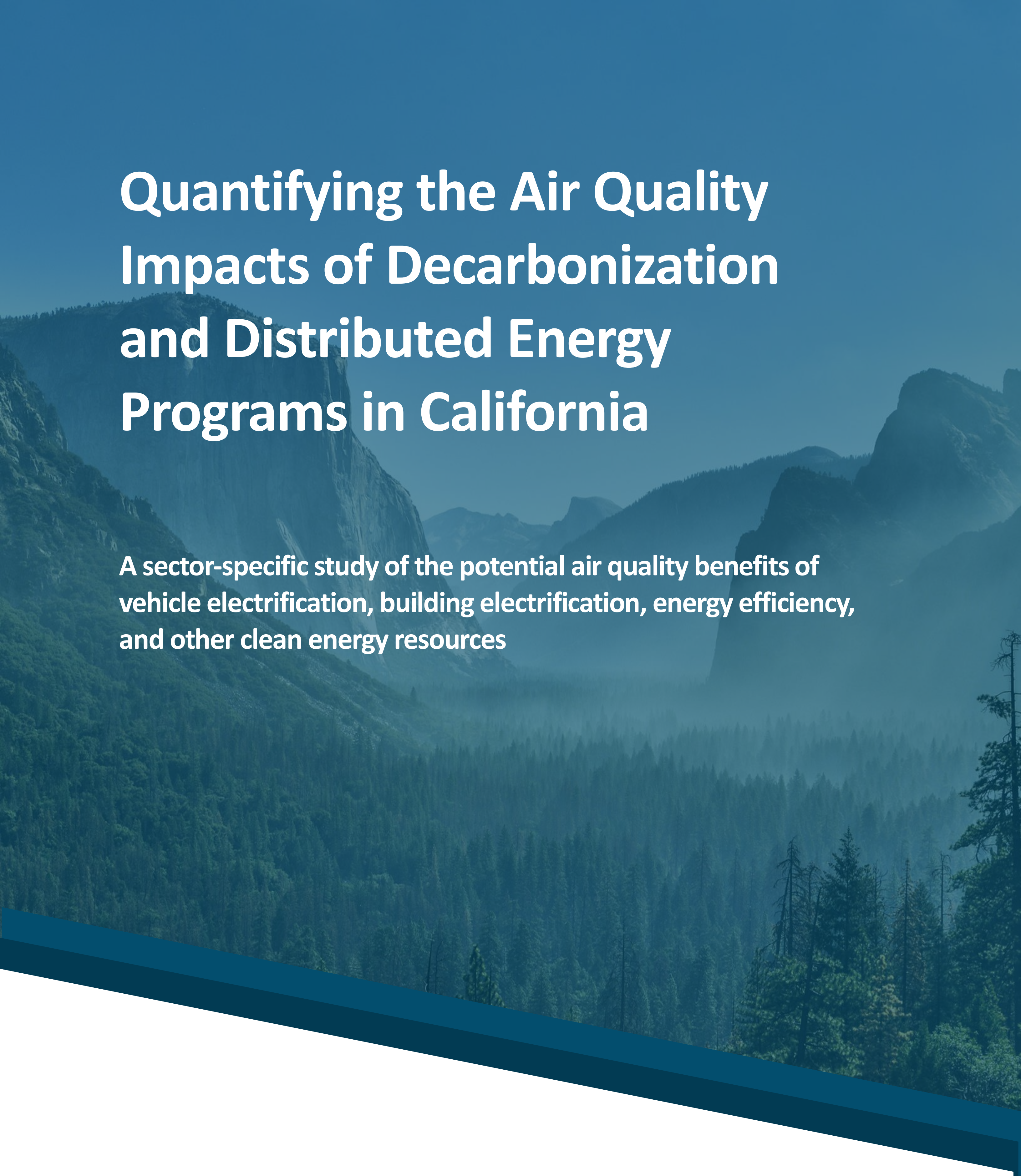

Quantifying the Air Quality Impacts of Decarbonization and Distributed Energy Programs in California

A sector-specific study of the potential air quality benefits of vehicle electrification, building electrification, energy efficiency, and other clean energy resources

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Acronym Definitions

Acronym	Definition
CPUC	California Public Utilities Commission
CEC	California Energy Commission
CARB	California Air Resources Board
CAISO	California Independent System Operator
IEPR	Integrated Energy Policy Report
SCAQMD	South Coast Air Quality Management District
USEPA	United States Environmental Protection Agency
AQMP	Air Quality Management Plan
NAAQS	National Ambient Air Quality Standards
SoCAB	South Coast Air Basin
SJV	San Joaquin Valley
IRP	Integrated Resource Plan
EMFAC	Emission Factors Model
SERVM	Strategic Energy & Risk Valuation Model
CEMS	Continuous Emission Monitoring Systems
COBRA	Co-Benefits Risk Assessment Health Impacts Screening and Mapping Tool
CEPAM	California Emissions Projection Analysis Model
BenMAP	Environmental Benefits Mapping and Analysis Program
SMOKE	Sparse Matrix Operator Kernel Emissions
CMAQ	Community Multiscale Air Quality Modeling System
LDV	Light-Duty Vehicle
MDV	Medium-Duty Vehicle
HDV	Heavy-Duty Vehicle
CHP	Combined Heat and Power
SCT	Societal Cost Test
NG	Natural Gas

VSL	Value of a Statistical Life
DAC	Disadvantaged Community
MWh	Megawatt-hour
GGE	Gasoline Gallon Equivalent
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter (inhalable particles) that is 2.5 microns in diameter or smaller
NO_x	Nitrogen oxides
CO	Carbon monoxide
ROG	Reactive Organic Gases
SO_x	Sulfur oxides
CO_2	Carbon dioxide
MD8H	Maximum daily 8-hour average
NH_3	Ammonia
O_3	Ozone

Executive Summary

Climate change mitigation and air pollution mitigation are inextricably linked. Climate policies such as renewable energy targets, energy efficiency, and building electrification are frequently assumed to benefit air quality, but the impact of these policies on human health in California is not fully understood. It is relatively straightforward to quantify the avoided criteria pollutant emissions resulting from a policy – for example, the pounds of nitrogen oxide emissions avoided from taking 1,000 gasoline vehicles off the road – but understanding the impact of actions like these on human health and in specific communities requires highly computationally intensive atmospheric transport modeling, which to date has not been comprehensively performed in a way that allows policymakers to determine the air quality impact of specific policies. Understanding the relative air quality co-benefits of climate change mitigation policies will give decision makers the information they need to target limited clean energy investment funds to programs that will maximize air quality co-benefits, particularly in disadvantaged communities that have been disproportionately burdened by air pollution.

This report seeks to address this research gap by providing comprehensive modeling of sector-by-sector air quality impacts, which will allow the quantification of air quality co-benefits for specific programs such as electrification and energy efficiency. To this end, we model the air quality impacts of four key fossil-fuel-consuming sectors in California, using state-of-the-art atmospheric transport modeling: 1) natural gas generators, 2) natural gas combustion in buildings, 3) on-road vehicles, and 4) off-road vehicles[1]. Each sector is modeled as the "removal" of emissions from that sector relative to a Reference case in 2035, which will allow the subsequent quantification of air quality impacts of programs that reduce fossil fuel combustion in one of these sectors. Thus, each scenario, which models the impact of "removing" the emissions from one sector such as on-road transportation, can be interpreted as modeling the impact of eliminating combustion in that entire sector, e.g., through complete electrification. It is important to note that this study does not include the *indoor* air quality impacts of removing fossil fuel combustion in buildings, nor does it include the impact of reduced emissions at refineries and oil & gas extraction sites that might result from reduced fossil fuel combustion. Since both of these are significant contributors to degraded air quality, the potential air quality impacts in these categories are important areas for future study.

The results of this study are summarized in Figure 1 and Figure 2 below. Figure 1 shows that elimination of natural gas generation would result in very small changes in annual average particulate matter (PM) concentrations. Elimination of fuel combustion in buildings, on-road transportation, and off-road transportation, by contrast, could lead to significant improvements in annual average PM concentrations, particularly in the Central Valley and the South Coast Air Basin (SoCAB, consisting of the greater Los Angeles area), where air quality is the most degraded.

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[1] Note that the off-road vehicles category includes a diverse set of end uses including agriculture, construction, mining, and port and warehouse operations. This sector is defined further in the Methodology section of this report.

