau. American Community Survey. Available at: https://www.census.gov/programs-surveys/acs

[3] US Census Bureau. American Household Survey. Available at: https://www.census.gov/programs-surveys/ahs

Figure 6: Energy System Modeling Assessment Framework



Source: UCLA

Once electricity load profiles were generated for the community scale energy system under each different transformation pathway, these profiles were fed to the coupled AVERT + COBRA modeling workflow to estimate changes in ambient and local air quality emissions of fine particulate matter ($PM_{2.5}$) and their public health impacts.

"Ambient" changes result from added loads on the electric grid and subsequent increases in electric generating unit emissions. "Local" changes result from reduced gas combustion due to residential appliance electrification. In both cases these are outdoor changes; there are currently no modeling tools that evaluate the assumed human health benefits of avoided indoor air emissions and exposures.

2.3.3 Transition Categories, Scenarios, and Pathway Descriptions

Modeling was conducted for three categories of residential energy system transitions, shown in Table 2.

Table 2: Residential Energy System Transition Categories

Transition Categories	Summary Description
Category 1*	Residential gas appliance electrification
Category 2	Residential distributed energy resource adoption
Category 3	Residential light-duty vehicle fleet electrification

***Embedded within Category 1 are assumptions about future improvements in the baseline energy efficiency of the residential building stock as guided by changing building codes and the current state of performance of key energy end-use technologies.**

Source: UCLA

Within each category various scenarios were defined at the building scale that corresponded with the discrete measures and new technologies applied to a representative prototype model of homes within the study area.

At the community scale, a set of pathways was identified within each category. These pathways corresponded with the breadth and specific rates of future scenario adoption, designed to span the range of foreseeable future transitions. Pathways were modeled using simulation techniques.

Transition Category 1. Residential Gas Appliance Electrification

The residential electrification scenarios will primarily focus on air and water heating systems, clothes dryers, and cook stove ranges/ovens, as these are the most common gas appliances in residential homes. Major current obstacles to appliance electrification include high up-front equipment costs, time-of-use considerations, required household retrofits, and performance concerns relative to gas alternatives. Results from the monitoring component of this project informed the designation of "indoor air quality focused" pathways, which prioritize the electrification of cooking appliances, followed by Heating, Ventilation and Air-Conditioning (HVAC) systems to provide the greatest reduction in indoor pollutant concentrations for a typical household in the study area (Table 3).

Table 4 lists the scenarios and pathways within this transition category.

Table 3: Household Scale Prototype Building Model Scenarios – Appliance Electrification

Scenario Name	Summary Parameter Description
Baseline Scenario	Household with common gas appliances
Indoor Air Quality-Focused Minor Electrification	Household with electrified induction oven/range systems and EE upgrades
Indoor Air Quality-Focused Moderate Electrification	Household with all electrified appliances except water heating, and with EE upgrades
Full Electrification	Households with all electric appliances including water heating, and EE upgrades

Source: UCLA

Table 4: Community Scale Energy System Pathways – Appliance Electrification

Pathway Name	Summary Description	Narrative Description
Baseline Growth	Current growth rates in appliance electrification continue as projected.	California fails to meet its appliance electrification objectives. Appliance electrification rates continue in accordance with recently observed historical trends.
Air Quality Focused Minor Electrification Growth	Future acceleration in electrification activities focuses on those appliances which deliver the greatest reductions in potentially harmful co-product emissions from indoor gas combustion.	Building occupants and owners become increasingly aware of and concerned with the potential health risks associated with the operation of their existing installed gas based cooking and domestic appliances. They begin to replace these gas systems with electrified alternatives with zero air emissions and immediate performance features. The availability of contractors experienced in the installation of the systems grows with the number of existing deployments, further amplifying savings. Additionally, more and lower cost equipment options progressively become available.
Air Quality Focused Moderate Electrification Growth	Future acceleration in electrification activities expands on the previous pathway to	Building occupants and owners become increasingly aware of and concerned with the energy costs associated with the operation of their existing installed gas-based end use appliances. They begin to replace these gas systems with electrified alternatives including high efficiency heat pump based HVAC

	additionally focus on those appliances with minimum user interaction, short periods of return on investment, and lowest installation costs.	systems. The availability of contractors experienced in the installation of these systems grows with the number of existing deployments, further amplifying savings. Additionally, more and lower cost equipment options progressively become available.
Full Home/Unit Electrification Dominated Growth	Future acceleration in electrification focuses on the full-scale conversion of all existing gas appliances within the home to state-of-the-art electrified end-use systems.	Building occupants and owners are incentivized to convert to all electric appliances, completely eliminating gas consumption within the home. Some of these appliances allow customers to shift their time of consumption and take advantage of off-peak electricity rates. The available incentives motivating this transition address structural barriers such as the need for main electrical panel upgrades, new wiring, and the upfront costs associated with purchasing and installing the new electrified versions of the major appliances. Water heating services are provided by heat-pump based electric water heaters.

Source: UCLA

Transition Category 2: Residential Distributed Energy Resource Adoption

The distributed energy resource scenarios focus on solar photovoltaic (PV) and battery storage systems. The different scenario prototypes developed will reflect households with: no solar PV or battery storage, solar PV and battery storage systems, solar PV only, and battery storage systems only. The optimal sizing and operational characteristics of the solar PV and battery energy storage systems were solved for each prototype model using REopt software. Scenarios and pathways within this transition category are included in Appendix B-Table B-1.

Transition Category 3: Residential Light Duty Vehicle Fleet Electrification

The vehicle electrification will focus on load profile changes associated with EV ownership. The high proportion of renters within under-resourced communities presents a problem when it comes to EV adoption as households may be prohibited from installing charging units on-premises. These charging concerns come in addition to the heightened range anxiety of community members, due to their longer than average working commutes. Scenarios and pathways within this transition category are included in Appendix Section B.3.2.

2.4 Building Scale Prototypes and Modeling

To characterize current and potential future household-scale energy use, a set of prototype building energy models was developed to reflect energy consumption levels and building stock characteristics common to the study community. These prototype models were informed by data collected from study participants. For each prototype, the following outputs were generated for baseline conditions, as well as for a series of future transition scenarios related to appliance electrification, EV adoption, and DER resources: total annual consumption and hourly load profiles for electricity and natural gas, GHG emissions, and estimates of utility bill costs. Key aspects of the building modeling methods are summarized here.

2.4.1 Modeling Tools

The Building Energy Optimization Tool[4] was used to develop the building energy models; BEopt is a National Renewable Energy Laboratory (NREL) open-source tool that can be used to analyze residential building designs and identify energy consumption trends, GHG emissions, and utility bill impacts from energy retrofits.[5] BEopt models heat transfer and other physical properties at a high-resolution time scale and yields hourly load profiles and quantitative energy and financial metrics. It requires a large data set on building characteristics including area, architecture, building envelope, occupancy, energy system and utility rate. The Renewable Energy Integration & Optimization Tool (REopt) was used to determine the cost of PV and batteries, part of the development of DER scenarios.

2.4.2 Modeling Steps

The following steps were taken to create the prototype models:

1. Used data from the air quality monitoring study, the questionnaire, and survey as the starting point for data inputs.
2. Defined a set of prototype buildings based on heating, ventilation, and air-conditioning (HVAC) configurations that represent the range of residential buildings in the study community.
3. Defined a set of energy efficiency measures and electrification measures for all gas appliances and their alignments with Title 24, 2022 code updates.

[4] BEopt.nrel.gov

[5] Christensen, C., Anderson, R., Horowitz, S., Courtney, A., and Spencer, J. *BEopt(TM) Software for Building Energy Optimization: Features and Capabilities*. 2006

4. Used BEopt for each prototype building, modeled each electrification measure to fully understand energy, thermal comfort, and economic impacts. The team used this information, along with findings from the indoor air quality analysis, to help define electrification scenarios.
5. Used BEopt for each prototype building, ran defined electrification scenarios, and created output (time series) files.
6. For each load shape generated, applied the REopt software to determine optimal cost and GHG-optimal scenarios for different configurations of DER adoption; created output files for hourly load profiles for each of the buildings' scenarios.

The process was iterative, beginning with defining averages and trends and ending with a rich set of prototype models of the most common buildings among study residents.

2.4.3 Data Sources

Data sources for model inputs are listed in Appendix B–Table B-5. and include residential questionnaire data on appliance types and frequency of use, measured temperature data, building stock information from both the residential questionnaire and the UCLA Energy Atlas, aggregated monthly electricity and natural gas consumption data from the UCLA Energy Atlas, and aggregated data based on one year of hourly account-level natural gas data obtained from SoCalGas.

The UCLA Energy Atlas backend database contains account-level electricity and natural gas consumption data from both Southern California Edison (SCE) and SoCalGas, sociodemographic data, and other contextual spatial layers. Data shared with project partners were aggregated for privacy according to State regulations and nondisclosure agreements.

Additional data was obtained from the California Energy Commission (CEC) Residential Appliance Saturation Survey,[6] the Pacific Northwest National Laboratory's California-specific residential prototype building energy models,[7] and the Title 24 code defaults for minimum efficiency.[8]

2.4.4 Key Input Variables

Building occupancy and heating and cooling temperature set points were two key variables that required special attention to ensure that the models accurately represented the study community.

[6] https://www.energy.ca.gov/appliances/rass/

[7] https://www.energycodes.gov/development/residential/iecc_models

[8] Excel versions of lookup tables were obtained from CEC staff for all code vintages of residential building energy codes and standards.

Building Occupancy

In BEopt, the number of occupants affects appliance usage, fixtures, and miscellaneous electric loads (MELs) such as plug loads. The BEopt formula for calculating the number of occupants is a function of the number of bedrooms:

$$\text{Occupancy Ratio} = 0.59 \times \text{Number of Bedrooms} + 0.87$$

However, because data on the actual number of occupants for each household was available from the questionnaires, new occupancy factors were created. In fact, the actual number of occupants by house type, on average, was often much higher than that assumed in BEopt, e.g., close to factor of two low for SF homes. Appendix B–Table B-6 shows the values that BEopt would have specified versus the values that were manually added to the models; average values are shown for each category of home. Therefore, a correction factor for each building category was applied to update the default occupancy values in BEopt.

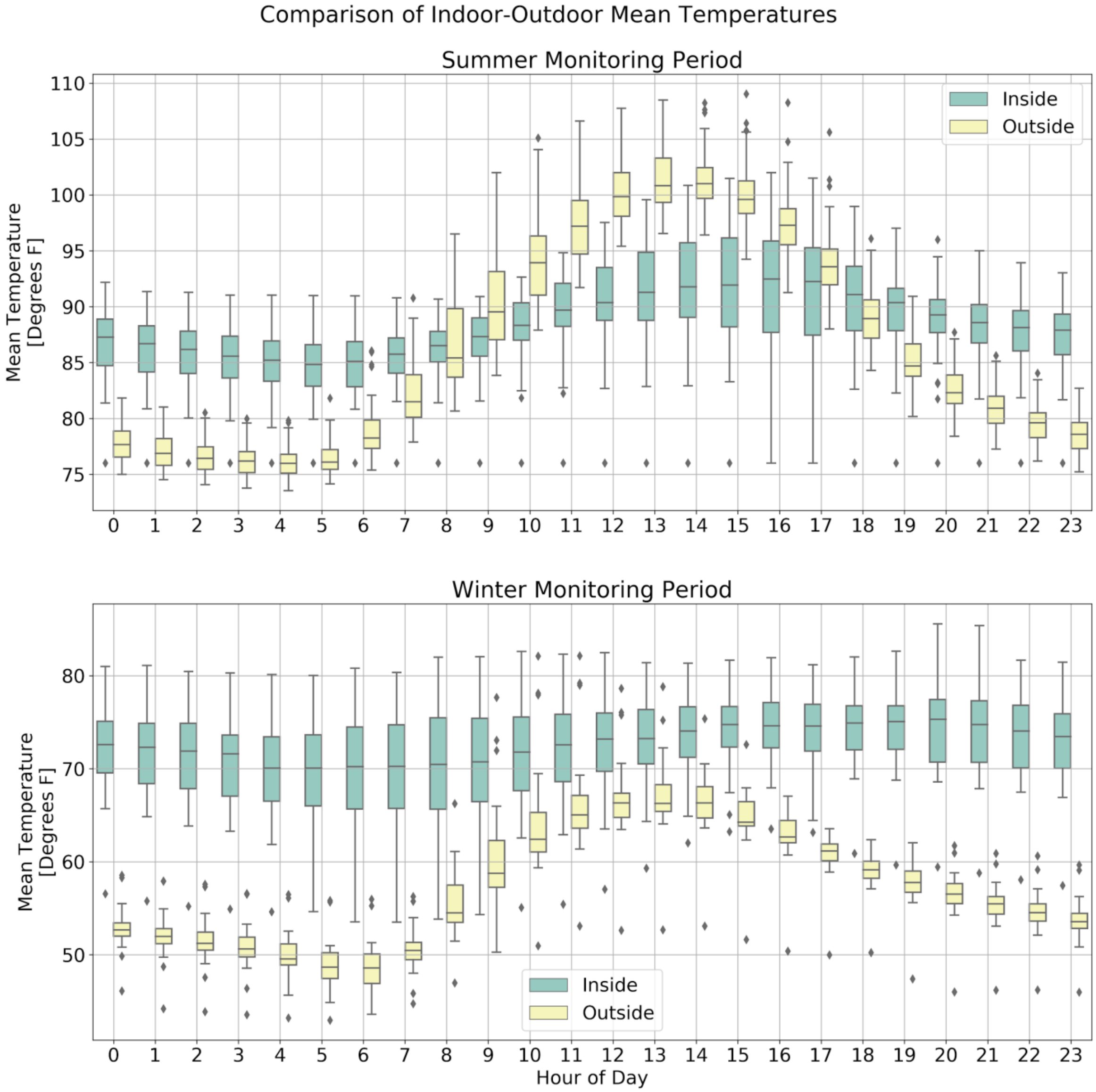
Automated Temperature Set Points

One of the most valuable pieces of monitored data from participant's homes was the hourly, site-specific data on paired indoor and outdoor air temperatures (Figure 7). Standard practice for the energy modeling community is to calibrate energy models only with energy consumption data; measured indoor air temperatures are not typically included. Questionnaires collected from participants included resident automated heating and cooling set points, but only half of participants in SF homes and fewer than 10 percent of participants in MF homes had programmable thermostats. The high summer temperatures inside the homes indicated that participants heavily self-regulated their cooling equipment, primarily using it only during a short period in the afternoon. Heating equipment, on the other hand, seemed to operate for longer periods for a more constant and comfortable indoor temperature. This information was used to set the automated heating and cooling set points and schedules to more accurately reflect indoor temperatures for homes in the study area.

2.4.5 Building Prototype Categories

Prototype building models were developed to represent different building classifications in the community. Of the 70 households studied, 53 were SF homes that did not have shared walls, three were townhouses or condos, five were multi-unit households, seven were apartment units, and two were mobile homes. Since there were similarities in the multi-unit households and apartment units, these two categories were grouped together as multi-family. Due to the low number of townhouses and mobile homes in the study and limited data, prototype models were not developed for these property types.

Figure 7: Box Plots of Hourly Indoor and Outdoor Recorded Temperatures



Source: UCLA

HVAC Systems as the Basis for Prototypes

The prototypes were defined by two main categories: SF detached home versus multi-unit, and then segmented by the most common combinations of HVAC systems. Appendix B–Table B-7 contains descriptions of the HVAC equipment types within the study homes. Table 5 shows the types of HVAC configurations present in SF homes among the study participants. The values in bold represent the five most common SF HVAC configurations, which were selected to be modeled as prototypes.

Table 5: Single-Family HVAC Configuration Frequency

	Space Cooling Method			
Space Heating Method	**Central AC**	**None**	**Window AC**	**Grand Total**
Central Furnace and Space Heater	**8**		4	12
Central Furnace and Wall Furnace	1			1
Central Furnace Only	**9**	**2**	1	12
Central Furnace, Wall Furnace and Space Heater			1	1
No Central Heat, Wall Furnace or Space Heating Indicated		2	5	7
Radiant Heat and Space Heater			2	2
Space Heater Only	1	2	7[9]	10
Wall Furnace and Space Heater			**6**	6
Wall Furnace Only	1	2	**10**	13
Grand Total	20	8	36	64

Source: The Energy Coalition

Table 6 shows the types of HVAC configurations present in MF homes among the study participants. The values in bold represent the MF homes' HVAC configurations modeled in the prototypes.

Table 6: Multi-Family HVAC Configuration Frequency

	Space Cooling Method		
Space Heating Method	**Central AC**	**Window AC**	**None**
Central Furnace Only			1
Wall Furnace Only		**6**	
Space Heater Only		**2**	
Wall Furnace and Space Heater		**3**	
Grand Total		11	1

Source: The Energy Coalition

2.4.6 Single-Family Building Prototype Models

Appendix Section B.4.4 shows the names and defining features of the SF building prototypes, as well as fixed and variable inputs to the SF home prototype models. Variable inputs were used for the parametric analysis and determined from analyzing the survey data for patterns. Heating and cooling set-point values were determined from analyzing the indoor air temperature collected from the monitoring devices installed in each participating home. For other variables such as HVAC efficiency, ACEEE building energy code vintage tables were used.

[9] The configuration of 'space heater only' was not modeled because the most common underlying survey response in this category was that the occupant did not know what type of heating system they had, and there was limited access to those homes during the site visit.

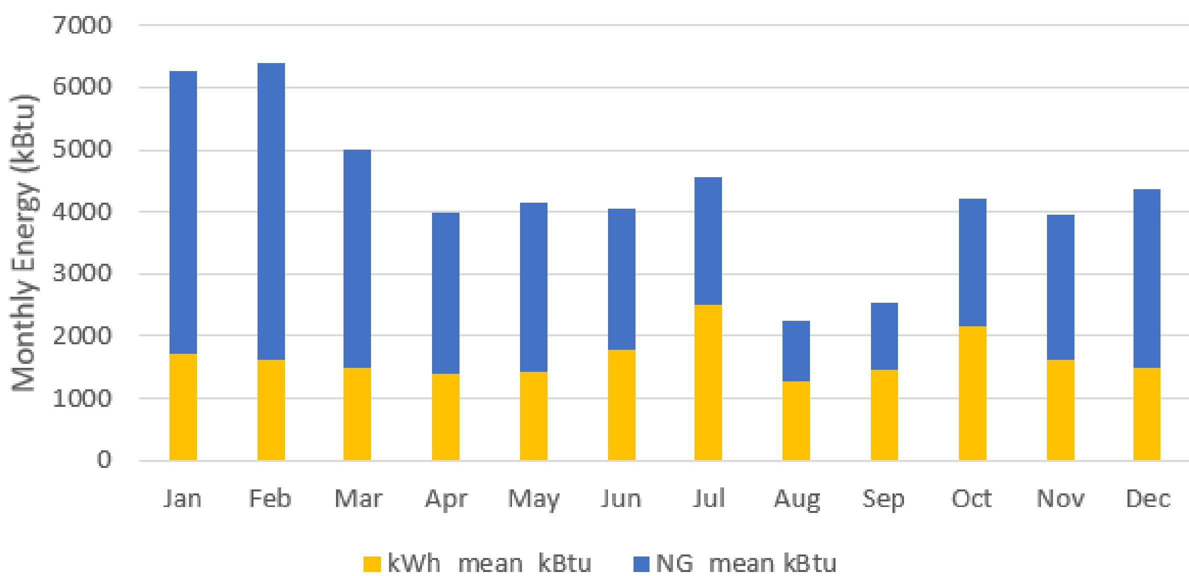
2.4.7 Multi-Family Building Prototype Models

Appendix Section B.4.5 shows the names and defining features of the SF building prototypes, as well as the fixed and variable inputs to the MF prototype models.

2.4.8 Model Calibration

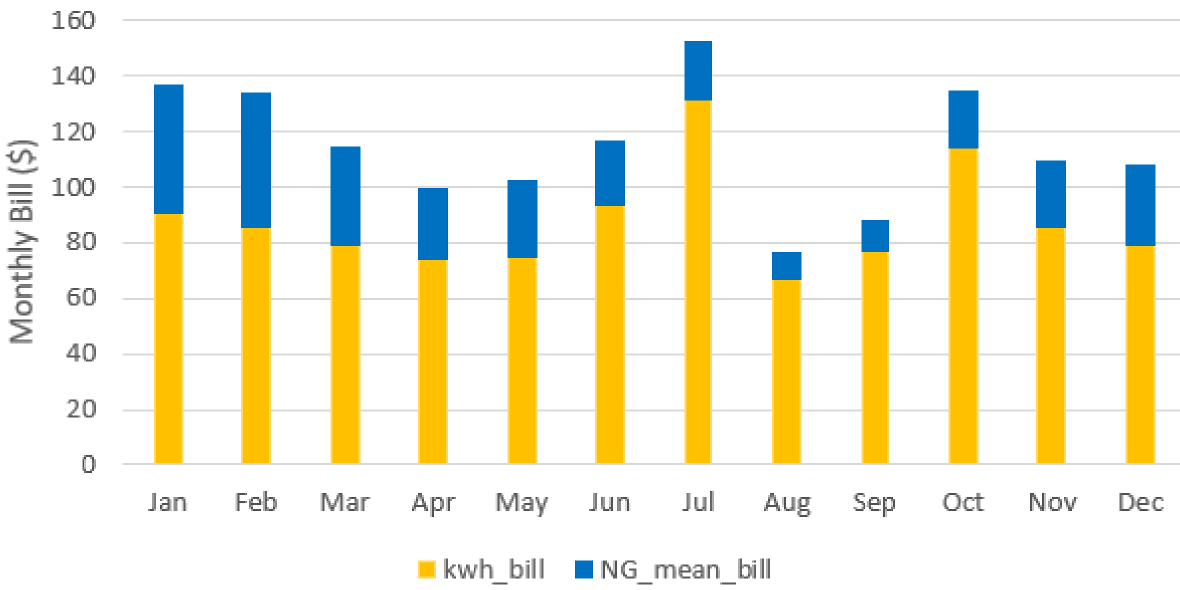
Model calibration was performed using privacy-aggregated energy consumption data from the UCLA Energy Atlas and from recorded indoor air temperature data, which determined the selection of automated heating and cooling set points. For each prototype, the BEopt model selected met the following criteria: was within one standard deviation of the community's average energy use intensity per square foot (EUI) for natural gas and electricity; reflected automated heating and cooling set points based on monitored temperatures; and was within or as close as possible to the EUI for the collection of parametric model runs for the specific prototype. The best fit model run was then isolated and picked as the prototype for a given single or multi-family home with a defined HVAC configuration. Figures were created to visualize the energy end use breakdown and baseline hourly consumption load profiles for each aggregated building type. An assessment was also conducted of how the model outputs reflected average customer bills by comparing values derived from representative electricity and natural gas consumption and residential tariffs. Figure 8 and Figure 9 show baseline energy consumption and bill data for the study area: electricity consumption is limited to regional averages, and the natural gas data is representative of the census tracts in the study.

Figure 8: Average Monthly Consumption by Fuel Source (2018-2019)



Source: The Energy Coalition

Figure 9: Average Monthly Energy Bills (2018-2019)



Derived from average fuel consumption and tariff.

Source: The Energy Coalition

2.4.9 Modeled Scenarios

As discussed in Section 2.4.3, the term scenario refers to specific interventions to each prototype building that represents potential retrofits or changes in either energy use or generation. The selected scenarios were:

- Electrification and Energy Efficiency (EE Scenarios).
  - Minor Indoor-Air-Quality-Focused Electrification.
  - Moderate Indoor-Air-Quality-Focused Electrification.
  - Full Home Electrification.
- Electric Vehicle Adoption.
- Distributed Energy Resources (DER) Adoption.
  - Solar PV Installation.
  - Battery Electric Storage Installation.
  - Solar PV and Battery Electric Storage Installation.

Electrification and Energy Efficiency (EE) Scenarios

Electrification scenarios were informed by the air quality monitoring analysis, which found that indoor pollutant concentrations were most closely related to natural gas-fueled stoves and ovens. Electrification scenarios, which also included energy efficiency improvements, are summarized in Table 7.

Table 7: Summary of Measures (EE and Natural Gas Appliance Replacements) for Each Electrification Scenario

Measure	Scenario			
	Baseline	Minor IAQ Focused	Moderate IAQ Focused	Full Home Electrification
Roof/Attic Insulation	Uninsulated/R13	R-49	R-49	R-49
Water Pipe	uninsulated	R2 copper	R2 copper	R2 copper
Air duct	n/a or 30% leakage	n/a or R-6 10% leakage	n/a or R-6 10% leakage	n/a or R-6 10% leakage
Lighting	40/60 or 80% LED	80% LED	80% LED	80% LED
Cooling equipment	Window Unit Or Central Cooling	Same as baseline	Mini-Split or AirSource Heat Pump	Mini-Split or AirSource Heat Pump
Heating equipment	Wall Furnace 60% AFUE/Central Furnace	Same as baseline		
Cooling Setpoint	72F from 3-5PM 95F Otherwise	Same as baseline	Same as baseline	Same as baseline
Heating Setpoint	71F w/ 65F setback	Same as baseline	Same as baseline	Same as baseline
Cooking	Gas Range	Induction Range	Induction Range	Induction Range
Water Heater	40 Gal Natural Gas	Same as baseline	Same as baseline	50 Gal HPWH
Clothes Dryer	Natural Gas	Same as baseline	Energy Star Electric Dryer	Energy Star Electric Dryer

Source: The Energy Coalition

For each individual measure considered, the Title 24 2022 codes and standards were reference points for determining the efficiency of the new equipment or retrofit. Additionally, the guiding principle for specifying a new HVAC system was to account for existing site infrastructure (such as whether or not air ducting was present in that prototype). If it was, then a ducted air source heat pump was specified. If ducting was not present, then a ductless mini-split heat pump was specified. Other considerations, such as whether new ducts were installed, or if insulation was added to the attic or other attributes, are described here. When comparing the retrofit scenarios with the baseline model, automated heating and cooling set points were not changed, consistent with the Building America Simulation protocol. This also kept the number of generated load profiles to a manageable number and maintained a like-for-like comparison. However, in future studies, this sensitivity will be of great interest since residents' interactions with new equipment in turn affect energy consumption and energy bills.

Electric Vehicle Adoption

Electric Vehicle charging at the residential level is expected to increase as EV adoption increases; this will impact electricity load profiles at home and community levels. Level 1 EV charging has a maximum power draw of 1.4 kW, assuming a 12-amp charge from a 120 V outlet.[10] Level 2 chargers charge substantially faster and have a maximum power draw of 7.2 kW. To account for this increase in power draw, Level 2 chargers need to be connected to a 240 V outlet and typically require an electrical inspection and retrofit. Since the residential homes in this project community are older, Level 1 EV charging was assumed to be used by both SF and MF households.

The load profile for EV charging is entirely dependent on when vehicle owners charge their vehicles. Since this will vary throughout the year and across households, a statewide average load profile was used to estimate household-level charging patterns (shown in Appendix Section B4.6). While this will produce slightly unrealistic charging load profiles at the household level, it will produce a more accurate representation of EV charging at the community level. Since the household level energy models represent the average home in the study area, this approach is believed to reflect the electricity demand of EV charging. In the *California Plug-in Electric Vehicle Infrastructure Projections: 2017-2025*[10] report, the aggregated electricity loads for both typical weekdays and weekends were modeled for residential, commercial, and public charging. Using the modeled load profile for residential Level 1 charging, the load profile was scaled to the maximum power draw of a Level 1 charger (1.4 kW) to reflect the time of day when peak and minimum loads occur. While the average daily EV charging electricity demand data reflects all of California rather than only under-resourced communities, it was the most detailed and regional specific data available. Each electrification scenario for each prototype was modeled with and without EV adoption.

Distributed Energy Resources Adoption

Three different DER adoption scenarios were assessed: with solar PV only, with battery energy storage systems (BESS) only, and with both PV and BESS. Each electrification retrofit scenario for each prototype was modeled to have solar PV and battery storage, only solar PV, and only battery storage.

DER sizing was modeled using REopt,[11] a tool developed by NREL that efficiently sizes energy systems based on user-defined priorities. REopt provides an optimal size for PV and BESS and generates an hourly load profile for building performance based on weather conditions and the input load profile. For example, REopt first uses the available rooftop area to determine the maximum size of a solar PV system, then scales that system size based on expected cost savings from load reductions and net energy metering. A building could install more solar PV based on the available area, but it would not be the best cost scenario based on the expected costs and savings. Battery storage systems are sized with the same logic, minus the consideration of available area. It is assumed that the battery storage system can be placed near the building without issue. This sizing approach reflects the process that is currently followed by solar and battery-storage contractors.

[10] https://www.energy.gov/eere/vehicles/articles/fact-995-september-18-2017-electric-vehicle-charging-home-typically-draws.

[11] reopt.nrel.gov.

For this analysis, REopt sized energy systems for optimal economic value, which compares system costs to electricity cost savings and revenue potential from net energy metering over the system's lifetime (typically 20 years). REopt sized solar PV and battery storage capacities for each residential prototype model and retrofit scenario, shown in Appendix Section B.4.7. For some prototypes, the minor electrification scenario had a smaller-sized battery than in the baseline scenario because the energy efficiency measures saved more energy than the electrification measures added to the home's energy usage.

The REopt modeling inputs and assumptions differed between the SF and MF models:

- The SF models assumed that the solar PV system would be installed on the rooftop and would be owned by the residents. A 25-percent rule of thumb was used to estimate how much of the SF rooftop would be usable for solar PV[12]. Further, the solar PV is assumed to be eligible for a net energy metering tariff that would allow for excess solar to be sold to the grid. Battery storage systems would be able to charge from the solar PV and the grid. Battery storage cells would need to be replaced every 10 years; replacement costs were accounted for in the capacity sizing analysis.
- MF units may not have a roof area for solar PV and most MF residents do not own the property they live in. Therefore, solar PV for MF was sized to the unit area and assumed to be provided by the building owner through a virtual net energy metering tariff.[13] Since the solar PV is not directly owned or controlled by the MF resident, net energy metering credits were not eligible for the MF models, which impacted the economic value of solar PV. For the battery storage systems, it was assumed that individual battery storage systems would be installed for each unit and could charge from the grid.

[12] https://www.nrel.gov/docs/fy14osti/60593.pdf, 'Estimating Rooftop Suitability for PV: A Review of Methods, Patents, and Validation Techniques'.

[13] https://www.sce.com/residential/generating-your-own-power/virtual-net-metering

2.4.10 Summary of Building Prototypes and Scenarios

Appendix Section B.4.8 illustrates the set of building prototypes and scenarios modeled for this study by showing the scenarios run for the SF Prototype 3 model. The same set of scenarios was run for all prototypes for SF and MF residences.

2.5 Baseline Growth Forecasts

2.5.1 Overview

This analysis established the baseline transition trajectory for the study community against which other possible transition scenarios could be compared. Additional detailed information about this analysis is in an interim deliverable report available upon request to UCLA.

A top-down modeling framework was used, which first entailed the collection and analysis of historic empirical data by ZIP code. Next, population growth forecasts were obtained from the responsible regional agency. Finally, appropriate mathematical growth rate models were selected and applied to the previous two data sets to create the forecasts. These forecasts reflect anticipated future changes in aggregate residential building energy demand, by ZIP code, in the absence of supplemental incentives.

The four transition pathways for which this analysis was conducted were:

1. Residential distributed energy resource adoption.
2. Residential light-duty vehicle fleet electrification.
3. Residential building energy efficiency improvement.
4. Residential natural gas appliance electrification.

2.5.2 Geographic Scope and Spatial Unit of Analysis

This analysis was conducted for all of Los Angeles County.

The ZIP code was determined to be the most appropriate spatial unit of analysis, as it is the scale at which historic data for vehicle registrations, DER adoption, residential electricity and natural gas consumption are all available and publicly accessible. However, the mismatch between the spatial unit (at which this data is available) and that of CalEnviroScreen (CES) scores, which apply at the census tract scale, introduced some unavoidable degree of uncertainty in the analysis.

To associate census tract-level CES 3.0 scores to ZIP code boundaries, a methodology was developed to estimate the degree to which each ZIP code should be designated as "majority disadvantaged" according to the 75th percentile CES score threshold. The centroid locations of each census tract were first calculated and then spatially joined to the boundaries of the ZIP codes that contained them. Next, the percentile scores of the census tracts whose centroids were associated with each ZIP code were averaged to compute an approximate percentile score for the ZIP code as a whole. Using this average ZIP code level percentile score, each ZIP code was then categorized as either "majority disadvantaged" or "majority non-disadvantaged" for subsequent steps of the analysis.

Appendix Section B.5.1 shows a map comparison of disadvantaged areas between CalEnviroScreen tracts and the resulting aggregation to the ZIP code scale, as well as statistics quantifying the associations between the two geographies; there is a high level of agreement between the two maps in terms of the percentage of population, which is the most important statistic for this analysis.

A similar spatial pre-processing method was used to estimate population growth forecasts at the ZIP code level, given that the Southern California Association of Governments' (SCAG) forecasts are generated using Regional Transportation Planning (RTP) Tier-2 zones, the boundaries of which do not precisely align with either ZIP code or census tract boundaries.

