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Net GHG emissions and air quality outcomes from different residential building electrification pathways within a California disadvantaged community

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ABSTRACT

Electrification of gas appliances in residential buildings will be necessary to rapidly decarbonize the energy system. In California however, recent rates of adoption of electric appliances, especially within disadvantaged and vulnerable communities (DVCs), have been insufficient to meet the state's ambitious GHG emissions abatement targets. In this study we use an integrated assessment modeling framework to quantify the holistic benefits of different electrification pathways within a representative study area DVC. Results indicate that aggressive electrification retrofits can deliver significant net reductions in GHG emissions, even when future grid emissions from increased electric loads are factored in. We also find that these measures can also create significant net public health benefits, in terms of overall avoided impacts from particulate matter (PM-2.5μ) exposures. However, the realization of these net benefits requires tradeoffs between local improvements in air quality in the areas where electrification occurs, for smaller, but still significant, reductions in air quality, in areas where fossil fueled electricity generators remain active. We conclude with a discussion of some of the persistent barriers to electrification within DVCs and the import role of electrification within broader efforts to combat climate change and improve equity within the energy system.

1. Introduction

1.1. Background

California is the world's fifth largest economy, the United States' second largest net consumer of primary energy resources, and, increasingly, a fertile testbed for the implementation of new technologies and policies to support the deep decarbonization of the energy sector. (BEA Bureau of Economic Analysis BEA, 2022, EIA Energy Information Administration EIA, 2022) Among the most visible of the state's ongoing decarbonization efforts has been its adoption of a binding renewable energy portfolio standard (RPS). (De Leon, 2015) This is an energy procurement policy which mandates that the state's electric utility providers purchase an increasing quantity of power from qualifying renewable sources over time.

However, eliminating the use of fossil fuels in electricity production alone will not be sufficient to achieve California's ambitious greenhouse gas (GHG) emissions reduction goals. There are three other, equally important initiatives which, only when pursued jointly with the RPS, actually constitute a viable decarbonization strategy. These include (1) wholesale electrification of the transportation fleet, (2) radical increases in the energy efficiency of end-use energy equipment, and (3) the comprehensive electrification of any remaining fossil fuel appliances, especially those which operate via the combustion of fossil hydrocarbon gas. (Long et al. 2011, Kenny et al. 2022) This latter goal, which we shall henceforth refer to simply as building electrification, is the principal focus of this study's analysis.

Of these three decarbonization policy initiatives, building electrification has proven to be the most challenging and contentious. (Deason & Borgeson, 2019) This is because the current approach to its implementation requires that individual consumers voluntarily choose to

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Abbreviations

AVERT	Avoided Emissions and genERation Tool
BEopt	Building Energy Optimization Platform
BEopt	Building Energy Optimization Platform
CCSC	California Center for Sustainable Communities
CEC	California Energy Commission
COBRA	Co-Benefits Risk Assessment Screening and Mapping Tool
CPUC	California Public Utilities Commission
EGU	Electricity Generating Units
IAQ	Indoor Air Quality
MF	Multi-Family
NREL	National Renewable Energy Laboratory
RDF	Regional Data File
REopt	Renewable Energy Optimization Platform
RPS	Renewable Portfolio Standard
SF	Single Family
SM	Supplementary Material
TEC	The Energy Coalition
UCLA	University of California Los Angeles
EPA	United States Environmental Protection Agency

adopt new end-use energy equipment, with different performance characteristics from their existing systems, that are associated with uncertain life cycle costs. Furthermore, recent building electrification initiatives have also faced organized opposition from well-funded special interest groups for whom the transition away from fossil fuels represents an existential threat. (Nadel, 2019) As a result of these and other factors, despite the impressive progress which has been made to date in terms of the volume of renewable energy procured under the RPS, to date, gas still remains the dominant source of primary energy within California (EIA Energy Information Administration EIA, 2022).

1.2. Study objectives

The goal of this study is to quantify the holistic benefits to disadvantaged and vulnerable communities (DVCs) from the accelerated adoption of residential electric appliances and other distributed energy resources (DERs). (McCormick, 2015, Carley & Konisky, 2020) These benefits encompass not only the GHG emissions reductions from electrification, but also any avoided exposures to particulate matter and other priority pollutants, both locally as a result of in-home gas combustion, as well as in the ambient air, due to the operations of grid connected fossil electricity generator units (EGUs). (O'Shaughnessy et al., 2021, Lukanov et al. 2019) As part of this effort, we also identify key sources of uncertainty in the size and distribution of these benefits as well as barriers to DVC participation which must be overcome.

Quantification of such holistic benefits is a complex undertaking. It requires detailed modeling of a given DVC's existing building stock, the types and performance characteristics of its installed end-use appliances, and patterns of appliance usage. It also requires empirical data on historical patterns of local participation in various energy system transformations that can be used to establish baseline expectations of future change under "business-as-usual" conditions, against which comparisons can be made. Beyond these local considerations, the broader impacts of any one community's enhanced pursuit of different energy transformations requires consideration of how changes in both the timing and volume of aggregate electricity demands over time are likely to alter grid operations. These changes include the output production, and associated environmental impacts, of the geographically dispersed fossil EGUs which supply the electrical power grid, not only today, but on into the future as well. This necessitates detailed simulation of the grid's fossil EGU's marginal responses to future changes in hourly electricity demands. It also requires detailed assumptions of grid EGU retirements that either have already been announced or will be necessary to comply with the future RPS targets.

2. Literature review

2.1. Disadvantaged and vulnerable community energy systems

Limited access to energy services supplied by clean and renewable generation sources has been shown to have profound and cross sectoral impacts for those affected. These include increased cost and decreased quality/reliability of service, increased exposure to indoor and outdoor air and water pollution burdens from primary energy resource production and use, and increased exposure to extreme weather events and other hazards caused by accelerating global climate changes. (Sirigotis et al., 2022) Moreover, the window of opportunity to mitigate these worst-case climate impacts is rapidly closing. (Zhongming, Linong, Xiaona, Wangqiang, & Wei, 2021)

Widespread electrification is not likely to be achieved either quickly or equitably enough within DVCs if we rely solely upon policies which prohibit the use of gas in new construction. (Deason & Borgeson, 2019) Recent estimates place the median lifespan of a U.S. single family home at 130 years. (Ianchenko et al., 2020) And it is well documented that housing stock turnover occurs at higher rates within more affluent communities. (Smith et al., 2022) Thus, so-called "gas bans," which prohibit the use of gas appliances in new construction, while both logical and necessary to pursue, must be augmented by efforts to provide electrification retrofits within a massive number of existing homes. The challenges and potential benefits associated with doing so are priority equity concerns.

According to data from the California Energy Commission's (CEC) most recently published Residential Appliance Saturation Survey (RASS), reproduced here in Table 1, it is estimated that gas appliances still enjoy the following penetration levels across all households where gas service is available. (Palmgren, Goldberg, Ramirez, & Williamson, 2021)

While the spatial resolution of the RASS' sample data is limited to the state's major electric utility service territories, evidence from other localized studies suggest that levels of end-use electrification are particularly low within the state's DVCs (Fournier, Cudd, Federico, & Pincetl, 2020; Gold, 2021) These are areas which, on average, tend to be characterized by: lower income households, with higher proportions of non-white and non-English speaking residents, living in older construction vintage buildings, with older, less efficient, end-use energy appliances, located in areas that are burdened by higher levels of air and water pollution, and which are exposed to greater and more varied sources of climate risk. (Faust et al., 2021; Fernandez-Bou et al., 2021; Truong, 2014)

2.2. The role of electrification in community climate action planning

Recent research has shown that the electrification of residential gas

Table 1
California statewide average gas appliance penetration rates by appliance category (in areas where gas service is available).

Gas Appliance Category	*Estimated Penetration Level*
Primary Heating	77%
Auxiliary Heating	53%
Water Heating	86%
Clothes Dryer	45%
Range/Oven	75%
Pool Heating	4%
Spa Heating	5%
Miscellaneous	10%

appliances is becoming an increasingly popular policy tool being considered by city and regional authorities engaged in urban climate action planning (Brozynski & Leibowicz, 2018, Deetjen et al., 2018; Ku et al., 2021) It was not long ago that the thought of proposing a climate action policy as sweeping and prescriptive as a gas ban would have been considered taboo within the U.S. (Green, 2018) However, today the number of municipalities which have passed these bans has grown to such an extent that the issue has drawn the attention of the fuel industry. As a result of their recent lobbying efforts, several conservative state legislatures have actually passed laws that actually prohibit local municipalities from adopting such measures. Clearly then, this is an active and contentious topic of debate over the future character of the urban built environment within the U.S. and one that may ultimately require Federal intervention to resolve.