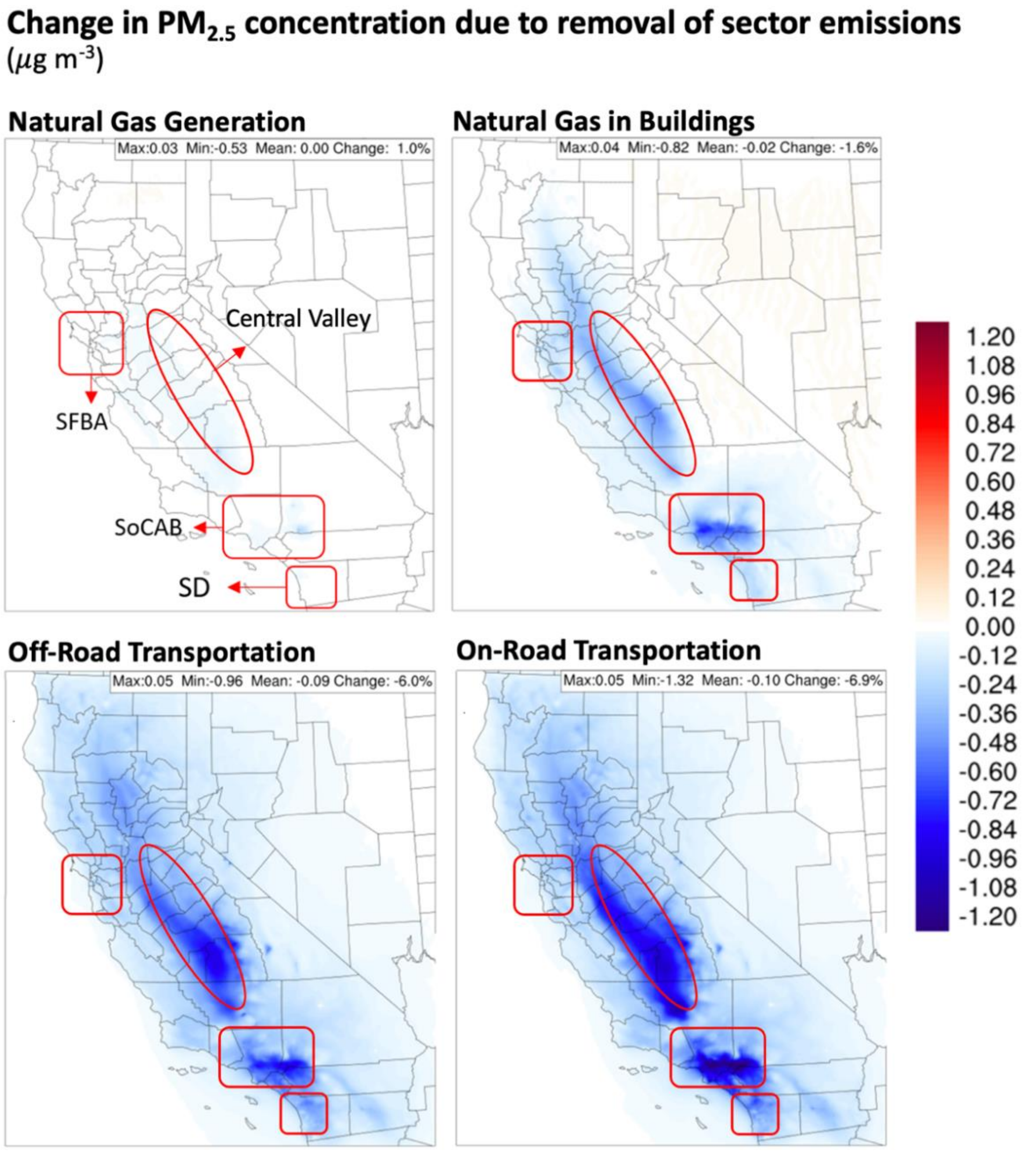

Figure 1. Change in PM2.5 concentration in 2035 due to removal of sector emissions in each scenario. Red shapes indicate air basins of interest (with highest population concentrations and currently degraded air quality).

These changes in ambient air quality are also converted into monetized impacts to human health, shown in Figure 2. The electrification of all on-road transportation would achieve human health benefits of about $20 billion per year, reflecting the avoidance of 2,265 premature deaths per year, which is equivalent to about $1.50 for every fossil fuel gallon equivalent burned (averaged across all vehicle types). The elimination of emissions from all off-road transportation and all natural gas combustion in buildings would also achieve significant health benefits, at $16 billion and $7 billion respectively. These benefits reflect the avoidance of 1,760 premature deaths per year for off-road transportation, and 818 premature deaths per year for natural gas combustion in buildings. For buildings, these benefits are equivalent to about $1.20 per therm of natural gas consumed, which is approximately equal to the statewide average natural gas rate. (Note that these benefits of reducing gas combustion in buildings apply not only to electrification, but also to anything that reduces gas combustion, such as natural gas energy efficiency.) Elimination of all emissions from natural gas generators would achieve much smaller, but non-negligible benefits, valued at $1 billion, reflecting the avoidance of 107 premature deaths per year. These benefits are equivalent to $14 per megawatt-hour of generation, when averaged across the state, although the benefits are concentrated in SoCAB due to the dense population living near generators in this area. It is important to note that the vast majority (>90%) of these benefits, across all sectors, are from avoided premature mortality (death) due to reduced $PM_{2.5}$ exposure, which is valued using the EPA's value of a statistical life of $9 million, which represents society's willingness to pay to avoid one lost life. Additionally, an important finding of this study is that the majority (~75%) of the potential air quality benefits from programs that reduce fossil fuel combustion would be experienced in SoCAB, due to the presence of a dense population living near many pollution sources in an area prone to temperature inversions, which highlights the importance of targeting fossil-fuel-reducing programs in this basin.

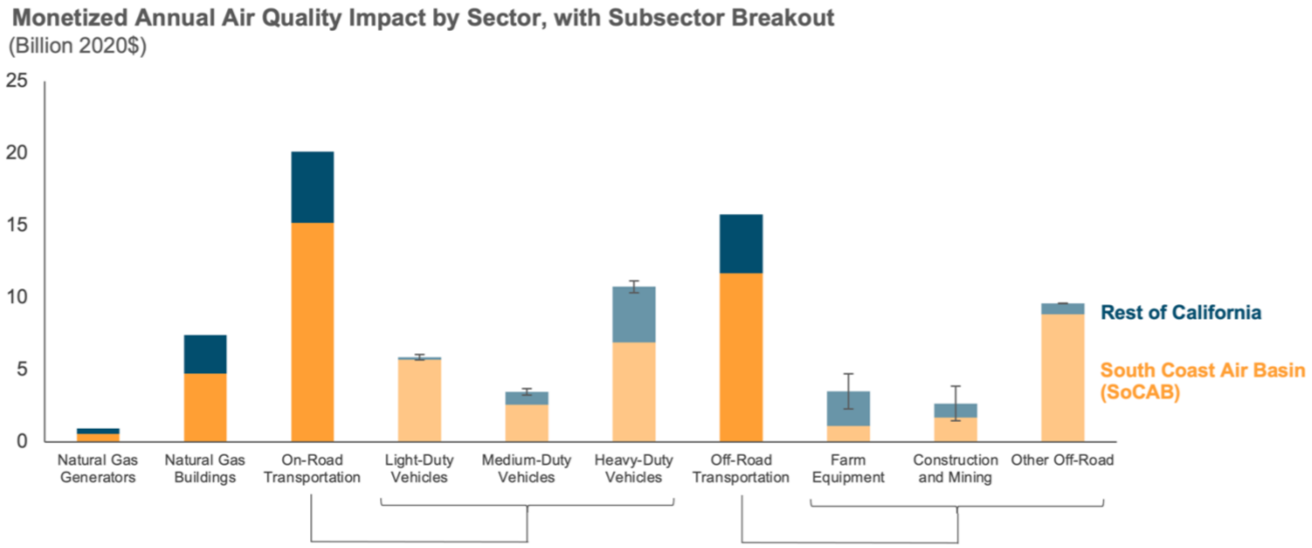

Figure 2. Monetized annual air quality impact by sector in 2035, with breakout of subsectors for on-road and off-road transportation. Error bars show uncertainty in subsector disaggregation based on difference between summer and winter episodes.

Our results also highlight that electrification of the sectors modeled has the potential to achieve significant benefits for disadvantaged communities. For example, 38% of the benefits of electrifying on-road transportation would occur in disadvantaged communities, which represent only 25% of the population.

This study has several key conclusions:

- The electrification of on-road transportation, off-road transportation, and natural gas combustion in buildings would achieve monetized human health benefits of about $44 billion per year in total, reflecting the avoidance of 4,843 premature deaths per year as well as other health benefits such as reduced hospital visits. These impacts can also be expressed as per-unit-energy impacts, highlighting the particularly high air quality impact of heavy-duty vehicles (all values in 2020$):

SECTOR	UNIT	$/UNIT	$/MMBTU
GAS GENERATION*	$/MWh	$ 14.00	$ 1.75
GAS COMBUSTION IN BUILDINGS	$/therm	$ 1.23	$ 12.30
ALL ON-ROAD VEHICLES	$/gge	$ 1.47	$ 10.97
LIGHT-DUTY VEHICLES	$/gge	$ 0.56-0.60	$ 4.18-4.48
MEDIUM-DUTY VEHICLES	$/gge	$ 2.77-3.14	$ 20.67-23.43
HEAVY-DUTY VEHICLES	$/gge	$ 4.20-4.52	$ 31.34-33.73

* for gas generation, the $/MMBtu is based on the quantity of natural gas consumed

- In comparison, the removal of emissions from all gas generators in the state would achieve air quality benefits of about $1 billion, reflecting the avoidance of 107 premature deaths per year. This value is lower than the values for other sectors due to the significant emissions controls already required for gas generators, the cleaner profile of natural gas combustion relative to other fuels including petroleum fuels, and efforts to locate large gas generators outside of population centers.
- Due to these relative benefits, programs that reduce direct use of fossil fuels, such as electrification programs and natural gas energy efficiency, are likely to have an air quality benefit that is orders of magnitude greater than that of programs such as electric energy efficiency and rooftop solar that impact air quality solely by reducing emissions from gas generators. (Note that this result would *not* hold for other states with less stringent emissions controls for point sources, and/or with a bigger dependence on coal generation.)
- Most of the potential air quality benefits achievable are in the South Coast Air Basin (LA Basin), highlighting the importance of targeting fossil fuel reduction programs in this region.
- Transportation electrification has the potential to achieve significant benefits for disadvantaged communities, since these communities are much more likely to be located near roadways. For example, we find that 39% of the air quality benefits from on-road transportation electrification can be expected to occur in disadvantaged communities, which represent only 25% of the population.

1 Introduction

To date, the topics of mitigating climate change and addressing air pollution have largely been addressed through separate regulatory structures in California, with the California Public Utilities Commission (CPUC) overseeing electric sector decarbonization and the California Air Resources Board (CARB) and local air districts overseeing air pollutant regulations. However, it has become increasingly clear in recent years that these two goals are inextricably linked. **Policies and regulations designed to mitigate climate change, such as electrification and energy efficiency, will inevitably bring air quality benefits.** Similarly, some regulations designed to mitigate air pollution, such as tailpipe emissions and efficiency standards, are likely to contribute to climate change mitigation to the extent that they involve reducing combustion of fossil fuels.

While this link between mitigating climate change and addressing air pollution is often recognized by decision makers and by the general public, there exists an urgent need for a quantification of this link to support decision making. It is frequently recognized that programs such as vehicle electrification will benefit air quality, but to date an accurate quantification of the air quality co-benefits of these programs has not been possible due to a lack of refined data on sector-specific air quality impacts. **This report seeks to address this gap by providing comprehensive modeling of sector-by-sector air quality impacts, which will allow the quantification of air quality co-benefits for specific programs such as electrification and efficiency.** These air quality co-benefits are societal benefits, meaning they will accrue not only to ratepayers, but to all Californians living across the state. These benefits are outside the scope of traditional cost-effectiveness testing, but could be incorporated into a future Societal Cost Test (SCT) framework. Adoption of an SCT alongside other cost-effectiveness tests could help decision makers understand which programs have the potential to bring significant societal benefits, both in disadvantaged communities and in the general population.