2.5.3 Temporal Unit of Analysis and Time Horizon

The primary driver for the choice of temporal resolution is the requirement that each transformation pathway forecast ultimately be translated into a realistic hourly load profile as part of the community scale energy system modeling exercise. It was determined that forecasts at a yearly resolution were appropriate, and that these could subsequently be downscaled to hourly energy system model projections.

A forecast time horizon to the year 2045 was selected; this corresponds to the year when state law requires that the state's electricity sources be 100 percent renewable.

2.5.4 Historic Empirical Data Sources

Appendix Section B.5.2 summarizes the data sources for each of the four transformation pathways. Because the 2019 Residential Appliance Saturation Survey (RASS) had not been released at the time of this study, and there were only two previous RASS survey result sets, there was not enough information from that source to develop a meaningful time series for appliance electrification trends. Furthermore, the RASS data is provided at the SCE territory scale, which is not aligned with the County of Los Angeles. Therefore, it was not possible to conduct a countywide analysis or to differentiate between the two study area ZIP codes. Instead, Survey data (N=449), collected during the Outreach portion of the project, was used to understand current energy use behaviors and appliances, as well as attitudes about new technologies and future purchasing plans.

2.5.5 Population Growth Forecasts

The SCAG is a regional planning organization that generates long-term population growth forecasts for the region at a high level of spatial granularity that supports regional transportation and land-use planning efforts. The most recently available SCAG population growth projections were released in 2016 and span a forecast period of 2015-2050, at a 5-year forecast interval. Individual RTP Tier-2 zones were associated with ZIP code geographic boundaries within Los Angeles County.

2.5.6 Mathematical Growth Rate Models

Baseline forecasts incorporate recently observed patterns of change (from historic empirical data sources described) but also must account for increasing levels of uncertainty associated with the application of these trends over time. For all transformation pathway forecasts that involved new technology adoption decisions (such as the purchase of EVs, DER assets, or electrified appliances), a logistic growth model was used. This growth model has an "S" shaped structure that reflects the notion that many new technologies diffuse according to a characteristic pattern: an initial slow growth phase, followed by an interim period of rapid accelerating growth, culminating with slowing of growth until the point at which the technology finally achieves market saturation.

For the transformation pathways that did not specifically involve these types of new technology adoption decisions—such as with future changes in per-capita electricity natural gas and electricity use—a fundamentally different growth model was used. For these pathways, future change rates were estimated by applying a logarithmic decay function to an initial set of annualized growth rates derived from recent historical data. This approach is conservative since it attenuates anticipated future rates of change relative to those experienced in the recent past.

2.5.7 Per Capita Forecasting

Baseline growth forecasts were developed on a per-capita basis, allowing for separate consideration and incorporation of disparate rates of population growth/decline within the project study area.

2.6 Community Scale Simulations

2.6.1 Simulation Framework

Individual energy system transition pathways were simulated at the community scale through a set of custom python scripts by specifying different rates of change in the combinations of household prototype models within the community.

A custom simulation framework was developed for this analysis that models community-scale energy system pathway transformations as an iterative, probabilistic selection procedure. At the start of each simulation run the study area community was represented as an initial collection of SF and MF prototype building models, with the scaling of each model category determined by the proportion of the total square footage of each building type within the study area community. In the initial time period, households within the community were assigned to one of the prototype models at rates consistent with the present characteristics of the community's building stock. Over the course of the simulation time horizon, the community-scaled energy system model evolved through the transition to the different prototype building models at different rates. Both the rate and extent of these transformations were determined by the scenario's narrative.

In addition to specifying the initial composition of the community's building stock, the initialization of a pathway simulation run also required that a set of input probability density functions (PDFs) be provided. These PDFs mathematically express the rate of change in the community's building stock over time. During a simulation, for each year of the forecast period, a subset of the communities' buildings was randomly selected for transformation to one of the eligible candidate scenario models. Once a building was transformed, this state persisted throughout the duration of the forecast period.

The numerical routine that was used to generate the input PDFs for each simulation run was based on a class of parametric sigmoid functions (saturating growth models), of which the Bass Model is one. According to this routine, parameters can be specified that dictate the rate of change in the probabilities of transforming to each building scenario alternative. In this way, each different pathway alternative reflected more or less aggressive adoption of different technologies or other measures.

Three different transformation categories were explored in this analysis: electrified alternatives to natural gas appliances, distributed rooftop solar PV energy generation and battery energy storage systems, and battery electric vehicles. Embedded within each of these transitions are a set of assumptions about future changes in the performance and penetration of basic energy efficiency measures within the building stock, over time.

With each pathway alternative, all the different building scenario models are present, only in different proportions. The differences between the pathway alternatives can be understood in terms of the relative dominance of the different scenario models. For each pathway simulation, during the initialization procedure a dominant scenario was specified. This scenario was twice as likely to be chosen as all the others combined. Introducing this concept of scenario dominance allowed the team to isolate and study load-change impacts associated with each different scenario while still ensuring that all the scenarios remain possible within each pathway simulation.

Simulation outputs included: hourly load profiles, annual loads, monthly load factors, and hourly peak loads.

2.6.2 Data Sources

Data for simulation development included: scenarios and transition pathways discussed in Section 2.4.3, forecasts discussed in Section 2.4.5, and parcel data for the study area ZIP codes.

Detailed data on parcel counts, use type, and square footage were obtained from the Los Angeles County assessor's parcel database. Appendix Section B.6.1 shows a map of parcel use designations within the project study area, and a summary of counts and square footage values for the SF and MF use types.

2.6.3 Starting Year Assumptions

The following choices were made to parameterize the starting year of the simulations.

Electricity Consumption

The total annual residential energy consumption value (SF + MF) used to calibrate the start year of the building electrification pathway simulations was 113.016 GWh. This value was generated by projecting recent historical trends in electricity load growth per capita and scaling by population projections for the 2020 start year of the simulation period.

Rooftop Solar

The total number of existing households with installed PV systems during the first year of the DER adoption simulation runs was 93. This value was generated by first projecting recent historical trends in the growth of residential scale PV system capacities per capita, then scaling by population projections for the 2020 start year of the simulation period, and then dividing by a typical rooftop PV system size consistent with the average available amount of suitable rooftop area per household within this community (3 kW).

Electric Vehicles

The total number of existing EV households (SF + MF) used to parameterize the start year of the vehicle electrification pathway simulation runs was 511. This value was generated by projecting recent historical trends in EV adoption per capita and scaling by population projections for the 2020 starting year of the simulation period. This process assumes only one EV registered per EV household.

Appliance Electrification

For SF households, during the initial time period of the pathway simulations, it was assumed that only 500 existing homes should be represented using non-baseline prototype scenario models. This constituted about 5 percent of the total. In the MF context, it was assumed that none of the existing units should be represented with non-baseline prototypes. These initial parameterizations reflect the community's existing building stock, as determined by data collected from project surveys and indoor air quality monitoring program questionnaires.

Under the baseline electrification pathway for SF households, by 2045 approximately 20 percent of the homes within the study area are expected to have undergone some form of electrification, from partial to full. For MF households, by 2045 only 10 percent of the units within the study are expected to have undergone some form of electrification.

2.7 Holistic Assessment of Residential Appliance Electrification

2.7.1 Overview

Among the major categories of residential energy transformations under consideration in this research, residential natural gas appliance electrification is the most contentious (from a policy standpoint) and it is therefore important to conduct a holistic assessment to evaluate public health benefits and impacts. That is the focus of this final portion of the project analysis.

The principal focus is on determining whether it is possible that future electrification efforts, occurring at any feasible rate, could potentially result in unanticipated consequences in terms of net increases in overall air emissions. It has been hypothesized that such an unintended outcome may be possible when ambient emissions from fossil fueled generators are considered. To this end, it is not necessary to quantitatively evaluate all the numerous transformation pathways developed in the previous forecasting work. Rather, it is sufficient to focus only on the highest-growth rate pathways since those reflect what can be considered as the maximum potential speed with which electrification could proceed within under-resourced communities. If the previous hypothesis can be disproven under the assumptions reflected in the high-growth rate pathways, then it logically follows that the same results would hold for each of the lower-growth rate pathways previously considered.

The approach taken in this report is to estimate and compare the mass of primary emissions to local environments eliminated through the electrification of gas appliances, relative to the mass of primary emissions to ambient environments created by the operation of fossil EGUs necessary to supply the new electric appliances' energy demands. This required a lengthy set of interacting assumptions described below and the use of dedicated modeling frameworks.

To estimate increases in ambient (grid) emissions, the following need to be determined:

- How much additional electricity must be consumed for each gas appliance replaced?

- During which hours of the day and which days of the year is this increased consumption likely to occur?
- At what rate is this electrification likely to proceed within the study community?
- How does this rate compare with the expected rate at which fossil EGUs will be retired or replaced to achieve compliance with the interim goals of the state's Renewable Portfolio Standard (RPS)?

To estimate decreases in local (community) emissions, the following need to be determined:

- What fraction of a home's total natural gas consumption is accounted for by different types of end-use appliances?
- Are there notable differences in the efficiency of the combustion processes and the rate at which emissions are produced, among different categories of appliances?
- What about between those that were produced in different vintages?
- Which gas appliances are typically installed inside the home and which are installed outside?
- Are there any emissions-capture technologies which are commonly implemented with different types of gas appliances?
- How effective are these emissions capture devices?

2.7.2 Estimating Increased Ambient Emissions from Grid Electricity Production

The modeling framework used to estimate primary ambient air emissions from future changes in grid electricity production was developed by the United States Environmental Protection Agency (EPA) and is called the Avoided Emissions and genERation Tool (AVERT). AVERT allows users to estimate spatial and temporal changes in the marginal emissions of three major categories of air pollutants (CO_2, NO_X, PM-2.5m) from anticipated changes in the output of electricity generator units (EGU) as required to meet demand.

Discussion of California's EGU fleet is provided in Appendix Section B.7.1.

The AVERT modeling framework supports the calculation of impacts from changes in fossil EGU operations stemming either from load reductions, load increases, or both. A detailed discussion of the AVERT model framework is provided in Appendix Section B.7.2.

Analysis conducted by Grubert et al. 2020, was used to set assumptions regarding future EGU retirement schedules (discussed in Appendix Section B.7.3), as well as future grid emissions intensities assuming RPS compliance (discussed in Appendix Section B.7.4).

2.7.3 Estimating Avoided Local Emissions From Gas Use Reductions

Estimates of residential gas appliance emissions for CO_2, NO_x, and PM were used for this analysis. Rather than assuming a single value, upper- and lower-bound values were used to calculate a range of avoided emissions, which reflect the variability and uncertainty in underlying emissions factor values.

The four major residential gas appliance types referenced in the table were grouped into two major categories: "Air & Water Heating" and "Cooking & Other." This grouping is intended to reflect major differences in the venting locations of these appliances (outdoors versus indoors, respectively).

Discussion of literature sources for CO_2 and NO_x emissions factors is included in Appendix Section B.7.5. Discussion of PM emissions factors is included here because it highlights several data gaps.

Residential Gas Appliance Particulate Matter Emissions Factors

Measurement studies conducted by Singer et al. (2009) report particulate matter emissions by particle number, a single value representing the total counts of all particles emitted over a given period of time across an entire particle size distribution. This reporting method makes it difficult to directly compare those indoor emissions estimates with the PM-2.5m size-fraction specific for ambient emissions of grid EGUs estimated using the AVERT framework.

As part of the work to fill this important data gap, an initial effort explored the possibility of developing PM-2.5m emission factors (EF) by synthesizing historical reported emissions data from the California Air Resources Board's (CARB) Emissions Projection Analysis Model (CEPAM), with historical gas consumption data from the CEC, and assumptions about the changing fractional usage of gas by different residential appliance types derived from multiple years of the CEC's RASS. This exercise would have amounted to a reverse engineering of the internal mechanics of CEPAM. Ultimately, based upon subsequent investigations of the CEPAM methodology and underlying data sources, it was determined that the model assumes a single EF value for all residential appliance types. There does not yet appear to be an established scientific consensus on whether notable differences exist between the rates of PM-2.5m emissions generated from the combustion of natural gas in different types of residential appliances.

In terms of the available literature on this subject, robust empirical measurements of PM-2.5m EFs which have been disaggregated according to different major appliance categories are both surprisingly scarce and becoming increasingly dated. Moreover, due to the technical and logistical difficulties associated with performing such measurements within "real world" environments, the sample sizes associated with these studies tend to be small, with the data collected exhibiting frustratingly wide ranges of variation, creating considerable uncertainty.

After investigating multiple potential sources for these EFs, a set of upper and lower value ranges for PM-2.5 EFs was established based on the EPA's AP-42 Compilation of Air Emissions Factors (Wheeler 2009). These AP-42 EFs form the basis of residential air emissions estimates reported by the widely used CEPAM model (California Air Resources Board [CARB] 2019). While these two resources were determined to be the most authoritative on this subject, more research is required on this issue if the potential health benefits of reduced PM-2.5 emissions exposures are to be used as a more prominent justification for targeted residential appliance electrification programs.

Summary Overview of Indoor Emissions Factors

Table 8 provides an overview of the range of emissions factors used to develop subsequent reported results for avoided mass of primary indoor air-emissions due to the electrification of various residential gas appliances. Note the difference in units between the CO_2 EFs and those for NO_x and PM-2.5m. These EFs have been organized according to the two major categories of residential gas end-uses just described. Note that for CO_2 and PM-2.5 the range of EFs used were the same for both appliance categories.

Table 8: Overview of the Range of Emissions Factors Values Two Different Major Categories of Residential Gas Appliances

Appliance Category	Pollutant Species	Lower Bound	Upper Bound	Units
Cooking & Other	CO_2	0.056999	0.059999	short-tons / MMBtu
	NO_x	0.083736	0.088388	lbs / MMBtu
	PM-2.5m	0.003489	0.005815	lbs / MMBtu
Space & Water Heating	CO_2	0.056999	0.059999	short-tons / MMBtu
	NO_x	0.058150	0.086062	lbs / MMBtu
	PM-2.5m	0.003489	0.005815	lbs / MMBtu

Overview of the range used to compute the mass of primary indoor emissions.

Source: UCLA

2.7.4 Estimating Public Health Impacts and Benefits

Overview of COBRA Screening Tool

Public health impacts and benefits were estimated with the EPA's CO-Benefits Risk Assessment (COBRA) model. COBRA is a screening tool that that can be used to estimate the human health impacts of changes in county-level PM-2.5 emissions. The tool is comprised of three core modules: a streamlined fate-transport module, a human-health impact module, and a monetization module that converts the number of human health incidents into a dollar value of either increased or decreased public health costs. The cases for which the tool was explicitly designed include energy planning agencies looking to estimate and promote the air quality, health, and associated economic co-benefits of their energy-efficiency or renewable-energy policies.

Results include changes in ambient PM-2.5 concentrations and changes in the number of cases of a variety of health end points associated with PM-2.5m. All health effects are monetized in the model results.

Appendix Section B.7.6 contains a more detailed description of the COBRA screening tool, including a discussion of atmospheric dispersion modeling.

Characterizing Local Versus Ambient Emissions Sources Within COBRA

COBRA allows users to specify detailed characteristics of the source of a given atmospheric emissions change. This specification follows a tiered classification system that is linked to assumptions about the physical attributes of the emissions source. These assumed physical attributes are then propagated through the model's atmospheric dispersion modeling calculations. Ambient emission increases considered as part of this analysis (associated with grid fossil EGUs) are automatically defined within the outputs of the AVERT modeling framework. The specific source characterization is designated as "Tier1: Electric Utility Fuel Combustion."

Calculated reductions in local emissions from avoided residential gas use can also be used as inputs to the COBRA model. However, care must be exercised in the interpretation of results. This is because COBRA was explicitly designed to estimate emissions impacts from changes in outdoor air concentrations and exposure pathways. Using COBRA in this way, therefore, implicitly assumes that all emissions generated by indoor gas appliances are directly exhausted to the outdoor air, either through active capture and ventilation at the point of combustion or through passive ventilation.

While this assumption is undoubtedly flawed since many gas appliances are physically installed indoors and their emissions are not fully ventilated, it can nevertheless provide a useful basis of comparison with ambient emissions impact estimates produced by COBRA for changes in fossil EGU operations. Furthermore, the impact estimates generated by COBRA for a given mass of emissions reductions is likely a lower bound on those which might otherwise be calculated if indoor emissions exposure pathways were explicitly evaluated. Unfortunately, the absence of established indoor air quality standards for gas combustion co-product emissions, combined with emerging scientific understanding of their associated health risks, prevent us from conducting such an assessment here. The specific source characterization used for modeling the impacts of these local emissions reductions was therefore designated within the modeling as "Tier1: Fuel Combustion Other; Tier2: Residential Other; Tier3: Natural Gas."

CHAPTER 3: Project Results

3.1 Community Survey Results

Appendix Section C1 contains a summary of results from the community survey (n=449) for key questions relating to the building modeling and forecasting analysis.

Only 20 percent of respondents had central air conditioning (AC), although 43 percent had wall or window-mounted AC units. Only 3 percent had rooftop solar, although an additional 5 percent stated they had plans for purchasing solar in the next two years. Twelve percent drove a hybrid or electric vehicle, and 14 percent said they had plans to buy one in the next two years. Twenty-eight percent were planning some sort of appliance electrification purchase in the next two years; of those respondents, nearly half indicated plans to purchase an electric stove. The average monthly electricity bill was $92, and the average gas bill was $48.

3.2 Air Quality Monitoring Results

3.2.1 Overview

A number of summary tables, QA/QC evaluations, analyses, and statistical tests were produced from the data collected. Key findings are summarized in this section, with additional information in Appendix C, as well as in the building modeling section discussion.

3.2.2 General Household Attributes

Key features of participants' household attributes, collected in Questionnaire #1, are summarized in Appendix Section C.2.1, which also includes a comparison with the American Housing Survey (AHS), a national housing survey sponsored by the Department of Housing and Urban Development (HUD) and conducted by the United States Census Bureau.

In cases where respondents did not provide information about home size, or provided only an estimate, this information was gleaned from the County Assessor's database to fill in the gaps.

Approximately 73 percent of sampled households were SF homes, both attached and detached single units; this is slightly greater than the estimated 70 percent for all of California. The average household size was 1,259 square feet (sq. ft.) and units ranged from 480 to 2,376 sq. ft. Average households were smaller than the average of 1,602 sq. ft. for the state and 1,589 sq. ft. for the Los Angeles/Long Beach metro area. Sampled homes were also, on average, 17 years older than the average home, statewide. Furthermore, the square footage per person was much lower than the state average. The mean square foot per person in the sample was 384 compared with 742 for the state; this was much more pronounced in the renter-occupied homes (269 sq. ft. per person) versus owner-occupied homes (553 per sq. ft.).

3.2.3 Appliance Fuel Sources and Ventilation

Information about the fuel source for several of the most common residential appliances that could be powered by natural gas, collected in Questionnaire #1, is summarized in Appendix

Section C.2.2, which also contains information on the number of homes with different types of ventilation and cooling systems.

The majority of participants used natural gas as the main fuel source for clothes dryers, water heaters, wall furnaces, stovetops, and ovens. More than 90 percent of participants had gas water heaters and gas stovetops and ranges. Approximately 17 to 18 percent of residents reported having all five of the gas appliances listed; between 76 and 81 percent indicated that at least four of the five, and 95 to 100 percent indicated at least three. The AHS estimates that 93 percent of statewide households utilize natural gas as a fuel source.

During the summer sampling time frame, an additional question was included to understand the percentage of participants that turned off or planned to turn off natural gas pilot lights over the summer. From the summer sampling group, 24 percent of respondents indicated that they either had already turned off or planned to turn off at least one natural gas pilot light during the summer; 57 percent responded that they neither turned off nor planned to turn off pilot lights over the summer. This is an important factor when comparing winter and summer air quality and natural-gas usage.

The total number of respondents with central forced air furnaces and central forced air AC units (21-50 percent) in their homes was much lower than the statewide AHS estimate (71 percent). The most common cooling appliances in the home were ceiling or standing fans, which were present in approximately 88 percent and 79 percent of homes in the winter and summer sampling, respectively.

Ventilation, exhaust, and purification systems can potentially impact indoor air quality. For example, Mullen et al. (2016) reported decreases in several measured pollutants with greater exhaust use frequency while cooking. A large portion of study participants indicated that their fireplaces, dryers, or kitchens were vented; more than 80 percent reported that their kitchen vented to the outdoors. (Note that the project team was unable to verify whether the exhaust actually vented to the outdoors; the team did note that renters in particular were sometimes unsure of the details of appliance and home attributes.)

3.2.4 Participant Behaviors

Questionnaires administered at the end of the first and second weeks of monitoring, collected detailed information on a variety of participant behaviors related to ventilation and energy use (for example cooking, laundry, showers, home heating, cooling). Appendix Section C.2.3 provides a summary of data collected around cooking behaviors (aggregated by weekdays and weekends), use of kitchen exhaust systems, and general ventilation behaviors.

Overall, the stovetop was the most used kitchen appliance with a mean weekly use of nine times per week (1.3 times per day), over both sampling time frames. Overall, ventilation behaviors increased in frequency during the summer sampling time. The largest increases were in the ventilation practices where a window or door was opened to the exterior of the home, likely indicating a seasonal-dependent behavioral shift. In the winter sampling time frame, approximately 35 percent of those who responded to the question indicated that they either usually or always used their kitchen exhaust vent while cooking, which was similar to statewide results from a small-scale survey[14]. This percentage increased to 61 percent over the summer sampling time frame.

3.2.5 Air Quality Measurements–Indoor and Outdoor

Particulate Matter Measurements

Overview

After final data reductions, measured indoor and outdoor particulate matter for the winter and summer sampling time frames are summarized in Table 9.

Table 9: Descriptive Statistics for Indoor and Outdoor PM at Various Sizes

Season	Indoor		Outdoor	
	Median	Range	Median	Range
Winter 2019 (temporal resolution of ~20 seconds)	(n = 389,517)		(n = 414,459)	
Temperature (°C)	64.1	24 - 94	48.6	17 – 91
Relative Humidity	38.0	4 - 72	49.3	4 - 99
$PM_{1.0}$ (μg/m^3)	4.5	0 – 705	6.1	0 – 719
$PM_{2.5}$ (μg/m^3)	6.3	0 – 990	8.7	0 – 999
Summer 2019 (temporal resolution of ~120 seconds)	(n = 413,839)		(n = 418,739)	
Temperature (°C)	80.1	26 - 103	78.7	37 – 111
Relative Humidity	40.1	17 – 68	44.6	13 - 76
$PM_{1.0}$ (μg/m^3)	7.8	0 – 685	9.8	1 – 345
$PM_{2.5}$ (μg/m^3)	12.0	0 – 988	15.1	3 – 706

Data is summarized for all homes included in the winter and summer data collection timeframes.

Source: UCLA

Monitoring Concentrations

The median indoor concentrations across all samples during the winter monitoring time frame were 4.5, and 6.3 μg/m3 for $PM_{1.0}$ and $PM_{2.5}$, respectively. The median indoor concentrations for the summer monitoring were 7.8 and 12.0 μg/m3 for $PM_{1.0}$ and $PM_{2.5}$, respectively, higher

[14] Klug, V. L., Lobscheid, A. B. & Singer, B. C. Cooking Appliance Use In California Homes—Data Collected From A Web-Based Survey. (2011).

than the winter sampling time frame. A similar seasonal trend was observed for the outdoor median concentrations that were slightly higher in the summer.

Indoor/Outdoor Ratios

The relationship between indoor and outdoor particle concentrations can be characterized by the indoor/outdoor (I/O) ratio, which is influenced by ventilation practices and the tightness of the building envelope, among other things. Generally, well-ventilated environments have I/O ratios closer to 1.0, while tighter building envelopes with closed windows and doors have I/O ratios further from 1.0.

Appendix Section C.2.4 shows a representative subset of I/O $PM_{2.5}$ concentrations for a subset of resampled homes. On average, there were higher ratios during winter compared with summer, indicating that concentrations between indoor and outdoor environments differed more during winter. During summer sampling, within the same set of homes, ratios decreased an average of 64 percent from winter sampling, indicating seasonal differences among the sampled homes that may be attributed to indoor emission sources, ventilation practices, or other factors that affect air-exchange rates.

From the questionnaire, the team observed increased ventilation practices during the summer compared with the winter. The largest increases were seen in ventilation practices where a window or door was opened to the exterior of the home. Improving indoor ventilation can lower concentrations from indoor air pollution; however, this advantage may be negated in communities where average outdoor pollution levels exceed indoor concentrations.

It is important to highlight the large variation in conditions among homes within this community and the need for greater understanding of individual home environments.

Nitrogen Dioxide (NO_2) Measurements

NO_2 Overview

Median indoor concentrations (Table 10, in parts per billion (ppb)) showed NO_2 was lower in the summer compared with winter sampling, and higher indoors than outdoors. This suggests dominant NO_2 sources in indoor environments.

Table 10: Descriptive Statistics for NO_2 Data

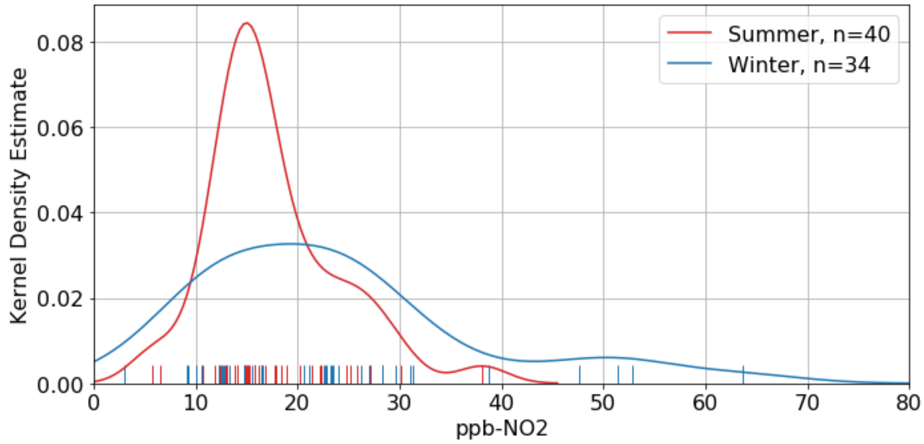
	Minimum NO_2 (ppb)	Maximum NO_2 (ppb)	Median NO_2 (ppb)	Mean NO_2 (ppb)
Winter (Indoor)	6.5	63.6	22.6	24.2
Winter (Outdoor)	15.9	21.2	18.8	18.7
Summer (Indoor)	5.8	38.1	15.8	18.2
Summer (Outdoor)	9.1	13.4	11.7	11.4

Source: UCLA

NO_2 Range of Concentrations

Kernel density estimate plots (Figure 10) for NO_2 samples showed a narrower range of concentrations in the summer sampling time frame compared with winter sampling.

Figure 10: Kernel Density Estimates for Indoor NO_2 Concentrations Between Winter and Summer Sampling Time Frames



Source: UCLA

NO_2 Indoor/Outdoor Ratios

Appendix Section C.2.5 shows indoor/outdoor ratios for sample pairs at homes located within the three zones identified in Section 2.4.2.

- Area A: Removed from identifiable competing sources.
- Area B: Near major roadways.
- Area C: Near industrial emissions.

In all instances, the outside value was lower than the value measured indoors. Ratios were higher in summer in Areas A and B, but nearly the same between sampling time frames in Area C.

3.2.6 Indoor Air Quality and Health

Comparisons to California Ambient Air Quality Standards (CAAQS) and National Ambient Air Quality Standards (NAAQS)

Particulate Matter ($PM_{2.5}$)

To allow comparison with available health benchmarks, an additional summary of $PM_{2.5}$data is shown as 24-hour rolling means (Table 11). These results were central to the information provided back to the community regarding indoor air quality. These means were calculated by setting a window equal to the average number of observations within a 24-hour period for all sampled homes and rolling the window over the two weeks of observations for each home to obtain a mean value for this set number of observations. The median value for all mean 24-hour rolling means is provided in the table.

Table 11: Descriptive Statistics for Mean 24-Hour Rolling Means of Indoor PM at Various Sizes and Comparisons to Available National Health Benchmark

	24-hour Rolling Means for Indoor $PM_{2.5}$ Concentrations (µg/m^3)				NAAQS Health Benchmark for $PM_{2.5}$ (µg/m^3)	
	Median	**Range**	**% Above NAAQS** (acute)	**% Above NAAQS** (annual)	**Acute**	**Annual**
Winter	11.3	0.7 – 391	11.1	47.2	35	12
Summer	15.3	0.7 – 149	2.4	74.2		

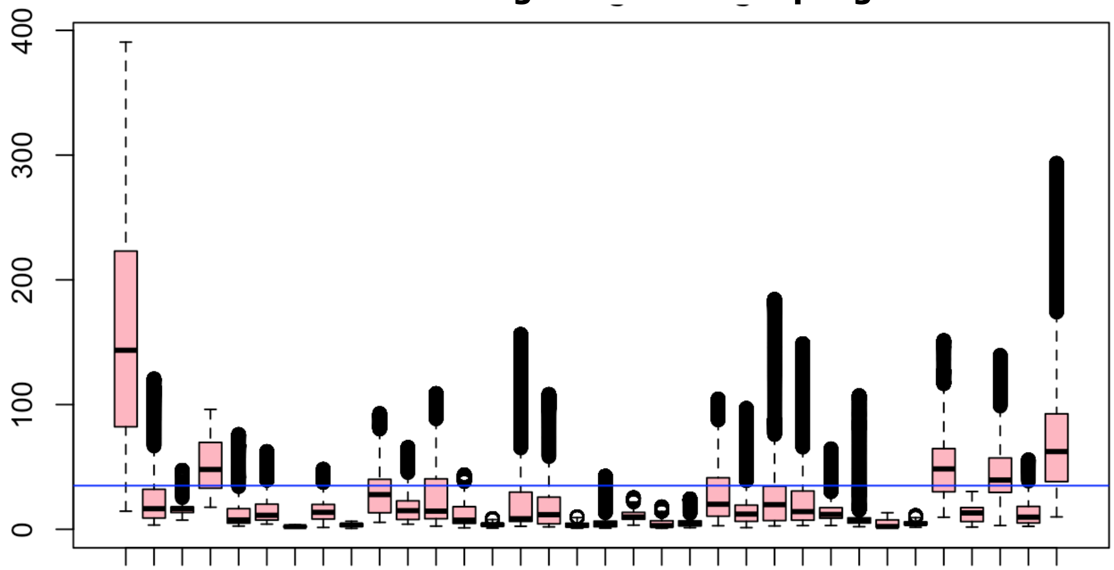
Source: UCLA

Median rolling averages did not exceed the 24-hour (acute) national heath benchmark for $PM_{2.5}$; however, the median summer value exceeded the annual health benchmark of 12 µg/m^3, and the winter was only slightly under this benchmark. These results are concerning if these values persist throughout the year, as the data appear to show.

Overall, 2 percent and 11 percent of the $PM_{2.5}$ 24-hour rolling means were over the acute health benchmark for both the summer and winter time frames, respectively. A wide range of concentrations in the winter sampling may be explained by indoor behaviors and exposures that differ from the summer sampling. Over the summer, chronic higher outdoor PM concentrations and increased ventilation behaviors may explain the smaller concentration range and overall higher median values indoors. This finding highlights the need for data evaluation by season (Figure 11).

Figure 12 show box plots of the same rolling 24-hr means by individual home for winter and summer sampling time frames respectively, as well as comparison with the 24-hour NAAQS of 35 µg/m^3.

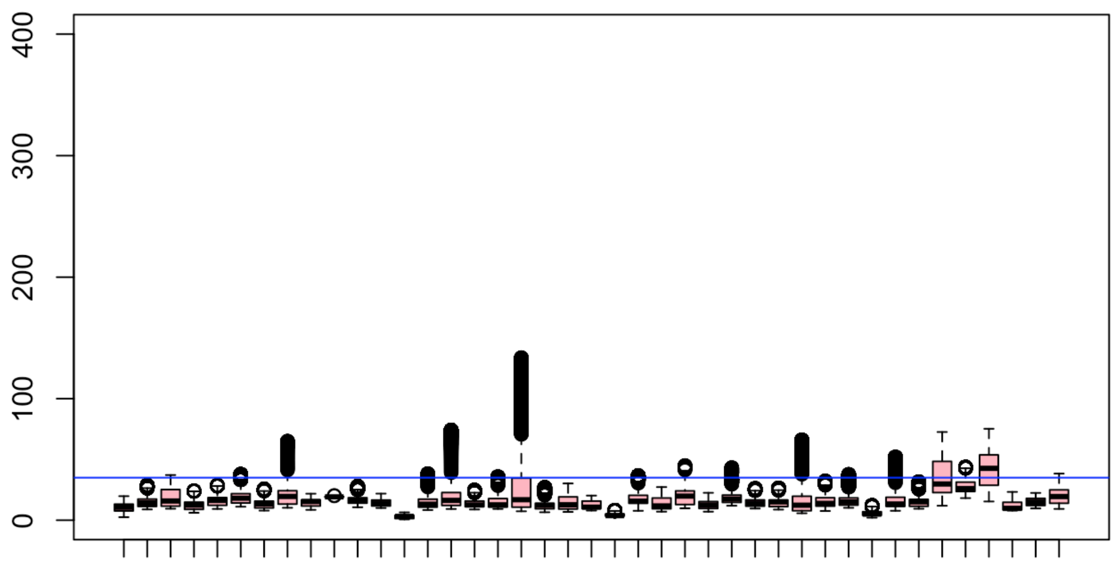
Figure 11: Rolling 24-Hour Means for Indoor $PM_{2.5}$ Concentrations for Individual Homes Measured During the Winter Sampling Time Frame



Blue horizontal line represents the 24-hour NAAQS health benchmark.