Part of the reason why residential electrification policies are attractive to local/regional authorities engaged in climate action planning is because the mechanisms of implementation tend to be well aligned with the domains of their jurisdictional powers. Electrification policies most commonly appear in the form of building energy efficiency code requirements, building construction and renovation permitting processes, and/or as conditions of property ownership transfers – all of which are under local government control. Another important explanation for electrification's appeal is that it offers a comprehensive suite of co-benefits in addition to GHG mitigation. These not only include improvements the end-use energy experience of households in local communities, but also the redress longstanding inequities in terms of the distribution of public health burdens and other pollution impacts associated with the supply side operations of the energy system. (Wang et al., 2020, Gallagher & Holloway, 2020, Creutzig et al., 2022)

3. Methodology

3.1. Overview

The integrated assessment methodology that we developed to evaluate the holistic benefits of gas appliance electrification to residents of DVCs comprised five distinct components, each of which required the use of its own dedicated modeling toolset. Fig. 1 provides a high-level graphical overview of this methodology and documents the number of different scenario alternatives, metrics, and impact categories evaluated within each.

3.2. Study area

This study's quantitative analyses intensively focus on a specific study area DVC which is defined by two adjacent zip codes (91,732 & 91,746) that are located in Eastern Los Angeles County's San Gabriel Valley. This study area spans portions of the cities of EL Monte, Industry, La Puente, Irwindale, Baldwin Park, as well as Unincorporated Los Angeles County and is home to an estimated 91,871 people. Climactically, this region is characterized by mild winters with minimal chances of frost, and very hot and dry summers, with an average of ~50 days per year where the maximum daily temperatures exceed a 95°F threshold for extreme heat.

Fig. 2 contains a set of maps which describe salient characteristics of this study area. These include local census tract CalEnviroScreen 3.0 scores, population counts, parcel use type characteristics, and city administrative boundaries. Nearly all of the census tracts within these two zip codes meet or exceed the California Public Utility Commission's (CPUC) threshold for DVC status which is defined as: having a composite CalEnviroScreen (CES) score that exceeds the 75*th* percentile statewide. There are several factors which contribute to the study area's high CES scores. These include the presence of two major freeway corridors which bi-sect the area both vertically (I-605) and horizontally (I-10), the San Jose Water Reclamation Plant, the decommissioned Puente Hills Landfill, and numerous point air and water pollutant emissions sources dispersed throughout local manufacturing and warehouse/distribution facilities.[1]

3.3. Baseline prototype building energy models

The first step in this process involves creating a set of baseline building energy prototype models designed to reflect the existing building stock and characteristic occupancy patterns of the project's study area DVC. For this first step we used NREL's Building Energy Optimization (BEopt) platform which uses advanced optimization techniques to solve for any unspecified building attribute parameters by using targeted monthly energy bill amounts as constraints. (Christensen et al., 2006) The design and specification of these baseline prototype models were informed both by property attribute information available from the LA County Assessor's office as well as average bill amount and appliance ownership data collected from surveys and questionnaires administered by project partners from households living within the study area DVC. More information about how details of the study area's local building stock were incorporated into the building energy modeling portion of the analysis are provided in the Supplementary Material (SM).

Prior to the development of the building energy models a multi-part questionnaire was administered to participants ($N = 64$) of an indoor air quality (IAQ) monitoring program conducted as a separate part of this same research project, led by partnering researchers from the UCLA Fielding School of Public Health. The responses to this questionnaire indicated that the appliance profiles within the study area do not conform to regional averages. Participant homes were dominated by gas appliances, especially cooking appliances (stove and oven). The percent of study participant homes with gas stoves and gas water heaters was approximately 93%, compared to the 2019 RASS estimate of 84% for each of those appliances in SoCalGas territory. The majority of homes did not have central temperature controlling appliances, such as central forced air furnaces or central AC. Residents relied mostly on fans and smaller window / wall AC units, as well as space heaters. The total number of study participants with central air conditioning (~33%) was much lower than the 2019 RASS estimate of 68% in SCE territory. (Palmgren, Goldberg, Ramirez, & Williamson, 2021)

After reviewing the major differences in the physical characteristics of the local building stock as well as penetration rates for key energy end-use appliances described above, it was determined that a total of eight residential prototype building models should be developed. These models would function as the baseline points of reference against which various retrofit cases would later be developed and evaluated. The baseline prototype group comprised five single-family (SF) variants and three multi-family (MF) variants. Each of the SF and MF models were assumed to be 1254 ft^2 and 700 ft^2 in size, respectively. Table 2. summarizes several of the more salient differentiating features of the suite of building prototype models created.

3.4. Retrofit scenario building energy models

For each of the eight, baseline prototype building energy models three different electrification retrofit scenarios were developed. These included two different partial electrification measure packages and one full home electrification (FHE) measure package. The two partial electrification retrofit packages were designed based upon previous research findings regarding the differential indoor air-quality (IAQ) benefits associated with the electrification of different end-use appliances. According to previous research, gas cooking appliances have the biggest

[1] More information about the data sources and methods which are used to compute CES scores is available from the California Office of Environment Health Hazard Assessment (OEHHA) website: https://oehha.ca.gov/calenviroscreen.

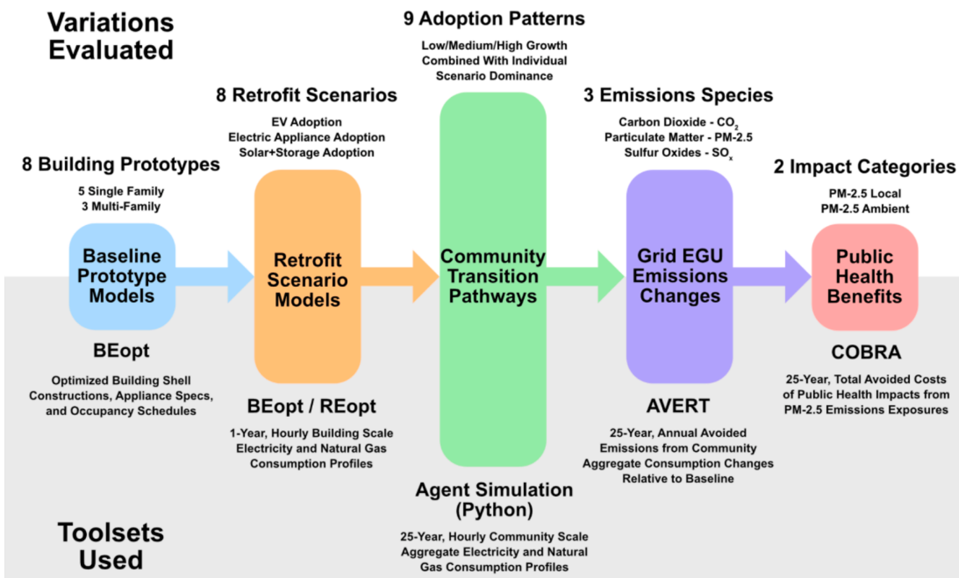

Fig. 1. Flow diagram illustrating the major components of the project's integrated assessment methodology. Different variations that were evaluated at each stage are detailed in the upper portion and the differing modeling tool sets that were used are detailed on the lower portion.

indoor air quality impacts, releasing significant quantities of particulate matter (PM) and nitrogen dioxide (NO_2) into indoor environments as co-products of incomplete gas combustion. (Mullen et al., 2016, Mullen et al., 2022; Singer et al., 2017) Thus, the first and most limited scenario, Minor-IAQ, involved the electrification of cooking appliances (stove + range), but was also accompanied by minor energy efficiency retrofits deemed to be minimally invasive and consistent with Title-24 energy efficiency code requirements. (California Energy Commission 2018) These basic efficiency measures were applied to all of three scenarios (including FHE), and in the case of the Minor-IAQ, were found to offset any increases in peak loads associated with cooking electrification by reducing loads associated with space cooling end uses. The second partial electrification scenario, Moderate-IAQ, is a superset of the previous and additionally includes electrification of heating and cooling equipment (Table 3).

In addition to these three electrification scenarios, marginal load profile changes associated with household adoption of level-1 EV charging, rooftop solar PV only, battery energy storage systems (BESS) only, and combined rooftop PV+BESS were evaluated using the Renewable Energy Optimization (REopt) platform. (Anderson et al., 2017) Although the load profile changes associated with electrification measures were designed to be the focus of the study, these additional energy system transformations were also included to assess their relative magnitude and potential to either exacerbate or mitigate undesirable load profile changes stemming from electrification measures. A discussion of the marginal impacts associated with differential rates of adoption of these technologies is provided in the results section.