This study is not designed to prescribe an optimal air pollution control strategy, as this is the jurisdiction of the State's air districts and Air Resources Board. Rather, it is designed to evaluate the air quality co-benefits of programs that are changing the amount of fossil fuel combustion for reasons other than air pollution mitigation, so that regulators and policymakers can gain a fuller understanding of the societal costs and benefits of these programs.

This study evaluates **four scenarios** that evaluate the air quality impact of one sector at a time: **1) natural gas power generation, 2) natural gas combustion in buildings, 3) on-road transportation, and 4) off-road transportation.** Each of these scenarios evaluates the air quality impact of fossil fuel combustion by the entire sector in question, and the results are subsequently reported on a "per-unit" basis, allowing us to obtain results such as the air quality impact of adding one MWh of gas generation or the air quality impact of removing one therm of residential gas consumption. These results can be subsequently processed to obtain an estimate of the air quality impact of programs such as building electrification, which both decrease natural gas consumption and increase electricity consumption. Note that the impact of natural gas combustion in buildings modeled here includes only impacts to *outdoor* air quality, and does not include any *indoor* air quality impacts from gas stoves or other natural gas devices.

1.1 Background: greenhouse gases (GHGs), criteria air pollutants, and air quality modeling

The combustion of fossil fuels impacts both climate change and air pollution, but these impacts result from different pollutants and occur at much different spatial and temporal scales. The primary pollutants emitted by fossil fuel combustion include oxides of nitrogen (NO_x), particulate matter (PM), carbon monoxide (CO), reactive organic gases (ROG), oxides of sulfur (SO_x), and climate pollutants including carbon dioxide (CO_2) and methane, with the exact amount of each varying by fuel. Some of these pollutants are only greenhouse gases and do not impact local air pollution, some of them are only air pollutants and not greenhouse gases, and some of them are both greenhouse gases and local air pollutants. In terms of direct emissions from combustion, CO_2 is the predominant contributor to climate change. However, methane is also a potent GHG that is primarily emitted from activities not at the point of combustion including leakage during oil & gas extraction and along natural gas transmission and distribution lines. In California, emissions of NO_x and PM are particularly important as they are major contributors to degraded air quality with well-known harmful health effects, while SO_x is less important as there are no coal plants in the state. In addition to climate change and air pollution being caused by predominantly different pollutants, these impacts occur at very different spatial scales: climate change is a global issue, meaning GHG emissions in California contribute to climate change at the global level, while air pollutant emissions in California primarily result in poor air quality in California.

The result of these dynamics is that most climate change mitigation strategies that lead to a reduction in fossil fuel combustion are likely to bring air quality benefits, because reducing fossil fuel combustion reduces the emissions of all pollutants, not just CO_2. However, air pollution mitigation strategies do not always bring climate benefits, because these strategies are often focused on simply reducing the emissions of pollutants such as NO_x and SO_x from fossil fuel combustion, rather than reducing combustion overall. The exception to this trend is electrification, which has received increasing attention as an air pollution mitigation strategy in recent years due to increases in cost effectiveness resulting from decreased battery costs, and due to its potential to remove combustion emissions completely.

It is also important to understand the difference between direct pollutant emissions and ambient air quality. Direct emissions of pollutants such as NO_x and PM cause degraded air quality, but the actual impact of these pollutants is determined by how they react and are transported in the atmosphere, not just by how much they are directly emitted. These pollutants react with each other and with sunlight in the atmosphere, to form other pollutants such as ozone and secondary PM (secondary PM is formed in the atmosphere via chemical reactions, rather than being directly emitted). In California, in many regions about 40-60% of ambient PM at ground level is secondary at various times of the year. The end result of these reactions and transport is ambient air quality, meaning what pollutants are in the atmosphere at ground level, and are breathed by humans. **Understanding the relationship between direct pollutant emissions and ambient air quality requires comprehensive modeling of air pollutant transport and chemistry**, which is undertaken in this study. The most important indicators of ambient air quality from a human health perspective are the concentration of particulate matter less than 2.5 microns in diameter

($PM_{2.5}$), and the concentration of ozone, which are the indicators that are focused on in the results section of this report.

Importantly, this complex relationship between direct emissions and ambient air quality means that the impact of air pollution mitigation strategies is not always obvious. For example, many power plants are located in or near disadvantaged communities, which have historically experienced much higher pollution burdens than the general population (Fowlie, Walker, and Wooley 2020). However, a power plant might not necessarily be the primary source of air pollution impacting a given community if it is located on the downwind side of the community. Conversely, there could be power plants and many other sources of pollution located outside of a given disadvantaged community that lead to significant disproportionate impacts if the pollutants are transported into the community. In some cases, the link between source and impact might be obvious, for example, if a community is located directly downwind of a large coal plant, but in a large, heavily populated basin with many emissions sources, such as the South Coast Air Basin (SoCAB), detailed modeling is necessary to understand which pollution sources are impacting which communities.

In this vein, this report uses a comprehensive methodology for assessing air quality impacts including a 3-D chemical transport air quality model to model all sources of pollution throughout the entire state of California with a 4 km x 4 km resolution, and subsequently quantifies the impact of reducing emissions from certain sources such as power plants or vehicles. This allows the determination of air quality impacts from specific sources on a highly granular scale, meaning we are able to understand which communities would be impacted by which mitigation strategies. It is important to note, however, that because this methodology is highly computationally intensive and not practical to run multiple times for different programs in question, it is mainly helpful for determining the impact of a mitigation strategy such as building electrification on average (i.e., what would happen if we electrified all buildings in the state), and not for determining the impact of one program on a single community. To give an example, this work is helpful for understanding which communities in particular would benefit most from building electrification occurring evenly across the SoCAB, and it can tell us what proportion of benefits from building electrification in the SoCAB can be expected to occur in disadvantaged communities. However, it does not give us any information about the impact of electrifying just one neighborhood.

1.2 Air quality in the California context: air districts and basins

Since the results of this study include some discussion of impacts in particular air districts and basins, a brief overview of these entities is warranted. California is divided up into 35 air districts, each of which is its own regulatory entity for local air pollution concerns. These air districts are in turn overseen by the California Air Resources Board, which is responsible for statewide air pollutant regulations. The air districts are designed to roughly overlap with physical entities known as air *basins*, which are regions of the state that are somewhat self-contained with regards to sources of air pollutants and their impacts. For example, the LA Basin is the most important air basin in the State in terms of air quality impacts, as it contains the most degraded air quality in the nation and is home to about half of the State's population. The LA Basin is often more formally referred to as the South Coast Air Basin, or SoCAB. Air quality regulations in the SoCAB are overseen by the South Coast Air Quality Management District (SCAQMD).

The SoCAB is also the only air basin in the State that can be reasonably approximated as a self-contained entity with regards to air quality impacts, due to its unique geography of being bordered by mountain ranges—that is, it is reasonable to assume that the majority of air quality issues in the SoCAB are caused by pollutants being emitted in the basin. Other basins, for example those in the Central Valley, are significantly less self-contained; for example, air pollutants emitted in the Bay Area frequently impact air quality in the Central Valley. The SoCAB has long suffered from degraded air quality and, though tremendous improvements have been made in recent decades, many areas within SoCAB continue to experience pollution levels that are harmful to human health (South Coast Air Quality Management District 2017). In addition, the SoCAB is densely populated and contains approximately 50% of California's population, many of whom (34.8% of the SoCAB population) live in disadvantaged communities. These factors amplify the importance of air quality benefits that are achieved in the region. Thus, in this study we report air basin-specific impacts only for the SoCAB, given its overall importance in terms of regional air quality impacts and that it is the only air basin where it is reasonable to assume that impacts in the basin are being caused by sources in the basin. Figure 3 shows a map of California's air basins, for reference.

Figure 3. California Air Basins.

2 Methodology

2.1 Summary

This study focuses on evaluating the air quality impact of four sectors: 1) natural gas power generation, 2) natural gas combustion in buildings, 3) on-road transportation, and 4) off-road transportation, with one air quality modeling scenario for each sector. It is important to understand that for each of these scenarios, **the actual scenario being modeled is the removal of the entire quantity of emissions from the sector in question, relative to a Reference scenario.** We first model the air pollution in a Reference or "business-as-usual" scenario, and subsequently, model four scenarios with the emissions of the sector in question removed. We then examine the difference in air pollution between the Reference scenario and each of the other four scenarios, and the subsequent benefits to human health such as avoided premature deaths and avoided hospital visits. Thus, this modeling is answering the question: "what would be the impact of removing all pollutant emissions from just this one sector, while keeping everything else the same?"[2] It is important to note that these scenarios consider the impact of the sectors modeled on outdoor air quality only, and do not include impacts to indoor air quality such as those from gas stoves.

These results – the impact of the removal of emissions for the entire sector – can then be used to subsequently evaluate the air quality impact of various strategies and programs. This methodology highlights a limitation of this study, which is that the study only attempts to quantify the *marginal* impact of each sector (i.e. what would happen if you removed just that sector), and not the combined impact of decarbonizing multiple sectors at the same time. These interactions are important as air quality impacts are nonlinear.

The air quality modeling in this study involves two main steps: 1) modeling air quality changes resulting from a scenario, and 2) modeling the public health benefits resulting from those air quality changes. In step 1), we examine the changes to air pollutant concentrations in the atmosphere resulting from the removal of emissions from one sector. This step uses a model called SMOKE to calculate where emissions are occurring, and a model called CMAQ to determine how the changes in emissions result in changes to ambient air quality. In step 2), these changes in air pollutant concentrations are then fed to a separate model called BenMAP, which examines the subsequent benefits to human health, such as avoided premature deaths and hospital visits, that can be expected to occur as a result of the changes in air

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[2] It is necessary to model air quality relative to a Reference and not relative to a baseline of zero emissions because air quality impacts are highly nonlinear. The air quality impact of starting with zero fossil fuel combustion and adding just natural gas combustion in buildings, for example, is different from the impact of starting from our current baseline of degraded air quality and removing natural gas combustion in buildings. The latter is much closer to the situation we are in when we are electrifying buildings, which is why we model the *removal* of emissions from each sector, and the subsequent air quality *benefits*. In short, when we say we are evaluating the "air quality impact of natural gas combustion in buildings," we are actually quantifying what would happen if we stopped all natural gas combustion in buildings (i.e. "removed" the emissions from the sector), and the subsequent air quality benefits of this removal of emissions.

pollutants modeled. These impacts are monetized, which involves the use of values such as the Value of a Statistical Life. These models are also described in further detail below.