Source: UCLA

Figure 12: Rolling 24-Hour Means for Indoor $PM_{2.5}$ Concentrations for Individual Homes Measured During the Summer Sampling Time Frame

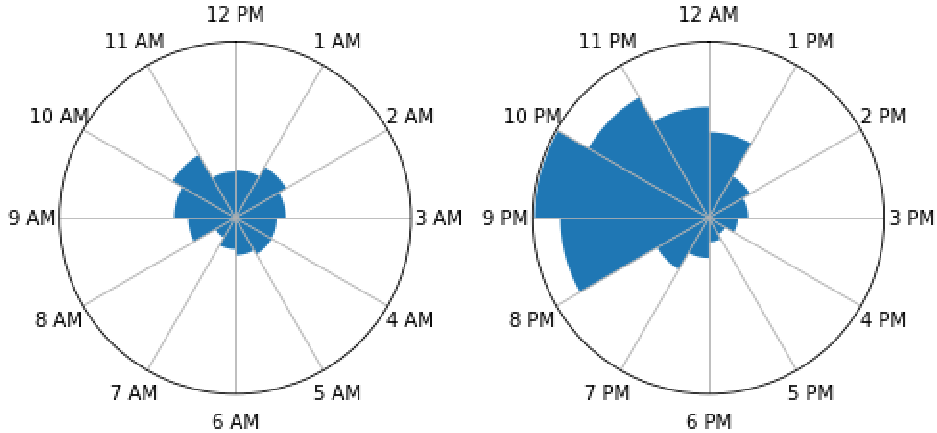


Blue horizontal line represents the 24-hour NAAQS health benchmark.

Source: UCLA

For communication of results back to individual participants, the number of $PM_{2.5}$ data points over the NAAQS health benchmark for the participant's home was divided by the total number of data points for the home; the resulting number was the percentage of time when the air quality in the home was considered unhealthy. $PM_{2.5}$ data for each home were analyzed using a 1-hour rolling mean and placed into a modified Windrose diagram to represent the mean value per hour of the day (Figure 13). The data were provided in this way so residents could identify specific daily patterns that may contribute to high concentrations of PM.

Figure 13: Sample of Modified Windrose Diagrams Representing Average $PM_{2.5}$ Concentration During Each Hour of the Day



Source: UCLA

Nitrogen Dioxide (NO_2)

The mean NO_2 concentrations indoors and outdoors, and comparisons to other studies, are presented in Table 12. During the summer sampling time frame, mean concentrations were 18.2 and 11.4 ppb for indoor and outdoor concentrations, respectively. During the winter sampling time frame, the means were 24.2 and 18.7 ppb for indoor and outdoor concentrations, respectively. Indoor air quality is the function of building stock, air exchange rates, residential behaviors, and the size and reactivity of pollutants. In theory, indoor air quality can be cleaner than outdoor air quality due to the protective quality of buildings and ventilation and air cleaning devices; however, according to the EPA, indoor air quality can be as much as 2-5 times more toxic than outdoor air.

Table 12: Comparison Between Study's Findings (blue shaded rows) and Results From Similar Studies

	Time (days)	Minimum NO_2 (ppb)	Maximum NO_2 (ppb)	Median NO_2 (ppb)	Mean NO_2 (ppb)
Outdoor					
This study (Summer 2019)	~7	9.1	13.4	11.7	11.4
This study (Winter 2019)	~7	15.9	21.2	18.8	18.7
Indoor					
Living Room					
This study (Summer 2019)	~7	5.8	38.1	15.8	18.2
This study (Winter 2019)	~7	6.5	63.6	22.6	24.2
Habre et al. (2014)	7	NA	NA	NA	28.5
Walker et al. (2018)	7	1.0	12.7	NA	3.9

	Time (days)	Minimum NO_2 (ppb)	Maximum NO_2 (ppb)	Median NO_2 (ppb)	Mean NO_2 (ppb)
Kitchen					
Mullen et al. (2016)	~6	NA	NA	NA	23.2
Paulin et al. (2013)[9]	7	3.2	71.4	17.9	NA
Bedroom					
Mullen et al. (2016)	~6	NA	NA	NA	17.7
Paulin et al. (2014)	7	3.4	41.8	13.1	NA
Hansel et al. (2008)[10]	3	2.9	39.4	NA	30

Source: UCLA

Concentrations of combustion-related air pollutants like NO_2 and CO can be emitted by indoor emission including tobacco smoking, wood-burning fireplaces, and gas appliances. Several studies examining the relationship between gas appliances and indoor air pollutant concentrations have found higher concentrations of NO_2 in homes with gas appliances compared to homes without gas appliances, and in homes with unvented or poorly vented gas appliances,[1–3] these concentrations have been found to exceed health thresholds.[4,5] Studies examining the seasonal differences of indoor NO_2 concentrations found higher concentrations in winter compared to summer and higher contributions to gas appliances[1,6]. In this current study, a wider range of NO_2 concentrations were found between individual homes, as well as overall higher mean NO_2 concentrations for all homes during the winter compared to the summer sampling timeframe. Time-weighted NO_2 concentrations for individual homes ranged between 6.5 and 63.6 ppb (range of 57.1 ppb) in the winter compared to the summer sampling time frame which ranged between 5.8 and 38.1 ppb (range of 32.3 ppb). This seasonal difference is likely due to various factors including indoor combustion sources and lower air exchange rates in sampled homes during the winter sampling timeframe. This is corroborated by the I/O ratios of resampled homes that shows high I/O winter ratios.[15]

Mean indoor and outdoor NO_2 concentrations across all monitored homes were lower than the 30-ppb California Ambient Air Quality Standards (CAAQ) annual average threshold set by the Department of Public Health; however, seven of the homes (21 percent) sampled in the winter and three of the homes (7.14 percent) sampled in the summer were measured above the 30ppb CAAQS annual average threshold. Due to the limitations of applying annual ambient air quality standards on one-week time weighted average samples, NO_2 results from similar indoor air quality studies were included for comparison. All studies used for comparison (and

[15] Summer I/O ratios were lower compared to winter but still slightly above 1.0 indicating indoor concentrations were higher than outdoor concentrations overall. The interpretation of the summer results are less clear and may be due to the varying types and presence of temperature controlling appliances and ventilation practices over the summer.

included in Table 12) used similar passive diffusion (Ogawa, USA) NO_2 collection methodology over a one-week timeframe.

Among the comparison studies, Habre et al. (2014) and Walker et al. (2018) both collected samples in central living room spaces in two varied residential environments. Habre and colleagues (2014) recruited asthmatic children living in the South Bronx and East Harlem area from the Mount Sinai Hospital pediatric pulmonary clinic, asthma clinic, and emergency room[7]. Walker et al (2018) measured concentrations in newly constructed California homes after installation of mechanical ventilation systems that meet the requirements of American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.2. Results from this study were more comparable to the results from Habre et al. than to results from the newly constructed homes. When comparing to studies that collected samples in other areas of the home, mean winter NO_2 concentrations from this study were higher than samples in the kitchen collected from Mullen et al. (2016). Similarly, median winter NO_2 concentrations from this study were higher than samples in the kitchen collected from Paulin et al (2013). Mean and median bedroom concentrations, often located further from residential emissions sources, were, on average, lower than the results found in the current study. It is important to note that many of the studies listed in the table below did not sample or report concentrations by season.

3.2.7 Relationships Between Household Attributes/Behaviors and Indoor Concentrations

Overview

A series of t-Tests were applied to mean NO_2 concentrations and each question in the questionnaires. This resulted in several hundred plots that were then ordered and filtered for significance. Only plots with statistical significant< 0.05 and plausible relationships were included in the Air Quality Report project deliverable. This report includes a subset of those results, to document the most meaningful findings.

Relationships with Heating and Cooling Appliances

Households where respondents indicated that the home had a programmable thermostat had lower concentrations of measured air pollutants compared to those that did not indicate having a programmable thermostat (Appendix Section C.2.6). Similarly, homes with central forced air conditioning systems and homes that used central forced air units during the day tended to have lower air pollutant concentrations (data not shown). On the other hand, homes that utilized window or wall air conditioning units had, in general, higher air pollutant concentrations (data not shown). Furthermore, concentrations of NO_2 were lower in homes that indicated daily use of central forced air furnaces over the winter sampling time frame (also in Appendix Section C.2.6). The findings among homes with varying heating and cooling appliances may be a proxy for additional variables not captured in this study. Programmable thermostats and central forced air conditioning and heating are temperature controlling appliances that are more likely found in newer homes and/or less affordable homes and the ability to use these appliances indicate the ability to afford the associated energy costs.

Relationships with General Home Ventilation

An interesting relationship emerged between PM monitoring results and general ventilation behaviors (Appendix Section C.2.7). During the Summer sampling timeframe, increased frequency in window and door ventilation practices were associated with increased particle counts and concentrations indoors; however, this trend was not identified during the winter sampling timeframe. This suggests that increased window and door ventilation practices during seasons dominated by higher outdoor particulate concentrations may be associated with increased indoor particle concentrations. This finding corresponds to trends identified in the indoor and outdoor correlation data, where correlations between indoor and outdoor particle concentrations strengthened over the summer compared to the winter sampling timeframe, and overall concentrations and particle counts of indoor environments were higher during the summer compared to the winter sampling timeframe.

Relationships with Cooking Equipment and Behaviors

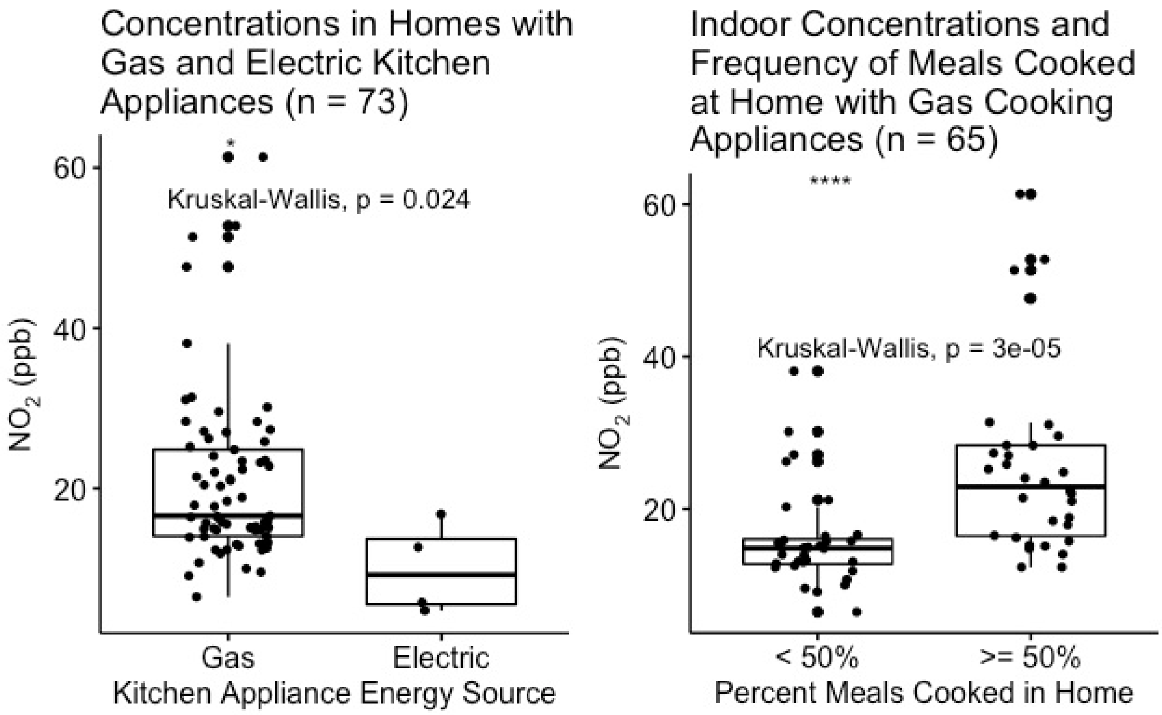
Cooking Appliances and Cooking Frequency

Natural gas appliance use is associated with the emissions of several air pollutants including NO_2, among others; and the use of gas ovens and stoves (collectively referred to as "cooking appliances" henceforth) increases residential NO_2 concentrations.[5,11] Similar to these previous studies, a relationship between gas stove use and NO_2 concentrations was identified within the sampled homes selected for the current study (Figure 14).[16]

Due to the high utilization of natural gas within the target community, only four homes self-reported all electric cooking appliances. While the test for significance suggests homes with electric cooking appliances have lower NO_2 concentrations, the sample size of the electric cooking appliance group does not meet the suggested group size for non-parametric comparison and, thus, should be interpreted cautiously. Therefore, among homes with gas cooking appliances, the percent of meals that each household reported cooking using either the oven or stove over the course of one week (out of three possible meals per day) was examined. Among the subset of homes with all gas appliances, those that cooked fewer than half of their meals at home using either an oven or stove to prepare the meal, NO_2 concentrations were significantly lower compared to those that reported higher meal cooking frequencies.

[16] The following symbols indicate statistical significance: ns: p > 0.05 *: p <= 0.05 **: p <= 0.01 ***: p <= 0.001 ****: p <= 0.0001

Figure 14: NO_2 Concentrations Between Households



Left: Homes with gas or all-electric stoves/ovens; Right: NO_2 concentrations between households that cooked meals more or fewer than 50 percent (over one week) in homes with both a gas stove and oven.

Source: UCLA

The median NO_2 concentration for homes that cooked at least one meal with gas was similar to median NO_2 concentrations in the "gas cooking + vented gas appliances" group in Mullen et al. (2016) (Table 13). This suggests that, if cooking frequencies and other NO_2 sources were comparable between groups, gas appliances within the sampled homes may be operating with similar capture efficiencies as those in the Mullen et al. study. A small sample of homes reported that either there were no gas cooking appliances within the home or indicated that residents did not use their gas cooking appliances during the sampling period. These homes, labeled as "No gas cooking," represent fewer than 10 percent of all sampled homes. Concentrations in this subset of homes exceeded those reported for an analogous group in the Mullen et al. study; however, this value should be interpreted with caution because of its small sample size.

Table 13: Median NO_2 Concentrations (ppb) in California Healthy Homes Indoor Air Quality Study and Concentrations From Comparable Groups in Currently Sampled Homes

	California Health Homes Study (Mullen et al.)		Current Study	
Parameter	**No gas cooking**	**Gas cooking + vented gas appliances**	**No gas cooking**	**Gas cooking (at least one meal cooked)**
Homes (N)	64	142	5	68
Bedroom NO_2	6.3	16	NA	NA
Kitchen NO_2	6.6	22	NA	NA
Living room NO_2	NA	NA	10.7	17.2

Source: UCLA

Recent American Community Survey (ACS) found approximately 4 percent of households reported using cooking stoves for supplemental heating.[12] The use of the oven as supplemental heating was included in the ACS survey, but that data was not reported as the data did not meet publication standards or was withheld to avoid disclosure. Among the study participants, approximately 9 percent of the sampled households indicated they used their ovens as a heating device during the Winter sampling time frame (stove use was not included as an option in the questionnaire). While the sample size is small, those that self-reported ovens as a heating source had higher indoor NO_2 concentrations than those that did not use their oven for heating. It should be noted, however, that many of these homes used a wall furnace and indicated their oven as a secondary source of heat, and similar results were measured over the summer sampling timeframe. Therefore, it is strongly suggested that further research into this important topic area be conducted, to determine possible emissions issues related to non-cooking stove and oven usage.

Kitchen Exhaust / Vent Usage

NO_2 concentrations trended up along with the indicated frequency of usage with kitchen exhaust and vent usage. This may be more of a reflection of the frequency of stove use than a reflection of ventilations practices. No trends were identified in the PM data.

Relationships with Non-Cooking Gas Appliances

Gas Heating Appliances

The current study did not find significant relationships between increased NO_2 concentrations and the presence of other non-cooking gas appliances within the sampled homes. Most homes indicated the presence of gas storage water heaters at various locations within or outside the main living area of the home. When comparing homes with gas storage water heaters inside the main living area to those with gas storage water heaters located in their garage or outside their home, no difference in NO_2 concentrations were identified (Appendix Section C.2.8). This suggests that, assuming all else equal, homes with storage water heaters inside the main living area of the home were vented properly or operated with a similar capture efficiency to homes where the gas storage water heaters were placed outside the main living area or in the garage.

Heating appliances were evaluated during the winter sampling time frame to control for heating-related behaviors. When comparing homes with wall or central forced air furnaces, no differences were identified between NO_2 concentrations. However, it was difficult to assess the impact of different heating appliances, especially in homes with wall furnaces since those respondents also reported using ovens as secondary heating sources. Homes that reported using a wall furnace at least once over the course of the 1-week sampling period (and did not use an oven as a secondary heating source) had similar concentrations to those that did not use any heating devices. Furthermore, homes that reported using a central forced air furnace for heating at least once over the course of a 1-week time frame had significantly lower mean NO_2 concentrations (14.66 ppb) compared with homes that did not report using any heating devices (26.8 ppb) or used a wall furnace without an oven as secondary heating sources (28.2 ppb). This difference may be attributed to increased use of gas cooking appliances in homes with wall furnaces and no heating options compared with homes with central forced air furnaces. However, this difference may also be representative of newer, better maintained and efficient appliances, fewer competing pollutant sources, or use of filtration systems. Similar results were found over the summer sampling time frame in homes with central forced air conditioning units.

The presence and location of appliances was an important indicator for cooking frequencies and indoor NO_2 air quality. Homes without dryers or central forced air (CFA) systems in the home reported higher cooking frequencies and higher indoor NO_2 concentrations. Appliance profiles based on appliance location showed lower mean NO_2 concentrations and cooking frequencies in homes with central forced air systems (CFA) and dryers (16.82 ppb), compared with homes without a CFA system or a dryer (22.39 ppb). Homes without certain appliances may be an indicator of household income and greater reliance on in-home cooking. It is important to note that homes without CFA systems and dryers constituted the largest group of homes (n = 26). These results could have important policy implications within low-income communities where gas cooking appliances are used more frequently and are associated with poorer indoor air quality.

3.3 Hourly Natural Gas Consumption Data Analysis

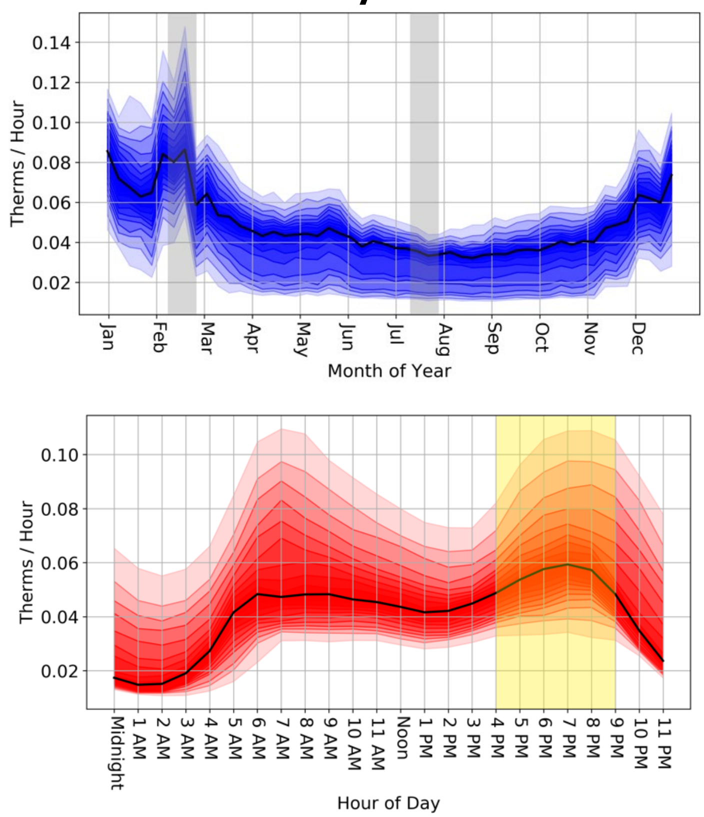
Hourly natural gas consumption data for the two study ZIP codes, obtained from SoCalGas, was analyzed for annual, weekly, and hourly patterns to better understand implications for the electrification of gas appliances. In addition, hourly gas consumption data for program participants was analyzed for relationships to measured indoor pollutant concentrations.

3.3.1 Community Level Variations in Hourly Natural Gas Use

The style of diagnostic plot used to depict variations in hourly gas use is called a "fan-plot." The horizontal axis represents varying time intervals; the vertical axis is the average rate of natural gas usage (therms per hour per account or per household, computed over each interval period). The shaded areas depict the quantiles of distribution of usage rates within the sample, over specified time intervals. Each individual shaded area corresponds to *n*-th percentile of the distribution, where the value of *n*, in this instance, was incremented by 5 percent. The top-most, lightest shaded area corresponds to the highest 95th percentile of mean-hourly gas usage intensities for each time interval, while the bottom-most shaded area corresponds to the lowest 5th percentile. The solid black line running through the middle of these shaded areas depicts the 50th percentile, or median value, across all of the sampled households within each time interval. The wider the spread of shaded areas within a given time interval, the higher degree of variation in observed usage rates during that period.

Figure 15 depicts monthly (top) and hourly (bottom) variations in average household natural gas use intensities for all of the households (17,072 customers) for which account-level data were obtained from SoCalGas. The vertical gray bars indicate the winter and summer monitoring periods. The maximum and minimum 95th percentile gas use rates occurred squarely within the winter and summer monitoring periods. These significant (>2x) observed monthly differences in peak rates of hourly gas use validate the decision to conduct monitoring over two distinct seasonal periods.

Figure 15: Fan Plots Illustrating Monthly (top) and Hourly (bottom) Variations in Hourly Natural Gas Use



Variations averaged across all account level data obtained for residential customers located within the target study area ZIP codes (17,072 customers) for the data period spanning 8-15-2018 through 8-15-2019. In the top plot, the timing of the two, summer and winter, air quality monitoring periods is highlighted in the gray shaded areas. In the bottom plot, the timing of common "on-peak" electricity rate tariff time-of-use periods are similarly highlighted in the yellow shaded area.

Source: UCLA

The horizontal yellow shaded area in plot C shows the common electricity time-of-use rate tariff on-peak period relative to the distribution of average hourly natural gas use levels across the 24 hours in the day. The timing of these on-peak hours largely overlaps with the timing of the highest median intensities of natural gas use. This was a troubling finding for the potential of residential appliance electrification within this community because it could exacerbate peak electricity loads.

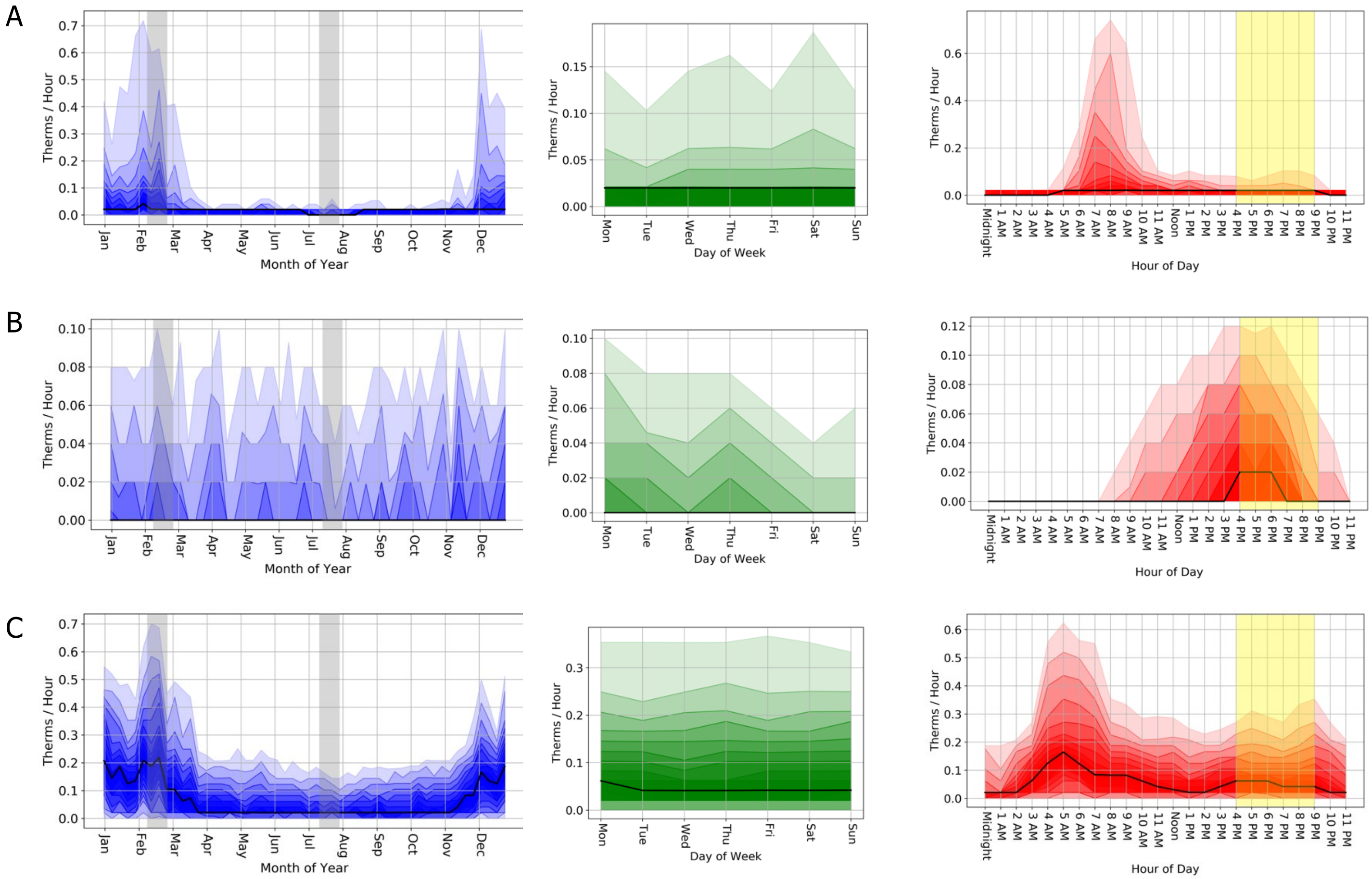
3.3.2 Participant Household Variations in Hourly Natural Gas Use

Appendix Section C.3.1 shows plots of monthly, daily, and hourly variations in average hourly natural gas use rates for just the subset of household accounts within the project study area. The homes in the participant group had various usage levels, though a small number of households had consumption levels exceeding the 95th percentile of the larger community group shown in Figure 15. Overall, the median consumption for the participant group homes was lower than that calculated for the larger community.

3.3.3 Individual Household Level Variations in Hourly Natural Gas Use

Figure 16 depicts a series of paired fan-plots depicting patterns of variation in monthly, daily, and hourly average gas-use rates for three individual households selected from within the participant study group. These plots have been included to illustrate the range of differences in individual usage patterns. For instance, Plot Series A shows an overall pattern of temporal variation characterized by extremely low rates of consumption during the summer months and extremely restricted hourly consumption peaks dominated by the morning period from 5 a.m. to 11 a.m. Plot Series B shows another individual household with nearly the exact opposite pattern of temporal variation in use: consistent monthly use rates and hourly usage patterns that peak during the evening hours of 4 p.m. to 7 p.m. Plot Series C shows yet another individual household use pattern that was broadly consistent with communitywide trends.

Figure 16: Paired Fan-Plots Depicting Monthly, Daily, and Hourly Variations in Average Hourly Natural Gas Use for Three Anonymous Individual Households



Households selected from the group of monitoring program participants. In all plots, the timing of the winter and summer air quality monitoring periods are highlighted in the gray shaded areas and the timing of common on-peak electricity rate tariff time-of-use periods are similarly highlighted in the yellow shaded areas.

Source: UCLA

3.3.4 Natural Gas Use Correlations with Indoor Air Quality

The majority of correlations between total gas usage and sampled indoor air quality indicators averaged over the entire monitoring period were not statistically significant. Particulate-matter counts and NO_2 concentrations do not generally correlate with total natural gas use. However, significant correlations were observed between hourly average PM counts and hourly gas use at individual household levels. Details of this analysis are provided in Appendix Section C.3.2.

Household-level hourly gas use profile data suggest that strong correlations between indoor air quality and gas are dependent upon dominant end-use activities within households. Findings support the hypothesis that the levels of unwanted pollutant species in the indoor air are highest during periods when the dominant end use is cooking. This observation corroborates the significant correlation for average NO_2 concentrations with the percentage of time that households used their ovens or stoves (discussed in Section 3.2.7).

Significant variations in hourly natural gas use rates among individual households (discussed in Section 3.3.3) reinforced the absolute necessity of account-level consumption data when attempting to correlate gas use to indoor air quality measurements. Modeled or aggregate hourly natural gas data are inadequate for this purpose and likely to be hugely inaccurate when applied to measurements from individual households.

3.4 Building Prototype and Scenario Modeling

The following outputs were generated from building prototype and scenario modeling:

- Hourly load profiles.
- Total annual energy use, broken down by electricity and natural gas.
- Greenhouse gas emissions.
- Utility bill estimates.
- Quantitative comparisons of baseline values and scenarios.

Due to the extensive number of models run, only an example set of key outputs is included here. Additional information appears in the appendices as noted.

3.4.1 Prototype Model Outputs

Example results for the SF Prototype 1 model (wall furnace for heating and window AC unit for cooling), are shown in Appendix Section C.4.1, including:

- BEopt results for hourly load profiles (by month) for the various electrification scenarios applied to the SF Prototype 1 model.
- Annual net electricity consumption for the SF prototype 1 model with various EV and DER scenarios.
- The breakdown of annual electricity and natural gas bills for SF Prototype 1 baseline configurations and electrification scenarios.

3.4.2 Quantitative Comparisons-Baseline vs. Scenarios

Table 14 shows summary results for all output metrics for SF Prototype 1 baseline configurations compared with electrification scenarios. Note that GHG calculations are based on current grid emission values only; later elements of the project analysis incorporate state mandates for renewable generation to calculate GHG changes through 2045.