3.5. Community transition pathways

Individual annual hourly electricity & gas load profiles (8760) generated from the different baseline prototype and retrofit scenario building energy models were then used to develop a series of agent-based simulations for the entire study area community's energy system. Within these simulations, individual agents, each representing a residential property, were assigned one of the SF/MF prototype models in proportion to the current number and assumed type of SF/MF housing units within the study area community. In this way, at the initial time-step ($t = 2020$), the total hourly loads corresponding to the study area community's 10,229 SF homes and 9744 MF homes were assembled. Comparisons of these synthetic community loads to historical metered residential electricity consumption data for the actual study area community published by the local investor-owned utility were performed and found to be in good agreement (±2.5%).

Following this initialization phase, the simulations proceeded by iteratively transforming the composition of the community's residential building stock on an annual basis for each year in the time horizon ($t =$ 2020, 2045). These transformations were accomplished by pseudo-randomly assigning agents to new retrofit scenario models on the basis of two parameters: (1) an assumed level of the "dominance" associated with each of the different scenario alternatives and (2) an assumed rate of growth - ranging between low, medium, and high. In each of these simulations, subsequently referred to as "transformation pathways," the dominant retrofit scenario was set to be two times more likely to occur than any of the others. Additionally, the different growth rates were implemented in the form of logistic growth models which were parameterized such that the following target saturation levels were achieved by the 2045 stop date of the simulation: low-growth: 50%, medium-growth: 75%, and high-growth: 95%. These are illustrated graphically in the SM.

In all cases, a set of baseline simulations were performed in which the scenario dominance and target growth rates were both specified using available zip code level historical data about recent rates of technology adoption as documented in previous work. (Fournier, Cudd, Federico, & Pincetl, 2020) These baseline pathways formed the point of reference against which future changes in loads associated with each different transformation pathway were subsequently evaluated. In this way, the results which shall later be reported reflect levels of deviation from these baseline rates of change.

3.6. Local emissions changes

Domestic gas appliances can generate harmful emissions co-products, such as small size fraction particulate matter ($PM - 2.5\mu$) and nitrogen dioxide (NO_2), when fuel/air mixture ratios are sub-optimal, and the combustion process is incomplete. The mass of these co-product emissions which is generated per unit of energy consumed is known as the emissions factor (EF) and can vary by appliance category type and vintage. The EFs used in this analysis, summarized in Table 4 are differentiated by major end use categories (air/water heating & other) and were developed using previously published experimental data taken from California household contexts. (Zhu et al., 2020) These

Fig. 2. Map panels depicting geographic attributes of the project study area, which is defined by the boundaries of zip codes 91732 & 91746. Attributes plotted include: CalEnviroScreen 3.0 designated DVC census tracts (upper-left), census tract populations (upper-right), parcel zoning designations, highways, & waterways (lower-left), city and county administrative boundaries (lower-right).

EFs were used to estimate the mass of avoided emissions - both for CO_2 and $PM-2.5\mu$ - associated with the elimination of varying quantities of gas demand due to different domestic appliance retrofit measures. Total masses of avoided emissions were computed by multiplying each appliance group's cumulative hourly gas usage contributions by the corresponding EFs and summing on an annual basis.

3.7. Ambient emissions changes

A key consideration when evaluating the holistic benefits of electrification measures is the quantification of potential emissions increases due to changes in the operations of the grid's fossil fueled EGUs. Grid electricity is supplied by a portfolio of different generation technologies with their own emissions profiles and whose output varies by time of day and year. Thus, the impacts of grid power consumption must be evaluated on the margin, taking into account the precise time at which they occur and relative to the magnitude of overall systems loads. In order to account for these temporal variations in the emissions intensity of grid power, we used the EPA's Avoided Generation Tool (AVERT). (Fisher et al., 2015) This is a modeling framework which uses historical operational data from grid connected fossil EGUs to simulate their likely behavior under different marginal demand conditions. More details about the internal mechanics of the AVERT modeling framework and how it was parameterized for use in this analysis are provided in the SM.

When seeking to model the marginal emissions of grid electricity in future time periods it becomes necessary to make assumptions about the timing with which individual fossil EGUs will be retired. In practice, such retirement decisions take into account numerous considerations

Table 2
Summary of different key appliance attributes which distinguish the different SF and MF prototype building energy models.

Name	*Description*	*Key Appliance Attributes*
SF-PT1	Single Family Prototype #1	Wall Furnace Only, Window Unit A/C
SF-PT2	Single Family Prototype #2	Central Furnace Only, Central A/C
SF-PT3	Single Family Prototype #3	Central Furnace Only, No A/C
SF-PT4	Single Family Prototype #4	Wall Furnace + Space Heater, Window Unit A/C
SP-PT5	Single Family Prototype #5	Central Furnace + Space Heater, Central A/C
MF-PT1	Multi-Family Prototype #1	Wall Furnace Only, Window Unit A/C
MF-PT2	Multi-Family Prototype #2	Space Heater Only, Window Unit A/C
MF-PT3	Multi-Family Prototype #3	Wall Furnace + Space Heater, Window Unit A/C

ranging from a given plant's age and location to its output capacity and other performance characteristics. (Grubert et al., 2020a) Regardless of these attributes however, the presumption of future compliance with the state's binding RPS requires that all existing fossil EGUs be retired and their outputs replaced with zero emissions power by 2045. Relative to this unprecedented scheduling problem, Grubert et al. have recently published an intensive study of this issue which includes a best-estimate schedule of the dates by which all of California's fossil EGUs are likely to be retired. (Grubert, Stokes-Draut, Horvath & Eisenstein, 2020) Within this study, we make use of Grubert et al.'s published fossil EGU retirement schedule to parameterize AVERT when modeling future years. In doing so, we were able to account for anticipated future reductions in grid emissions intensities associated with interim RPS compliance for each year in the forecast time horizon (2020, 2045). Finally, within the AVERT framework, distributed renewable energy generation assets, such as the type of residential scale rooftop solar systems evaluated in this study, are not considered as eligible for curtailment. Thus, one caveat associated with this approach, is that any issues which must be faced by grid operators associated with potential net overproduction from these systems (i.e., reverse power flows) are not explicitly addressed.

3.8. Public health impacts

Public health benefits from electrification accrue from reductions in exposures to gas combustion co-products. In order to quantify a portion of these benefits, we used another USEPA tool called the Co-benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA). (Bridges et al., 2015) This is a tool which has been developed in conjunction with the previous AVERT model to facilitate the process of calculating the changes in public health impacts from PM-2.5μ emissions exposures stemming from a proposed energy policy or program. COBRA is not a fully mechanistic fate-transport simulation model. Instead, it is a streamlined screening tool which makes use of a simplified dose-response relationships and source-receptor transport matrices to estimate the geographic dispersion of impacts from fugitive air emissions. More details about the internal mechanics of the COBRA screening tool and how it was parameterized for use in this analysis are provided in the SM.

We used COBRA to estimate the public health impact reductions at the county level within the state of California. We did this both to estimate benefits from the avoided gas use from residential appliance electrification as well as to estimate impacts from the increased output of the grid's fossil EGUs required to supply newly electrified loads. By comparing these two over time, we were able to estimate the overall net public health benefits from the different electrification pathways previously described.

Relative to residential gas appliances, combustion emissions can be produced either directly within indoor environments, which may or may not be perfectly captured and ventilated to the outdoors, or indirectly by appliances which have been installed external to the home. The public health impacts from indoor emissions exposures are still an area of emerging epidemiological research, and thus, established exposure-response relationships for different classes of pollutant emissions do not yet exist in the same way that they do for ambient exposure pathways. In acknowledgment of this uncertainty, when using COBRA to evaluate the benefits of avoided gas use, we conservatively assumed that all emissions would be perfectly captured and ventilated to the outdoor air. Thus, in the discussion of the modeling results, we characterize these emissions as being *local* as compared to the emissions from grid EGUs which we describe generally as being *ambient*. For all monetized impacts a future year discount rate of 7% was used. Investigations into the use of alternative discount rates were found to have no effect on the relative magnitude of geographically dispersed impacts, which are the primary

Table 4
Overview of the range of emissions factors values used to compute the mass of primary indoor emissions for two different major categories of residential gas appliances.

Appliance category	*Pollutant species*	*Lower bound*	*Upper bound*	*Units*
Cooking & Other	CO_2	0.05699999	0.05999999	short-tons / MMBtu
	NO_x	0.08373600	0.08838800	lbs / MMBtu
	PM-2.5m	0.00348900	0.00581500	lbs / MMBtu
Space & Water Heating	CO_2	0.05699999	0.05999990	short-tons / MMBtu
	NO_x	0.05815000	0.08606200	lbs / MMBtu
	PM-2.5m	0.00348900	0.00581500	lbs / MMBtu

Table 3
Detailed breakdown of key differentiating attributes between each of the different building electrification retrofit scenario alternatives.