2.2 Scenario development

As stated above, the purpose of this work is to measure the air quality co-benefits of programs such as electrification and energy efficiency, and more generally from any program that changes the amount of natural gas generation, natural gas combustion in buildings, or fossil fuel combustion in vehicles. Four scenarios that quantify the impact of removing all fossil fuel combustion from one sector at a time are modeled: 1) natural gas generation, 2) natural gas combustion in buildings, 3) on-road transportation, and 4) off-road transportation. The results from each scenario are then processed into "per-unit" results, such as the $/MWh air quality benefit of reducing natural gas generation or the $/vehicle air quality benefit of taking a gasoline vehicle off the road. This subsequently allows the quantification of air quality impacts from programs such as electrification. These four core scenarios model a full year of air quality conditions, which we refer to as "annual air quality" modeling or "annual runs."

In addition to these four "annual runs," which are necessary to obtain a comprehensive picture of air quality impacts but are highly computationally intensive and not practical to run many times, we also model several subsectors within these four core categories using a methodology known as "episodic air quality modeling." To perform episodic air quality modeling, we model two different two-week periods of the year ("episodes") where air quality conditions are worst, one period in the summer and one in the winter. These "episodic runs" are useful for comparing multiple air quality scenarios, but do not provide a comprehensive picture of air quality impacts because they do not model a full year of air quality conditions and thus cannot be paired with long-term health impact functions. Thus, we use the episodic runs only to compare relative impacts between the subsectors within each broader sector rather than to tell us the total impact of a subsector. We also use the episodic runs to "decompose" the results of each of the four core scenarios into impacts by subsector. For example, our annual air quality scenario for on-road vehicles tells us the air quality impact of all on-road vehicles, and we subsequently use episodic air quality scenarios for light-duty vehicles, medium-duty vehicles, and heavy-duty vehicles (which collectively make up the entirety of on-road vehicles), to tell us the breakdown of impacts from the annual run into each of these three subsectors. This approach is not ideal as it provides only an approximation of the annual changes in pollutant concentrations but allows for a reasonable estimation of the annual health impacts of each subsector and represents an improvement over other currently available tools.

Table 1 provides an overview of the scenarios considered and the following section provides more detail on the scenario design for each. The scenarios in this table are marked as either "annual air quality" or "episodic air quality," which refers to the type of air quality modeling used for each scenario.

Table 1. Overview of considered scenarios and corresponding air quality simulation periods.

SCENARIO	SCENARIO DESCRIPTION	ANNUAL AIR QUALITY	EPISODIC AIR QUALITY
REFERENCE	Reflects a business-as-usual scenario for criteria pollutant emissions in 2035.	**X**	**X**
NATURAL GAS ELECTRIC GENERATION	In-state natural gas generation expected to be operating in 2035. CHP is excluded.	**X**	
NATURAL GAS COMBUSTION IN BUILDINGS	Natural gas appliances in residential and commercial buildings.	**X**	
ON-ROAD VEHICLES	Light-, medium-, and heavy-duty on-road vehicles with the exception of buses and motorcycles	**X**	
+ **LDV**	Only light-duty on-road vehicles		**X**
+ **MDV**	Only medium-duty on-road vehicles		**X**
+ **HDV**	Only heavy-duty on-road vehicles		**X**
OFF-ROAD VEHICLES AND EQUIPMENT	All off-road vehicle and equipment categories	**X**	
+ **AGRICULTURAL**	Only agricultural off-road vehicles and equipment		**X**
+ **CONSTRUCTION AND MINING**	Only construction and mining off-road vehicles and equipment		**X**
+ **ALL OTHER SUB-SECTORS**	All other off-road vehicle and equipment categories		**X**

2.2.1 *Reference scenario*

The Reference scenario modeled in this work reflects a business-as-usual scenario for criteria pollutant emissions in 2035 that includes emissions from all sectors, i.e., a complete inventory of emission sources. Emissions projections for this scenario are taken from CARB's CEPAM model, which incorporates the projected impact of all currently implemented regulations impacting criteria pollutants. The CEPAM model is aligned with the California Energy Commission's (CEC's) Integrated Energy Policy Report (IEPR) California Energy Demand forecast (Mid-Mid scenario), and reflects current trends with minimal electrification. Thus, CEPAM includes all policies that are currently in effect (for example, currently implemented air pollutant regulations), but not new policies that might be necessary to reach the state's climate goals. This Reference scenario is the baseline that other scenarios are compared against to measure air quality impacts.

2.2.2 Natural Gas Generation scenario

The first sectoral impact scenario focuses on the air quality impact of natural gas electric generators assumed to be operating in the state in 2035, excluding combined heat and power resources (CHP) and biomass resources. This scenario models all natural gas power plants in the State and not just those located in CAISO-controlled areas of the state. However, episodic modeling is also used to estimate impacts for CAISO plants only. CHP and biomass plants are excluded because the purpose of this scenario is to allow the quantification of the air quality impact of marginal changes in electricity usage, and CHP and biomass units are generally not dispatched as marginal generators[3].

Data on gas generators expected to be operating in 2035, as well as the quantity of electric generation from these generators, was obtained from the Strategic Energy and Risk Valuation Model (SERVM) production cost model used for the CPUC's Integrated Resource Planning (IRP) process[4]. The quantity of emissions from these generators modeled is representative of 2030 levels, not 2035, as the SERVM model is currently only run through 2030. Since 2030 gas generation is likely to be higher than 2035 gas generation due to ongoing electric sector decarbonization, this scenario will result in a liberal (high) estimate for the air quality impact of gas generation in 2035. However, the main result of this scenario, the $/MWh impact of gas generation, is not likely to be significantly impacted by this discrepancy.

This result for MWh of natural gas generation in 2035 from SERVM (using 2030 data as described above) is then combined with NO_x emission factors from the United States Environmental Protection Agency's (USEPA) CEMS database for the operating generators to arrive at an expected 2035 NO_x emissions amount. Emission factors for other criteria pollutants, such as PM, are taken from CARB's CEPAM database. CEMS data from 2012 is used for the NO_x emission factor calculations because 2012 is the base year for the CEPAM model used to project emissions for other sectors. Thus, the impact of potential increased NO_x emission factors due to more frequent cycling in 2035 compared to 2012 is not modeled.

2.2.3 On-Road Vehicle scenario (On-Road)

On-road vehicles represent one of the largest sources of NO_x and PM emissions in California and are frequently concentrated in urban regions with large populations and pre-existing air quality challenges, including the Central Valley and Southern California (CARB 2017c). To provide a comprehensive valuation of the impacts of the on-road sector, this scenario evaluates the collective removal of emissions from all light-, medium-, and heavy-duty vehicles in California. Emissions from transit buses and motorcycles were not included. An important caveat for this scenario is that only tailpipe and evaporative emissions were included in the assessment, as PM generated from brake and tire-wear still occurs from battery electric

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[3] In other words, changing the amount of electricity demand at the margins will almost never change the amount of generation from CHP or biomass plants because these plants are generally treated as "must-run." Rather, changing electricity demand at the margins is more likely to change the amount of generation from traditional gas plants such as combustion turbines (CTs) or combined cycle gas turbines (CCGTs), or in some cases renewables.

[4] SERVM data from the 2020 Reference System Plan modeling was used for this study.

vehicles. Thus, this scenario evaluates the impact of removing all emissions from on-road vehicles that could be conceivably removed through electrification.

Further, episodic modeling is used to quantify the impact of each of three subsectors of on-road vehicles: light-duty, medium-duty, and heavy-duty vehicles. Emissions data for on-road vehicles is obtained from the Emission FACtors model (EMFAC) developed by CARB (ARB 2019). A description of the vehicles mapped to the EMFAC categories that are assumed for both the on-road scenario and the individual sub-sectors can be found in Table 2.

Table 2. Vehicle categories defined by EMFAC by subsector in the on-road vehicle scenarios.

Light-Duty Vehicles (LDV)	Medium-Duty Vehicles (MDV)	Heavy-Duty Vehicles (HDV)
Light Duty Auto	Light Heavy Duty Trucks 1 & 2	All other T6 categories
Light Duty Trucks 1 & 2	T6 CAIRP small	All T7 categories
Medium Duty Vehicles	T6 instate construction small	
	T6 instate small	
	T6 OOS small	

2.2.4 Off-Road Vehicle and Equipment scenario (Off-Road)

The off-road sector encompasses a highly diverse group of technologies used for many different purposes including agriculture, construction, mining, port and warehouse operations, and many other activities. Off-road vehicles are used throughout the state and have different activity patterns and emissions than on-road vehicles. An annual simulation is conducted to determine the impacts of off-road vehicles and equipment collectively in California.

Within the off-road sector, two sub-sectors are identified as being particularly notable from an air quality standpoint, and both are evaluated independently via episodic modeling. These include 1) construction and mining and 2) agricultural vehicles and equipment. Off-road construction vehicles and equipment are one of the most substantial sources of pollutant emissions in the heavy-duty off-road sector, including NO_x and PM. Additionally, construction activity is often correlated with urban areas. Agriculture is a key industry in California and off-road diesel engines are widely used in agricultural production and supply processes. Emissions from agricultural vehicles and equipment are important contributors to poor air quality for PM and ozone in regions that currently experience degraded air quality, e.g., the San Joaquin Valley (SJV) experiences nonattainment for ozone and $PM_{2.5}$ and contains over half of California's agricultural equipment[5].

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[5] https://ww2.arb.ca.gov/resources/documents/off-road-equipment-research

Additionally, an episodic scenario of all other remaining off-road equipment categories including commercial and industrial equipment, transport refrigeration units, logging equipment, aircraft ground support equipment, port and rail equipment, lawn and garden equipment, and others is also modeled to provide a comparison.