Table 14: Single-Family Prototype 1–Summary of Impacts

Metric	Scenario			
	Baseline	**Minor Indoor AQ Focused**	**Moderate Indoor AQ Focused**	**Full Home Electrifica-tion**
Annual Total Bill ($/yr)	$1,142	$1,164 +2%	$1,163 +2%	$1,696 +49%
Annual Electric Bill ($/yr)	$771	$1,025 +33%	$870 +13%	$1,696 +120%
Annual Natural Gas Bill ($/year)	$371	$269 -27%	$293 -21%	$0 -100%
Annual Electricity consumption (kwh/yr)	5,580	5,964 +7%	6,152 +10%	9,121 +63%
Annual Natural Gas Consumption (therms/year)	312	258 -17%	223 -28%	0 -100%
Annual GHGs (metric tons/yr)	5.9	5.8 -2%	5.7 -3%	6.5 +10%

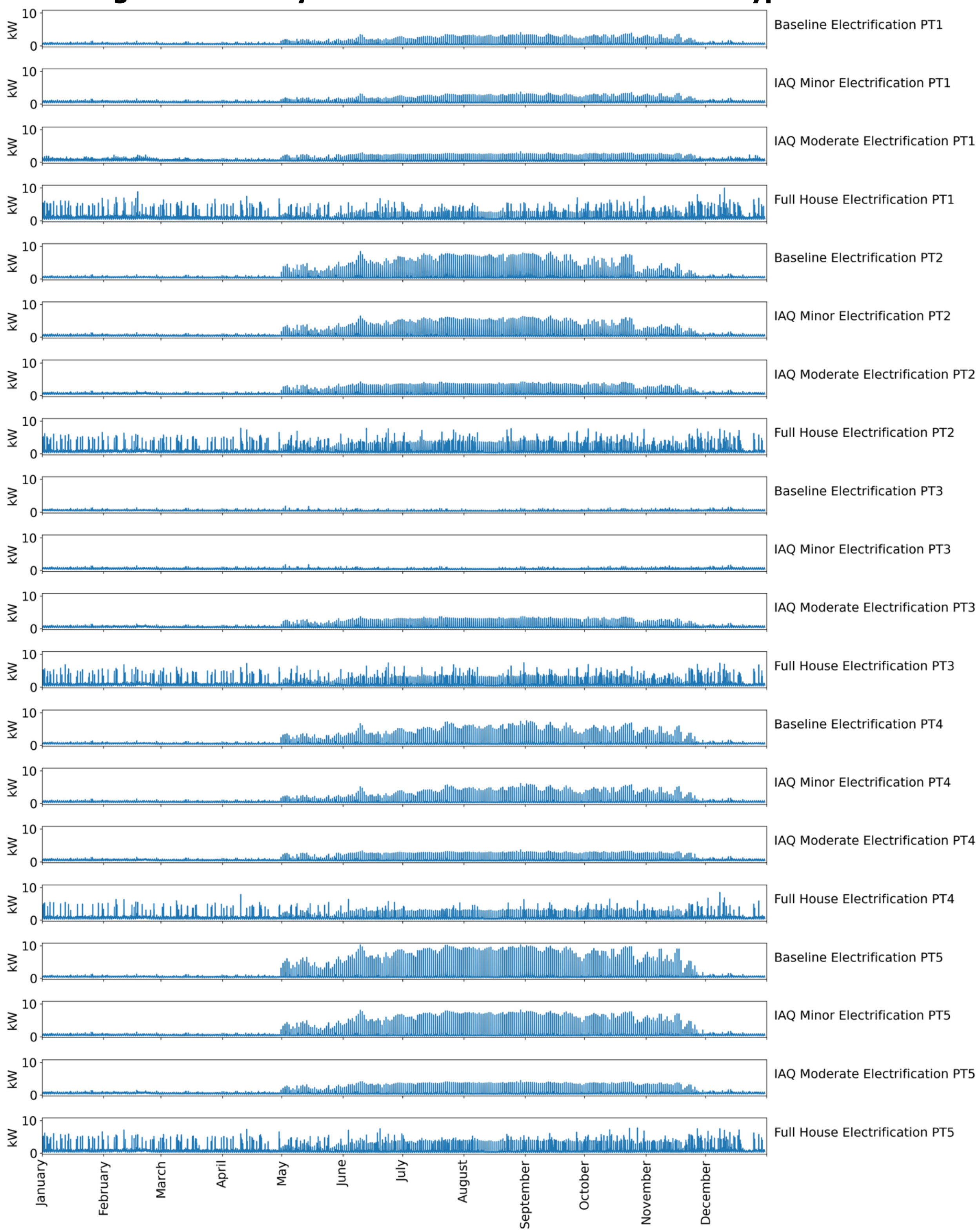
Source: The Energy Coalition

3.4.3 Hourly Load Profiles

Figure 17 and Figure 18 show hourly load profiles for each of the 20 SF prototype models generated for the appliance electrification and DER scenarios (five baseline prototypes with three scenario alternatives each). Figure 19 shows hourly load profiles for each of the 10 SF prototype models generated for the EV adoption scenarios (five baseline prototypes with one alternative scenario each).

A complete set of figures for building-scale hourly load profiles for all transformation scenarios can be found in the report entitled "Load Profile Changes from Transformation Pathways," available upon request to CCSC.

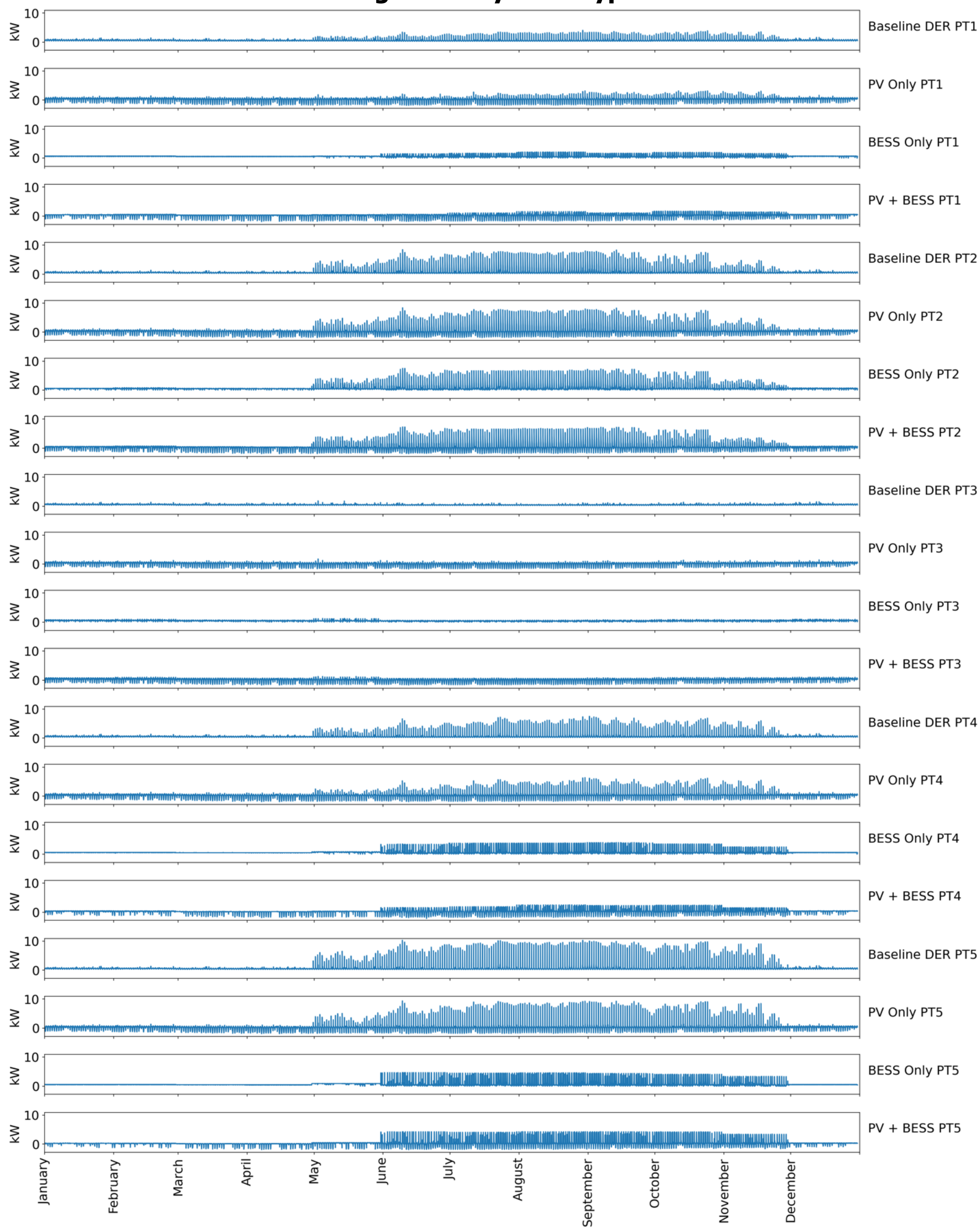
Figure 17: Hourly Load Profiles Generated for Prototype Models



Load profiles generated for each of the 20 total single-family prototype models for the appliance electrification scenarios – five baseline prototypes with three different alternative scenarios each.

Source: The Energy Coalition and UCLA

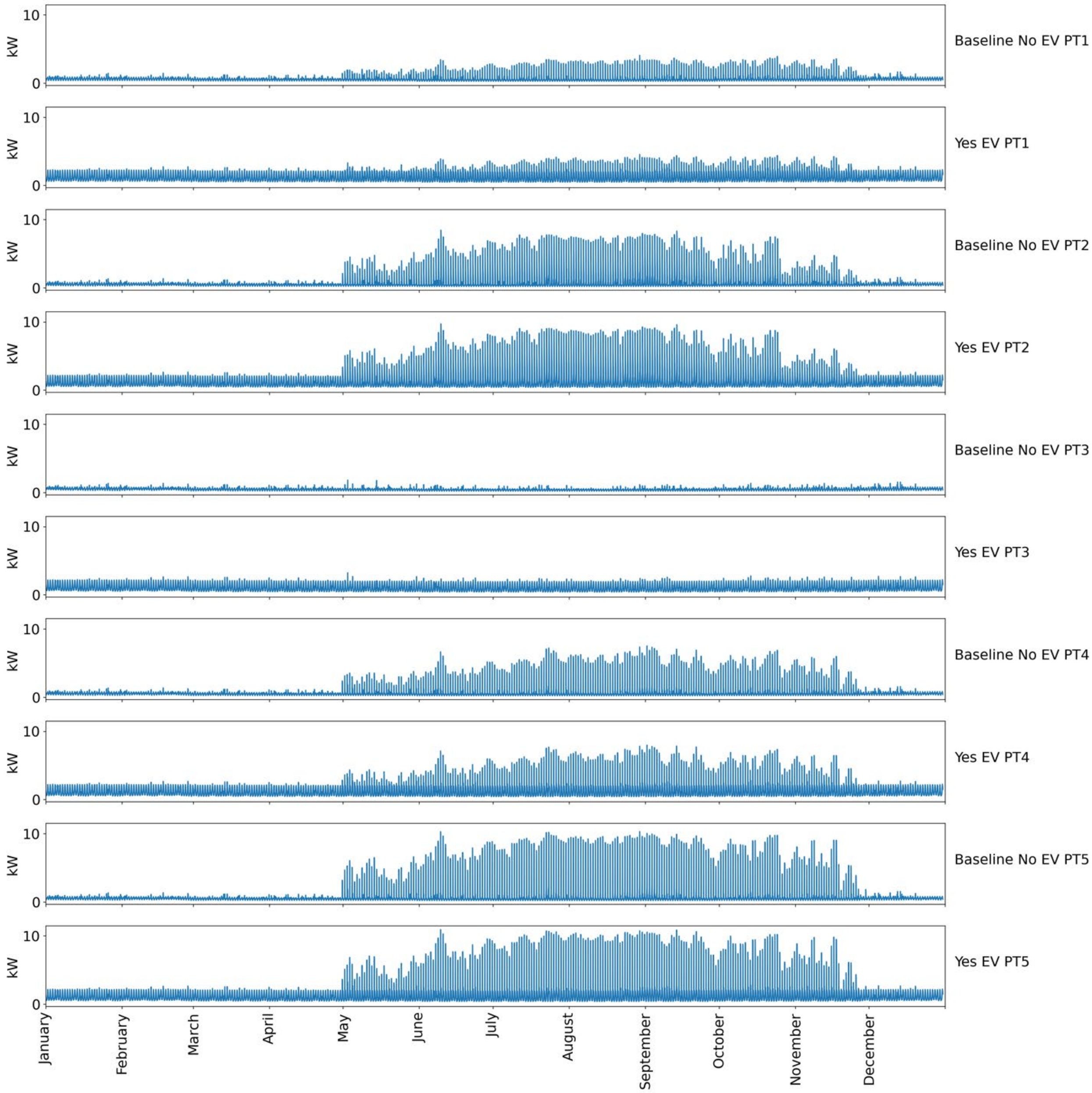
Figure 18: High-Level Overview Comparison of Hourly Load Profiles for 20 Single-Family Prototype Models



Comparison of load profiles generated for each of the 20 total single-family prototype models used for the distributed energy resource adoption pathway simulations (five baseline prototypes with three different alternative scenarios each)

Source: The Energy Coalition and UCLA

Figure 19: High-Level Overview Comparison of Hourly Load Profiles for 10 Single-Family Prototype Models



Comparison of the hourly load profiles generated for each of the 10 total single-family prototype models used for EV adoption pathway simulations (five baseline prototypes plus one alternative scenario each)

Source: The Energy Coalition and UCLA

3.4.4 Summary of Scenario Impacts on Energy Bills

Table 15 summarizes the changes in total annual utility bills for each prototype and retrofit scenario.

Table 15: Summary of Changes in Total Annual Utility Bills for Each Prototype and Retrofit Scenario

Prototype	Baseline	Minor Indoor Air Quality Focused	Moderate Indoor Air Quality Focused	Full Home Electrification	Full Home Electrification with PV and BESS	Full Home Electrification with EV	Full Home Electrification with EV, PV and BESS
Single-Family 1	$1,142	$1,164 +2%	$1,163 +2%	$1,696 +49%	$947 -17%	$3,106 +172%	$1,428 +25%
Single-Family 2	$1,610	$1,418 -12%	$1,234 -24%	$1,654 +3%	$966 -40%	$3,097 +92%	$1,571 -2%
Single-Family 3	$977	$916 -6%	$1,205 +23%	$1,478 +51%	$811 -17%	$2,954 +202%	$1,364 +40%
Single-Family 4	$1,253	$1,072 -14%	$1,003 -20%	$1,167 -7%	$534 -57%	$2,757 +120%	$1,176 -6%
Single-Family 5	$1,648	$1,387 -16%	$1,091 -34%	$1,466 -11%	$710 -57%	$3,046 +85%	$1,285 -22%
Multi-Family 1	$750	$745 -1%	$727 -3%	$680 -9%	$500 -33%	$1,349 +80%	$1,036 +38%
Multi-Family 2	$730	$730 0%	$725 -1%	$710 -3%	$627 -14%	$1,771 +143%	$1,221 +67%
Multi-Family 3	$913	$805 -12%	$805 -12%	$834 -9%	$797 -13%	$1,671 +83%	$1,043 +14%

Source: The Energy Coalition

Table 15 demonstrates substantial variations in the load impacts of electrification across typical homes in the study community. This is primarily due to the difference in baseline energy system configurations for each prototype model, most notably the HVAC systems. There is also a high degree of sensitivity to home energy use based on even minor changes in the age and type of equipment in the homes. This highlights the difficulty of making generalizations about any typical home and underscores the need for electrification scenarios that target both capital upgrades and operational efficiencies tailored to each home.

For example, SF Prototype 5 saw reductions in total annual utility bills for the two indoor air quality focused scenarios and the full home electrification scenario, while SF Prototype 1 saw annual bill increases for the same scenarios. SF Prototype 5 had a wall furnace with space heaters and a central AC unit, while SF Prototype 1 had a wall furnace with only a window AC unit. The Moderate IAQ and Full Home electrification scenarios replaced the heating and cooling systems with high-efficiency heat pumps. This system switch provided significant savings for SF Prototype 5, but an electricity use increase for SF Prototype 1. While a split system heat pump provides better thermal comfort for an entire home, its operating cost exceeded that of the window unit AC.

There were some trends between bill impacts and scenarios. Although the full home electrification included high-efficiency systems, the fuel cost of switching from natural gas to electricity caused a bill increase when compared with the moderate IAQ scenario. However, when solar PV and battery storage were added to the full home electrification scenario, all prototype models saw annual bill reductions.

MF prototypes all saw bill reductions under full home electrification scenarios, which was not the case for all of the SF prototypes. There were several reasons for this. First, the MF prototypes had inefficient appliances. The efficiency improvement with new electric appliances outweighed the fuel-cost transition. Second, the MF prototype homes had less square footage, so when the window AC unit and space heater were replaced with a highly efficient heat pump for air conditioning, the transition did not significantly increase energy use.

Electric vehicle charging significantly increased annual utility bills. Every prototype model saw a bill increase when EV charging was added to the full home electrification scenario. When solar PV and battery storage were included, some SF prototype models saw annual bill decreases though none of the MF prototypes did. It is important to note, however, that the research team did not model savings that residents would accrue from not purchasing gasoline and spending less on vehicle maintenance.

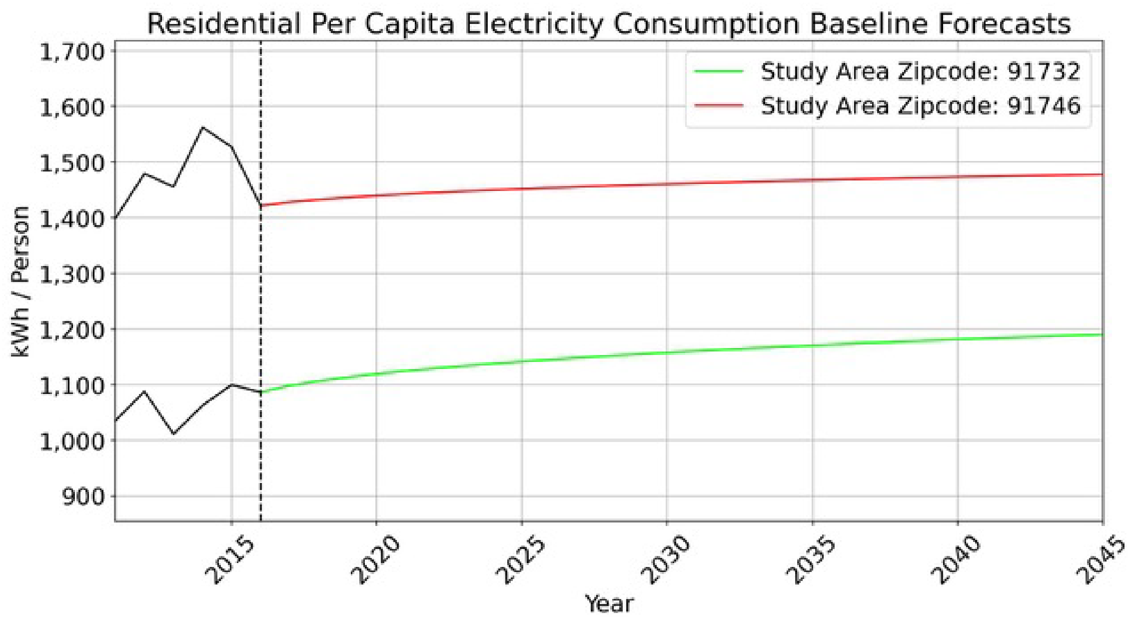
3.5 Baseline Growth Forecasts

A time series of historic and forecasted growth was produced for each of the residential energy transitions shown in the following sections, to serve as a baseline against which to compare possible future scenarios discussed in Section 2.4.3. Each of the two study area ZIP codes is shown as a separate line on the time series graphs. Historical data are plotted to the left, in black; forecasted data are shown in red and green.

3.5.1 Electricity Consumption

Historical and forecasted residential per capita electricity consumption data are shown in Figure 20. Overall, per-capita consumption levels within both ZIP codes were found to be lower than the countywide average figures, reflecting the strong positive correlation between per-capita energy consumption and the levels of affluence observed throughout the region. Annual rates of change have been relatively modest in recent years. These neutral growth rates reflect a balance which currently exists between the increased use of electricity for various end-use applications within homes and the increased energy efficiency of the appliances and technologies associated with those end uses.

Figure 20: Time Series Data for Historical and Projected Electricity Consumption for the Two ZIP Codes in Study



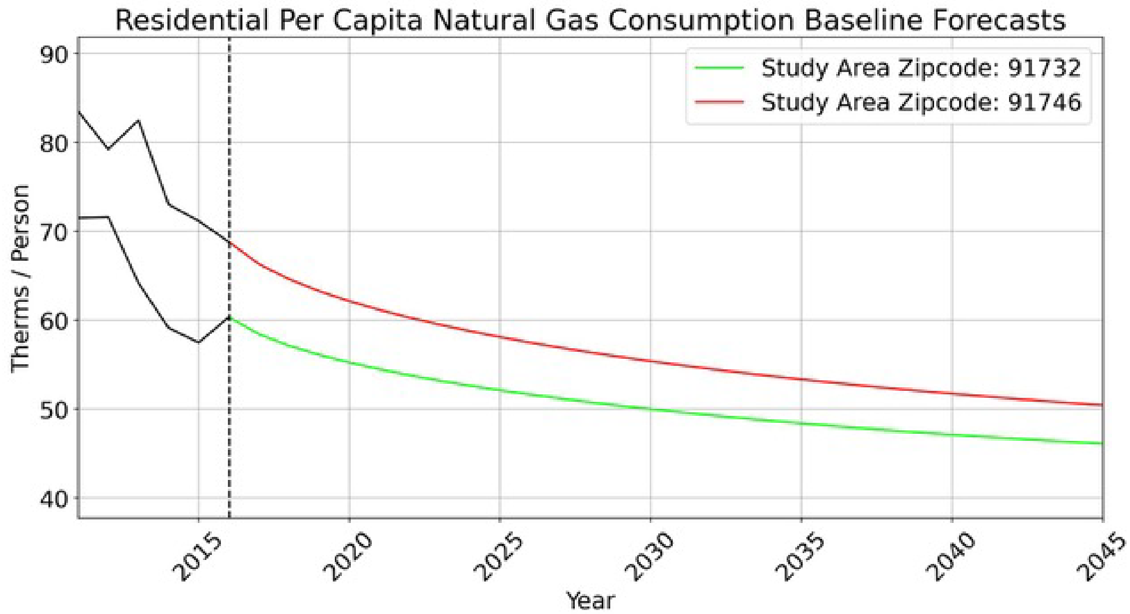
Historical (black) and projected future annual residential electricity consumption per capacity per for the project's two study area ZIP codes (red and green). (UCLA Energy Atlas)

Source: UCLA

3.5.2 Natural Gas Consumption

Historical and forecasted residential per capita natural gas consumption data is shown in Figure 21. Recent trends towards decreasing consumption within the historical data are forecast to continue. These baseline projections indicate that consumption levels will decline by around 30 percent from current levels by the end of the forecast horizon in 2045. These forecasts reflect expectations that the efficiency of natural gas appliances is likely to improve in the future. These forecasts additionally reflect recent background rates of natural gas appliance electrification.

Figure 21: Time Series Data for Historical and Projected Natural Gas Consumption for the Two ZIP Codes in Study



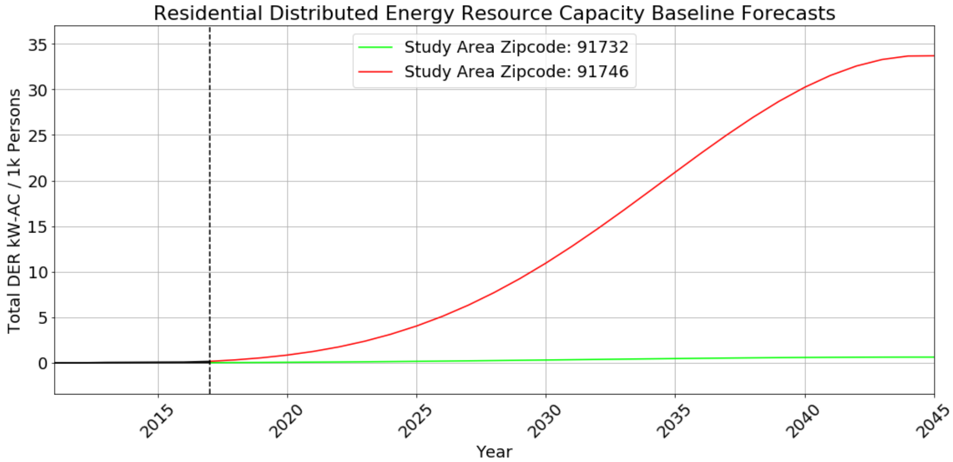
Historical (black) and projected future annual residential natural gas consumption per capita for the project's two study area ZIP codes (red and green). (UCLA Energy Atlas)

Source: UCLA

3.5.3 Distributed Energy Resource Adoption

Historical and forecasted per capita cumulative installed capacity of net-energy metering rate tariff, grid-connected DER systems are shown in Figure 22. The difference between the two is quite significant, with per-1k capita penetration rates in ZIP code 91732 lagging far behind those in the 91746 ZIP code, which also has a higher median household income. The magnitude of this difference can best be understood by focusing on recent historical growth rates. Figure 23 provides a zoomed-in view of the values plotted in Figure 22 from 2011 to 2018. Recent rates of DER growth in ZIP code 91746 were significantly higher than in 91732. Furthermore, the fact that the total population within ZIP code 91732 is roughly twice that of 91746 plays a significant role. Preliminary calculations suggest that even with these seemingly high rates of DER adoption in ZIP code 91746, cumulative installed DER capacities by the end of the forecast horizon will still be well below each ZIP code's maximum technical capacity potential.

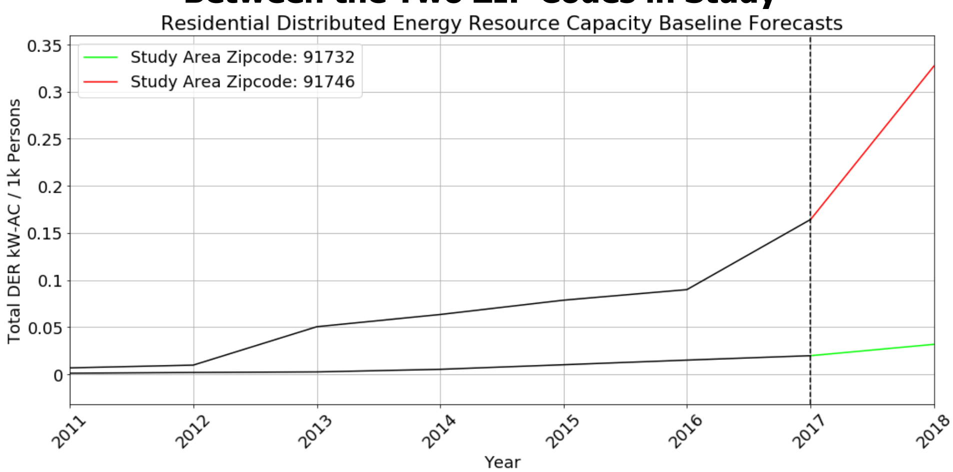
Figure 22: Time Series Data for Historical and Projected Installed DER Capacity for the Two ZIP Codes in Study



Historical (black) and projected future per-1k capita installed DER capacity for the project's two study area ZIP codes (red and green).

Source: UCLA

Figure 23: Difference in Historical DER Adoption Rates Between the Two ZIP Codes in Study



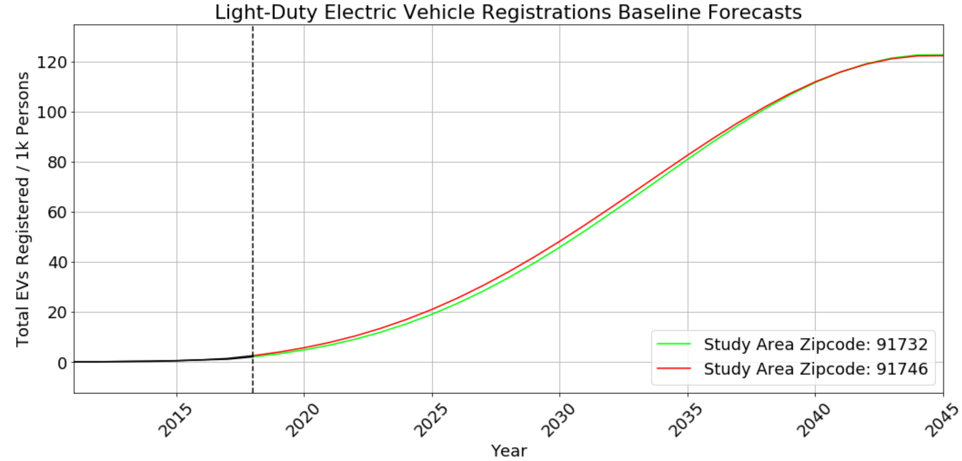
Zoom inset of lower left portion of Figure 22, highlighting the difference in historical DER adoption rates between the two ZIP codes.

Source: UCLA

3.5.4 Light-Duty Battery Electric Vehicle Adoption

Historical and forecasted per-1k capita adoption levels of light-duty battery electric vehicles are shown in Figure 24. These forecasts indicate that if recent historical EV growth rates continue, significant numbers of EVs will likely be present within these communities by the end of the forecast time horizon (about 120 per 1k persons). While these penetration levels are still well below full market saturation, they are non-trivial from an energy load-planning standpoint. Between the two ZIP codes, per-capita EV adoption rates have been similar in recent years, so their forecast projections closely mirror one another.

Figure 24: Time Series Data for Historical and Projected Light-Duty Battery Electric Vehicle Registrations



Time series data for historical (black) and projected future per-1k capita light-duty battery electric vehicle registrations within the project's two study area ZIP codes (red and green).

Source: UCLA

3.5.5 Appliance Electrification

As explained in the methodology, a countywide analysis could not be conducted to differentiate between the two study area ZIP codes for appliance electrification trends. Assumptions around initial conditions and baseline trends are described in the following section on community-scale modeling.

3.6 Community-Scale Simulations

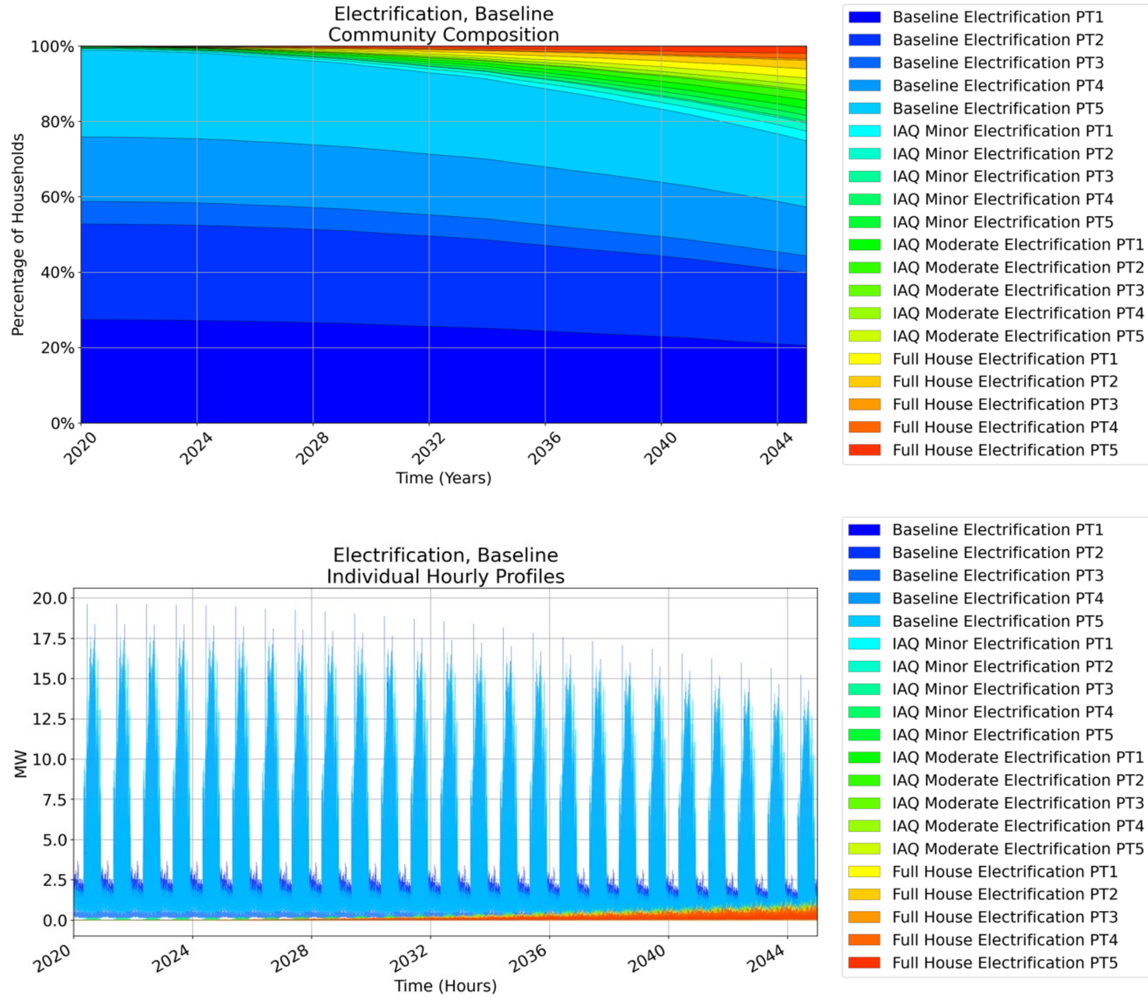
Selected results are shown in this section, with additional information in Appendix C. The report is available upon request to the CCSC.

3.6.1 Appliance Electrification Scenarios

Baseline Composition and Load Profiles

Figure 25 shows the baseline community composition and individual hourly load profiles for SF building appliance electrification.