Measure	Scenario Baseline	*Minor-IAQ*	*Moderate-IAQ*	*FHE*
Roof/Attic Insulation	Uninsulated / R-13 *	R-49	R-49	R-49
Water Pipes	Uninsulated	R2 Copper	R2 Copper	R2 Copper
Air Ducts	N/A, 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	Same as Baseline	Mini-Split or Air Source Heat Pump	Mini-Split or Air Source Heat Pump
Heating Equipment	Wall Furnace 60% AFUE/Central Furnace	Same as Baseline	Mini-Split or Air Source Heat Pump	Mini-Split or Air Source Heat Pump
Cooling Set-point	72F from 3 to 5PM 95F otherwise	Same as Baseline	Same as Baseline	Same as Baseline
Heating Set-point	71F with 65F set-back	Same as Baseline	Same as Baseline	Same as Baseline
Cooking Equipment	Gas Stove + Range	Electric Stove + Induction Range	Electric Stove + Induction Range	Electric Stove + Induction Range
Water Heater	40-gal Natural Gas	Same as Baseline	Same as Baseline	50 Gal HPWH
Clothes Dryer	Gas	Same as Baseline	Energy Star Electric Dryer	Energy Star Electric Dryer

* Detailed specification depends upon choice of individual building prototype model.

focus of this particular portion of the analysis.

4. Results and discussion

4.1. Total annual loads

The upper row of plots in Fig. 3 depicts modeled future changes in the total annual electricity consumption for all of the SF and MF homes within the project study area community for each electrification pathway simulated. The bottom row plots depict these load changes as deviations computed relative to the load growth assumed within each SF and MF baseline electrification pathway. As these plots illustrate, the choice of the scenario dominance is a stronger driver of load increases than the specification of the growth rate - with the three high load growth pathways all being of the "Full-Home Dominant" variety.

For brevity, subsequent results focus solely on the high-growth transformation pathways. These are the pathways which produce near full (∼ 95%) penetration of full/partial electrification retrofits by the end of the 2045 simulation time horizon, with the relative proportions of each determined by assumptions of scenario dominance. This subset of pathways reflects a rapid acceleration of electrification relative to the business-as-usual behaviors assumed in the baseline pathway. Thus, they provide the strongest litmus test in terms of assessing the potential for unintended consequences to arise from interim load growth being served by an only partially decarbonized grid.

The projected load increases from aggressive electrification retrofits are expected to be significant. For example, under the most extreme High-Growth, Full-Home Electrification Dominant pathway, which eventually achieves a 95% penetration of electrification retrofits with 60% of households being fully electrified, the community's SF housing stock would be expected to require an additional +13 GWh/year by 2045. This constitutes a + 20% net increase over the baseline - which itself is already expected to experience +2 GWh/year of load growth under the BAU assumptions. Similarly, in the MF context, under the same pathway simulation assumptions, annual total loads are expected to grow by +9 GWh/year by 2045 - a net increase of +24% above the baseline.

4.2. Average hourly and average monthly loads

The plots contained in Fig. 4 illustrate changes in average hourly loads (left column) and total monthly loads (right column) relative to the baseline for each of the high growth SF electrification pathways. The patterns described for the SF context are broadly similar to those for the MF which, for brevity, have been omitted here. As the lower left plot within this Figure illustrates, the IAQ-Moderate Dominant electrification pathway has the potential to decrease average hourly loads by as much as −2 MW during the late afternoon / early evening hours (2–6 PM). Much of these savings can be attributed to the retrofit packages making use of mini-split heat pumps which provide combined heating/cooling with extremely high (>100%) energy efficiencies. By comparison however, under the FHE Dominant pathway, the increases in average hourly loads, especially in the morning hours from 8 to 10 A.M., exhibit significant load growth. These increases can largely be attributed to new morning air and water heating demands which predominantly occur during winter months among the fully electrified homes.

Turning next to the three plots on the right column of Fig. 4, we can see the seasonal changes in energy consumption associated with each pathway, depicted in terms of deviations from the baseline monthly total loads. In the IAQ-Minor Dominant case (top right), relative to the baseline, the combination of electrifying cooking appliances and implementing code compliant energy efficiency retrofits leads to slight load reductions in the summer months and slight increases throughout the rest of the year. Moving on the IAQ-Minor Dominant pathway

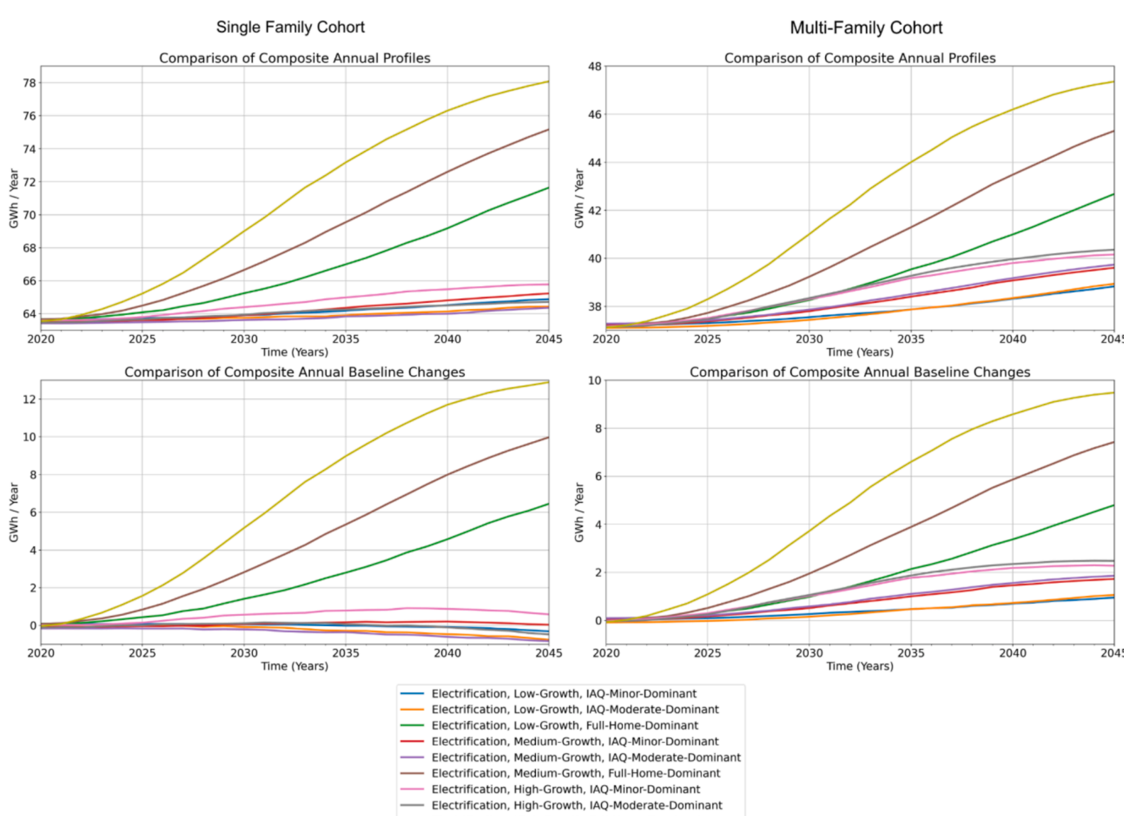

Fig. 3. Changes in composite SF (left) and MF (left) loads both in absolute terms and relative to the baseline for each electrification pathway for each year in the simulation time horizon (2020, 2045).