2.2.5 Residential and Commercial Natural Gas Appliances scenario (NG Buildings)

Emissions from the use of natural gas (NG) in buildings can have important impacts on air quality due to 1) the very large number of buildings in California and 2) the high concentration of buildings within population centers (Aas et al. 2019). The use of natural gas appliances in buildings results in direct emissions from the building location, in contrast to electric appliances which generate no emissions from the buildings themselves but use electricity that may have been generated from emitting natural gas power plants (“indirect” emissions). In this scenario, an annual simulation is conducted which evaluates the removal of all emissions associated with direct natural gas use in building appliances for both the residential and commercial sectors, including space heating, water heating, cooking, and clothes drying. Emission reductions correspond solely to sources supplied by natural gas and do not assume changes in emissions from other fuel sources in buildings, such as wood burning, which remain constant for all cases. Therefore, the air quality impacts described for buildings can be attributed solely to the direct use of natural gas in the residential and commercial sectors. Note that indoor air quality impacts are not modeled in this scenario but several studies have examined these impacts (e.g., Y. Zhu et al. 2020). Monetization of these impacts is an important area for future study.

2.3 Criteria pollutant emissions projection

The first step in assessing impacts to regional air quality is to comprehensively determine the direct emissions for each scenario. These are the pollutants that are directly released from sources like power plants, cars and trucks, industrial facilities, and many others. Direct emissions from energy sectors that contribute to air pollution include oxides of nitrogen (NO_x), particulate matter (PM), carbon monoxide (CO), reactive organic gasses (ROG), and oxides of sulfur (SO_x). Energy sectors are very different in terms of activity, technologies and fuels, energy demands, and other characteristics. These differences lead to differences in the characteristics of emissions including quantitatively (in total), spatially (where), temporally (when), and in composition (what), all of which subsequently affect the type and levels of air pollution in a region. All of these aspects must be determined to produce an emissions file for each scenario that is appropriate to serve as input into the air quality model. To do this requires two steps: 1) projecting emissions from current levels to 2035 based on the expected changes to energy systems and 2) determining when and where these emissions are in California consistent with the activity of the emission sources in energy systems.

For step 1, for all sectors with the exception of natural gas generation (for which emissions projections are described in more detail above) a California state-wide emissions inventory for 2012 developed by the California Air Resources Board (CARB) (CARB 2017a) was projected to 2030 using a CARB tool that provides emissions in future years called the California Emission Projections and Analysis Model (CEPAM) tool

(CARB 2017c). The CEPAM inventory accounts for current and expected regulations and other drivers that affect future pollutant emissions, e.g., requirements for low NO_x furnaces in buildings and regulations for on-road vehicle emissions. Those impacts are included in both the Reference and four sector scenarios in 2035, so the air quality impacts estimated in this work are only from emissions in the individual sector being assessed.

Step 2 uses an emissions processing tool called the Sparse Matrix Operator Kernel Emissions tool (SMOKE) ("SMOKE v4.0 User's Manual" 2016) to develop a file that includes the location and timing of the emissions. SMOKE accomplishes this by using data for the location and activity of the technologies that produce emissions, e.g., the location of NG power plants, the locations of residential and commercial buildings, the locations of major roadways and the traffic patterns for on-road vehicles. The output from SMOKE is an emissions file that represents a scenario (both the Reference and the sector scenarios) in 2035 with all of the information that the air quality model needs to simulate atmospheric chemistry and transport.

An important clarification for both the on- and off-road scenarios is that emissions associated with fuel production and distribution infrastructure are held constant relative to the Reference. Reductions in petroleum fuel consumption from both sectors will reduce emissions from petroleum fuel infrastructure associated with notable air quality impacts, including large petrochemical refinery complexes. However, they are not included in the modeling because there are considerable uncertainties in quantifying and allocating emission reductions from such sources. For example, refineries are large complex plants with various emission sources that also produce other products in addition to transportation fuels. Further, a fair assessment would then require that sources of emissions from current and possible future fueling infrastructure for zero emission vehicles to also be included, e.g., hydrogen production and distribution. Therefore, only direct vehicle emissions are reduced in the scenarios modeled in this report to avoid uncertainty and provide an estimate of the air quality impacts of on- and off-road vehicles. However, the potential fuel infrastructure impacts are important and should be considered in future work.

2.4 Air quality modeling

The next step in assessing air quality is to model the atmospheric chemistry and transport above California to develop an understanding of how changes in emissions result in differences in air pollution. This is particularly important in understanding impacts on secondary air pollutants. Two of the most important pollutants from both a regulatory and human health standpoint include ozone and fine particulate matter ($PM_{2.5}$). These two pollutants are used in this work to assess air quality as many regions of California experience levels that do not meet State and Federal health-based standards (CARB 2017b), and both cause serious human health effects which is supported by a strong body of scientific literature (Dockery et al. 1993; Samet et al. 2000; Pope III and Dockery 2006). It is important to note, however, that emissions of all air pollutants are modeled in this study, and it is just for assessing ambient air quality results that we focus on ozone and $PM_{2.5,}$ as these are the most important pollutants from both a regulatory and human health perspective.

The air quality model used in this work is the Community Multiscale Air Quality Model (CMAQ). CMAQ is a comprehensive air quality modeling system developed by the USEPA and widely used for various air quality assessment needs, including regulatory compliance and atmospheric research associated with tropospheric ozone, PM, acid deposition, and visibility (K M Foley et al. 2010; Kristen M. Foley et al. 2014). To properly model air quality, CMAQ uses the emissions from SMOKE and accounts for factors including meteorological conditions, geography, and the emissions from natural sources as these play an important role in the chemical reactions that result in the formation of other pollutants. Although the CMAQ modeling is conducted with emissions that have been projected to 2035, the meteorological conditions are held constant to ensure the impacts that result are solely from the changes in emissions from the sectors of interest. Therefore, it should be noted that additional factors impacting air pollution in the future are not considered, including the impacts of climate change and transported pollution from outside California.

Of particular importance is the ability of CMAQ to resolve the impacts on secondary pollutants including secondary $PM_{2.5}$ and ozone. NO_x, one of the most important criteria pollutants emitted within the sectors considered, impacts air quality primarily by reacting with other pollutants and sunlight in the atmosphere to form ozone and fine particulate matter (i.e., secondary $PM_{2.5}$). The word "secondary" refers to the fact that this pollutant is generated via chemical reactions in the atmosphere, rather than being directly emitted. All of the sectors considered also directly emit *primary* $PM_{2.5}$, but the secondary $PM_{2.5}$ impacts associated with emissions of NO_x are also important because secondary $PM_{2.5}$ often represents significant fractions of the total $PM_{2.5}$ in the atmosphere in California. Thus, the modeling of secondary $PM_{2.5}$ formation is essential to provide a comprehensive and accurate estimation of air quality impacts in California.

As noted, CMAQ is used in this study to model scenarios both annually and in episodes as a measure of balancing the high computational cost relative to the benefits of annual modeling. For annual modeling, an entire year is simulated including seasonal differences in meteorology and energy demand fluctuations. For the episodic modeling, two simulation periods are conducted to capture the effect of seasonal variation on meteorology and emissions: a summer period (July 8-21) and a winter period (January 1-14). The periods are selected from observational data to correspond to conditions associated with high pollution formation ($PM_{2.5}$ for the winter (S. Zhu et al. 2019) and ozone for the summer (Carreras-Sospedra et al. 2006)) in important regions of the state, including the South Coast Air Basin (SoCAB), comprising Los Angeles and surrounding areas, and the Central Valley.

CMAQ performance is validated by comparison with observational data from the U.S. EPA Air Quality System for hourly ozone and $PM_{2.5}$, with acceptable performance demonstrated through the criteria recommended in Emery et al. (2017). More details regarding the model performance including a complete report of statistical parameters is presented in Zhu et al. (2019). More detailed information on the CMAQ methodology is contained in this report's technical appendix.

2.5 Health analysis

Finally, the changes in air quality that are modeled in CMAQ are used to conduct a health impact assessment, which quantifies and values the reductions in harmful health effects that occur in populations resulting from air quality improvements. The health outcomes considered in this study include incidence of premature mortality, and also a range of morbidity (i.e., non-fatal) health effects including hospital admissions for various respiratory disease and school loss days.

To conduct the health analysis, USEPA's Environmental Benefits Mapping and Analysis Program-Community Edition (BenMAP) is used (Abt Associates Inc 2018). BenMAP combines pollutant concentration data from CMAQ with population projection and location data, concentration-response (C-R) functions which are used to relate the pollutant changes to health outcomes, and baseline incidence rates for health effects which are the rates that they occur normally within a population. As a final step, BenMAP uses functions from the health economics literature to value the avoided health incidences and provide a monetary estimate of the health savings. The methods and selected inputs used for the BenMAP modeling framework in this study were primarily guided by those used in an analogous study conducted by the South Coast Air Quality Management District (Shen, Oliver, and Dabirian 2017) and additional details on the health impact assessment methods can be found in (Wang et al. 2020).

C-R functions are an important input to BenMAP as they determine the translation of pollutant concentration changes into avoided health incidence and have a large impact on the results. The selected C-R functions for this work (shown in Table 3) are based on a comprehensive review of the epidemiological literature for applicability to California populations including consideration of peer-review, date, geography, population characteristics, and study design (Industrial Economics 2016a). The most important C-R functions to consider are those used to estimate the avoided mortality incidence that result from reductions in annual $PM_{2.5}$ exposure because they contribute more than 90% of the estimated health benefits. For this work, avoided mortality was estimated using fixed random pooling from three studies including Jerrett et al. (2005), Krewski et al. (2009) and Jerrett et al. (2013). Similar methods have been used to quantify annual $PM_{2.5}$ mortality in recent studies of California (Alexander et al. 2019; Zapata et al. 2018). Health impacts from short-term exposure to $PM_{2.5}$ are not included to avoid the potential for double counting.

Table 3. Concentration Response Functions Selected for the Health Analysis.