Figure 25: Single-Family Baseline Building Electrification Pathway Community Composition (top) and Load Profiles by Prototype Model (bottom)



Source: UCLA

Alternative Pathways and Community Composition

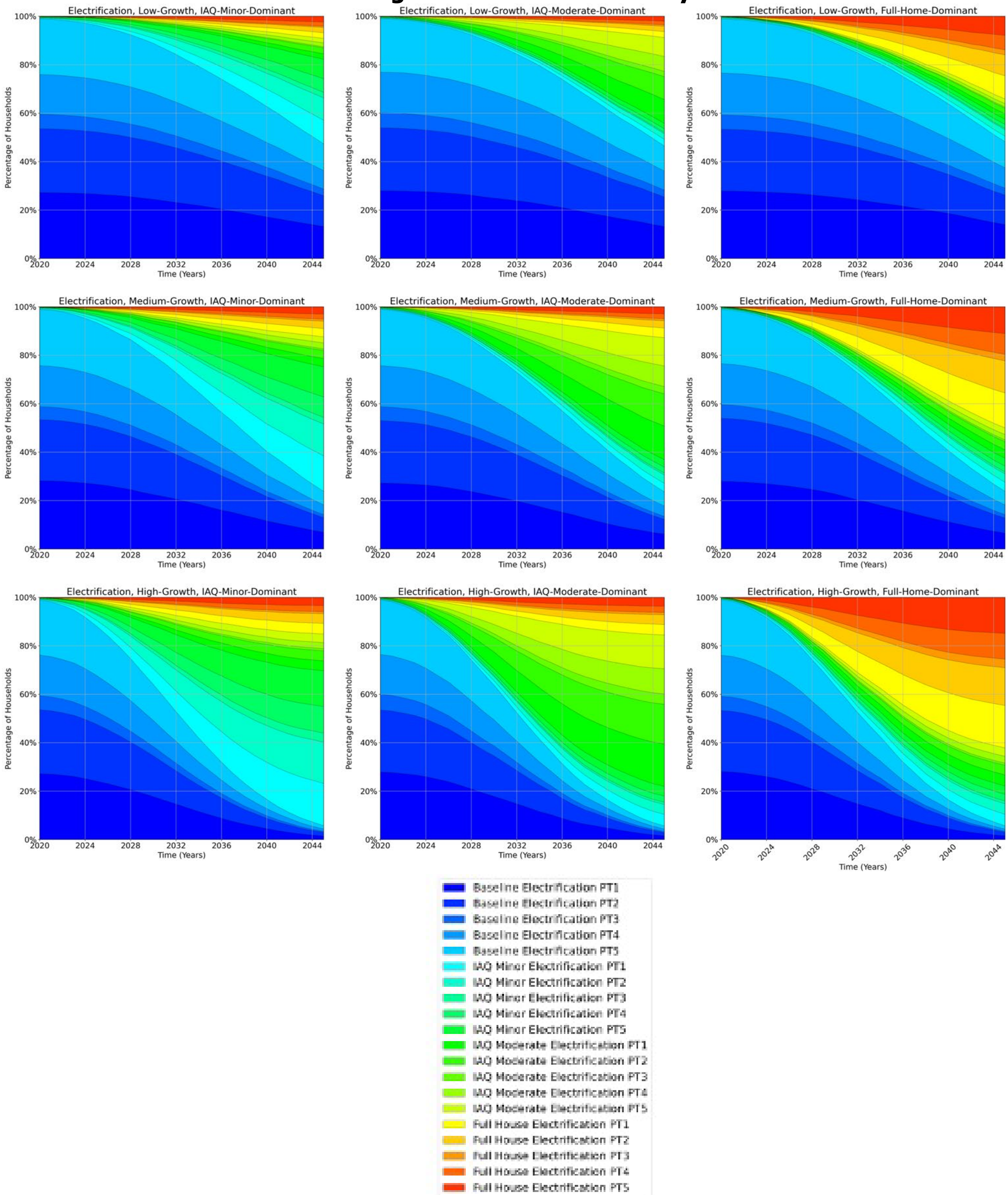
Table 16 shows the nine alternative pathways that were evaluated, and Figure 26 shows the development in community composition over the simulation period for each of the pathways.

Table 16: Overview Depiction of the Different Building Electrification Pathways

Low Growth	Medium Growth	High Growth
IAQ Focused, Minor Electrification Dominant	IAQ Focused, Minor Electrification Dominant	IAQ Focused, Minor Electrification Dominant
IAQ Focused, Moderate Electrification Dominant	IAQ Focused, Moderate Electrification Dominant	IAQ Focused, Moderate Electrification Dominant
Full Home Electrification Dominant	Full Home Electrification Dominant	Full Home Electrification Dominant

Source: UCLA

Figure 26: Comparison of Single-Family Building Stock Compositions Under Nine Building Electrification Pathways



Source: UCLA

Annual Load Growth

Plots of total annual load growth for the SF and MF baseline pathways and expected future changes in annual total loads associated with each pathway alternative are shown in Appendix Section C.5.1. All "Full Home Dominant" pathways resulted in significant increases in total annual loads relative to the baseline. Under the most extreme "High-Growth, Full Home Electrification Dominant" pathway (which eventually achieved 95 percent penetration of electrified households with around 60 percent fully electrified), the community's SF housing stock is expected to require an additional 13 GWh/year by 2045. This constitutes a 20-percent net increase over the baseline. Similarly, in the MF context, under the same pathway assumptions, annual total loads are expected to grow by 9 GWh/year, a net increase of 24 percent over the baseline.

Monthly Load Factors

Load factors are calculated as the ratio of the average load to the peak load over a specified period of time. This metric is useful for system operators and planners since it indicates the system's operational efficiency—both in terms of generator ramping requirements and distribution capacity utilization levels. Higher load factors are generally desirable as they reflect the more efficient use of both these categories of assets.

The monthly load factor for each year of the simulation period between the nine electrification pathway alternatives for SF buildings is shown in Appendix Section C.5.2. During the initial years of the simulation, load factors in the summer and early fall (May-Nov) were substantially lower (>2x) than in the winter and early spring. This trend reflects the seasonal cooling demand for electricity within the study area's climate zone.

For both SF and MF (not shown), load factors in the spring and winter months under the "High Growth, Full Home Dominant" pathway deteriorated substantially, with the values in December and January being worse than the values in July and September by the end date of the simulation period. The pattern reflects significantly higher heating demand for electricity under this pathway, with the majority of buildings in the community no longer using natural gas for air and water heating during these cooler months.

Monthly Total Loads-Changes From Baseline

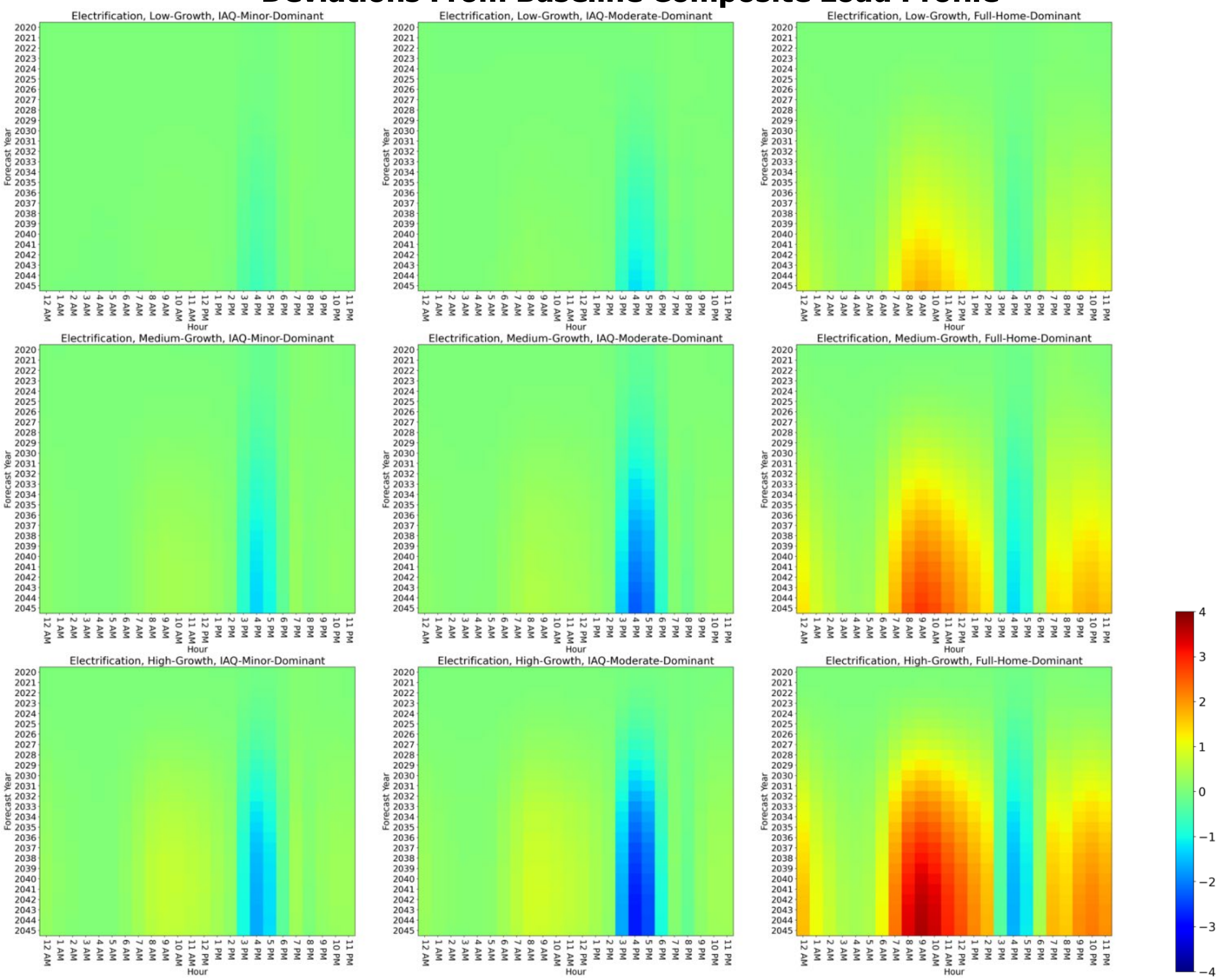
Changes in total monthly loads relative to the baselines for SF buildings (showing net increases and decreases in monthly demand) are shown in Appendix Section C.5.3. For the Full Home Dominant pathways, the magnitude of winter load increases is far greater than that of summer load decreases, reflecting a smaller contribution from energy efficiency improvements compared with the impact of new electric loads.

Hourly Peak Load–Changes From Baseline

The timing of diurnal peak loads is of serious concern given the predictable (but intermittent) cadence of solar PV system outputs. For system operators and planners, the fact that current peak loads, which occur in the early evening, largely coincide with the rapid reduction of solar PV system outputs is deeply problematic because it necessitates rapid ramping of output from other generator classes to serve remaining loads. This peak period ramping is principally accomplished using natural gas fired thermal generators. This causes the marginal GHG emission impacts of peak period power consumption to be higher than average.

Plots of hourly changes in average peak loads across the 25-year simulation period for SF buildings are shown in Appendix Section C.5.4. Figure 27 plots average changes from the baseline for the same period. In the early years of the simulation time horizon, the highest peak loads are concentrated in the early evening hours (4 p.m. to 9 p.m.) when residents return home and have the strongest demand for energy, particularly for cooling during summer months.

Figure 27: Comparison of Single-Family Building Electrification Pathway Mean Deviations From Baseline Composite Load Profile



Comparison of SF building electrification pathway mean deviations (MW) from the baseline composite load profile, by hour of day for each year of the simulation period

Source: UCLA

For SF and MF (not shown), the IAQ focused pathways have a moderating influence on the magnitude of the diurnal peak loads. These improvements are largely due to improved thermal performance from the addition of roof, attic, air duct, and water pipe insulation in the IAQ-Minor and IAQ-Moderate scenarios, as well as the significantly increased efficiency of the mini-split/air-source heat-pump units that replaced wall-mounted air conditioning (A/C) units and furnace units in the IAQ-Moderate scenarios. In the SF case, under the "High Growth" IAQ-dominant pathways, the largest observed reductions in peak loads were on the order of 35 percent. In the MF case (not shown), the largest observed reductions were smaller, at around 25 percent.

The average hourly peak load impacts from the "Full Home Dominant" electrification pathways are much more significant. For both SF and MF (not shown), under the most aggressive pathway alternative, average peak loads during the morning hours (7 a.m. to 10 a.m.) in the final year of the simulation rise to nearly the same levels as the currently prevailing early evening peak. This change corresponds to increases of between 200 percent and 260 percent for those hours. The appearance of this new average hourly morning peak is largely attributable to new water-heating loads during winter months.

3.6.2 Distributed Solar PV and Storage Scenarios

Baseline Composition and Load Profiles

Figures in Appendix Section C.5.5 illustrate the evolution of the baseline composition of the community's building stock and how this evolution is reflected in the contribution of each prototype model category to the community's composite hourly load profile.

According to this baseline pathway, the expectation is that under the status quo, "PV-only" systems will continue to outpace the "BESS-Only" and "PV+BESS" alternatives within the project's study community. This expectation is grounded in the lower cost of PV-only systems and interconnection challenges that currently hinder adoption of behind the meter BESS-only systems.

In the DER adoption transition category, the final outcome of the baseline pathway projects that only around 13 percent of SF households and around 8 percent of MF households in the community will convert to one of the DER prototype scenario models by the 2045 end date of the simulation horizon.

This tepid future growth in installed rooftop PV system capacity under the baseline pathway, combined with the adoption of minimally invasive EE measures, is expected to contribute to only minor reductions in the community's future composite hourly electricity loads.

Alternative Pathways and Community Composition

A total of nine pathways, shown in Table 17, were evaluated.

Table 17: Overview of Distributed Energy Resource Adoption Pathways

Low Growth	Medium Growth	High Growth
PV-Only-Dominant	PV-Only-Dominant	PV-Only-Dominant
BESS-Only-Dominant	BESS-Only-Dominant	BESS-Only-Dominant
PV+BESS-Dominant	PV+BESS-Dominant	PV+BESS-Dominant

Source: UCLA

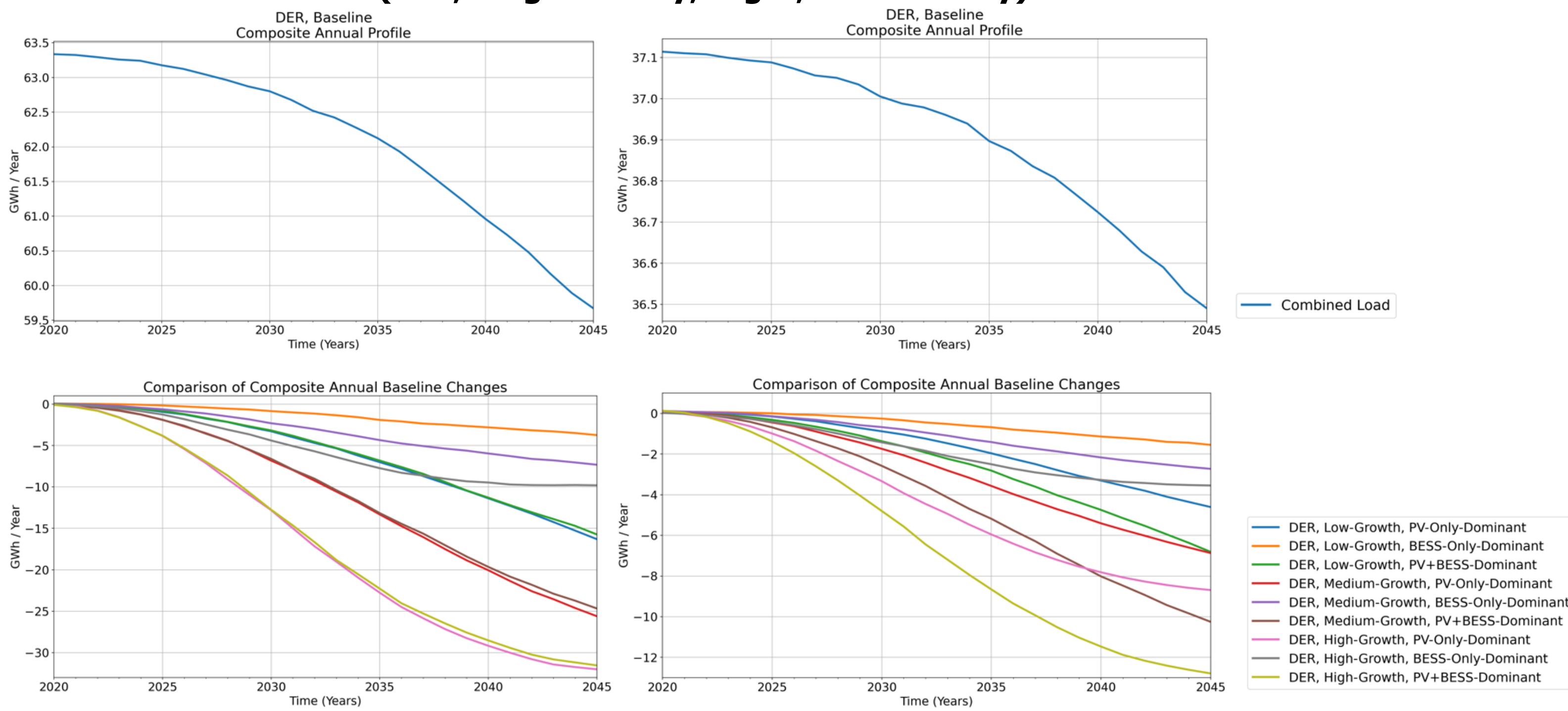
Appendix Section C.5.6 includes plots of the changing composition of the SF housing stocks over the 25-year simulation period.

Annual Load Growth

Figure 28 plots the change in the absolute total annual loads as well as the deviation from the baseline pathway for each the SF and MF contexts, between the different DER adoption pathway alternatives. As the plot in the lower left portion of the figure illustrates, in both contexts, all of the pathways resulted in a net decrease in total annual loads relative to the baseline by the end of the simulation period.

The largest benefits in terms of load reductions were in the "High-Growth Rate" pathways, which incorporate PV generation systems (PV-only and PV+BESS). These resulted in a maximum reduction of 32 GWh/year by 2045 and 13 GWh/year for the MF context. The slight differences in load reductions between the "PV-Only-Dominant" and "PV+BESS Dominant" pathways stem from the fact that the addition of battery storage systems largely shift the timing of net grid loads instead of significantly reducing them. According to the optimized battery discharge schedules generated using REopt, the majority of the stored energy within the battery systems was used to offset peak loads to provide maximum electricity cost savings for residents.

Figure 28: Comparisons of Distributed Energy Resource Pathways (Left, Single-Family; Right, Multi-Family)



Comparison of each DER pathway simulations' total annual loads and annual total change from the baseline composite load profile for the community's single-family housing stock (left column) and multi-family housing stock (right column)

Source: UCLA

Monthly Load Factors

By 2045, under the High-Growth, PV-Only-Dominant and PV+BESS-Dominant pathways for SF buildings, average load factors during the late winter and early spring months substantially decreased (not shown). During these months, when cooling loads are minimal but solar PV production is strong, there are more midday (off-peak) hours in which PV systems are able to either completely supply household electricity demands or even overproduce. The export of this electricity back to the grid therefore manifests as a notable reduction in average loads during these periods. The effects of these pathways for MF are similar but less extreme.

Interestingly, across the SF and MF contexts, the magnitude of the load factor improvements associated with the BESS-Only pathways were not as significant as the magnitude of load deterioration with the PV dominant pathways. This is because building-scale modeling assumed that the PV + BESS components were sized to deliver maximum financial returns to residents.

Under existing net-metering tariffs, the most valuable use for the BESS is for peak shaving rather than load shifting. Consequently, the optimal storage capacity of the BESS components tends to reflect the duration of the peak load periods. With proportionally larger-sized PV systems, substantial quantities of excess power are generated at midday hours during spring months when PV performance is strong but onsite demand is weak. This power must be absorbed by the grid during these periods. These net exports of power reduce average community loads and negatively affect grid load factors. All these results suggest that BESS systems could provide extensive benefits to the grid if they were differently sized or their operations differently scheduled.

Monthly Total Loads-Changes From Baseline

With respect to monthly total load changes relative to the baseline (not shown), the dominant trend is for the community to experience the largest net load reductions in the months with the highest solar PV system output in the pathways with the largest PV growth rates. The BESS-Only dominant pathways have minimal net changes in load as these systems primarily shift the timing of demand for energy from the grid rather than reduce the overall magnitude.

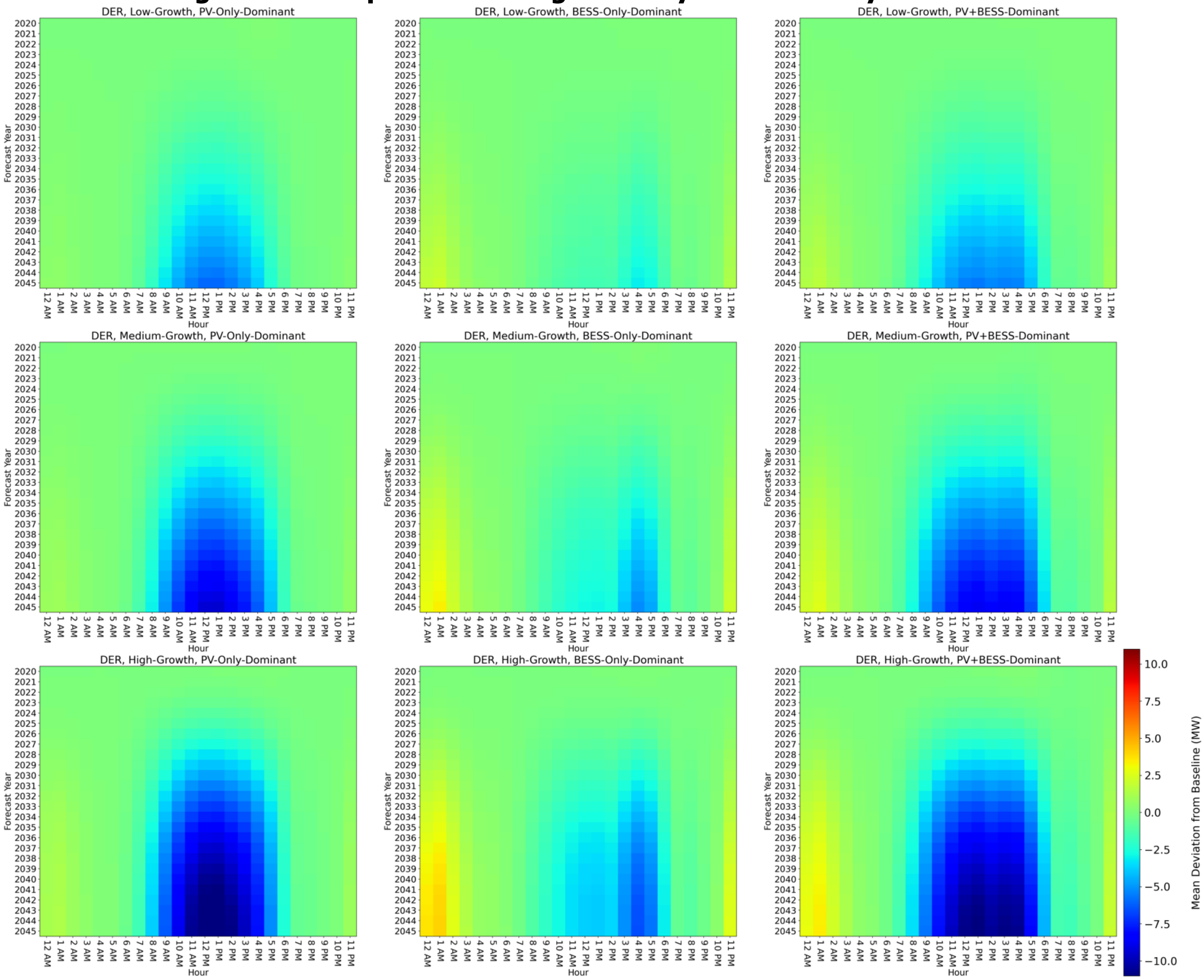
Hourly Peak Load–Changes From Baseline

Figure 29 depicts the mean percentage change in hourly loads for each pathway alternative for SF buildings. The contribution of each component (PV versus BESS) can be clearly seen in the timing of the areas that are red (net increases) versus blue (net decreases).

As the first and third column illustrate, the diurnal pattern of the PV systems' outputs produces net reductions in the study area community's total monthly demand for grid-supplied electricity from the baseline of approximately 12 MW (and 6 MW for MF–not shown) during midday hours. The magnitude of these reductions increases in proportion to the growth rate level associated with each pathway alternative.

For the PV+BESS pathways, the net load reductions from the inclusion of PV systems are substantially larger than the net load increases associated with battery charging from the grid during late evening/early morning off-peak hours. This proportional difference reflects the relative sizing of the BESS to PV systems' capacities, under an economically optimal configuration.

Figure 29:Comparison of Single-Family DER Pathway Mean Deviations



Comparison of single-family DER pathway mean deviations from the baseline pathway composite load profile, by hour of day for each year of the simulation period

Source: UCLA

3.6.3 Electric Vehicle Adoption Scenarios

Baseline Composition and Load Profiles

Appendix Section C.5.7 shows changes in the community composition, individual prototype model load contributions, and communitywide composite hourly loads for SF buildings for baseline EV adoption over the simulation period. The total number of EVs currently registered within the project study area community is only 511 across the SF and MF contexts. However, the growth rate assumptions applied to the baseline SF EV adoption pathways—which are based upon ZIP code level EV adoptions forecasts previously developed as part of this analysis, using historical consumer adoption data—estimated that around 60 percent of households would adopt EVs by 2045. This is higher than the terminal conversion rate of 50 percent associated with the “Low-Growth” pathway within the SF context. Alternatively, in the

MF context (not shown), growth rates are expected to be less aggressive under the baseline pathway due to the difficulties associated with implementing any type of in-home charging solutions within renter-occupied structures. Consequently, the MF baseline pathway only achieved a final conversion rate of approximately 20 percent by 2045.

Alternative Pathways and Community Composition

Table 18 shows the three alternative pathways evaluated.

Table 18: Different Distributed Energy Resource Adoption Pathways

Pathway
Low Growth /Yes-EV-Dominant
Medium Growth /Yes-EV-Dominant
High Growth /Yes-EV-Dominant

Source: UCLA

Appendix Section C.5.8 shows the community composition over the simulation period for each of the pathways.

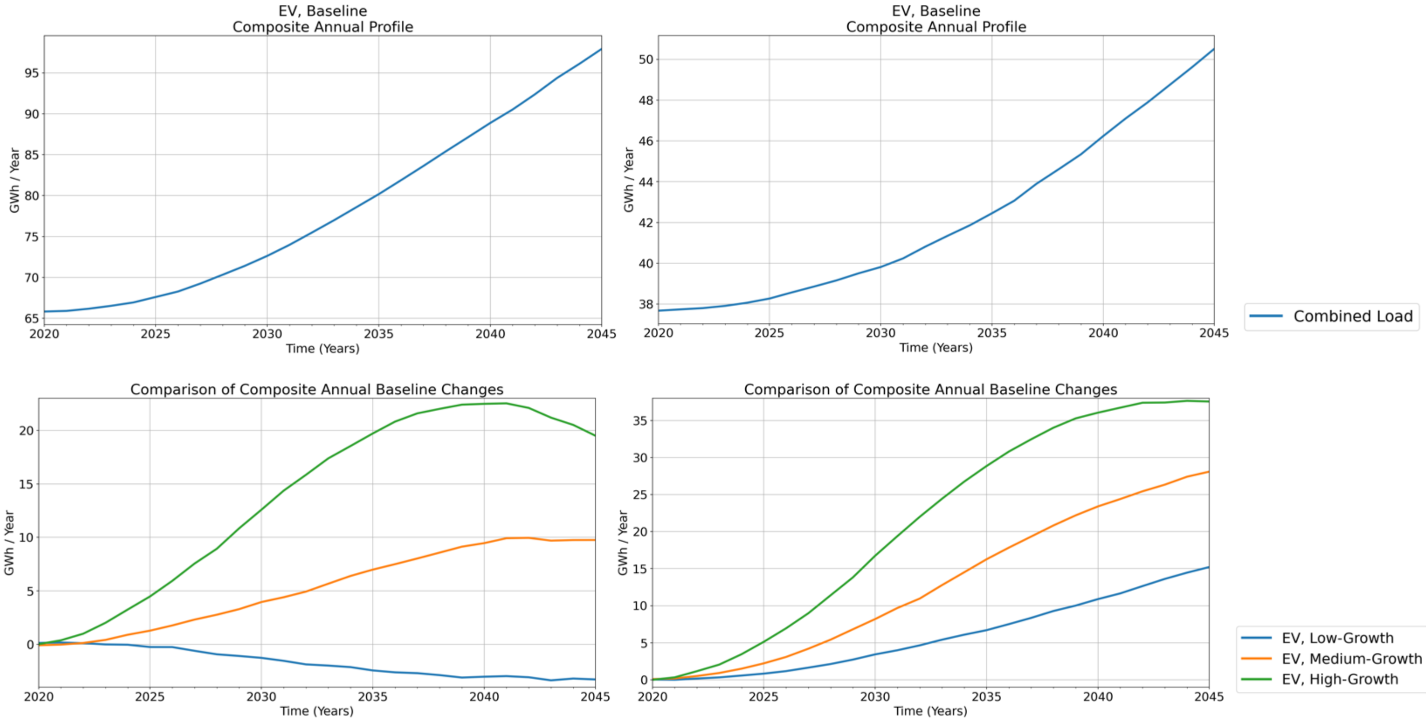
This analysis assumed "uncontrolled charging," meaning that future charging behaviors, both the proportion of charging done at home and the relative timing of charging, are consistent with current patterns. While it is possible (and perhaps even likely) that future EV charging behaviors will become subject to some mechanism of control (for instance, through the requirement that EV charging be subject to dedicated rate tariffs or even implementing some sort of remote control or regulation system) these have not been fleshed out so, consequently, were outside the scope of this analysis.

Annual Load Growth

Figure 30 plots total annual load growth for the SF and MF baseline pathways (top row) and the expected future changes in annual total loads associated with each pathway alternative (bottom row).

Even with the assumption of only level 1 charging infrastructure use, EVs constitute substantial loads when compared with a typical suite of residential end-use electricity appliances. This is evident in the size of total annual load profile changes associated with the different EV adoption pathways considered. Under the baseline pathway total annual loads are anticipated to grow by 34 GWh (42 percent) in the SF context and 15 GWh (40 percent) in the MF context.

Figure 30: Comparisons of Electric Vehicle Pathways (Left, Single-Family; Right, Multi-Family)



Comparisons of each electric vehicle pathway simulations' total annual loads and annual total change from the baseline composite load profile for the community's single-family housing stock (left column) and multi-family housing stock (right column).

Source: UCLA

The Low Growth pathway resulted in load reductions from the baseline because the Low-Growth pathway actually exhibited slower rates of EV adoption than expected under the baseline. Under the two higher-growth pathways, increases in total annual loads relative to the baseline become significant. The High Growth scenario, which corresponds to 95 percent EV penetration by 2045, shows that by the end of the simulation period total annual loads in the SF context will increase by 20 GWh, relative to the baseline. This increase, when combined with the 34 GWh expected under the baseline, corresponds to an overall net increase of 78 percent from current loads. In comparison, within the MF context, if the same High Growth pathway were to be realized it would result in 37 GWh, relative to the baseline. Again, adding this figure to the growth already assumed under the baseline resulted in a 140-percent increase from current MF loads.

Monthly Load Factors

Load factors (not shown) tended to increase as the penetration of EV households increased. In the SF context, in the High Growth pathway, the magnitude of these changes range between 0.15 and 0.2, depending upon the month, by 2045. In the MF context, these final increases are slightly higher, ranging from 0.2 to 0.25.

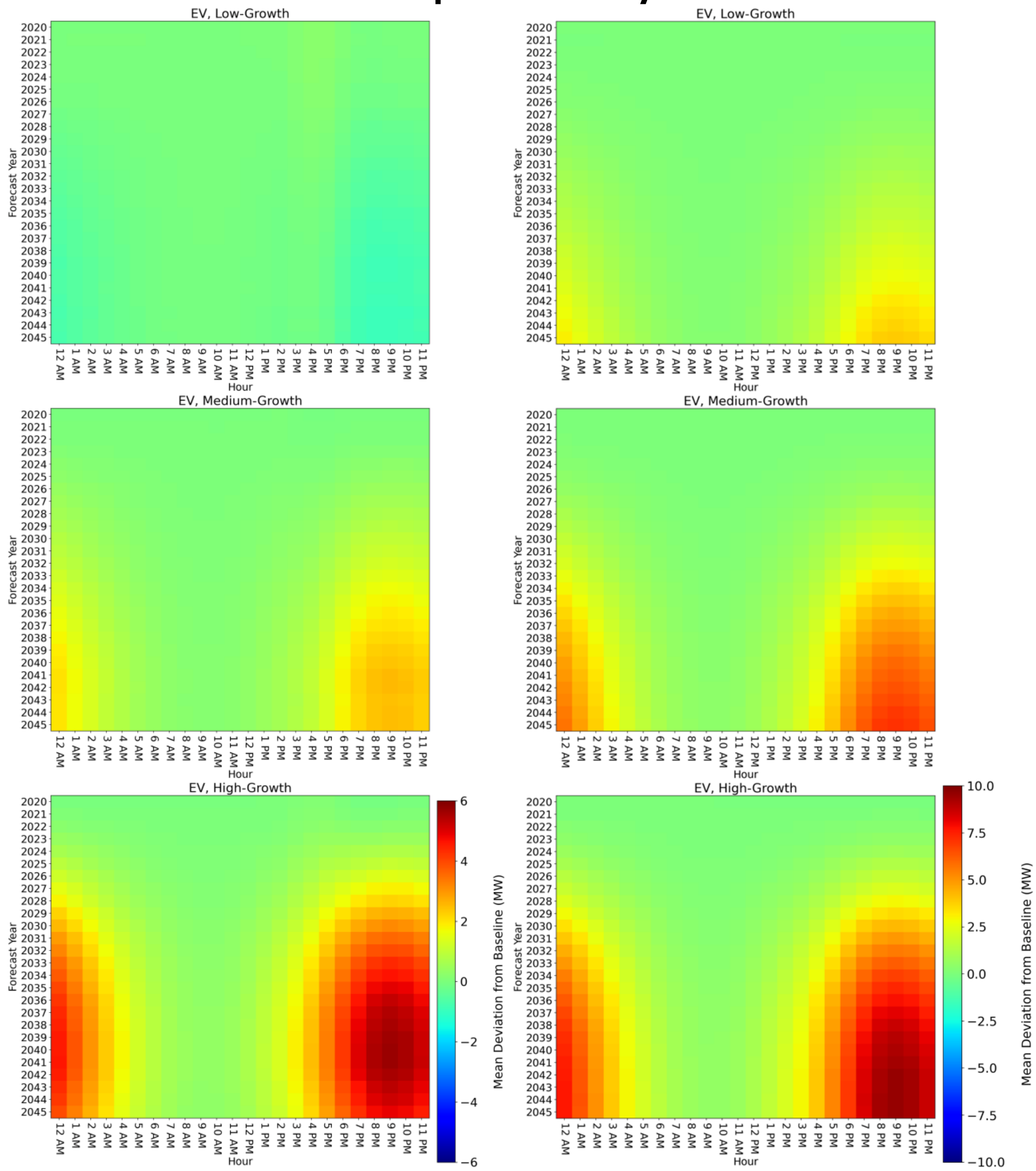
Monthly Total Loads-Changes From Baseline

Monthly total load changes relative to baseline (not shown) are characterized by the seasonal invariance of EV loads, in which monthly patterns of EV charging are fairly consistent across all months of the year.