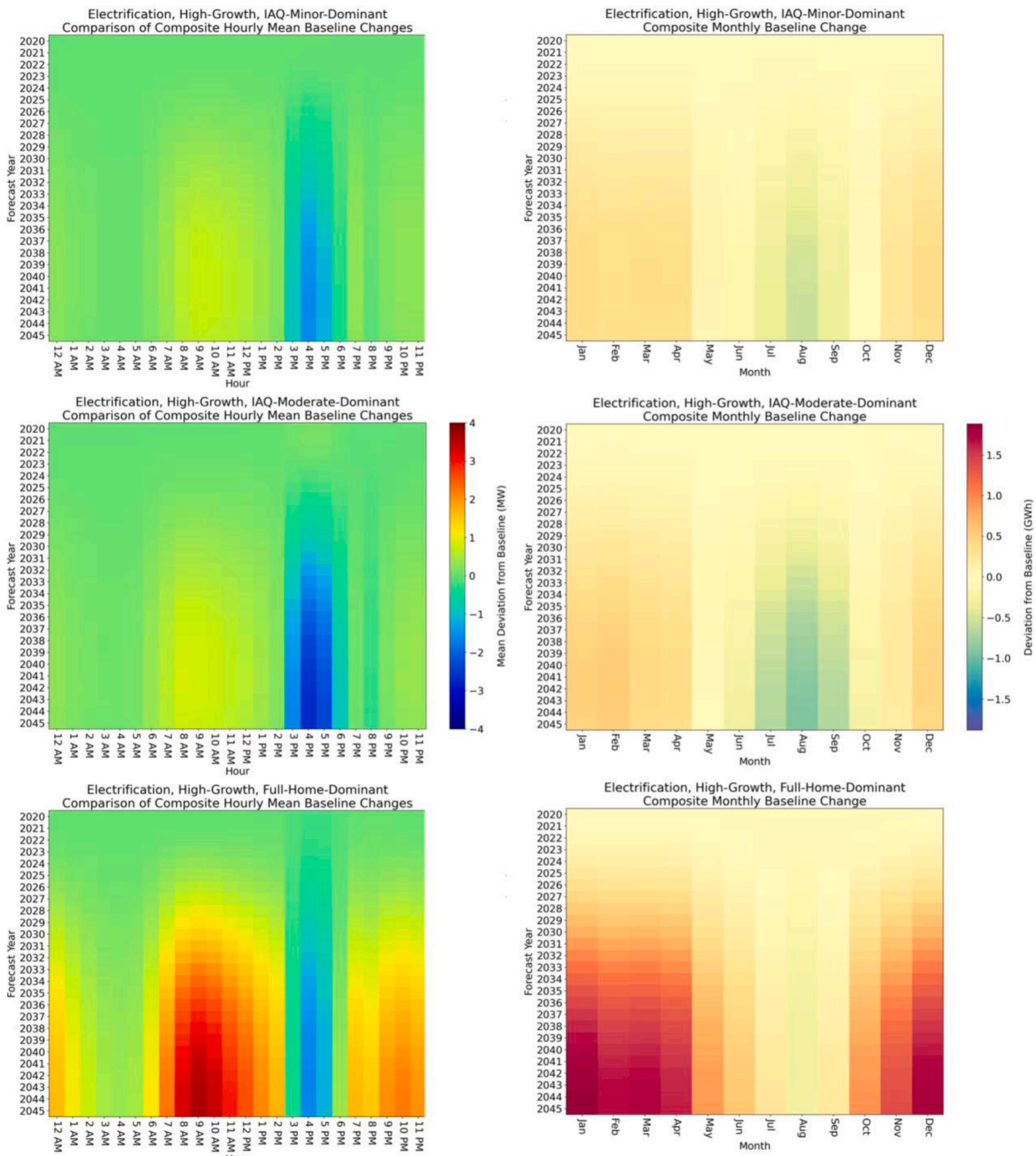

Fig. 4. Changes in composite SF loads relative to the baseline among the for each high growth rate electrification pathway average by hour of day (left column) and month of year (right column) for each year in the simulation time horizon (2020, 2045).

(middle right) the use of mini-split heat pumps delivers as much as −1 GWh in total load reductions during the summer months. By contrast, in the FHE Dominant pathway (lower right) significant load increases occur due to the use of electricity for winter heating energy demands. These load increases are largely non-coincident with the system's current summer peaks. However, they are an important consideration for efforts to decarbonize the energy system using solar PV generation assets, which have significantly reduced capacity factors during these months.

4.3. Hourly peak loads and monthly load factors

In terms of grid operations and planning, there is a great deal to be learned from the pathway simulation results. Fig. 5 depicts data for two key metrics, hourly peak loads, and monthly load factors, again relative to the SF context. Focusing first on the plot's location in the left-top and left-middle portions of the figure, we can see electrification does not always have to result in peak load growth. In fact, just the contrary: in the IAQ-Minor and IAQ-Moderate dominant pathways significant peak load reductions are achieved. These reductions can be attributed to the implementation of more intelligent controls and higher efficiency HVAC equipment. In the FHE dominant case, peak loads during the traditional 4–9 PM period also decrease slightly.

The emergence of new peak demand periods, during morning hours, primarily in the winter months emerges as a new issue of potential concern. These results suggest that the full electrification of a significant number of homes in communities throughout the state would have the potential to create a new dual-peaking pattern of system behavior. One in which the current, cooling dominated system peak in the summer is augmented by the emergence of a new heated dominated winter morning peak with similar grid generation ramping capacity requirements. These conclusions are further supported by the plots

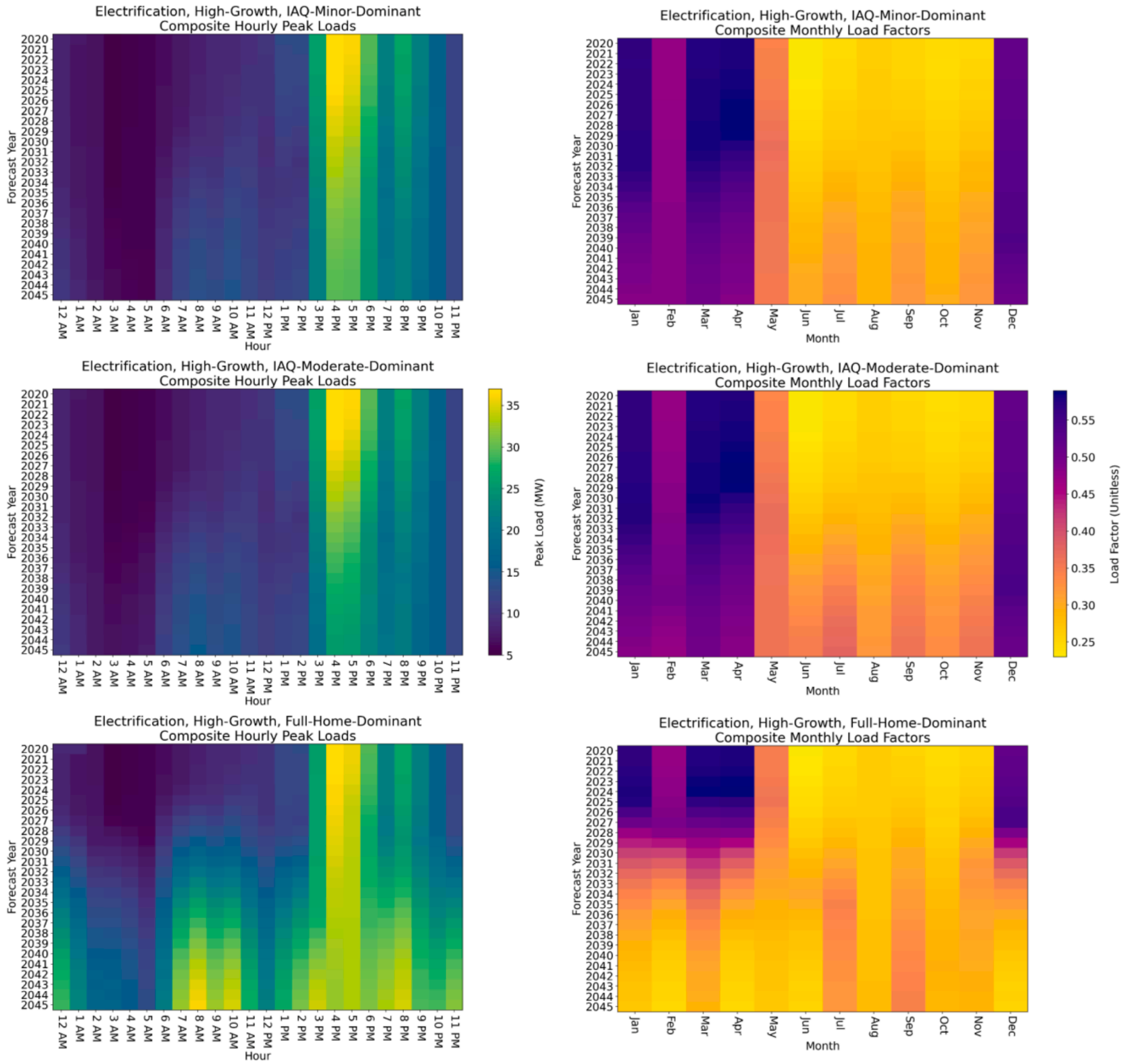

Fig. 5. Composite SF peak loads (left column) and load factors (right column) for each high growth rate electrification pathway for each year in the simulation time horizon (2020,2045).

depicted on the right column of the same Figure. These show changes in the monthly load factors (peak loads / average loads) for each pathway and for each year of the simulation time horizon. As the figure on the lower right shows, under the FHE Dominant pathway by 2045 the community's SF load factors are much more consistent throughout the months in the year. This, it could be argued from a business/capacity utilization standpoint, is a marked improvement from the present status quo - where much of the grid infrastructure's capacity goes unused for significant portions of time due to strong seasonal variations in the demand for electricity.