	$PM_{2.5}$	**OZONE**
MORTALITY, ALL CAUSES	Krewski et al. (2009); Jerrett et al. (2005); Jerrett et al. (2013)	Bell et al. (2005)
HOSPITAL ADMISSIONS, ALL RESPIRATORY	--------	Katsouyanni et al. (2009)
EMERGENCY ROOM VISITS, ASTHMA	--------	Mar et al. (2009)
HOSPITAL ADMISSIONS, ASTHMA	--------	Moore et al. (2008)
SCHOOL LOSS DAYS, ALL CAUSES	--------	Gilliland et al. (2001)

Population projections are developed using data with 1 km spatial resolution (ORNL 2017) which is then projected to 2035 using forecasts from the California Department of Finance (California DOF 2017). Baseline incidence rates at the county level by five-year age groups of the health endpoints are obtained for the current California population (Industrial Economics 2016b).

The monetary benefit of avoided incidence of mortality is estimated using a Value of Statistical Life (VSL) of $9 million (2013$) as recommended in Industrial Economics and Lisa Robinson (2016b). This VSL represents the midpoint of a range ($4.2 million to $13.7 million) identified through a survey of the literature (Robinson and Hammitt 2016). It is important to note that the VSL does not place a monetary value on a human life, nor does it represent an estimate of avoided health care costs. Instead, it represents a societal willingness-to-pay to reduce the risk of premature death by one person. The values used for the morbidity endpoints were similarly selected by using the results of a detailed and thorough review of the scientific literature (Industrial Economics and Lisa Robinson 2016a). The total estimated health savings are then converted to real 2020 dollars.

Current health burdens associated with exposure to air pollution are not uniformly distributed across California populations. Rather, certain regions and population segments bear disproportionate shares, and many of the same communities also suffer additional socio-economic burdens that increase their vulnerability to air pollution (Fowlie, Walker, and Wooley 2020). These socially and environmentally disadvantaged communities are known as “disadvantaged communities” (DACs), and we focus on the potential to achieve benefits for these communities in this report, given their disproportionate exposure to health hazards.

In this study, the estimated health savings are evaluated within DACs using CalEnviroScreen 3.0 (Faust et al. 2017). CalEnviroScreen is a screening tool developed by the California Office of Environmental Health Hazard Assessment that identifies communities burdened by a disparate share of air pollution, in addition to socioeconomic and health challenges that increase their vulnerability to environmental health effects. CalEnviroScreen ranks each of the state’s 8,000 census tracts according to pollution, environmental quality, and socioeconomic and public health conditions. The lowest scoring 25% are considered DACs. For this work, the total health savings that are estimated to fall within the DAC census tracts are quantified and reported for both California as a whole and SoCAB specifically, in addition to the savings for all communities.

2.6 Comparison to COBRA

The CPUC previously estimated the health impacts of natural gas generation using the COBRA tool developed by US EPA to derive an interim estimate for the health benefits of avoided NG generation of $6/MWh (Commission 2019). This estimate, referred to as the “Interim Air Quality Adder,” was intended to serve only as an interim value until more robust research is available. The updated research described in this document represents this more robust research and the values for natural gas generation presented here are intended to replace the interim adder.

COBRA provides the benefit of being a streamlined and user-friendly method of estimating the health savings of reducing pollutant emissions. However, according to the USEPA, "COBRA serves as a preliminary screening tool to identify those scenarios that might benefit from further evaluation with the more sophisticated air quality modeling approaches that are currently available."[6] The methodology used for this work represents a significantly more granular, precise, and holistic evaluation of air quality health impacts for California relative to COBRA.

COBRA is a 2-D dispersion model (meaning that it only models pollutant movement horizontally, and not in the vertical direction) that uses simplified assumptions for secondary $PM_{2.5}$ formation and does not account for impacts on ozone. Dispersion models essentially track pollutants from where they are emitted to where they end up. In contrast, CMAQ is a 3-D atmospheric transport model that simulates atmospheric chemistry and transport in three dimensions to develop fully resolved distributions of both $PM_{2.5}$ and ozone, as this allows for secondary pollutant formation to be modeled. In particular, the more detailed accounting of secondary $PM_{2.5}$ chemistry in relation to NO_x emissions within CMAQ provides a more comprehensive accounting of impacts, e.g., COBRA accounts for only 5 species of PM while CMAQ accounts for 46. These impacts are important as many sectors considered in this study -- particularly natural gas generation, natural gas combustion in buildings, and light duty vehicles -- impact air quality significantly through the formation of secondary PM resulting from NOx emissions. Given the importance of $PM_{2.5}$ to the results of the health impact valuation, the enhanced impact estimated in CMAQ is a major factor in the larger health valuation. Other factors that are important to note include the improved resolution of population density and location, meteorology, emission inventories, inclusion of biogenic emissions, and others, as shown in Table 4.

Table 4. Comparison of the COBRA tool with methods used in this study.

	COBRA	CMAQ AND BENMAP
AIR QUALITY MODEL	2D-Simple Dispersion	3D-Eulerian Chemical Transport
SECONDARY PM	Simple conversion	Sophisticated chemical-physical reactions
PM SPECIES	5	46
OZONE	Not considered	Calculated through photochemical reactions
METEOROLOGY	Statistical summaries	Dynamically resolved
EMISSIONS DATA	National Inventory 2011	CARB 2012
EMISSION PROJECTION	Year 2025	Year 2035
EMISSIONS	Sector based, bulk estimate	Temporally and spatially resolved
RESOLUTION	County level	4 km X 4 km
BIOGENIC EMISSIONS	Not considered	Dynamically resolved based on meteorology
HEALTH IMPACT INPUTS	U.S. level	California-specific when possible

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[6] https://www.epa.gov/statelocalenergy/co-benefits-risk-assessment-cobra-health-impacts-screening-and-mapping-tool

3 Results

3.1 Criteria pollutant emissions

This first section of results shows the changes in total *direct* criteria pollutant emissions for each scenario modeled. This is distinct from the sections below which show the changes to ambient air quality resulting from each scenario, and the subsequent health impacts.

As a reminder, these results show the impact of *complete removal of emissions from each sector in question.* For example, the natural gas buildings scenario is showing the impact of removing all natural gas combustion from buildings in California.

The reductions in total 2035 NO_x emissions for each scenario are shown in the top half of Figure 4 for both California as a whole and the SoCAB, given its importance as an impacted region. The On-Road scenario results in the largest reductions by far, followed by the Off-Road and NG Buildings scenarios. By comparison, the NG Generation scenario results in only minor NO_x reductions, highlighting the much lower contribution relative to the other sectors modeled. In contrast, reductions in 2035 emitted $PM_{2.5}$ are largest from the NG Building scenario as shown in the bottom half of Figure 4, followed by the Off-Road and NG Generation sectors. It is important to note that the direct emissions shown for the On-Road scenario includes only $PM_{2.5}$ generated by exhaust and evaporative mechanisms, and do not include those from brake- and tire-wear. This is because brake- and tire-wear emissions are held constant as they are not eliminated by transitions to zero emission vehicles. It should also be considered that the 2035 On-Road fleet (particularly HDV) is assumed to be comprised of cleaner vehicles, including the widespread use of newer engine technologies and the use of control devices such as diesel particulate filters, in line with CARB's projections in CEPAM as described in the Methodology section above.

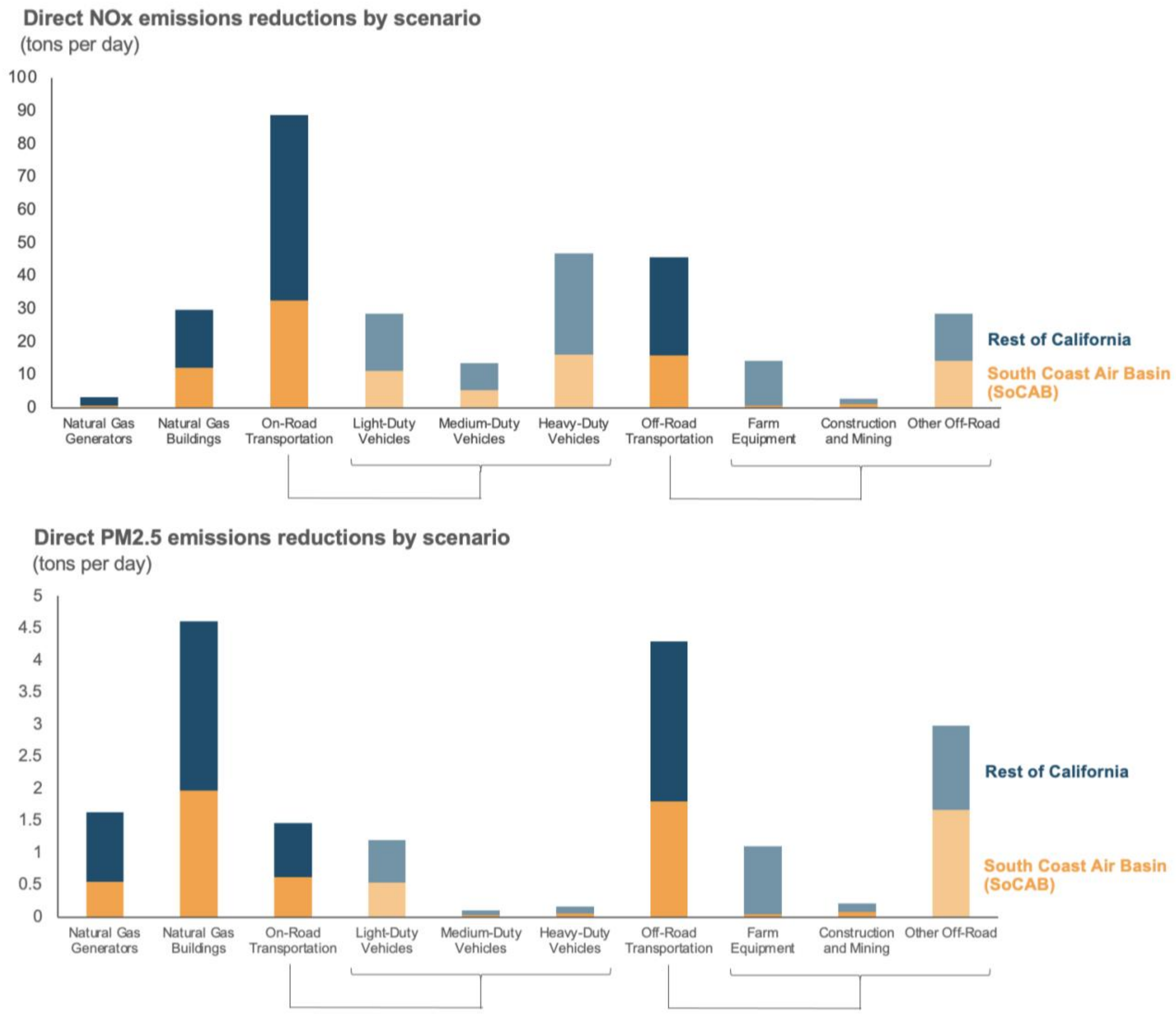

Figure 4. Reductions in direct NO_x and $PM_{2.5}$ emissions in 2035 for each scenario modeled (episodic scenarios shown in lighter shade).