Hourly Peak Loads–Changes From Baseline

The influence of increased future EV adoption on average diurnal peak loads (Figure 31) is significant and highlights the need for mechanisms to help regulate the timing and intensity of EV charging. Such regulation would limit the need for future grid infrastructure capacity expansion and ensure reliable grid operations through reduced generator ramping requirements. As the plots contained in Figure 31 show, under the High Growth pathway, in the SF case additional EVs cause the maximum hourly average peak loads to increase from 38 MW to 46 MW, or 20 percent. In the MF case, the increase is from 19 MW to 27 MW, an increase of 38 percent.

Figure 31: Comparison of Mean Deviations for Single-Family and Multi-Family in EV Adoption Pathway



Comparison of mean deviations from the baseline single-family (left column) and multi-family (right column) electric vehicle adoption pathway composite load, by hour of day for each year of the simulation period.

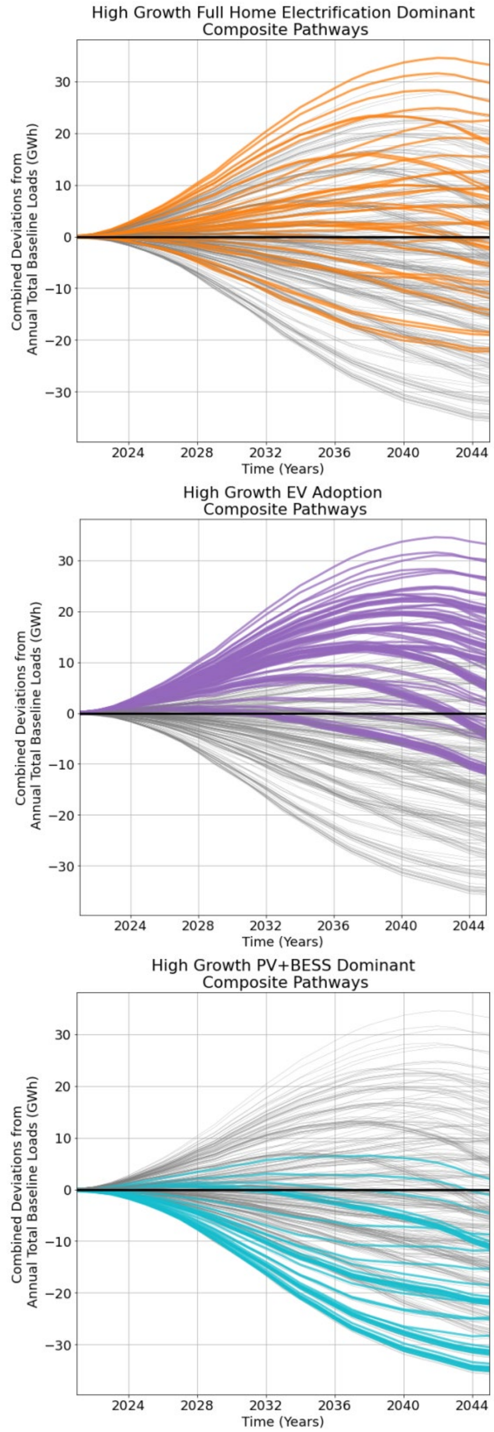
Source: UCLA

3.6.4 Composite Load Growth Assessment

The total annual load growth impacts from increasing rates of full home electrification will largely be determined by parallel rates of growth in EV and DER adoption.

By combining the marginal contributions of all discrete pathways generated within each transition category, the future range of possible combined load growth outcomes becomes clear. Figure 32 shows the annual combined deviations from the baseline loads produced by all of the combinations of the discrete SF pathway alternatives (in gray). At the top of this figure, all composite pathways with high amounts (around 95 percent) of fully electrified homes are highlighted in orange. Along the bottom, all composite pathways that achieved similarly high numbers of EV adoptions (left) and PV+BESS adoptions are highlighted in purple and blue, respectively. As these plots illustrate, the magnitude of the load reductions that can be realized through adoption of optimized PV+BESS systems is roughly equivalent to load increases associated with either Full House Electrification or EV adoption.

Figure 32: Total Annual Load Deviations for All Composite Pathways



Total annual load deviations for all composite pathways involving high levels of full home electrification (top, orange), all composite pathways involving high levels of EV Adoption (middle, purple), and all composite pathways involving high levels of PV+BESS adoption (bottom, cyan).

Source: UCLA

The minimally invasive energy efficiency improvements incorporated into the building prototype scenario models were not impactful enough to offset load-growth impacts from future adoption of new major energy end-use technologies. This suggests that deeper home energy retrofit measures will be necessary to achieve further meaningful load reductions.

In all EV adoption and building electrification transition pathways where high-growth rates were applied, consistent with a 2045 target date for full community conversion, load growth levels were significant. This suggests that far more aggressive energy efficiency measures would have to be implemented to fully offset these impacts within residential retrofit contexts.

3.6.5 Discussion

Baseline growth pathways developed for the study anticipate that EVs will experience the highest rates of future adoption. This is followed by home electrification measures; DER systems show the lowest rates of expected future adoption. Stimulating levels of DER adoption and appliance electrification within under-resourced communities will require new policies or incentives that mitigate the upfront costs of financing new equipment purchases and, in the case of electrification, the ongoing costs of transitioning to a more expensive fuel source.

The relative dominance of the EV Adoption pathway in terms of baseline impacts can largely be attributed to the rapid growth of EV adoption, which was underway even within disadvantaged communities. The relative magnitude and coincident timing of EV loads, assuming unrestricted charging, have a dramatic and potentially destabilizing influence on load levels at the community scale. Additionally, if more level 2+ chargers are installed within the community the severity of those impacts will only increase.

In terms of the broader investigation of the building electrification transition, it does not have to be an all-or-nothing proposition. Rather, building electrification can be pursued in more incremental terms, particularly within retrofit contexts, where partial electrification retrofits can focus on improving indoor air quality by first replacing natural gas appliances (whose use has been found to most strongly correlate with reductions in indoor air pollutants).

Other results from the building electrification pathway simulation indicate that the complete replacement of all gas appliances within homes is likely to significantly alter the structure, and, to a lesser extent, the magnitude, of the community's composite hourly load profile. These changes will most negatively impact the timing and magnitude of diurnal peak loads and, by extension, monthly average load factors. Specifically, the pathways involving the most extensive transition to fully electrified homes will not only amplify existing summer evening peak loads but also introduce significant new peak load periods in the morning hours of winter months when heating energy demand dominates. From the perspective of grid operators and generator fleet managers, dealing with this new seasonal pattern in peak-load periods would necessitate significant operational changes in the generator fleet. This development could also lead to changes in existing time-of-use rate structures.

Exploration of different DER adoption pathways supports the conclusion that battery energy storage systems will need to play an increasingly prominent role in DER installations to both maximize the value of, and mitigate potential grid impacts from, increased penetration levels of rooftop solar PV systems. Increasing the adoption of optimized PV+BESS could potentially improve onsite generation rates, reducing the frequency and magnitude of energy exports back to the grid. Additionally, the ability to selectively charge batteries off peak and discharge them on peak has the potential to significantly reduce peak loads and reduce the costs of new electricity end uses (such as electrified natural gas appliances or more EVs). However, there may be additional opportunities to revise existing time-of-use tariff structures so that the operation of large numbers of cost-optimized PV+BESS systems also delivers the best possible outcomes for grid operators.

As previously noted, EVs are perhaps the most significant and potentially problematic energy transition category because of their rapid public adoption. In-home EV charging essentially transfers the energy demands of an entire separate segment of the transportation sector to an electricity infrastructure system designed to service only the types of loads traditionally found within residential buildings. The number of gasoline filling stations that currently exist and the magnitude of the primary energy supplied by them every day demonstrate the scale of electricity transformation necessary.

Reflecting on the fact that the EV load profiles used in this analysis assumed uncontrolled charging, these findings offer a glimmer of hope. This is because, if properly regulated, EV loads can be timed so that they actually improve the asset utilization efficiency of grid infrastructure. Additionally, if the majority of EVs were charged during the middle of the day during off-peak hours, this would better coincide with the timing of peak renewable outputs, reducing the marginal GHG emissions intensity of the electricity consumed. There are different ways to pursue this outcome. One might be to further discourage on-peak charging through even higher EV focused, time-of-use (TOU) rate tariffs. Another way might be to reward behavioral changes by investing substantially in the development of convenient away-from-home charging infrastructure, either at places of work, economic activity, or public use. If these types of public EV chargers were additionally co-located with renewable generation, as with carport PV systems for example, the benefits could be multi-faceted. Additional future investigations of these and other potential solutions to this looming challenge must be undertaken.

Finally, the possibility of future vehicle-to-grid functionality could have important consequences. This technology allows grid-connected EVs to strategically discharge when it is advantageous to do so. How such a process should be coordinated (for instance, through dynamic price signals or direct command and control mechanisms) is still a topic of active debate. However, this would be a transformational capability, one that would increase the value of an EV's most expensive single component: its battery.

3.7 Holistic Assessment of Residential Appliance Electrification

This portion of the analysis focused on residential building electrification to more fully understand if future electrification efforts, occurring at any feasible rate, could potentially cause unanticipated consequences including net increases in overall air pollutant emissions. It has been hypothesized that such an unintended outcome may be possible when accounting for ambient emissions from the grid's fossil-fueled generators. Therefore, only the highest growth-rate pathways were evaluated, as these reflect the maximum speed of electrification within the study community.

Results from this analysis are organized as follows. More detailed information appears in the Appendix C.

- Grid Emissions and Impacts.
    - Increases in Ambient Emissions From Fossil EGUs.

        - Annually (figures included in Appendix Section C.6.1).
        - Monthly (figures and discussion included in Appendix Section C.6.1).
        - Geographic.
    - Ambient Air Quality Impacts Expressed as Changes in Human Health.
        - Annual Breakdown.
        - Categorical Breakdown (tables included in Appendix Section C.6.2).
- Local Emissions and Impacts.
    - Decreases in Local Emissions From Electrification.
        - Annual (figures included in Appendix Section C.6.3).
        - Monthly (figures and discussion included in Appendix Section C.6.3).
    - Local Air Quality Benefits Expressed as Changes in Human Health.
        - Annual Breakdown.
        - Categorical Breakdown (tables included in Appendix Section C.6.4).
- Combined Emissions Changes and Impacts.
    - Combined Annual Emissions Changes.
    - Combined Air Quality Impacts Expressed as Changes in Human Health.
        - Annual Breakdown.
        - Categorical Breakdown.
        - Geographic Breakdown.
- Discussion.
    - Ambient Emissions Production.
        - Potential Implications of Future RPS Non-Compliance.
        - Considering Secondary Emissions Production From Atmospheric Processes.
    - Local and Indoor Emissions Exposure.
        - Establishing Indoor Emissions Exposure Standards.
        - Options for Improving Indoor Air Pollutant Capture Efficiency with Forced-Air Ventilation.
    - State and Local Electrification Policies.
        - Evaluating the Optimal Phasing-In of Potential Electrification Mandates for New Construction.
        - The Potential for DER Adoption to Mitigate Electrification's Ambient Air Quality Impacts.

3.7.1 Grid Emissions and Impacts

Increases in Ambient Emissions from Fossil EGUs

Appendix Section C.6.1 contains plots of annual and monthly changes in total ambient emissions of CO_2, NO_x, and PM-2.5m, calculated using the AVERT framework. These changes are attributable to projected future changes in fossil-fueled EGU operations required to supply electric power under each of the three high-growth rate residential electrification pathways. The shapes of the curves in these plots are determined by simultaneous interactions between:

(1) Anticipated future rates of change in the number and emission intensities of fossil EGUs supplying grid power, assuming an EGU retirement schedule consistent with future compliance with interim RPS goals.

(2) Anticipated future rates of change in the number of homes within the study area which are presumed to have undergone full or partial electrification of their existing gas appliances under a set of High-Growth rate assumptions.

(3) Anticipated future changes in the shape of the community's aggregate hourly electricity load profile (stemming from the evolving composition of these electrified end uses) relative to the operational characteristics of the remaining fleet of fossil EGUs.

As a reminder, the term "net emissions" refers to values relative to a baseline pathway that reflects future rates of electrification consistent with recent historical patterns within the study community. All the values plotted begin at zero in the initial year and deviate in subsequent years as the composition of homes within each pathway deviates from the baseline. All net emissions converge at zero upon the 2045 end of the forecasted time horizon since the assumption is that all grid electricity in that year is assumed to be delivered by zero-emissions sources.

As these plots illustrate, the Full Home Dominant pathway is associated with the largest net increases in annual total emissions relative to the two other IAQ-dominant electrification pathways. This is due to both the time and the magnitude of load increases from fully electrifying all space and water heating appliances within the home. There were major differences in the timing of peak net-emission increases between different pollutants, largely due to the assumed sequencing of EGU retirements.

For example, net NO_x emissions associated within the FH dominant pathway peak around 2025, while CO_2 and PM-2.5m emissions peak much later, around 2032. This difference can be explained by the fact that the individual EGUs with the highest effective NO_x emissions are associated with the few remaining large out-of-state coal-fired power plants that still operated during this period. In these early years, despite modest load growth, NO_x emissions increase rapidly due to the continued operation of these polluting facilities. Once they are retired, around 2025, net emissions decrease significantly despite an acceleration in the growth in the community's electricity loads over the same period (2025-2030).

Relative to the two IAQ-dominant electrification pathways, their influences on net emissions are broadly similar in relative magnitude, though there were important differences in the absolution timing of peak levels and temporary periods of net-emissions reductions. For example, the IAQ-Minor dominant pathway produced initial net reductions (values below zero). This can be explained by the fact that the IAQ Minor scenarios resulted in modest load reductions relative to the baselines because they included some basic code requirement related EE retrofit measures in addition to the specific natural-gas appliance electrification.

Note that every pathway incorporates all the different building electrification scenarios, just at different relative rates. Therefore, even in IAQ-dominant scenarios, incremental increases in the number of electrified homes contributed significantly to overall load growth, causing net emission increases from EGU operations through the end of the forecasted time horizon. This is an important finding as it suggests that growth in net loads, and corresponding net fossil

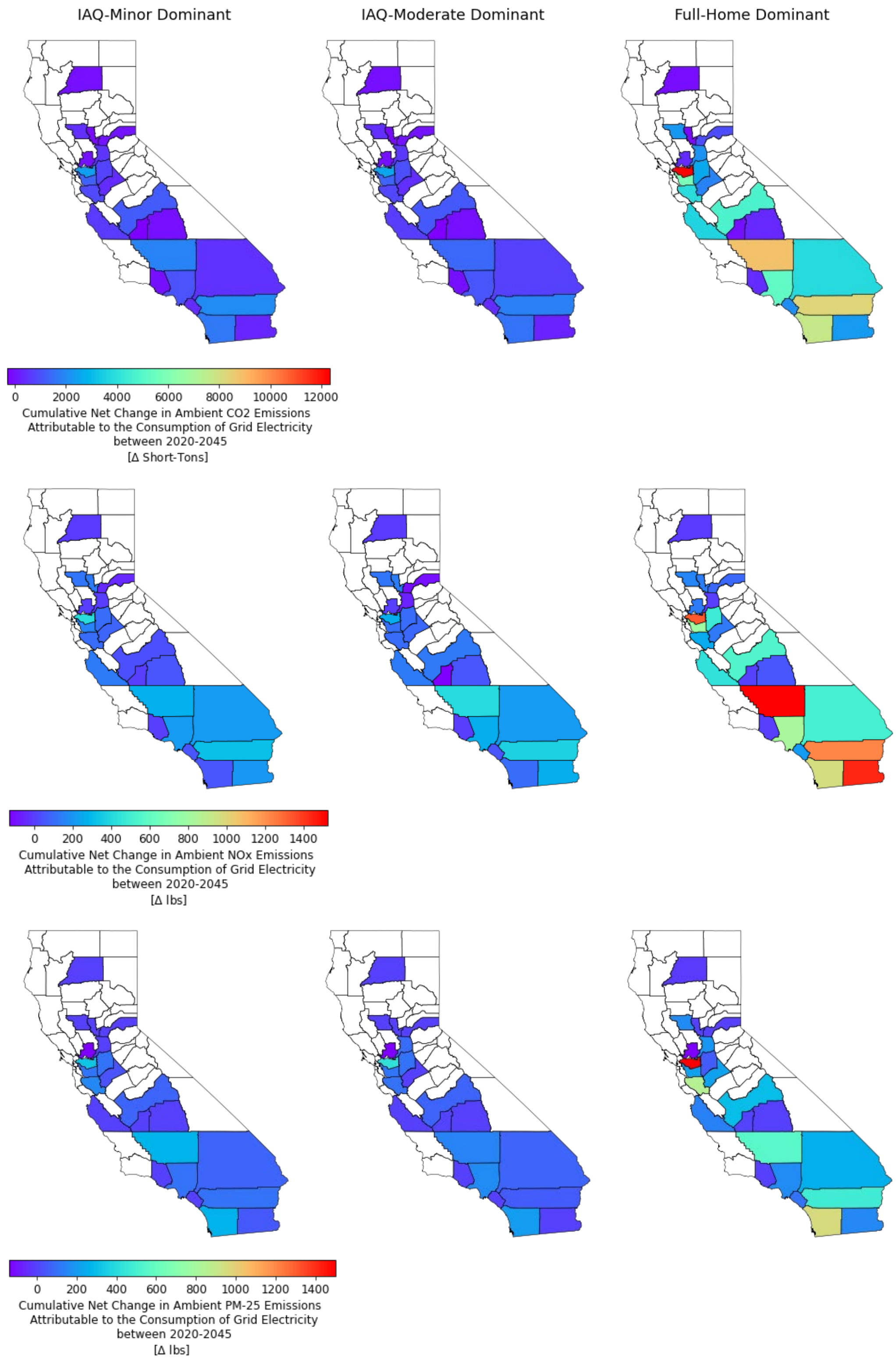
EGU emissions, can be effectively managed through partial electrification strategies that focus initially on electrifying only those gas appliances with the highest effective rates of indoor air emissions and most direct emissions pathways.

Geographic Breakdown

Because the AVERT framework modeled generator outputs from the bottom up, results generated for anticipated future emissions changes could be represented spatially. This has been done in Figure 33, where the cumulative total net emissions of CO_2, NO_x, and PM2.5, calculated over the entire time horizon (2020 to 2045), are plotted at the county level for each energy transformation pathway considered. The scope of the data mapped here was limited to California's in-state fossil EGU fleet. However, a significant fraction of the total ambient emissions was associated with a small number of large, out-of-state polluting facilities.

Spatial patterns in cumulative emissions reveal some important insights, relative to the distributional outcomes of electrification efforts – particularly those that may be implemented on smaller geographic scales. For example, the study area only comprises two adjacent ZIP codes located within the eastern portion of Los Angeles County. As the maps clearly show however, in-state fossil-fueled EGUs that supply this community's electricity are widely distributed geographically. Maps also indicate that the largest increases in cumulative emissions are likely to occur in counties outside of the study area. The potential for increased emissions from ongoing EGU operations reflects an important equity consideration that must be accounted for, relative to future electrification policy decisions and fossil EGU retirements.

Figure 33: County Level Aggregated Cumulative Net Change in Emissions Attributable to Increased Grid Electricity Consumption



Aggregated cumulative net change in ambient [D short-tons] (top), NO_x [D lbs] (middle), and PM-2.5 emissions [D lbs] (bottom) attributable to increased grid electricity consumption – computed relative to the baseline for each high-growth transformation pathway over the full forecast time horizon (2020-2045).

Source: UCLA

While CO_2 emissions from fossil EGU's are typically not associated with local public health concerns, emissions of NO_X and $PM_{2.5}$ can have significant negative impacts on public health, particularly among sensitive populations. The two counties expected to have the largest increases in cumulative EGU emissions, resulting from electrification measures implemented in the Los Angeles County study area, are Contra Costa County, located in the San Francisco Bay Area, and Kern County, located in the southern part of the Central Valley.

The reason for this pattern of concentrated emissions increases has largely to do with the recent dates at which several large fossil EGUs were commissioned, and thus, the expected prolongment of their continued operations. Specifically, within Contra Costa County, two large natural gas generator facilities (Marsh Landing [capacity: 828 MW] and Gateway [capacity: 613 MW]) were commissioned in 2017 and 2009, respectively. Similarly, in Kern County, while there has been recent development of major solar and wind EGU capacity over the past decade, there remain three major gas generator facilities (La Paloma [capacity: 1,200 MW], Pastoria [capacity: 778 MW], and Elk Hills [capacity: 567 MW], commissioned in 2003, 2005, and 2003, respectively.

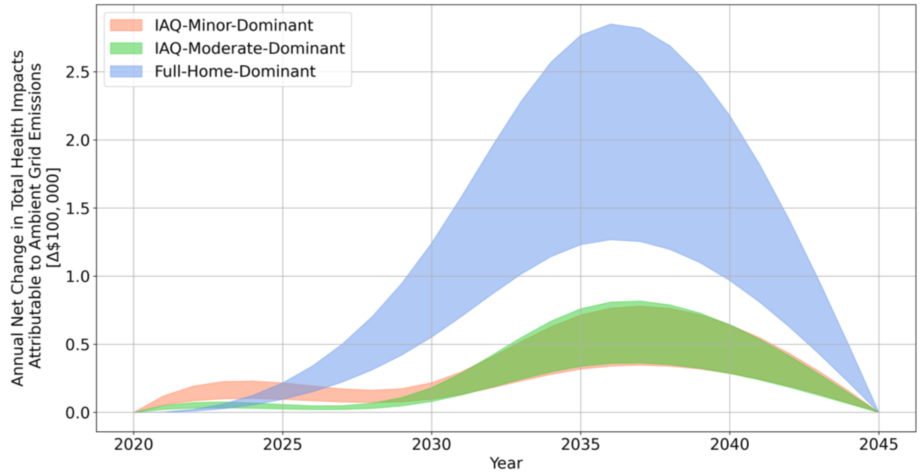
Ambient Air Quality Impacts Expressed as Changes in Human Health

Annual Breakdown

Figure 34 plots the annual net change in estimated human health costs attributable to increased ambient $PM_{2.5}$ emissions from changes in the operations of grid fossil EGUs relative to the baseline pathway. These changes stem from modifications to the study area community's electricity load profile with each high-growth transformation pathway. The peak magnitude of these annualized impacts is on the order of $100,000's per year, from 2035 to 2040 when electricity consumption levels from increased gas appliance electrification are high and fossil EGUs have not yet been retired. The Full Home Dominant electrification pathway showed the largest net changes in air quality related health impacts from increases in ambient $PM_{2.5}$ emissions.

Interestingly, the IAQ Moderate Dominant and IAQ Minor Dominant pathways exhibit slight initial increases in human health impacts from 2020-2025, despite those pathways' low and slightly negative rates of growth in annual $PM_{2.5}$ emissions over the same period. This phenomenon illustrates an important finding: a net decrease in total electricity consumption can still result in a net increase in human health impacts if there is a significant change in the timing of loads and the locations of EGUs called into operation. In this instance, despite the fact that the overall mass of emitted $PM_{2.5}$ was reduced during this period, net health impacts increased because there were changes in the timing of electricity loads in these pathways, which in turn caused EGUs located closer to larger populations to operate more frequently.

Figure 34: Annual Net Change in Estimated Human Health Impacts From Increased Ambient Emissions From Grid Electricity Consumption



Annual net change in estimated human health impacts attributable to increased ambient emissions from grid electricity, computed for each high-growth pathway relative to the baseline pathway from 2020 to 2045.

Source: UCLA

Categorical Breakdown

Appendix Section C.6.2 provides a breakdown of the human health costs computed for each of 12 impact categories for each of the three high growth rate transformation pathways evaluated. The reported dollar values in the table reflect the cumulative discounted sum of health impacts experienced across the entire 2020-2045 forecasted horizon, assuming a 3 percent discount rate. As the values in the table illustrate, across the board the majority of these monetized impacts can be attributed to increases in premature mortality caused by elevated $PM_{2.5}$ concentrations. In terms of event frequency however, minor restricted activity and lost workdays are expected to comprise the largest share of health impacts.

The range of total cumulative increases in assessed human health impacts, summarized across all 12 individual impact categories, are shown in bold on the bottom line. The Full-House-Dominant pathway has the highest projected impacts, with a maximum high-range value of $3.3 million. This was expected given the relative magnitude of electricity load increases and EGU emissions growth associated with this pathway. This figure is more than three times the maximum values incurred by the other two partial electrification scenario pathways.

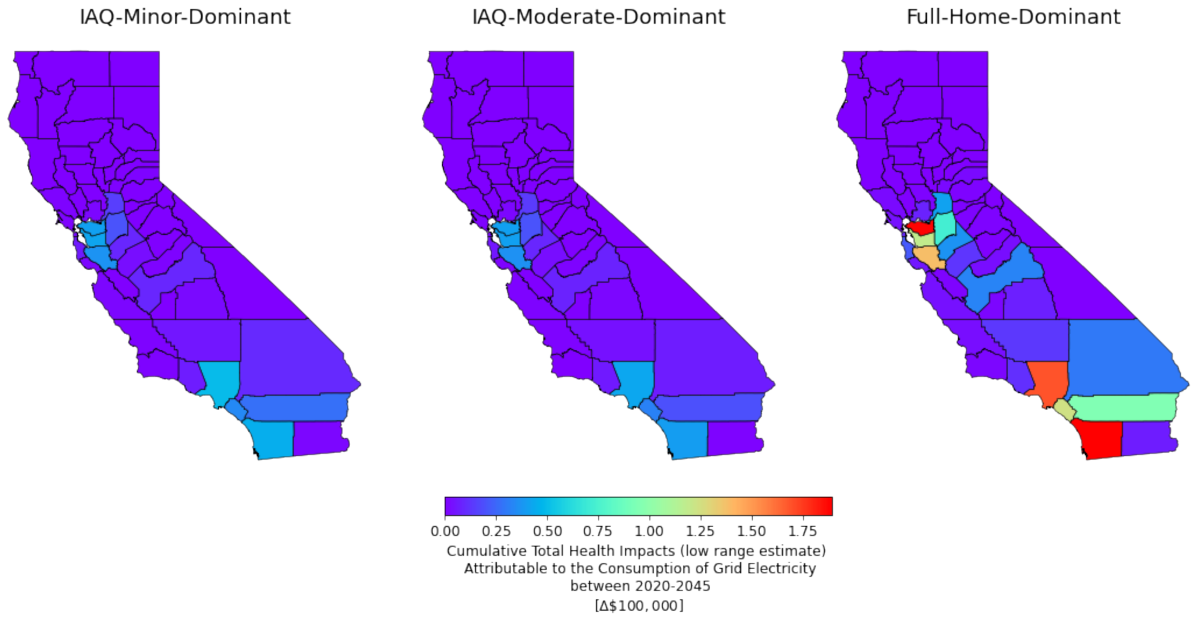
Notably, the IAQ-Moderate-Dominant pathway has a slightly lower range of expected total human health impacts than the IAQ-Minor-Pathway, despite its larger projected total electricity demand. This is due to the relationship between the timing of electricity consumption and the location of generators.

Geographic Breakdown

The panel of maps shown in Figure 35 illustrate the geographic distribution of cumulative human health impacts experienced within each of California's counties over the entire forecasted horizon. As these maps illustrate, despite all the electrification measures being implemented within two ZIP codes in a single county, significant health impacts are experienced as far north as the Bay Area. This geographic distribution is due to the location of the fossil-fueled EGUs expected to supply net increases in electricity demand for each scenario.

An important finding of note is that these impact maps do not precisely mirror the spatial distribution of emissions discussed previously. This is due to a combination of factors. The first is that the COBRA modeling framework performs basic analysis of primary pollutant fate and transport processes largely based on prevailing historical climate conditions, which sometimes cause emissions produced by EGUs located in one county to be physically transferred into the air of other down-wind counties. The second factor is that assessed impacts are not only determined by the effective atmospheric concentrations of a pollutant but also by the size of the population exposed to them. Significant differences in populations between counties can therefore play a significant role in the relative spatial distribution of health impacts.

Figure 35: County-Level Estimated Human Health Impacts From Increased Ambient Emissions From Grid Electricity Consumption



County level aggregated cumulative net change estimated human health impacts attributable to increased ambient emissions from grid electricity consumption, computed relative to the baseline for each high-growth transformation pathway over the full forecast time horizon (2020-2045).

Source: UCLA

3.7.2 Local Emissions and Impacts

Decreases in Local Emissions From Residential Gas Appliances

Annual and Monthly Breakdown

Appendix Section C.6.3 contains a series of plots that illustrate net annual and monthly reductions in local emissions from the avoided residential gas use calculated for each pathway. Here again, these net reductions are computed as the difference between each pathway's total emissions minus those for the baseline pathway. The plots are organized with net emissions CO_2 [short-tons] at the top, net NO_x emissions [lbs] in the middle, and net $PM_{2.5}$ emissions [lbs] at the bottom. The data in each plot comprises annual total changes by year in the 2020-2045 forecasted time horizon. The different colors used for each data series follow the naming conventions used throughout this report.

One important point of difference between these reported local annual net emissions totals when compared with the ambient net totals from the AVERT simulation outputs, is that there is a range of values for each pathway year. These ranges are depicted in bands of color within the plots and reflect the upper and lower bounds on the emissions factors used to perform the calculations.

Overall, these plots show that all of the electrification pathways deliver significant net reductions in local emissions for all of the air-pollutant emissions considered. As expected, the largest magnitude reductions were associated with the FH dominant pathways. The rates of change in these reductions directly reflect the percentage of the study area community's households assumed to be electrified for each pathway year. Similarly, the degree of separation between each pathway's results reflects the magnitude of the differences in the amount of gas-use reductions achieved by the dominant electrification scenario.

Relative to both the NO_x and $PM_{2.5}$ results, there is significant overlap between the range of net emissions reductions computed for both the IAQ-Minor and the IAQ-Moderate pathways. This should be interpreted as a more significant reflection of the range of uncertainty and variation in the emission factors used than as a definite statement about the equivalence of the net emissions reductions between the two IAQ-Focused pathways.

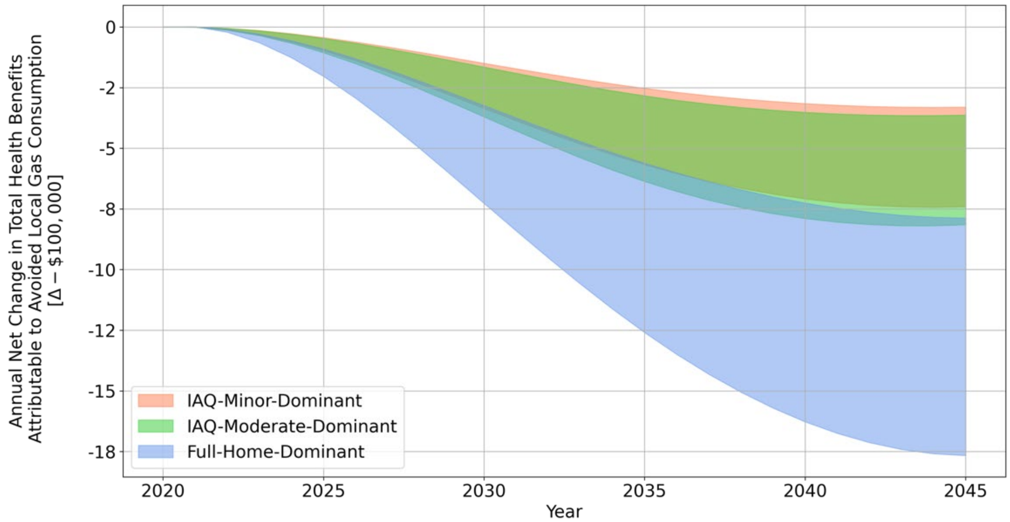
Local Air Quality Benefits Expressed as Changes in Human Health

Annual Breakdown

Figure 36 plots the annual net change in estimated human health costs attributable to the avoided local $PM_{2.5}$ emissions from the electrification of various residential natural gas appliances within the project's study community. As the scale of this plot clearly illustrates, over the 25-year forecast horizon, the absolute magnitude of these local benefits clearly exceeds the ambient impacts. In the latter years, the scale of this excess grows to be as large as an order of magnitude.