4.4. Changes in local and ambient air emissions

The plots contained in Fig. 6 depict the annual changes in total ambient emissions (upper plots) and local emissions (lower plots) of CO_2 [short-tons] and PM-2.5μ [lbs] calculated using the AVERT framework. In the ambient case, emissions increases are attributable to projected future changes in fossil EGU operations necessary to supply the increased demand for electric power under each of the three, community energy system transformation pathways under consideration. In the local case, emissions decreases are attributable to the electrification of various gas appliances within homes.

Relative to the ambient emissions results plots, the shapes of the curves shown are determined by simultaneous interactions between:

(1) Anticipated future rates of change in the number and emissions intensities of fossil EGUs supplying grid power assuming an EGU retirement schedule that is 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 computed relative to a baseline pathway which reflects future rates of electrification that are consistent with recent historical patterns observed within the study area community. Thus, all the values plotted begin at zero in the initial year, and deviate in subsequent years, as the composition of homes within each pathway changes relative to the baseline. Additionally, all the net emissions values depicted can also be observed to converge at zero upon the 2045 end of the forecast time-horizon. This is due to the assumption of future RPS compliance – meaning that by this time period all grid electricity is assumed to be supplied from zero-

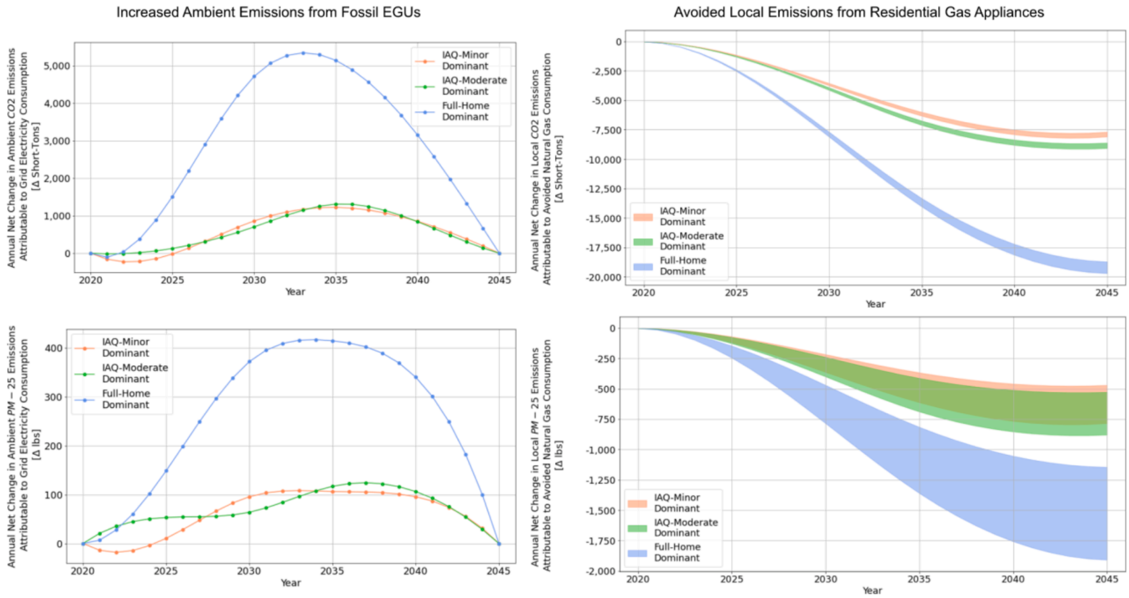

Fig. 6. Changes in ambient (top) and local (bottom) CO2 and PM − 2.5μ for each high growth rate electrification pathway (SF+MF, combined) for each year in the simulation time horizon (2020, 2045).

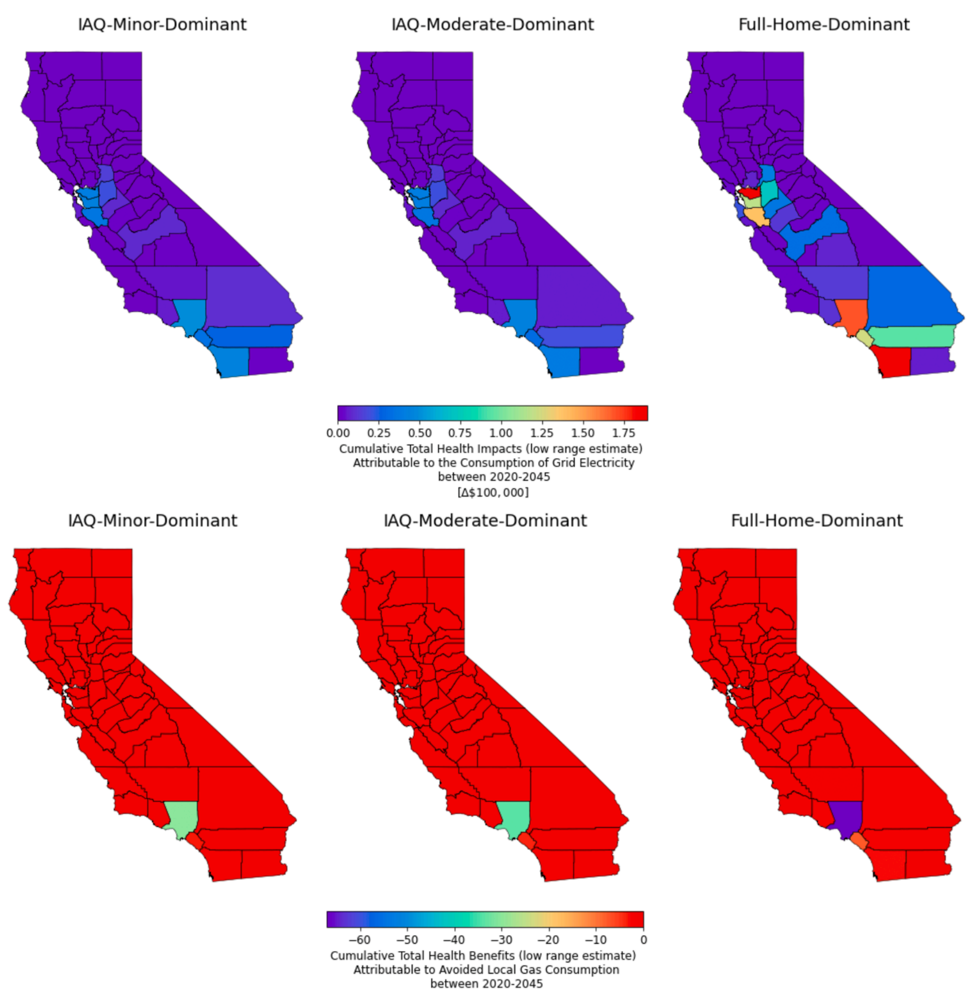

Fig. 7. Cumulative total change in monetized ambient health impacts (top row) and local health benefits (bottom row) from changes in PM − 2.5μ emissions associated with each high growth rate electrification pathway (SF+MF, combined) at the county level over the entire simulation time horizon (2020, 2045).

emissions sources.

As the plots in Fig. 6 illustrate, the Full-Home electrification dominant pathway (blue) is associated with the largest net increases in annual total emissions relative to the two other IAQ-dominant electrification pathways considered. This is due to both the hourly timing and the magnitude of the load increases associated with fully electrifying all space and water heating appliances within the community's homes. Also of note relative to the FH dominant pathway results are major apparent differences are the anticipated future years in which net-emissions increases are expected to peak between the different pollutant species. These anticipated differences are largely due to the assumed sequencing of EGU retirements, with individual EGUs exhibiting wide variations, most especially, in their PM-2.5μ emissions intensity factors.

4.5. Changes in local and ambient health impacts

The maps contained in Fig. 7 illustrate the projected geographic distribution of cumulative human health impacts/costs within California counties over the entire 2020–2045 forecast horizon from both the ambient EGU emissions increases (top series) and the local appliance emissions decreases (bottom series) attributed to the different natural gas appliance electrification pathways considered. Detailed tabular versions of these results, collated across different health impact categories evaluated by the COBRA modeling framework, are also provided for reference in the SM.