3.2 Air quality simulations

The following section discusses the results for the air quality simulations conducted using CMAQ, which are presented as difference plots showing the improvement in $PM_{2.5}$ and ozone air pollution (i.e., reductions) that occur when direct emissions from the sectors are removed. First, the results of the annual simulations for On- and Off-Road vehicles and equipment, NG buildings, and NG Generation are presented. Subsequently, the results of the episodic simulations are shown for the On- and Off-Road sub-sectors, for the episodes modeled which represent periods of high pollutant formation conditions in winter and summer.

3.2.1 Annual simulations

The improvements in annual average $PM_{2.5}$, which are particularly significant for the health impact assessment, are shown in Figure 5 for the four scenarios. When interpreting air quality impacts, it is important to consider both the quantity and the spatial extent of the reductions, as well as their coincidence with priority regions that contain large populations and/or currently degraded air quality (several of which are noted in Figure 5). For example, the results highlight the coincidence of air quality improvements with population centers in both the Central Valley and SoCAB. Decreased $PM_{2.5}$ burdens occur from both reduced direct $PM_{2.5}$ (i.e., emitted) and secondary $PM_{2.5}$ resulting primarily from avoided gaseous precursor emissions including NO_x, SO_x and ROG.

Among the sectors considered here, the On-Road scenario attains the largest $PM_{2.5}$ reductions, both in quantity and in spatial occurrence demonstrating the very large vehicle fleet that is active throughout the state, particularly in urban areas. It follows that removing emissions from On-Road vehicles markedly improves $PM_{2.5}$ air pollution in the SoCAB and the Central Valley, with reductions reaching 1.32 $\mu g/m^3$ in regions that experience the most degraded $PM_{2.5}$ levels in the Reference scenario. For context, around ~2 $\mu g/m^3$ of reductions are likely needed in SoCAB to meet the levels required by the Clean Air Act, given that SoCAB achieved an annual average of 14.4 $\mu g/m^3$ in 2020, and the EPA's standard for compliance with the Clean Air Act is 12.0 $\mu g/m^3$. While $PM_{2.5}$ reductions from the Off-Road scenario are slightly smaller than for the On-Road scenario, they are still substantial, with a peak of 0.96 $\mu g/m^3$ and widespread impacts extending throughout the SoCAB and the Central Valley. Results from both of these scenarios reflect the large concentration of on- and off-road vehicles and equipment that are present in those regions, and the benefits electrifying them could achieve. The NG buildings scenario results in reductions that reach 0.82 $\mu g/m^3$ and are most prominent in the SoCAB due to the dense population of residential and commercial buildings. While the impacts are much lower than the other sectors (indeed hardly visible when scaled in Figure 5), the removal of emissions from NG generators in California does achieve improvements in $PM_{2.5}$ that reach 0.53 $\mu g/m^3$. The results also highlight the importance of reduced secondary $PM_{2.5}$ from reduced NO_x emissions, as even sectors with relatively low direct PM emissions such as On-Road transportation (see Figure 4) still have significant impacts on ambient $PM_{2.5}$.

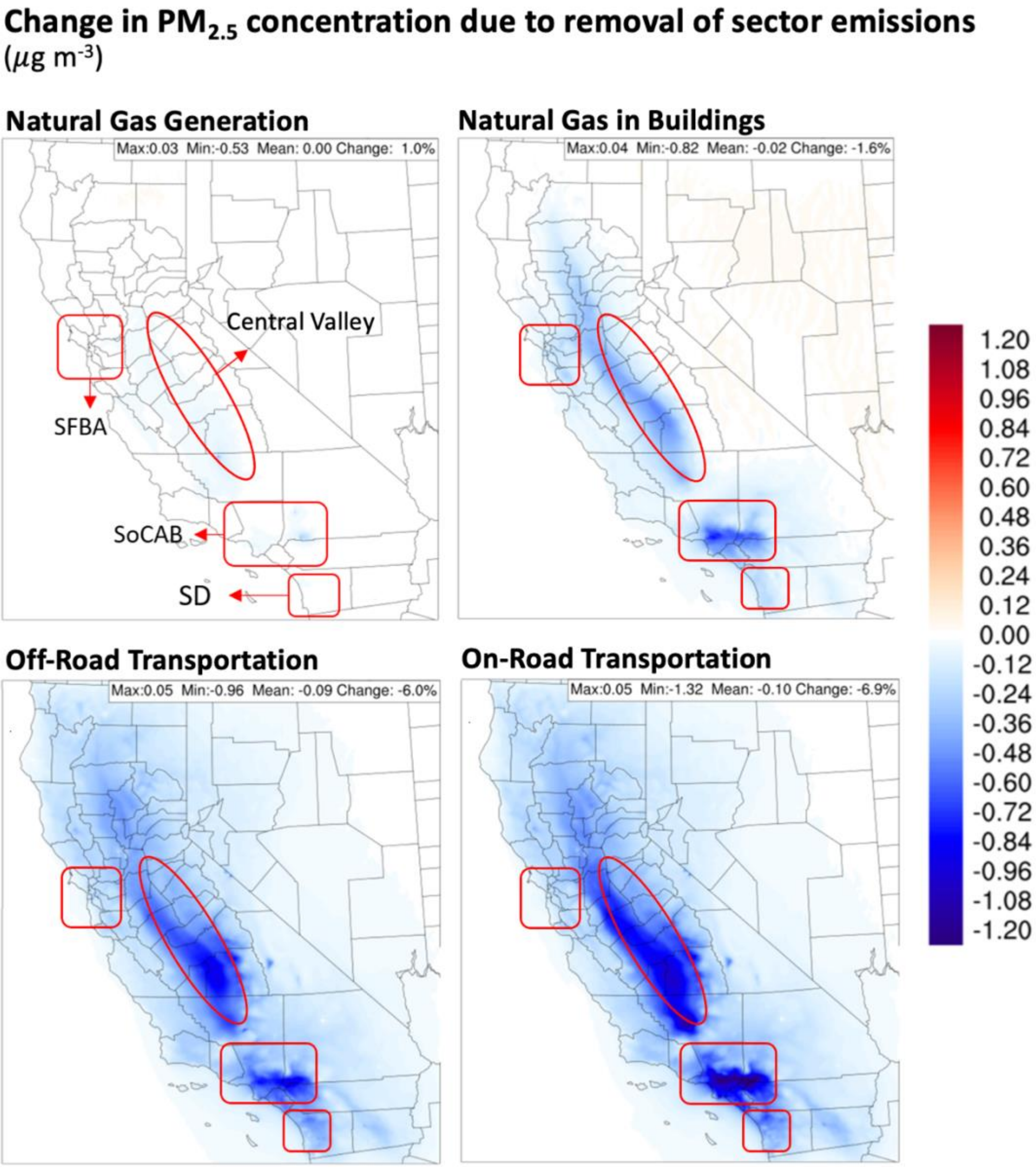

Figure 5. Change in $PM_{2.5}$ concentration in 2035 resulting from removal of emissions for each scenario relative to the Reference scenario. Arrows in top left map included for labeling.

Despite contributing a smaller fraction of the total health savings relative to $PM_{2.5}$, ground-level ozone is an important pollutant to consider due to the inability of many California regions to satisfy the health-based National Ambient Air Quality Standards (NAAQS), putting them in “nonattainment” status. This nonattainment status triggers costly regulatory procedures in addition to causing deleterious health effects (South Coast Air Quality Management District 2017). Reductions in ozone occur solely from reductions in pre-cursor emissions, primarily NO_x and Reactive Organic Gases (ROG), as there is no meaningful primary (i.e., directly emitted) pathway for tropospheric ozone.

The reductions in maximum daily 8-hour average (MD8H) ozone averaged for the months of April through October are shown for each scenario in Figure 6. The maximum daily 8-hour average ozone concentration is the highest of the 24 possible 8-hour average concentrations computed for that day. This averaging method is used to determine compliance with NAAQs. The overall trends for ozone are very similar to those discussed for $PM_{2.5}$, including the magnitude and spatial location of reductions from each of the four sectors. The large contribution of NO_x and ROG emissions from the on- and off-road sectors to ground-level ozone concentrations are evident throughout the state, and particularly in the SoCAB. Indeed, the largest reductions (-11 ppb and -10 ppb, respectively) occur in eastern portions of the SoCAB that currently experience the worst ozone air quality in the U.S.[7] Additionally, pronounced reductions are also visible in nearly every populated region including the Central Valley, S.F. Bay Area, greater Sacramento, and metropolitan San Diego. Impacts from NG buildings comprise peak reductions of 2.6 ppb and are most notable within SoCAB. With similarity to the results for $PM_{2.5}$, NG generation has a minor impact on ozone with peak reductions reaching 0.50 ppb.