The scale of these differences can be attributed to the following two factors. Firstly, these local emissions are all being released within Los Angeles County, the most densely populated county in the state and therefore the site of significant potential exposure. A second important contributing factor has to do with fundamental differences in the energy efficiencies of the two approaches to providing residential energy services. Each unit of avoided gas combustion within the home likely only requires, at most, the combustion of between 1/2 and 1/5 of a unit of natural gas by a fossil EGU to generate the amount of electricity required to operate an electrified version of the same appliance. A major component of this overall performance gain is the significantly higher thermal efficiency of natural gas combustion in fossil EGUs, many of which take advantage of the higher-heating values enabled by combined cycle processes. In addition to the higher average heat rates of the fossil EGU fleet, end-use efficiencies of electric appliances are also higher; some achieve thermal efficiencies above 100 percent with heat pump technologies. This combination is likely the primary driver of the significant differences in overall emissions and public health costs.

Figure 36: Annual Net Change in Human Health Benefits From Decreased Emissions From Avoided Gas Consumption



Annual net change in estimated human health benefits [D-$100,000] attributable to decreased local air emissions from avoided gas consumption–computed for each high-growth transformation pathway relative to the baseline pathway from 2020-2045.

Source: UCLA

Categorical Breakdown

Appendix Section C.6.4 provides the same breakdown of estimated changes in human health impacts as depicted within the ambient context. Here, however, negative dollar values illustrate the benefits that accrue from avoided local natural gas combustion emission exposure. The discounted benefits of electrification for the project's study area community (and some adjacent counties) are quite substantial. For example, the cumulative avoided health costs attributable to the Full Home Dominant electrification pathway range from $10.8 to $24.4 million over the period from 2020 to 2045. Once again, as with ambient impacts discussed previously, the primary source of these monetized benefits can be attributed to reduced premature mortality. In terms of the frequency of event occurrence, decreases in the number of restricted activity and work loss days are expected to be among the most significant. Additionally, there are a substantial number of avoided upper and lower respiratory and asthma related health impact events.

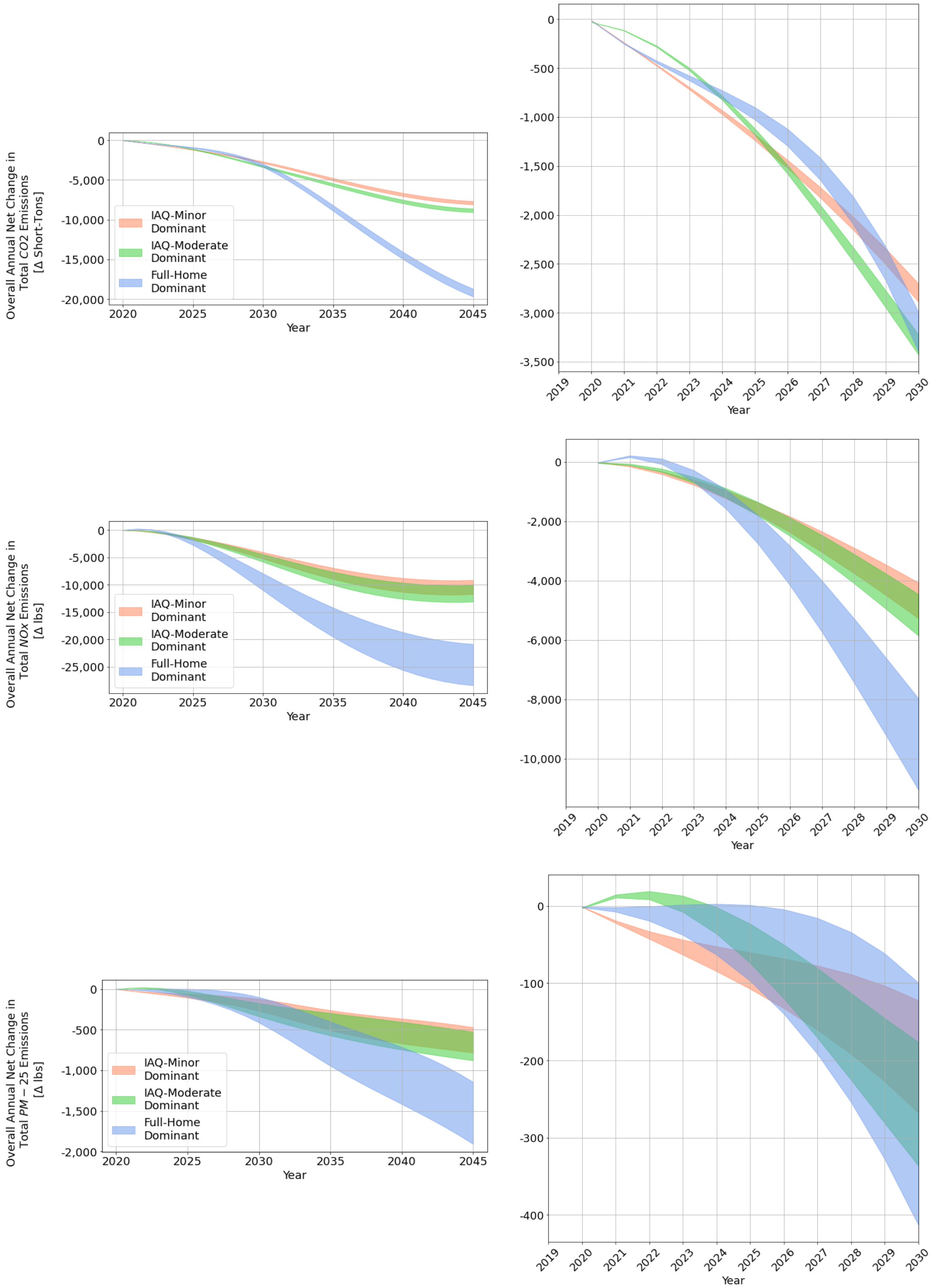
3.7.3 Combined Emissions Changes and Impacts

Combined Annual Emissions Changes

The series of plots in Figure 37 reflect the integration of ambient emission increases calculated for future EGU operations with the local emissions reductions calculated for future avoided gas use. The plots on the left-hand side show computed annual totals across the full forecast time horizon, while the inset plots on the right-hand side depict detailed results over the course of the next decade (2020-2030). These inset plots were produced to better illustrate some of the complex interactions of the overall avoided net emission changes during this period.

Most importantly, all the electrification pathways considered in this analysis exhibit overall net-emissions reductions over the long term when local and ambient changes are combined. This indicates that electrification efforts, even when pursued under extremely aggressive deployment timelines relative to the interim goals of the state RPS, should be considered beneficial both from an overall GHG reduction standpoint and from a criteria pollutant emission reduction standpoint.

Figure 37: Annual Net Change in Overall Combined Emissions Relative to Baseline for High-Growth Pathways



Annual net change in overall combined CO_2 emissions [short-tons] (top), NO_x emissions [lbs] (middle), and $PM_{2.5}$ emissions [lbs] (bottom) specifically local decreases + ambient increases – computed relative to the baseline for each high-growth transformation pathway from 2020-2045. Inset plots at right focus on results for the near-term period from 2020-2030.

Source: UCLA

Focusing next on some of the trends visible in the inset plots on the right, relative to CO_2 emissions, the rates of reductions in the upcoming decade can be seen to exhibit complex trajectories. These trajectories reflect the varied interactions between the early phase load growth experienced in each pathway and early phase EGU retirements. For example, in the FH dominant pathway, combined CO_2 emissions reductions are initially quite rapid from 2020-2023 as many older, less efficient, fossil EGUs are presumed to be retired first. The pace of these reductions then slows from 2024-2027 as the effective rate of load increases stemming from rapid growth in the number of electrified homes outpaces the effects of continued EGU retirements required for RPS compliance. Overall, however, the growing magnitude of avoided local emissions eventually overwhelms all ambient increases, so that by 2035 the combined results are broadly similar to those presented previously for the local case only.

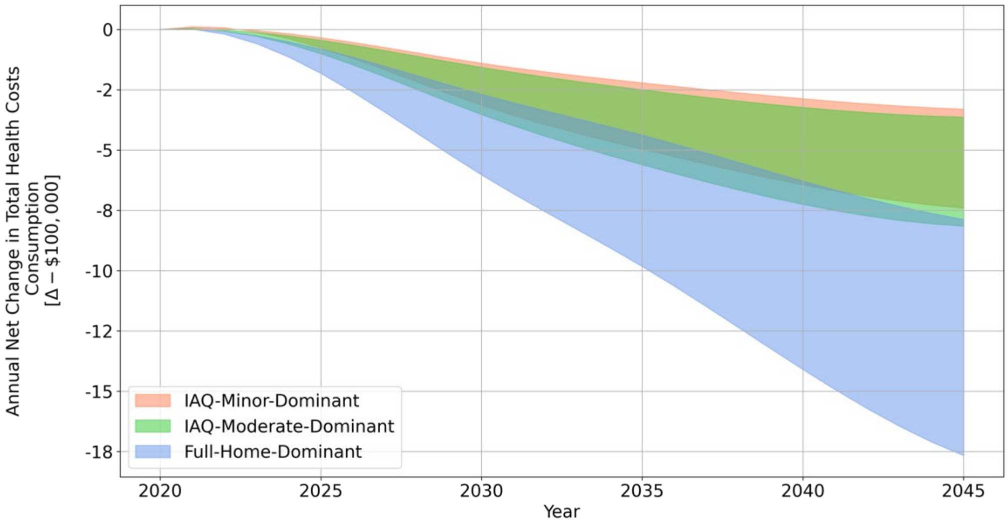
Relative to the NO_x emissions inset plot, the FH dominant pathway is the only one that temporarily experiences net increases in total combined emissions over the interim period from 2020 to 2023. This is the same period when the single EGU in California's fleet with the highest NO_x emission intensity—the 1,900 MW Inter-Mountain Coal Generation Facility located in Central Utah—is assumed to still be operating. While this facility is owned and operated by the Los Angeles Department of Water and Power (LADWP) and slated for retirement by the end of 2023, its effect on the net benefits of electrification efforts is clear and significant. These results suggest that adhering to an EGU retirement strategy which prioritizes the removal of the highest emissions intensity facilities first is the best way to ensure the overall effectiveness of electrification policies.

Combined Air Quality Impacts Expressed as Changes in Human Health

Annual Breakdown

Figure 38 plots annual net changes in human health costs when the effects of ambient increases in fossil EGU emissions are additively combined with decreases in local emissions stemming from gas appliance electrification. As this plot clearly illustrates, the local benefits significantly outweigh the ambient impacts in terms of overall magnitude. All three pathways exhibit negative costs (positive benefits) for all of the years in the forecasted period. This result provides strong support for the pursuit of an aggressive electrification agenda even during the early transitional years when the grid's EGU fleet has not yet been fully decarbonized.

Figure 38: Annual Net Change in Combined Human Health Costs for High Growth Transformation Pathways



Annual net change in overall combined human health costs [D-$100,000] – i.e., local benefits + ambient impacts – computed for each high-growth transformation pathway relative to the baseline pathway from 2020 to 2045.

Source: UCLA

Categorical Breakdown

Table 19 provides a detailed view of the overall change in human health costs when the impacts of fossil EGU operations are combined with benefits from avoided local gas combustion. Here again, all the dollar values are negative, indicating the production of positive net benefits (health cost reductions) for different high-growth electrification pathways. Note that the COBRA model outputs the number of estimated events in each category, as well as the estimated dollar amount associated with those events.

Table 19: Cumulative Net Change in Overall Combined Human Health Costs

Human Health Impact Category	IAQ Minor Dominant		IAQ Moderate Dominant		Full Home Dominant	
	Dollars	Events	Dollars	Events	Dollars	Events
Mortality (low - high range estimates)	$-4,297,202 – $-9,711,128	<1 - 1	$-4,861,633 – $-10,986,935	<1 – 1	$-9,224,996 – $-20,847,050	1 – 2
Infant Mortality	$-21,325	<1	$-24,196	<1	$-45,802	<1
Nonfatal Heart Attacks (low - high range estimates)	$-2,449 - $-22,759	<1	$-2,815 - $-26,159	<1	$-4,990 - $-46,366	<1
Hospital Admits, All Respiratory	$-3,517	<1	$-3,983	<1	$-7,563	<1
Hospital Admits, Cardiovascular (except heart attacks)	$-3,954	<1	$-4481	<1	$-8,474	<1
Acute Bronchitis	$-409	1	$-463	1	$-880	1
Upper Respiratory Symptoms	$-514	12	$-582	13	$-1,107	26
Lower Respiratory Symptoms	$-228	8	$-258	9	$-490	18
Emergency Room Visits, Asthma	$-73	<1	$-84	<1	$-155	<1
Minor Restricted Activity Days	$-31,422	354	$-35,541	401	$-67,706	764
Work Loss Days	$-12,034	60	$-13,614	68	$-25,927	130
Asthma Exacerbation	$-911	12	$-1,031	14	$-1,960	26
Total Health Impacts (low - high range estimates)	$-4,374,039 – $-9,808,275		$-4,948,681 – $-11,097,327		$-9,390,050 - $-21,053,480	

Cumulative net change in overall combined human health costs [$] by benefit category–i.e., local benefits + ambient impacts – computed for each high-growth transformation pathway relative to the baseline pathway over the full forecast time horizon (2020-2045).

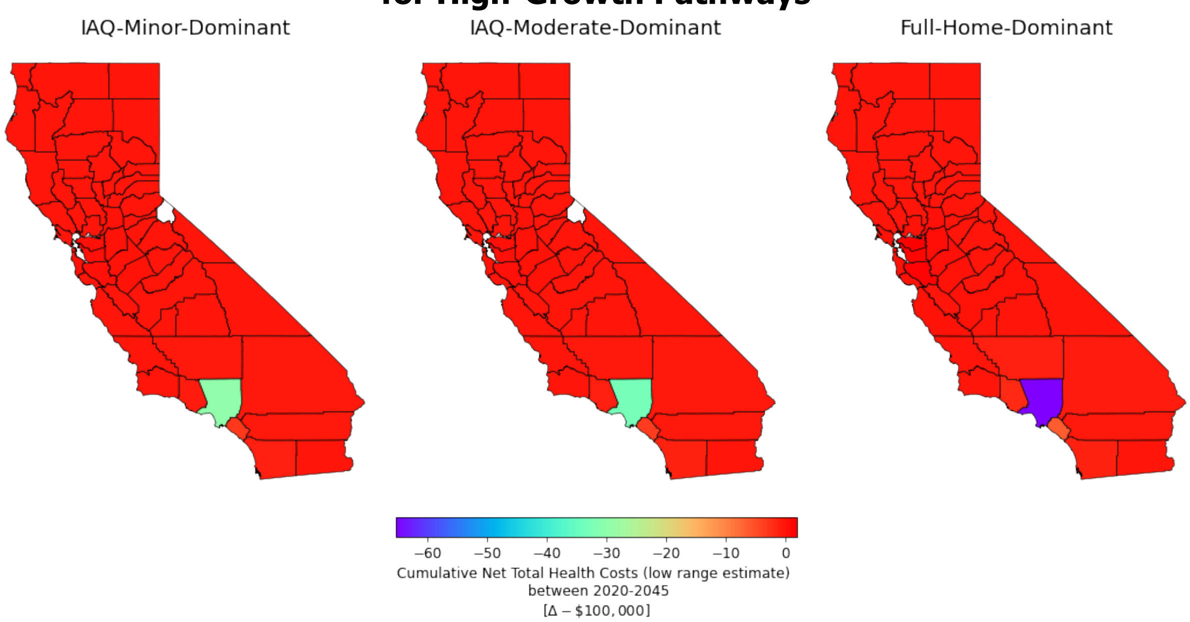
Source: UCLA

Geographic Breakdown

A geographic breakdown of overall changes in human health costs associated with the different transformation pathways is depicted in Figure 39. The ambient impacts created by increased fossil EGU emissions in other counties are overwhelmed by the local benefits within Los Angeles County where the electrification measures would be implemented. Additional noticeable reductions in overall health costs can also be seen in adjacent Orange County to the south.

This finding is important but needs to be evaluated with care. For example, these maps might suggest that the ambient emissions impact in other counties are not significant enough to merit concern. However, it is important to keep in mind that the location of the fossil EGUs is fixed relative to the variable locations where electrification policies would be implemented throughout the state. There is, therefore, the potential for a significant accumulation of ambient emission increases (which we refer to as a "hot spot") in counties where EGUs are situated should electrification measures become much more widespread. The potential for the creation of such "hot spots" is a matter that should be factored into future decisions about the rank prioritization of when individual EGUs are scheduled to retire.

Figure 39: Aggregated Net Change in Human Health Costs for High-Growth Pathways



County level aggregated cumulative net change in overall combined human health costs [D-$100,000] – i.e., local benefits + ambient impacts–computed relative to the baseline for each high-growth pathway over the full forecast time horizon (2020-2045). All pathways show benefits from reduced health costs.

Source: UCLA

3.7.4 Discussion

Ambient Emissions Production

Potential Implications of Future RPS Noncompliance

The encouraging recent progress toward California's interim RPS targets suggests that the ultimate goal of 100 percent net-zero carbon electricity production by 2045 may be within reach. However, the law of diminishing returns suggests that the levels of future effort and investment required to secure additional marginal gains are likely to increase going forward.

One of the core assumptions of this analysis has been that future fossil EGU retirements will proceed at a rate consistent with the achievement of all RPS interim goals. It is possible however, that some of these interim targets may not be met, due to unforeseen technical, economic, or political developments. Given this possibility, the potential implications of future RPS non-compliance must be considered.

The electrification of residential appliances requires substantial up-front costs both for the initial purchase of the electric appliance hardware and for their integration into aging buildings, which is often the case for retrofits. These costs, combined with the durability of many classes of large appliances, suggest that once electrification retrofits have been performed, they are unlikely to be "undone" in the absence of unprecedented increases in the cost of electricity. If full electrification is built into new homes, this technological lock-in becomes even more secure since appliance configurations are unlikely to change within the effective lifetime of the home itself.

Based upon the results of this analysis, from a total primary emissions standpoint, if extensive residential appliance electrification were to occur without any further progress toward RPS goals, it is unlikely that net growth in air emissions would occur. This is due to the combined influence of relatively high fossil EGU thermal efficiencies and high end-use electric appliance efficiencies.

Despite little likelihood of net growth in air emissions, it remains to be seen whether or not extensive electrification could result in net growth in human health impacts. This is because health impacts are significantly dependent on the geographic locations of emissions, relative to the locations of potentially sensitive human populations. As this study has demonstrated, even minor emissions reductions can cause minor net increases in human health impacts if the location of the emissions changes significantly due to shifts in the timing of energy demand.

What is extremely likely, however, is that if future electrification proceeds in the absence of subsequent fossil EGU retirements there will be further increases in human health burdens within communities in close proximity to remaining generators. It is broadly known that fossil EGUs are disproportionately sited within low-income, under-resourced communities. As a result, attention must be paid to the geographic distribution of costs and potential benefits from regional electrification policies and initiatives.

Considering Secondary Emissions Production from Atmospheric Processes

The scope of this analysis was restricted to only primary air emissions and their associated human health impacts. Secondary emissions produced through subsequent reactions with other chemical species and light at different levels of the atmosphere will increase the pollution burden experienced at a given location, but it is beyond the scope of this analysis. However, these secondary emissions must be considered as an important missing contributor to the overall pollution burden created by fossil fuel combustion and a potentially significant missing component of the actual human health impacts generated by ambient and local emissions sources.

Unfortunately, accurately estimating the rate and location of secondary emissions production is complex. It requires the development of detailed 4D simulations (in three spatial dimensions plus the temporal dimension) of fluid dynamics, chemical constituents, and reactivity profiles of columns of atmospheric air. It also requires more detailed knowledge about the characteristics of fossil EGU emissions. And while such detailed impact assessments are beyond the scope of this project, they could be performed to more comprehensively evaluate the holistic benefits of specific electrification policies and programs.

Local and Indoor Emissions Exposure

On the Need to Establish Indoor Emissions Exposure Standards

One challenge cited in this report relates to the current lack of indoor air emissions standards. A major part of the reason that these standards do not yet exist is that this is an emerging public health concern and therefore primary epidemiological research is ongoing. It is important that these standards be developed so that existing exposure levels experienced within households in different communities can be placed into accurate risk contexts. The indoor air quality monitoring work performed within the context of this project and study area community used federal outdoor exposure threshold concentrations to provide this context for residents. This is obviously not ideal as these outdoor standards are likely higher than what the safe thresholds for indoor air concentrations of pollutants should be, thus providing a false sense of safety.

Options for Improving Indoor Air Pollutant Capture Efficiency With Forced-Air Ventilation

One option that has been proposed to mitigate indoor risks is improvement of the emissions capture efficiency of gas appliances through more robust forced-air ventilation systems. It is important to note that this study assumed 100 percent of indoor gas appliance emissions were evacuated to the local outdoor air. This assumption is obviously highly optimistic in terms of the actual capture efficiency of installed appliances, particularly within under-resourced communities. However, the lower boundary on avoided health impacts from local emissions exposures was still about 11 times greater than increased health impacts from changes in fossil EGU operations. Thus, if indoor emissions exposures were indeed found to be more harmful in the future, the overall net public health benefits associated with aggressive electrification measures would be even greater.

State and Local Electrification Policies

Evaluating the Optimal Phasing of Potential Electrification Mandates for New Construction

The majority (over 85 percent) of the total volume of gas consumed by residential homes was used for heating air and water. Water heaters and furnaces are usually either physically installed outdoors or well ventilated to the outdoor air. The minority of gas consumed (less than 15 percent) was used by indoor cooking appliances (ovens and ranges) and clothes dryers. Monitoring for this study revealed that the use of gas in cooking appliances tended to be associated with the largest increases in indoor concentrations of harmful gas combustion co-products. This creates something of a split incentive in the design of optimal electrification policies because the appliances that would result in the greatest net GHG emissions reductions are different from those that would result in the greatest net public health benefits.

Much of the opposition to electrification can be attributed to an individual’s preferences or familiarity with using gas for the provisioning of certain types of end-use energy services. A good example of this is the preference that many homeowners have for gas cooking. It is important, however, to understand why such preferences exist and how they might be progressively overcome by phasing in electrification mandates, particularly in retrofits.

Different appliances require different levels of personal interaction. A stove is something that a person physically touches numerous times throughout the day. By comparison, a water heater or a furnace is something which largely exists out of sight and does not require regular resident interaction. There is therefore accumulated experience with stoves and other similar domestic gas appliances, which contributes significantly to the formation of user fuel preference or bias. These preferences need to be accounted for in terms of the different ways that electrification can best proceed.

Along these lines, one of the most logical places to begin is with water heating. This end use constitutes more than half of total residential gas use in most California homes and requires minimal day-to-day user interaction. One thing that needs to be better understood, however, is the extent to which efficiency improvements associated with the use of electricity versus gas will be large enough to completely offset the higher per-unit energy costs of electricity. The interactions between household hot water consumption and future time-of-use electricity prices will ultimately determine the net impact of this electrification measure on total household energy costs. The fact that this cannot be clearly determined ahead of time for any given household creates a significant barrier to promoting retrofits.

For new construction, the optimal pathway is more straightforward: simply require electrification of everything from the start and design accordingly. In new construction, the marginal cost of increasing the rated amperage of a home's electricity service panel is minimal, while in many retrofits there may be limited headroom in a current panel's capacity to support the addition of major electric appliances.

The Potential for DER Adoption to Mitigate Electrification's Ambient Air Quality Impacts

It is important to understand the potential for increased DER adoption to reduce future demands for fossil EGU output to mitigate ambient air quality impacts. The simultaneous deployment of DERs such as solar PV and BESS could avoid the creation of localized "hot spots" of air pollutants from statewide electrification policies and initiatives. However, it is uncertain whether the current state of DER system performance would be enough to completely offset the ambient emissions impacts of load profile changes brought about by different levels of electrification.

The marginal GHG and criteria pollutant emissions of a unit of grid power can fluctuate widely both throughout a single day and between the months in a year. Along these lines, a specific DER measure to mitigate ambient emissions impacts can be evaluated by the degree to which it reduces peak-load growth. This is because off-peak loads, both at present and to an increasing degree in the future, are more likely to be powered by zero-emissions generation.

There are several caveats to performing such an assessment. The first involves considerable uncertainty about the structure of future net energy metering (NEM) rate tariffs and the introduction of new DER-system adoption fees recently proposed by California's investor-owned utilities (IOU). An ongoing California Public Utilities Commission (CPUC) proceeding around the development of a new NEM 3.0 tariff would have significant impacts on the cost feasibility of future DER system configurations. For example, BESS charging and discharging schedules are highly optimized with respect to NEM tariff structures and the timing and price escalation rates in peak demand periods. Any significant changes to the status quo, which has been incorporated in the modeling framework, will affect any conclusions reached.

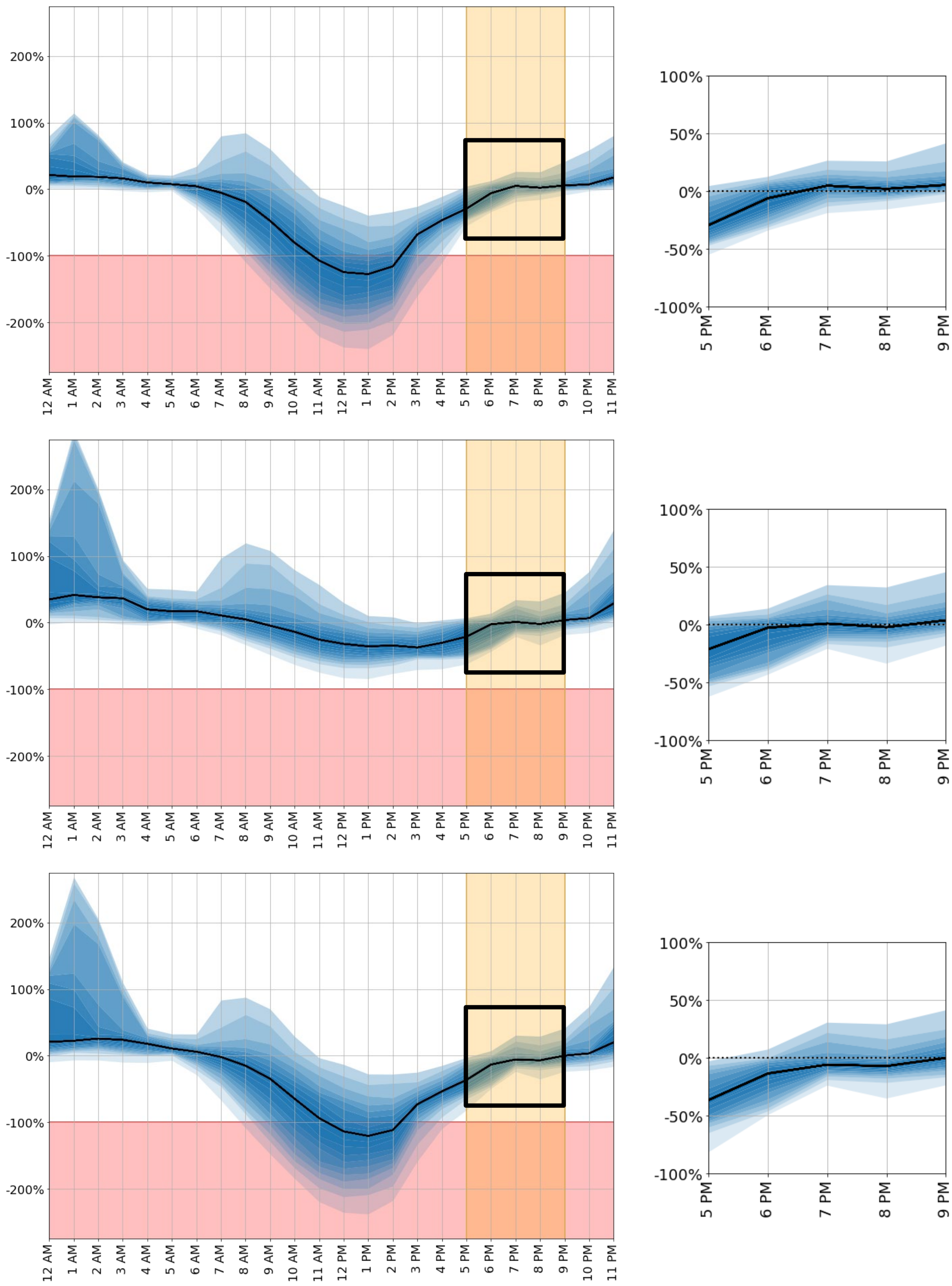
Another significant source of uncertainty which must be acknowledged relates to future improvements in the cost and performance characteristics of DER technologies. While the cost of solar PV panels, battery cells, and models has declined rapidly over the past decade, technology learning curves suggest that these rates are likely to decline and plateau at some point in the future. How these DER technologies evolve will determine the degree to which they mitigate peak-load growth from future appliance electrification. In this study, when developing the individual building prototype energy models upon which the pathway transformations were based, several key assumptions facilitated the "right-sizing" of PV panels and BESS system components. These assumptions were based upon the current size, cost, and performance characteristics of these technologies and evaluated relative to the average hourly load profile of each prototype scenario model. Here again, if these key parameters change significantly in the future, the modeling assumptions used in this study could become invalid, invalidating their conclusions.

The following two series of plots illustrate the potential scope of the parallel deployment of DER systems to mitigate peak-load growth, which is the most significant contributor to ambient emissions increases. These plots focus on modeling results that this analysis produced for the year 2035. This year was selected because, relative to the high-growth rate pathways considered and the fossil EGU retirement schedule required to achieve RPS compliance, it is anticipated to be the single year with the highest levels of ambient emissions increases.

The first series of plots, contained in Figure 40, depict the distribution of hourly load changes, measured as percentage deviations from the baseline, in the year 2035. These distributions are illustrated using horizontal bands of blue color that range from the 95th percentile at the top all the way down to the 5th percentile at the bottom, expressed in 5-percentile point steps. The 50th percentile, corresponding to the median percentage change computed across all the hours in the year, is shown as a solid black line. Moving from top to bottom, the three plots illustrate load growth changes from the combination of the High Growth, Full Home Dominant electrification pathway with different types of DER adoption. The top plot shows the effects of simultaneously pursuing the PV-Only Dominant pathway. The middle plot shows the effects of simultaneously pursuing the BESS-Only Dominant pathway. And finally, the bottom plot shows the effects of simultaneously pursuing the PV+BESS Dominant pathway.

For context, within each of these plots, the hours associated with current peak loads (defined as between 5 p.m. to 9 p.m.) are highlighted in a shaded orange color. Areas shaded in red correspond to expected load changes of negative 100 percent or greater (periods where the community's installed DER systems generate more electricity than needed for local demand. During these times, it is expected that reverse power flows to the grid would occur. Finally, the inset plots shown on the right-hand side focus on peak-hour load changes associated with each combination of pathways. These are the changes with the greatest relevance to ambient emissions impacts from the fleet of fossil EGUs.

Figure 40: Hourly Load Growth Impacts in 2035 From Combined Pathways



Comparison of the distribution of hourly load growth impacts in the year 2035, measured as percentage deviations from the baseline pathway, derived from the combination of the high-growth rate full-house electrification dominant pathway with the high-growth rate PV-only dominant pathway (top), the BESS only dominant pathway (middle), and PV+BESS dominant pathway (bottom). Inset plots at right focus on the impacts during peak hours.