As these maps clearly illustrate, despite all the electrification measures having been assumed to have occurred within a single county – Los Angeles, the site of the two zip codes which define the project study are community – significant health impacts from increased emissions of PM-2.5μ by fossil EGUs are likely to be experienced in other areas across the state, up to and including those within the Bay Area. This geographic distribution of impacts is due to the location of fossil EGUs which were anticipated to supply net increases in the demand for electricity associated with each different electrification scenario. The maps in the lower portion of Fig. 7 notice the significant difference in the scale of the local benefits plotted. This means that, in absolute terms, the cumulative size of the ambient impacts from changing fossil EGU operations are expected to be completely overwhelmed by the local benefits which accumulate within Los Angeles County where the electrification measures are presumed to be implemented. Additional noticeable reductions in overall health costs can also be seen to occur in the adjacent county of Orange (immediately to the south).

The presence of significant net public health benefits from reduced PM-2.5μ emissions exposures due to residential gas appliance electrification is an important finding. However, it is one that needs to be interpreted with care. For example, these maps might suggest that the ambient PM-2.5μ emissions impacts which occur in other counties are not large enough to warrant significant concern. However, it is important to keep in mind that the locations of the fossil EGUs responsible for these ambient emissions are fixed, whereas residential electrification policies may come to be implemented across a wide range of localities throughout the state. Thus, there is the potential for a significant accumulation of ambient emissions increases in those areas where the largest and most polluting fossil EGUs are located, should electrification measures come to be adopted elsewhere. The potential creation and/or exacerbation of pollution "hot-spots'' is a matter which should be factored into future decisions about the rank prioritization with which individual EGUs are slated for retirement.

Another important finding is that these human health impact maps do not precisely mirror the spatial geographic distribution of the underlying source emissions. This is due to a combination of factors. The first is that the COBRA modeling framework performs some basic analysis of primary pollutant fate-transport processes – largely based on prevailing historical climate conditions – which sometimes cause the emissions produced by EGUs located in one county to be physically transferred into the air of other counties which are "down-wind." 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 which could potentially be exposed to them. Significant differences in populations between counties therefore play an important role in the spatial distribution of the final health impact results.

4.6. Compounding effects of simultaneous der and ev adoption

By additively combining the marginal contributions of all of the discrete pathways generated within each transition category we can gain a sense of the range of combined load growth outcomes which are possible in the future for the study area community. The plots contained within Fig. 8 plot the annual combined deviations from the baseline load forecasts resulting from all of the unique pairwise combinations of the discrete SF pathway alternatives considered in this analysis (gray traces). The three plots contained in the top row of this figure illustrate different subsets of these pathways which have been labeled according to the following criteria:

- Orange (top left) - composite pathways which achieve high penetrations (~95%) of fully electrified homes.
- Purple (top middle) - composite pathways which achieve high penetrations (~95%) of PV+BESS adoption.
- Cyan (top right) - composite pathways which achieve high penetrations (~95%) of EV adoption.

As these three plots illustrate, the magnitude of the load reductions which can be achieved through the deployment of optimized PV+BESS systems are roughly equivalent to the load increases which are associated with either Full House Electrification or EV adoption. This tells us that the total annual load growth impacts from increasing rates of full home electrification will largely be determined by the parallel rates of growth in EV and DER adoption.

The plot on the bottom left of Fig. 8 isolates just those composite pathways where the growth rates in each transition category are all equivalent to one another (red, blue, green). Here we can see that the overall load growth impacts from increasingly high levels of EV adoption and Full House electrification can largely be avoided by equivalent and parallel rates of growth in the adoption of PV+BESS. Finally, the plot on the bottom right of Fig. 8 illustrates two single composite pathways that result in the most extreme load changes. The largest total annual load increases (Olive) result from the pathway which combines the high levels of EV adoption, high levels of Full Household Electrification, and the lowest (i.e., baseline) levels of DER adoption. Alternatively, the largest total annual load reductions (Pink) result from the pathway which combines the lowest rate of IAQ-Moderate focused Household Electrification, the lowest rate of EV adoption, and the highest rate of PV only dominant DER systems. Thus, the most extreme (high and low) load growth outcomes are associated with composite pathways whose individual component growth rates substantially differ between the three transition categories.

5. Conclusions and policy implications

5.1. Changes in the timing and magnitude of electricity loads

The future electrification of residential gas appliances within California DVCs portends significant changes to currently dominant patterns of grid electricity demand. Today, seasonal peaks in DVC electricity loads occur primarily in the summer months for cooling. Additionally, diurnal peaks occur most prominently in the early evening hours for domestic activities like cooking, laundry, and entertainment. With gas being primarily used for heating water and air within residential households, our modeling showed that the future aggressive adoption of comprehensive, full-home electrification retrofit packages is likely to

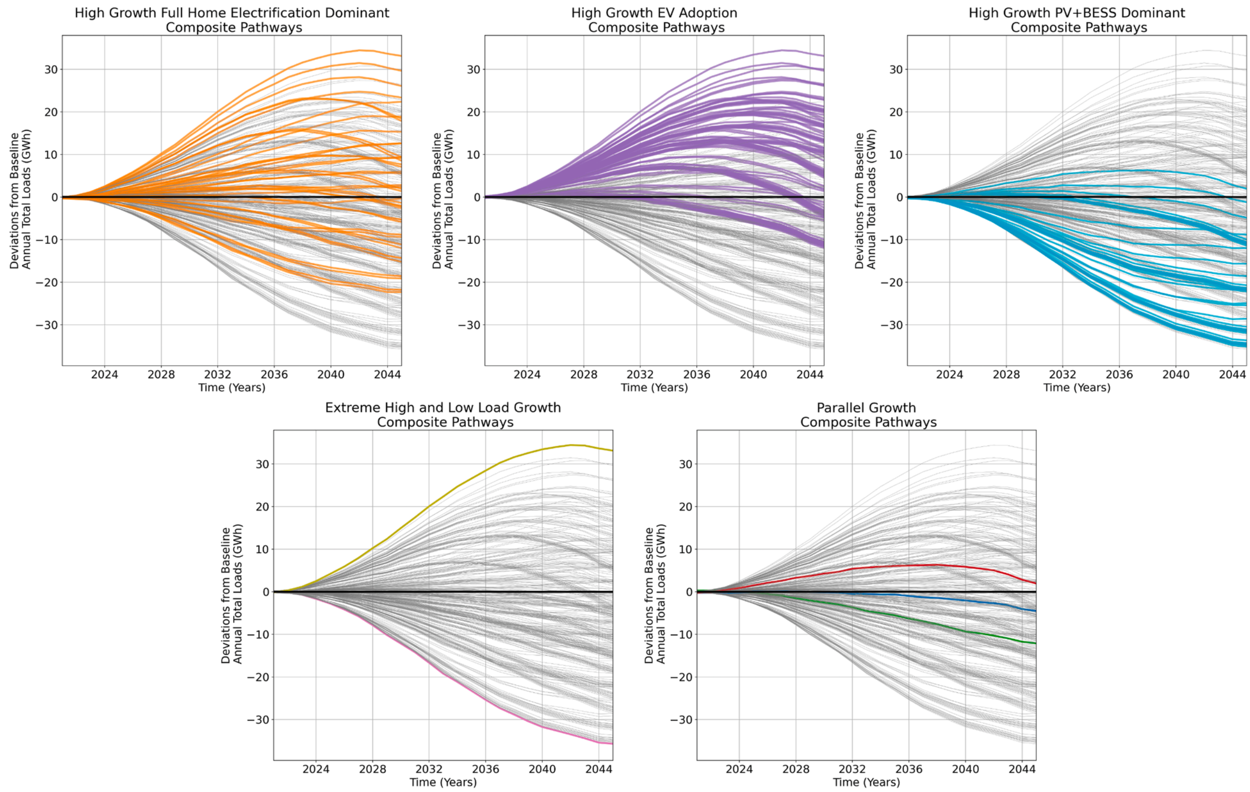

Fig. 8. Changes in composite SF loads relative to the baseline when coupling different pairwise combinations of energy system transformation category growth rate assumptions for each year in the simulation time horizon (2020, 2045).

lead to new seasonal peak loads appearing during the morning hours in cold winter months.

Heating and cooling electricity demands are non-coincident in time. Thus, the electrification of gas appliances is not expected to unduly increase the absolute magnitude of peak system loads despite significant increases in overall electricity consumption. The extent to which peak loads increase in the future will be central in determining the overall magnitude of the grid's GHG and criteria pollutant emissions as well as the amount of grid infrastructure investment necessary to achieve full decarbonization. Consequently, technologies and policies which seek to minimize peak load growth should continue to be prioritized going forward.