Source: UCLA

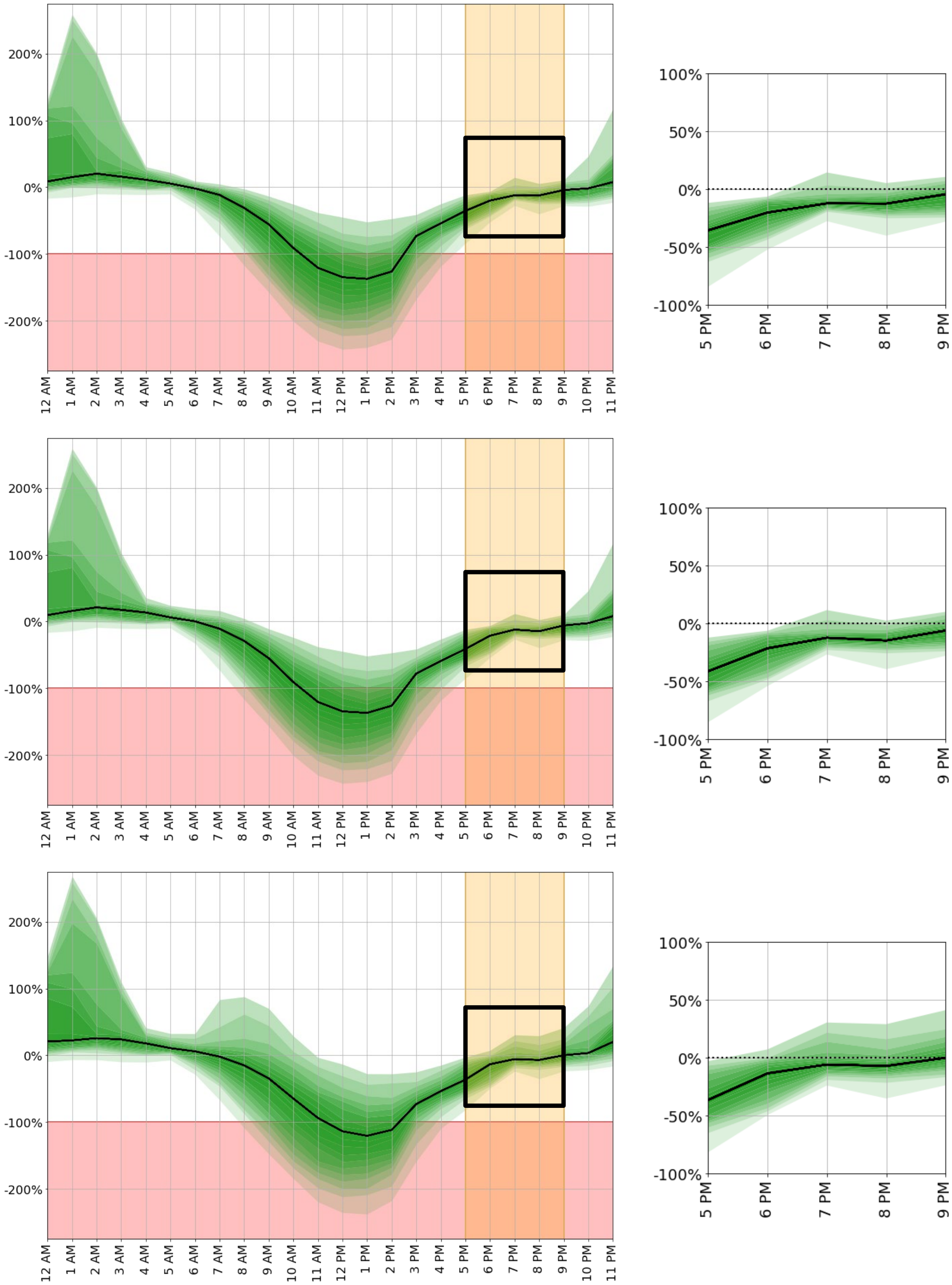
To understand the extent to which different types of DERs mitigate ambient emissions increases, it is best to focus on the inset plots shown at right, especially on the relative amount of blue shaded area above (versus below) the horizontal line representing zero-percent change. DER system configurations that will prove most successful at mitigating ambient emissions increases have the smallest blue areas above this line, indicating peak load growth, and the greatest area below it, indicating peak load reductions.

Perhaps unsurprisingly, the results show that the parallel aggressive adoption of DER, principally in the form of combined PV+BESS systems, is likely to have the greatest benefits in mitigating ambient emission increases from widespread full-house electrification. However, it is important to note that even with such assumed high levels of DER penetration, it is unlikely that ambient air emission increases from aggressive full-house electrification would be eliminated entirely. This is because the current sizes of available, cost-competitive BESS systems do not have enough energy storage capacity to completely offset increased demand for peak-period electricity.

Figure 41 provides a similar set of results for a different combination of DER and electrification pathways and explores how aggressive adoption of PV+BESS systems could potentially mitigate peak-load growth impacts (and associated ambient emission increases) resulting from different partial electrification dominant pathways. The plot at the top of the figure illustrates deviations from the baseline loads in 2035 when the IAQ-Minor Dominant pathway is paired with similarly high-growth rates in the adoption of PV+BESS. The middle plot shows the combination of rapid PV+BESS adoption with the IAQ-Moderate pathway. And finally, the bottom plot shows results for the combination of rapid PV+BESS adoption with the Full Home Dominant pathway.

Inset plots on the right-top and right-middle of Figure 41 show that for the IAQ-Minor and IAQ-Moderate dominant pathways the addition of PV+BESS systems can mitigate growth in peak loads more than 90 percent of the time during peak load hours from 5 p.m. to 9 p.m. These findings indicate that the present capabilities of PV+BESS, which have been "right-sized" to average residential building characteristics within the community, should be capable of offsetting nearly all the ambient air emission impacts that would otherwise be anticipated. When taken together, the results of the analyses presented in Figure 40 and Figure 41 suggest that the present capabilities of common DER systems are not yet sufficient to completely avoid localized ambient emission increases from full-house electrification efforts. However, if the electrification measures are more targeted in nature, it is possible for ambient emissions growth to be minimized, if not nullified completely.

Figure 41: Distribution of Hourly Load Growth Impacts in 2035 From Combined Pathways



Comparison of the distribution of hourly load growth impacts in the year 2035, measured as percentage deviations from the baseline pathway, derived from the combination of the high-growth PV+BESS dominant pathway with the IAQ-Minor dominant pathway (top), the IAQ-Moderate dominant pathway (middle), and Full-House Electrification dominant pathway (bottom). Inset plots at right focus on impacts during peak hours.

Source: UCLA

3.8 Community Outreach

3.8.1 Outreach Approach

Before COVID-19 pandemic restrictions, the project team planned to schedule two in-person events in the City of El Monte and the unincorporated area of Bassett and Avocado Heights to present study findings to community members. Due to ongoing public health concerns and the stay-at-home order, the communications strategy was shifted, and a decision made to share the project findings through two online events. The first was held on Thursday, June 11, 2020 (6 p.m. to 7 p.m.) to present preliminary findings; the second was held on Thursday, July 22, 2021 (6:30 p.m. to 7:45 p.m.) to present final results.

3.8.2 Format of Community Events

Active SGV hosted the meetings as Healthy Active Homes "socials" via Zoom, which allowed the project team to connect with community members inside their homes and create a recorded version of the presentation that could be shared post-event with community members.

In preparation for the events, Active SGV, UCLA, and The Energy Coalition collaborated to translate the technical study findings into a digestible, plain-language presentation for community members with limited technical backgrounds. Active SGV invited community members to participate in the online event through phone calls and text messages to study participants, paid social media advertising, invitation via Active SGV's monthly newsletter, and communications with local community groups, schools, and organizations.

The online events included a 15-minute presentation of study findings, interactive quiz, question-and-answer session with project team members, and participant raffle. The presentation portion of the event included background information on the purpose of the study, a recap of the outreach and data collection methods, the definition of pollutants measured in the study, overview of study findings and their impacts, and a list of recommendations for improving air quality within the home that support a clean air future at the community level.

During question-and-answer sessions, attendees asked about indoor-versus-outdoor air quality monitoring, expressed concerns about asthma and exposure to outdoor pollutants, and expressed interest in learning ways to promote public acceptance of electrification. Raffle items including a Purple Air monitor, a portable solar charger, and electric kettles.

Both events were recorded and posted to Active SGV's website, along with presentation materials, which were translated into Spanish.

A full description of outreach activities is in the Summary Report of Community Events deliverable report, available upon request to CCSC.

CHAPTER 4: Key Findings

4.1 Working in the Community

Understanding on-the-ground conditions in under-resourced communities is essential to State planning efforts aiming to ensure an equitable transition.

Access to people's homes for indoor AQ monitoring was the basis for all the other work on this project. Active SGV's participation on the project team provided unprecedented insights into the study community. Tremendous levels of effort, time, and leveraging of trusted community relationships were required to gain access to people's homes, and to collect data that represented actual conditions in an under-resourced neighborhood. Conducting the interviews and distributing questionnaires in English and Spanish was essential for obtaining accurate information.

The team found that many participants, especially renters, were unfamiliar with aspects of their appliances (for example, if their dryer was gas or electric, or what type of hot water heater they had). Therefore, in-person home visits allowed for more accurate information collection compared with studies that use phone or mail-in surveys. The team also found that participants were reluctant to share their energy data, whether electronically or verbally, even with trusted groups.

Many people in the study community live in poor conditions (such as old windows, old appliances, knob and tube wiring, very high summer indoor temperatures). The upfront costs of electrification related to panel upgrades and new circuits put the electrification transition beyond the reach for most homeowners in this community. Beyond those costs, homeowners still need to navigate a challenging set of additional issues, including new appliance costs, appliance efficiency, electrification logistics, and hard-to-anticipate changes in energy bills. This study raises another consideration important to households: the tradeoffs between indoor air quality benefits and total emissions reductions when deciding which appliances to prioritize for electrification.

Extensive, upfront investments for home retrofits are needed to make homes healthier, to support the 100-percent renewable transition, and to provide livable conditions in the face of climate change.

These transition costs are currently out of reach for most households in under-resourced communities.

Actual, on-the-ground information pertaining to under-resourced communities must be collected and used for future energy-system transition planning.

The unique circumstances that exist in these communities must be recognized and integrated into research approaches and planning projections, rather than current assumptions based on affluent household appliance profiles and energy use patterns. Research teams must include local, trusted community-based organizations as fully paid, fully participating project partners who can guide and help implement data collection and communication.

Clear and honest information is essential to help households navigate the complex set of decisions around electrification of existing residential buildings.

This is especially true in under-resourced communities. Communication tools such as The ABC's of Electrifying Your Gas Appliances should be disseminated widely and updated as needed.

4.2 Indoor Air Quality and Natural Gas Appliances

Households in the study community are exposed to indoor pollutant levels above ambient standards.

More than 20 percent of the homes monitored during the winter sampling timeframe had NO_2 levels above the annual air quality standard of 30 ppb (California Ambient Air Quality Standard). Approximately 11 percent of the winter sampling dataset had average $PM_{2.5}$ concentrations above the acute air quality standard of 35 µg/m^3 (National Ambient Air Quality Standard).

Multiple lines of evidence point to gas stoves and ovens as a primary source of indoor NO_2 and suggest that cooking is also a source of PM, although the relative contributions of the food being cooked versus the gas combustion to PM levels remain unclear.

Cooking Frequencies

Homes that reported cooking more than 50 percent of their meals at home with gas cooking appliances had significantly higher NO_2 concentrations compared to homes that cooked less than 50 percent of their meals at home with gas cooking appliances. No similar relationships between gas appliance usage and increased NO_2 concentrations were identified with any other gas appliances. This suggests that non-cooking gas appliances (for example water heaters, wall furnaces, dryers) were likely vented or functioned with high efficiency or located outside of the home (such as water heaters). But it is important to note that these appliances can be a major source of pollutant emissions if not properly maintained or correctly vented.

Cooking Fuel Source

Due to the high utilization of natural gas within our study community, only two homes reported all-electric cooking appliances in both sampling time frames. While the test for significance suggests homes with electric cooking appliances have lower NO_2 concentrations, the sample size of the electric cooking appliance group does not meet the suggested group size for non-parametric comparison so therefore should be cautiously interpreted.

Analysis of Hourly Gas Consumption

Significant positive correlations were observed between reported percentages of time spent using ovens and stoves and the average hourly PM-1.0. However, prior studies suggest that food-derived PM associated with cooking can be a significant contributor to PM load (i.e., not all PM is derived from fuel combustion).

Health risks from gas cooking appliances are higher in under-resourced communities.

Nearly 10 percent of homes indicated using ovens as a heating source. These homes did not have a central forced air system and were more likely to have a wall furnace. The use of ovens as a primary or secondary heating source increases the risk of exposure to air pollutant emissions so this should be examined in more detail in future research.

Temperature data from in-home particle monitors suggested high indoor temperatures during summer months, exceeding 90 degrees in multiple homes.

While temperature sensors can be influenced by internal device temperatures, feedback regarding uncomfortable temperatures within residential environments was confirmed by team members and volunteers who were in participants' homes during the summer monitoring period, as well as by team members who live and work in the study community. This raises concerns for occupants' health, with implications for energy modeling.

This study found wide variations and seasonal differences across indoor and outdoor PM concentrations and household ventilation practices.

During the winter monitoring timeframe, mean PM concentrations were higher indoors compared to mean outdoor concentrations. It is possible that during the winter, when windows and doors are opened with less frequency, air pollutants from indoor sources have more time to accumulate within the building envelope. These results highlight the need to understand individual home environments within the study community.

A focus on the electrification of gas cooking appliances in under-resourced communities is recommended for several reasons.

First, cooking appliances were the most common gas appliances found within the main living area of the homes. Second, a relationship was found between increased NO_2 concentrations in homes with higher frequencies of gas cooking appliance use. Third, a subset of the homes indicated they used ovens for heating, which could have a significant impact on indoor exposure.

Additional research in similar communities is highly recommended to confirm the findings of this current study.

Future studies should compare all-electric households to those using gas appliances; monitoring designs that distinguish between winter and summer are also essential. Future studies should further understand the reasons for and the extent to which households use stoves and ovens for space heating.

A lack of indoor air quality standards prevents a full evaluation of the human health impacts of pollutants emitted from indoor gas combustion.

It is important that these standards be developed as soon as possible so that existing exposure levels experienced within households can be placed into an appropriate risk context. This study had no choice but to use federal outdoor exposure threshold concentrations when attempting to provide context for participating residents. This is not ideal because these outdoor standards are likely higher than what the safe thresholds for the indoor air concentrations should be, giving residents a false sense of safety.

4.3 Building-Scale Modeling and Impacts of Electrification in Under-resourced Communities

Appliance profiles within participant households do not conform to regional averages.

Homes within the study were dominated by gas appliances, especially stoves and ovens. The percent of study participant homes with gas stoves and gas water heaters was approximately 93 percent, compared with the 2019 RASS estimate of 84 percent for each of those appliances in SoCalGas's service territory as a whole.

The majority of homes did not have central temperature controlling appliances such as central forced air furnaces or central A/C. Residents relied mostly on fans and small window or wall A/C units and space heaters. The total number of study participants with central air conditioning (33 percent) was much lower than the 2019 RASS estimate of 68 percent in SoCalGas's service territory as a whole.

Load impacts of electrification can vary significantly across typical houses found within under-resourced communities.

Across the prototype homes modeled, there was a high level of sensitivity to, and variance in, the impacts of electrification. Depending on the baseline appliance profile, a wide range of bill changes could result from the same electrification scenario. In one case, this ranged from plus 51 percent to minus 11 percent.

Electrification of water heating was the main source of modeled bill increases associated with appliance electrification. Electric vehicle charging, even assuming only Level 1, had nearly a doubling effect on customer bills; installing a Level 2 charger would further increase bills. Adding solar PV reduced energy bills and is therefore critical to couple and sequence with appliance electrification and electric vehicles. However, it is also important to recognize that in-home EV charging represents the transfer of the energy demands of an entire separate segment of our economy (the transportation sector) to an electricity infrastructure system designed to service only traditional residential appliance loads.

The default heating and cooling setpoint schedules in BEopt and the Building America House Simulation Protocols were not reflective of the average household patterns in the study area.

Home automated heating and cooling set points had the greatest effect on energy model outputs. However, the presence of a cooling system within study participant households did not mean that it was used to keep occupants cool. The temperatures during the summer monitoring months were, on average, over 85°F for every hour of the day over a 24-hour period. In contrast, during the winter months the temperature was relatively constant at a comfortable temperature of around 70°F. The model required an unusually high cooling setback temperature of 95°F to reflect these conditions, as well as limiting the cooling schedule to a 2-hour window between 3 p.m. and 5 p.m.

BEopt and Building America House Simulation assumptions for relationships between occupancy and number of bedrooms did not hold true for study participant households.

Questionnaires provided information on the actual number of occupants, which was higher in all cases than default model assumptions. Those protocols also assumed a linear relationship between the number of occupants and energy use. However, a diminishing relationship was observed in the models between the number of occupants and energy-end-use consumption for appliances and miscellaneous electric loads when the number of occupants exceeded the number of bedrooms.

It is critical to account for the unique circumstances and attributes in under-resourced communities that are not traditionally captured in energy modeling.

This includes assumptions about appliance types, occupancy levels, and cooling set points. Modeling conducted to inform state or local policies and programs should be required to demonstrate how under-resourced communities are represented in the model, and to describe how model assumptions might impact results.

A higher resolution of the RASS study should be conducted for under-resourced homes.

This would provide better data to characterize appliances and understand viable electrification pathways in communities. Data on electric service panel amperage rating should also be collected because it is a major cost driver for residential electrification.

Programs should account for the possibility that the installation of new equipment could result in greater use of heating and cooling.

While standard practices in energy modeling recommend that occupant schedules and set points be constant, behavioral changes and the desire for thermal comfort must realistically be accounted for. Strategies such as combining solar and storage through subsidized programs are recommended to lower the risk of bill increases, especially in underserved communities.

Residential energy modeling tools, including BEopt, could benefit from refinements.

Models should allow schedules to be refined for space heaters and possibly other loads to correspond with factors like the weather. Models for this study used the fan motor of central furnaces and wall furnaces (by increasing and parameterizing the watts/cfm) to simulate space heater operation that corresponds to both heating-degree days and internal temperatures. The building energy modeling (BEM) community should consider updating ASHRAE Guideline 14 to include procedures to calibrate energy models to indoor air temperature (in addition to energy consumption).

Investor-owned-utility Green Button websites should be translated into Spanish for the step-by-step enrollment process.

Absence of instructions in Spanish is a barrier to participation for households with predominantly Spanish speakers, which are prominent in the state's under-resourced communities.

4.4 Implications of the Timing of Natural Gas Use for Building Electrification

Peak diurnal rates of natural gas use appear to largely coincide with peak diurnal rates of electricity consumption.

Hourly patterns in the intensity of residential gas use present important challenges to widespread appliance electrification, both from the perspective of grid operators and utilities as well as individual consumers. If widespread electrification of residential gas appliances were implemented today it would likely significantly increase peak electricity loads on the distribution systems serving residential communities, further exacerbating grid-balancing challenges.

Aggressive electrification of existing buildings will significantly alter the average load profile of residential customers, producing new winter season system peaks and likely amplifying current summer peaks.

Significant energy is required to heat air and water during cold winter months. Switching from gas to electricity will benefit from the improved end-use efficiency of electricity appliances, but not enough to completely avoid load growth from the transition.

In California, electricity costs more per unit than natural gas. However, these cost premiums increase during peak electricity demand periods. Time-of-use electricity rates could make the electrification of certain gas appliances more financially painful for residents.

With time-of-use electricity rates, where the price of electricity increases significantly during peak periods, the electrification of certain gas appliances may create significant bill increases. How much total energy expenditures change will largely depend upon which appliances are electrified as well as when and how they are used. These costs would be over and above any upfront capital costs incurred for the purchase and installation of the electric appliances themselves.

A statewide electrification strategy must account for multiple aspects of residential appliance electrification.

These aspects include: indoor air quality benefits, total percent of household energy use attributable to different appliances, the ability to implement load shifting for given end uses, the replacement and installation costs of different appliances, and the need for electric service panel upgrades or new 240V circuits. Further research is needed to understand the full cost of this transition across the state.

Strategic pursuit of partial electrification retrofits can mitigate many of the undesirable load growth outcomes associated with full home electrification.

Electrification of gas cooking appliances provides the greatest indoor air quality improvements but only limited GHG emission abatements because of their low gas use. Electrification of air and water heating equipment can abate more GHGs but will likely lead to significant load profile changes and, thus, uncertain bill outcomes for customers and system reliability challenges for grid operators. Decisions must be made about the relative priorities of these currently competing objectives.

Data on household service panel amperage ratings is critical to supporting much-needed research, and to make these data available to academic researchers.

Service panel amperage information is essential for estimating costs associated with electrification of existing buildings, especially in underrepresented communities with older housing stock. Utilities should use these data to plan for future distribution infrastructure investments, and should make them available to academic researchers under non-disclosure agreements. This would be similar to other data maintained by utilities, including whether the account has a heat pump water heater, solar PV, or Level 2 EV charger.

4.5 Building Electrification Benefits and Impacts

Residential building electrification measures can significantly improve local air quality for residents of communities where they are implemented.

Resulting air quality improvements are associated with significant reductions in associated monetary costs stemming from unwanted public health outcomes including mortality, hospital visits, asthma, and lost-work days.

The overall magnitude of local public health benefits exceeded the estimated value of ambient public health impacts by a significant margin.

Ambient impacts are caused by changes in the operations of the EGU fleet required to support new electricity demand profiles in electrified homes. Note that this analysis was based on grid responses to marginal increases in electricity load but did not examine the effects of statewide residential electrification, which could result in a regime change in grid operations (see further discussion on the AVERT model below).

Overall, the ratios of local benefits to ambient impacts associated with each of the different electrification pathways tend to improve over time.

This was due to the assumption that the grid's fossil EGUs will be progressively retired to comply with the interim targets of the state's renewable portfolio standard. It is unlikely that future RPS non-compliance would result in overall net impacts from residential electrification but would likely still reduce the magnitude of overall net benefits.

Impacts associated with increased grid emissions are geographically localized and may accrue to different populations from those benefiting from electrification.

Ambient air quality impacts from electrification, though significantly outweighed by local benefits overall, tend to be geographically concentrated within communities that are situated near existing fossil EGUs. Which specific appliances are electrified in the majority of households will play a significant role in determining the magnitude and geographic distribution of ambient impacts from fossil EGUs. It is possible that minor net reductions in overall pollutants emitted from fossil EGUs could be associated with minor net increases in health impacts. Such an outcome can occur if the timing of electricity consumption changes so that different EGUs, located closer to larger population centers, must operate more frequently.

The present capabilities of common DER (solar PV and battery) systems are not yet sufficient to completely avoid localized ambient emissions increases from full-house electrification efforts.

However, if electrification measures are more targeted, it is possible to minimize or even eliminate ambient emissions growth. Distributed energy resources also mitigate increases in electricity bills from appliance electrification. However, given current net-energy metering rules and the many rooftop solar installations that will come online *before* buildings become fully electrified, it is likely that solar installations could be significantly undersized compared with what is required to offset even targeted appliance electrification.

The present capabilities of tools to quantify avoided emissions and associated health impacts preclude the analysis of statewide electrification initiatives.

AVERT and similar tools use historical data from grid electricity generators to evaluate *marginal* changes in their operations from *marginal* changes in electricity loads. When assessing widespread, extensive increases in electricity use, however, historical plant operations data cease to become relevant and the entire framework for conducting the analysis breaks down. Different simulation tools and approaches will be required to quantitatively evaluate the emissions and co-benefits associated with higher levels of electrification across the state.

Electrification policies and planning for fossil EGU retirements must address the possibility of creating new air pollution hot spots or exacerbating existing hot spots.

Consideration should be given to policies that directly fund upgrades to homes in hot-spot communities including air conditioning, filtration, full appliance electrification, proper ventilation of cooking appliances, and building-shell upgrades that provide households with the best-possible indoor air quality and reduce emissions to the ambient environment. A related tariff should also be considered to further extend CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (CARE)-type rates to a broader population of middle-to-low-income households near EGUs.

The COBRA modeling framework should be expanded to account for changes in indoor emissions exposure pathways and changes in NO_2 and other pollutants.

As of the time this study was conducted, COBRA accounts for only ambient exposure pathways for particulate matter. Modeling changes in indoor air-pollutant concentrations from avoided gas use and reductions in indoor exposures would have produced larger estimates of overall net benefits from the electrification pathways considered in this study. Additional changes, including the establishment of indoor AQ standards and improved residential appliance emissions factors (especially for stoves and ovens), will also be required to support this recommendation.

More work is required to understand the complexity of indoor environments and the human health implications of gas combustion co-product emission exposure.

Overall, the electrification of gas end uses that heat water and air has the greatest potential to reduce net CO_2, NO_x, and $PM_{2.5}$ emissions. However, this study indicates that electrifying gas cooking appliances will also provide significant health benefits for residents. Different gas appliances have different seasonal and diurnal patterns of use. An electrification effort that focuses on one appliance category, for example water heaters, will likely have a very different overall net impact profile than an effort that focuses on stoves. This holds true even if the two programs result in similar annual net increases in total electricity loads.

CHAPTER 5: Knowledge Transfer Activities

This section discusses knowledge transfer and dissemination activities for this project.

5.1. Meetings

5.1.1 Technical Advisory Committee Meeting

The project team engaged with a technical advisory committee (TAC) that included representatives from the CA Air Resources Board, Lawrence Berkeley National Labs, CA Department of Public Health, NRDC, Sacramento Municipal Utility District, SCAQMD, USDOE, Grid Alternatives, LA County Chief Sustainability Office, and Earthjustice, among others.

Two project TAC meetings were held for this project, and TAC members were contacted individually for specific questions related to their areas of expertise; TAC members attended the project's final event and asked to use their networks to help disseminate findings and recommendations.

5.1.2 Presentation of Results to the Community

Two meetings were held with community members to disseminate project results related to indoor air quality monitoring. Both events were virtual, held via Zoom due to COVID-19 restrictions. The initial community meeting was held on June 11, 2020 and included a presentation of preliminary project findings and recommendations. The final community meeting was held on July 22, 2021 and presented a final set of project findings and recommendations as well as a guidebook on household electrification, specifically designed for the meeting. For both events, the team focused on creating clear messages for the local community that encapsulated project findings as they pertain to households. Active SGV led outreach efforts to invite community members and organize the session.

5.1.3 Final Project Presentation to CEC and TAC

A final project presentation was made on Sept 17, 2021, via Zoom. The audience was made up of CEC project agreement managers, other CEC staff, and TAC members. Copies of the presentation slide decks, a recording of the meeting, the agenda and invitee list, and the summary of major findings and recommendations are all available at this link:

https://ucla.box.com/s/zwdeoa7izf7raonpcw1p9e8atkck1lqt

5.2 Documentation

5.2.1 Project Deliverable Reports

These reports provide detailed descriptions of project methods, findings, and conclusions, and will be maintained on the CCSC website. The following reports were developed as part of this project:

- Survey/Monitoring Design Plan.
- Summary Report of Survey Findings.
- Air Quality Monitoring Report.

- Summary Report on the Specification of Local Indoor and Ambient Natural Gas Combustion Correlations.
- Modeling Scenario Methodology Report.
- Building Models Report.
- Energy System Pathway Transformation Scenarios report.
- Report on Expected Hourly Load Profile Changes from Various Energy System Transformation Pathways.
- Report on the Holistic Benefits from Various Energy System Transformation Pathways.
- Summary Report of Community Events.
- Final Project Report.
- Project Fact Sheet.
- Journal Articles.
- Meeting Presentation Materials.

5.2.2 Project Websites

- **Active SGV's Website:** This website was set up to communicate information about the project to the study participants and the greater Avocado Heights/Bassett community, and to provide educational information about natural gas, air quality, and appliance electrification. https://www.activesgv.org/healthy-home-study.html
- **CCSC Website:** The CCSC website will be updated to host information on this project, including links to final project reports and findings.
- **TAC Website:** A UCLA Box shared folder is available to TAC members and CEC project managers and contains copies of meeting agendas, attendees, presentations and related materials.

5.2.3 Papers, Products, and Conference Presentations

The following is a list of journal articles and conference presentations related to this project, along with status information.

Journal Articles

- Fournier, E.D., Cudd, R., Federico, F., Pincetl, S. (2020) *Implications of the Timing of Residential Natural Gas Use for Appliance Electrification Efforts*. *Environmental Research Letters*, 15 (2020) 124008. Status: published.
- Quantifying the Holistic Benefits from Different Residential Electrification Pathways within California Disadvantaged Communities. Fournier, E.D.; et al, 2021. (In progress).

Invited Papers and Talks

- Invited white paper submitted to The Justice Collaborative Institute in April 2021 on the topic of Natural Gas Bans: *The Case for Gas Bans and Residential Building Electrification: Equity Perspectives on an Emerging Socio-Technical Energy Transition*. Status: published on June 4, 2021 - https://theappeal.org/the-lab/report/the-case-for-gas-bans-and-residential-building-electrification/

Products

- An electrification guidebook for households in the study community, entitled *The ABC's of Electrifying Your Natural Gas Appliances*. Available at the Active SGV project website: https://www.activesgv.org/healthy-home-study.html

Conference Presentations

- 10th Anniversary Energy Policy Conference, Oct 14-15, 2021, Boise State University: virtual event. Paper presented by Robert Cudd. Co-authors: Fournier, Federico, Pincetl: *Gas Bans and Residential Building Electrification: Limitations of Traditional Policy Instruments for Accomplishing a Socio-Technical Energy Transition.* See https://www.boisestate.edu/epi/epc2021/
- The American Council for an Energy Efficient Economy (ACEEE), 2022 Summer Study on Energy Efficiency in Building, Aug 21-26. Submitted paper: *Using Big Data to Assess Energy System Transitions in Under-resourced Communities*. Costa, M., et al., 2022 (in progress)

CHAPTER 6: Benefits to Ratepayers

6.1 Benefits for Under-resourced Communities

This study was one of the first indoor air quality studies specific to under-resourced households, to monitor particulate matter, and to conduct seasonally-specific monitoring to allow comparisons between winter and summer, thereby demonstrating the importance of seasons when assessing the influence of appliance usage and ventilation practices.

Research and policy needs were identified for indoor air quality standards, appliance emission factors, and the quantification of benefits from cooking-appliance electrification.

This work also produced an introductory, plain-language guide to household electrification, including an appliance-by-appliance discussion of benefits and costs. Although utility incentive program information was specific to SCE's service territory and the South Coast Air Basin, it could be easily revised by universities or non-profits that serve the state.

Analyses conclude that residential appliance electrification will result in significant local air quality improvements (a major benefit to communities with high CalEnviroScreen pollution burden scores) and recommend investments and tariff designs that reduce the upfront and ongoing costs of electrification for under-resourced communities.

The potential for air quality hot spots near fossil-fueled electricity generators was identified and recommendations made for investments and tariff designs that mitigate air quality impacts through 2045.

This study also identified considerations that could increase costs for under-resourced households, including the coincidence of peak gas usage with peak electricity usage, which could trigger an even higher time-of-use rate during peak hours.

6.2 Benefits for Grid Management

This project included one of the first analyses of hourly natural gas data, which revealed the coincidence of peak gas use with peak electricity consumption and flagged it as a potential issue of concern for grid managers.

6.3 Benefits for State Planning Efforts

This study demonstrated the potential for geographic dislocation between areas of local air quality improvement from appliance electrification versus areas of ambient air quality deterioration from grid emissions due to added electricity loads. It also showed the potential of annual net reductions in grid emissions to increase annual health impacts if the timing of electricity consumption causes EGUs located closer to larger population centers to operate more frequently in response.

LIST OF ACRONYMS

Term	Definition
AB	California State Assembly Bill
ACS	American Community Survey
A/C	Air Conditioning
AHS	American Housing Survey
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AVERT	Avoided Energy Generation Tool
BEM	Building Energy Modeling
BEopt	Building Energy Optimization Tool
BESS	Battery Energy Storage Systems
CAAQS	California Ambient Air Quality Standards
CAISO	California Independent System Operator
CARB	California Air Resources Board
CAMD	Clean Air Market Database
CARE	California Alternative Rates for Energy
CCA	Community Choice Aggregation
CCSC	California Center for Sustainable Communities at UCLA
CEC	California Energy Commission
CEPAM	California Emissions Projection Analysis Model
CES	CalEnviroScreen
CFA	Central Forced Air
CHHIAQ	California Healthy Homes Indoor Air Quality
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COBRA	CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool
CPUC	California Public Utilities Commissions
DER	Distributed Energy Resources
EF	Emissions Factor
EE	Energy Efficiency
ER	Emissions Rate

Term	Definition
EGU	Electricity Generator Unit
EUI	Energy Use Intensity
EV	Electric Vehicle
FH	Full Home
GHG	Greenhouse Gas
HEPA	High-Efficiency Particulate Absorbing
HUD	Housing and Urban Development (US Dept. of)
HVAC	Heating, Ventilation and Air-Conditioning
IAQ	Indoor Air Quality
IOU	Investor-Owned Utility
LAC	Los Angeles County
LADWP	Los Angeles Department of Water & Power
MELs	Miscellaneous Electric Loads
MF	Multi-Family
MUD	Multi-Unit Dwelling
NAAQS	National Ambient Air Quality Standards
NEM	Net Energy Metering
NO_X	Nitrogen Oxides
NO_2	Nitrogen Dioxide
PM [X]	Particulate Matter [X microns or smaller]
PPB	Parts per Billion
PT	Prototype
PV	Photovoltaic
PDFs	Probability Density Functions
QA/QC	Quality Assurance/Quality Control
RASS	Residential Appliance Saturation Survey
RDF	Regional Data File
REopt	Renewable Energy Integration and Optimization Tool
RPS	Renewable Portfolio Standard
RTP	Regional Transportation Planning
SB	California State Senate Bill
SF	Single-Family
SCAG	Southern California Association of Governments

Term	Definition
SCAQMD	South Coast Air Quality Management District
SCE	Southern California Edison
SCG	Southern California Gas
SGV	San Gabriel Valley
SO_X	Sulfur Oxides
TAC	Technical Advisory Committee
TEC	The Energy Coalition
T&D	Transmission and Distribution
UCLA	University of California, Los Angeles
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
WECC	Western Electricity Coordinating Council

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