Related to this, the load growth impacts from the future adoption of electric vehicles and residential PV+BESS are considerably more uncertain. This is due to the many disparate ways in which the charging/discharging of these systems could potentially be managed/coordinated, or not. Although it was not a central feature of discussion in this analysis, the addition of a single EV can effectively double the annual electricity usage of a typical DVC household. Moreover, based upon historical residential EV charging behaviors, it is possible that unregulated charging could increase diurnal peak loads by as much as +50% when level 2+ fast chargers are in use. An increase of this scale would require significant grid infrastructure capacity upgrades in the absence of other corrective action/solutions.

PV+BESS' provide a readily available solution to the problems of both total and peak load growth that are likely to result from the electrification of gas appliances and light duty vehicles. The output of the solar panels reduces the need for additional generation capacity on the grid and the BESS function to shave peak demand and improve community load factors. In terms of relative scale, the current average sizes of common PV+BESS system offerings are almost sufficient to offset the negative impacts of available EV charging and domestic electric appliances loads. We are hopeful that continued improvement in the cost and performance of these offerings will improve this situation further and make it possible to implement zero-net-load growth DVC residential electrification packages in the future.

5.2. Local versus ambient air quality tradeoffs

The aggressive pursuit of natural gas appliance electrification during the present interim period, where many of the grid's polluting fossil EGUs remain online, has the potential to create new or exacerbate existing air-pollution hot-spots despite resulting in overall net-benefits. These hot spots are locations where remaining fossil EGUs are caused to operate more frequently and intensively to output the additional marginal electricity demand from newly electrified appliances. Anticipating when and where such hot-spots are likely to occur is a complex undertaking - one which requires simulating the dispatch behavior of the wholesale electricity market under, in many cases, as yet unprecedented electricity supply and demand conditions.

This is an important consideration for policy makers seeking to ensure that electrification programs do not unduly burden front-line communities that may not receive any local benefits from the avoided domestic gas use. Additionally, it is also an important consideration for environmental scientists and modelers seeking to build tools which allow us to better plan for a transition to a fully decarbonized energy system. If the modeling tools which we have available only provide reasonable results when provided with input parameters that reflect the historical status quo of supply and demand - these tools will be incapable of assessing the challenges that must be overcome under changing demand conditions and higher renewable penetration levels.

5.3. Structural barriers to electrification

There are numerous structural barriers currently inhibiting the electrification of residential gas appliances within low income and

DVCs. (Scavo et al., 2016) First and foremost among these however, is the lack of agency afforded to the types of renter households which constitute the majority population within most DVCs. Renters fundamentally lack the ability to make important decisions about the replacement of major household appliances as well as the timing of maintenance and upgrades to household energy infrastructure - i.e., wiring, service panels, etc. Meaningfully addressing this lack of agency will likely necessitate the implementation of policies focused on owners/landlords requiring the replacement of gas appliances with electrified alternatives either (1) by a certain specified date (2) upon an appliance's end of life (3) upon a change of occupancy (4) as a condition of property sale or (5) other.

Second only to this aforementioned issue of agency are concerns related to the life cycle cost of fuel switching. For DVC households' energy costs already represent a significant financial burden. Moreover, there is considerable uncertainty in terms of the relative future costs of electricity versus gas. In recent history, gas has been significantly cheaper than electricity, at roughly ~1/6th the price on average per unit energy. (Fournier, Cudd, Federico & Pincetl, 2020) However, this price differential needs to be considered within the context of the significantly higher end-use energy efficiencies of many electric appliance alternatives, particularly those based upon heat-pump technologies.

Longer term, there are other, deeper sources of uncertainty that must be considered relative to this cost issue. For example, no one can say for sure whether the state's push to decarbonize electricity generation under the RPS will encounter diminishing returns, leading to higher electricity costs as the fraction of renewably generated power goes up. Alternatively, it is also possible that the price of gas could begin to spiral upwards as more and more customers begin to fully electrify their end-uses and disconnect from the gas network. Given this legitimate uncertainty about the future cost implications of electrification, it is understandable that many households may be given pause when contemplating the switch. The decision to electrify a major appliance represents a multi-year commitment to a different energy source, to the volatility in its supply markets, and to the intricacies of its pricing structures.

Fig. 9 highlights the nested relationship between these and other significant barriers to electrification within DVC. Additional, ancillary concerns shown in this figure relate to different performance characteristics of electric appliances, the different tastes of consumers in terms of the physical design and features of available devices, and the logistical challenges associated with coordinating the removal and replacement of their existing gas equipment. The combination of these additional barriers prevents homeowners from developing a sound intuitive understanding of the overall balance of costs and benefits associated with the switch. This feature, combined with the relative paucity of other households - possibly those of friends or family - who have already electrified their gas appliances and might be available to consult about their experiences, further contributes to the uncertainties involved with the decision.

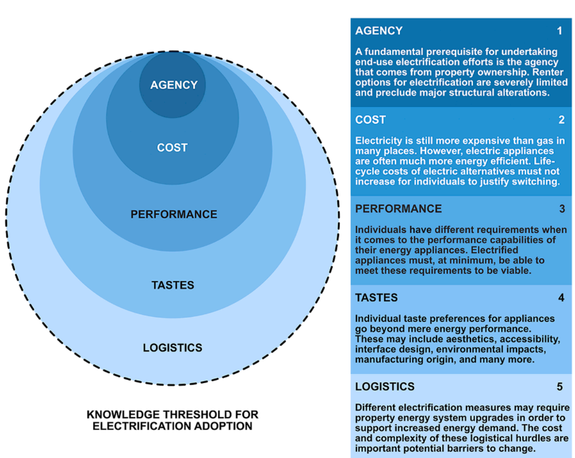

Fig. 9. Conceptual illustration of the nested barriers to residential appliance electrification within Disadvantaged and Vulnerable Communities. Core issues include the lack of agency among renter households and the uncertain life cycle costs of many electric appliance alternatives. Additional, ancillary concerns include the variable tastes of consumers in terms of appliance performance levels, and the complex logistics of home energy system upgrades - particularly within older homes.

5.4. *The equity and inclusivity imperative*

Despite the fact that DVCs are nominally meant to be "prioritized" in future energy system investment plans under development by the California Public Utilities Commission and other state energy agencies - there remains a staunch unwillingness to directly allocate funds to these communities for the direct purchase and installation of new DER technologies. Instead, the current extent of this "prioritization" is mostly constrained to program administration and outreach efforts. The fundamental problem with this is that these underlying programs overwhelmingly rely on market economic incentives to determine actual outcomes - i.e., what gets built where. Thus, despite the best intentions to increase program participation within DVCs, their below average per-capita energy usage and above average transaction costs make it such that real world projects seldom "pencil out" as easily as they do within more affluent communities.

If we are truly serious about creating a more equitable energy system, one which improves the quality and reliability of energy services accessible within DVCs while simultaneously reducing the financial burdens and pollutant exposures that must be endured - we need to look beyond market-based solutions alone. Rather, it may in fact be necessary to additionally undertake more direct, redistributional investments within these communities. If we rightly acknowledge that the residents of DVCs have been disproportionately burdened by the historical development and operations of the energy system, then we must similarly accept that this harm can only be undone by disproportionate future investments. These investments must be used both to accelerate the adoption of new DER technologies and the electrification of existing gas end-use appliances with DVC homes as well as to accelerate the decommissioning of the fossil EGUs which negatively impact the health of their residents and the condition of their local environment.

Author contributions

Conceptualization, E.D.F., F.F., M.J., and S.P.; methodology, E.D.F., F.F., D.G., M.C., A.R.; software, E.D.F.; writing—original draft preparation, E.D.F.; writing—review and editing, E.D.F., F.F., R.C., S.P., D.G., M.J., M.C., and A.R..; visualization, E.D.F.; supervision, F.F. and S.P.; project administration, F.F.; funding acquisition, E.D.F., F.F., S.P., M.J., M.C., and R.F. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The BEopt/REopt energy model outputs as well as the python code which were developed to perform the community scale energy system pathway transition simulations are both hosted at the following public repository: https://github.com/ericdfournier/pathways

CRediT authorship contribution statement

Eric Daniel Fournier: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Felicia Federico:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Robert Cudd:** Writing – review & editing. **Stephanie Pincetl:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Alex Ricklefs:** Methodology, Writing – review & editing. **Marc Costa:** Methodology, Writing – review & editing, Funding acquisition. **Michael Jerrett:** Conceptualization, Writing – review & editing, Funding acquisition. **Diane Garcia-Gonzales:** Methodology, Writing – review & editing.

Declaration of Competing Interest

Work that was completed under this project by Co-Author Alex Ricklefs took place while he was a staff employee at the Energy Coalition. Mr. Ricklefs has since transitioned to a position at the Clean Power Alliance (CPA). As such, this work does not in any way reflect the opinions or research of the CPA.

Data Availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2022.104128.

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