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[7] https://www.lung.org/research/sota/city-rankings/most-polluted-cities

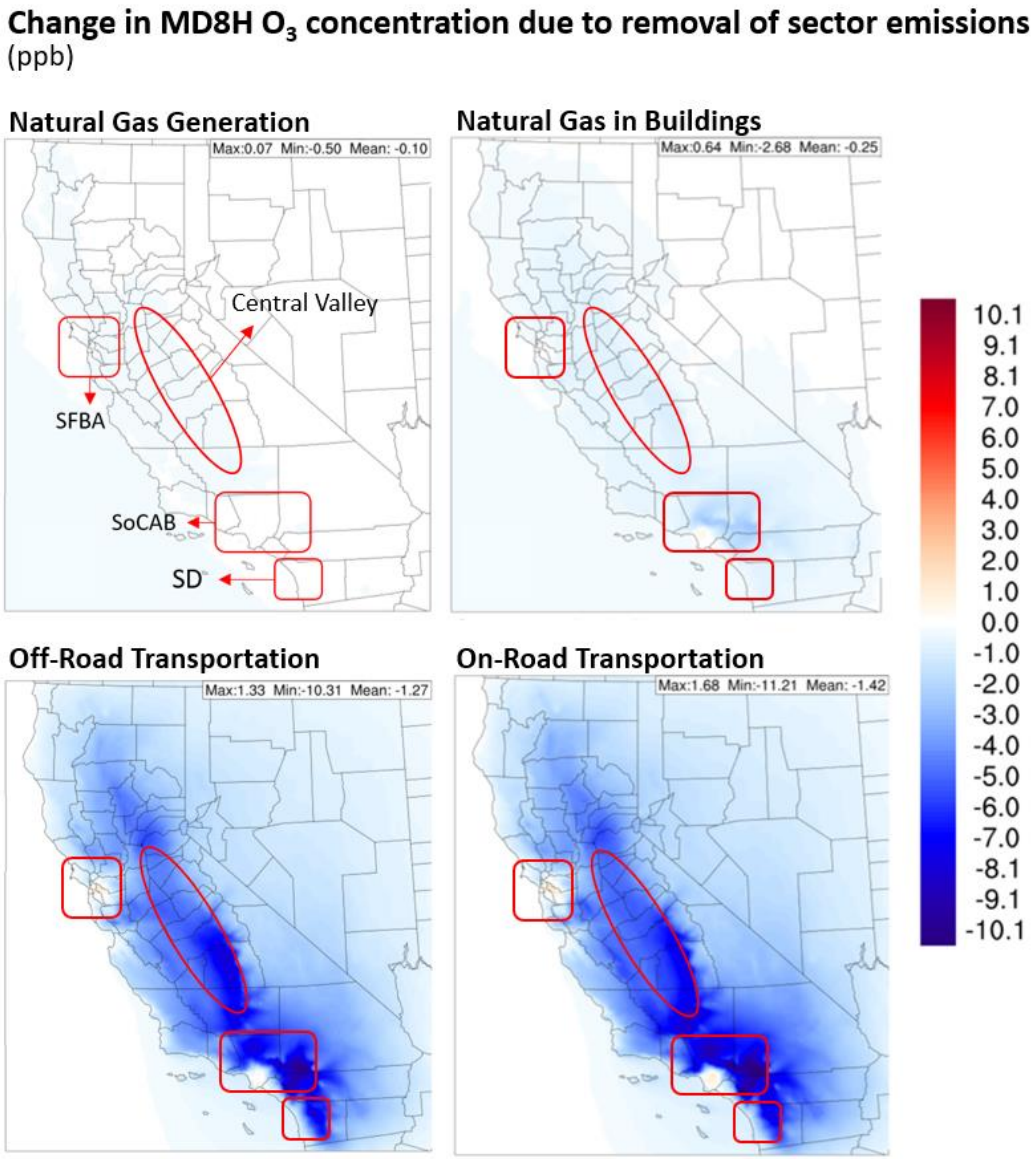

Figure 6. Change in O_3 (ozone) concentration in 2035 resulting from removal of emissions for each scenario. Note MD8H = Maximum Daily 8-hour Average.

3.2.2 Episodic simulations

The following section presents the results for the episodic simulations conducted using CMAQ to provide insight into the key on- and off-road sub-sectors including LDV, MDV, HDV, and construction/mining equipment, farm equipment, and all other remaining equipment types.

The difference in seasonal drivers of air quality concentrations including meteorology (e.g., surface temperatures, wind patterns, relative humidity, etc.) and emission signatures from energy systems (e.g., larger demands for space heating in the winter) lead to significant differences in the results between the summer and winter episodes.

3.2.2.1 On-road vehicle sub-sectors

The improvements in ozone and $PM_{2.5}$ for the on-road sub-sectors (i.e., LDV, MDV, and HDV) modeled during a summer and winter episode are shown in Figure 7. Note that results for ozone are shown for the summer episode only, as ozone is only a major contributor to degraded air quality during the summer "ozone season." Emissions from HDV are the largest contributors to ozone (-4 ppb), while LDV (-1.3 ppb) and MDV (-1.3 ppb) are less impactful but still important given the reductions occur in SoCAB. Interestingly, the HDV scenario also achieves the largest $PM_{2.5}$ reduction at 0.82 ug/m^3, while the largest reduction in the LDV scenario is 0.33 ug/m^3. However, the peak HDV reductions occur in the Central Valley, while those for LDV occur in the SoCAB. A similar pattern emerges in the results modeled for winter $PM_{2.5}$, with the largest impacts by far from HDV in the Central Valley but LDV contributing important reductions in SoCAB. This is largely because of the sizeable number of LDV operating in SoCAB; e.g., in 2035 it is projected there will be 17 times as many LDV operating in SoCAB than MDV and HDV combined (ARB 2019). Thus, even though PM emission rates per vehicle are much lower for LDV relative to HDV, the sheer number of LDVs yields emissions that in total are substantial enough to have sizeable impacts on $PM_{2.5}$. Similarly, impacts of other pollutant species from LDV including ROG and NH_3 are important to the formation of secondary $PM_{2.5}$ in winter and could be contributing to the winter impacts in SoCAB.

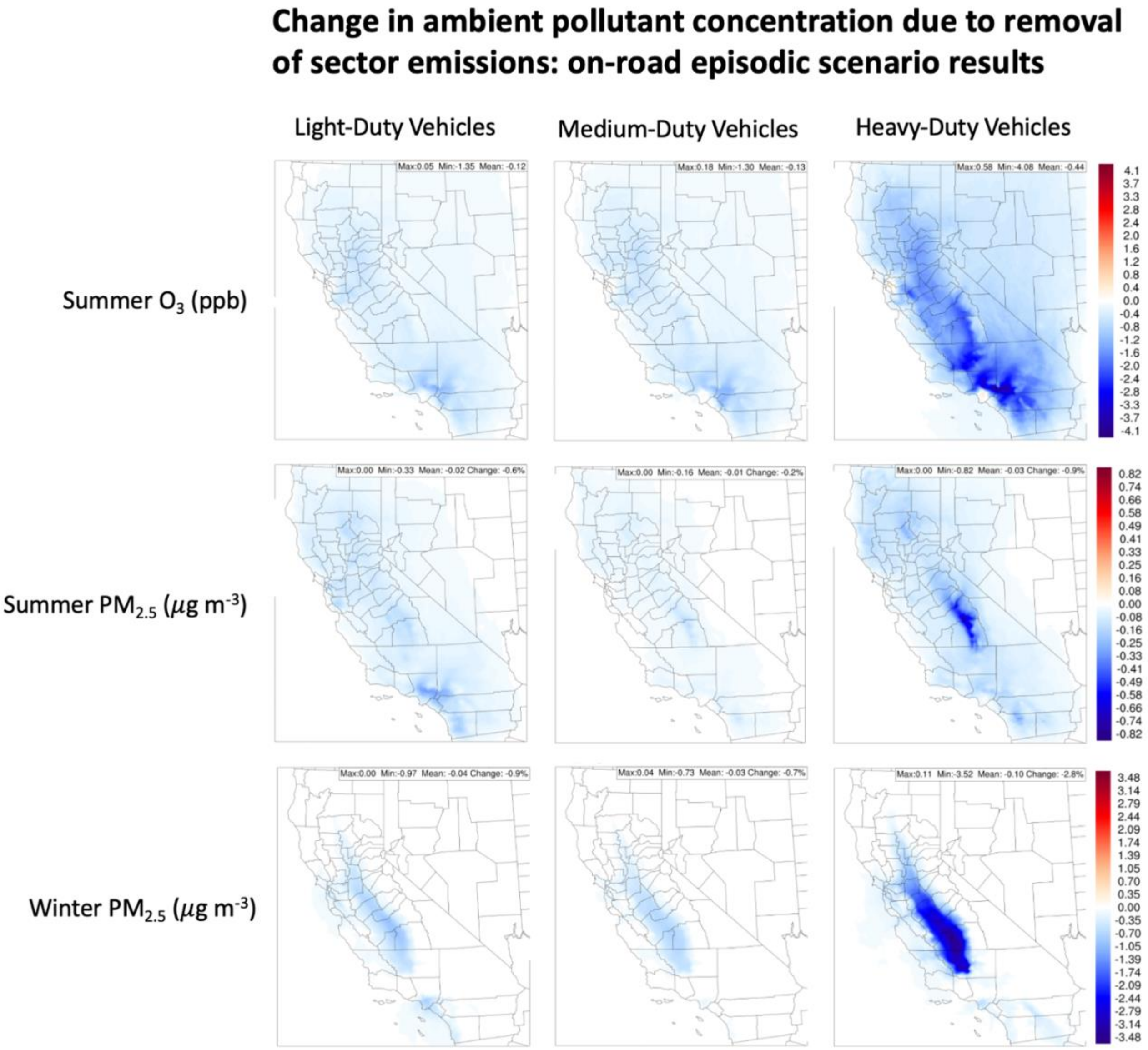

Figure 7. Change in ambient pollutant concentration due to removal of sector emissions: on-road episodic scenario results.

3.2.2.2 Off-road equipment and vehicle sub-sectors

The improvements in summer ozone as well as summer and winter $PM_{2.5}$ that result from the removal of emissions from construction and mining equipment, farm equipment, and all other off-road vehicle types are shown in Figure 8. Differences in the activity patterns among these sectors yield spatial variation in the results. The importance of agricultural activity in the Central Valley results in farm equipment having prominent impacts in that region, but little impact in SoCAB. In contrast, construction and mining equipment yield impacts in both SoCAB and the Central Valley, as does the scenario comprising all other off-road equipment. Quantitatively, all off-road equipment not associated with construction/mining and farming achieve a much greater improvement in all pollutant metrics, particularly for summer ozone and winter $PM_{2.5}$, than do those two sectors individually.

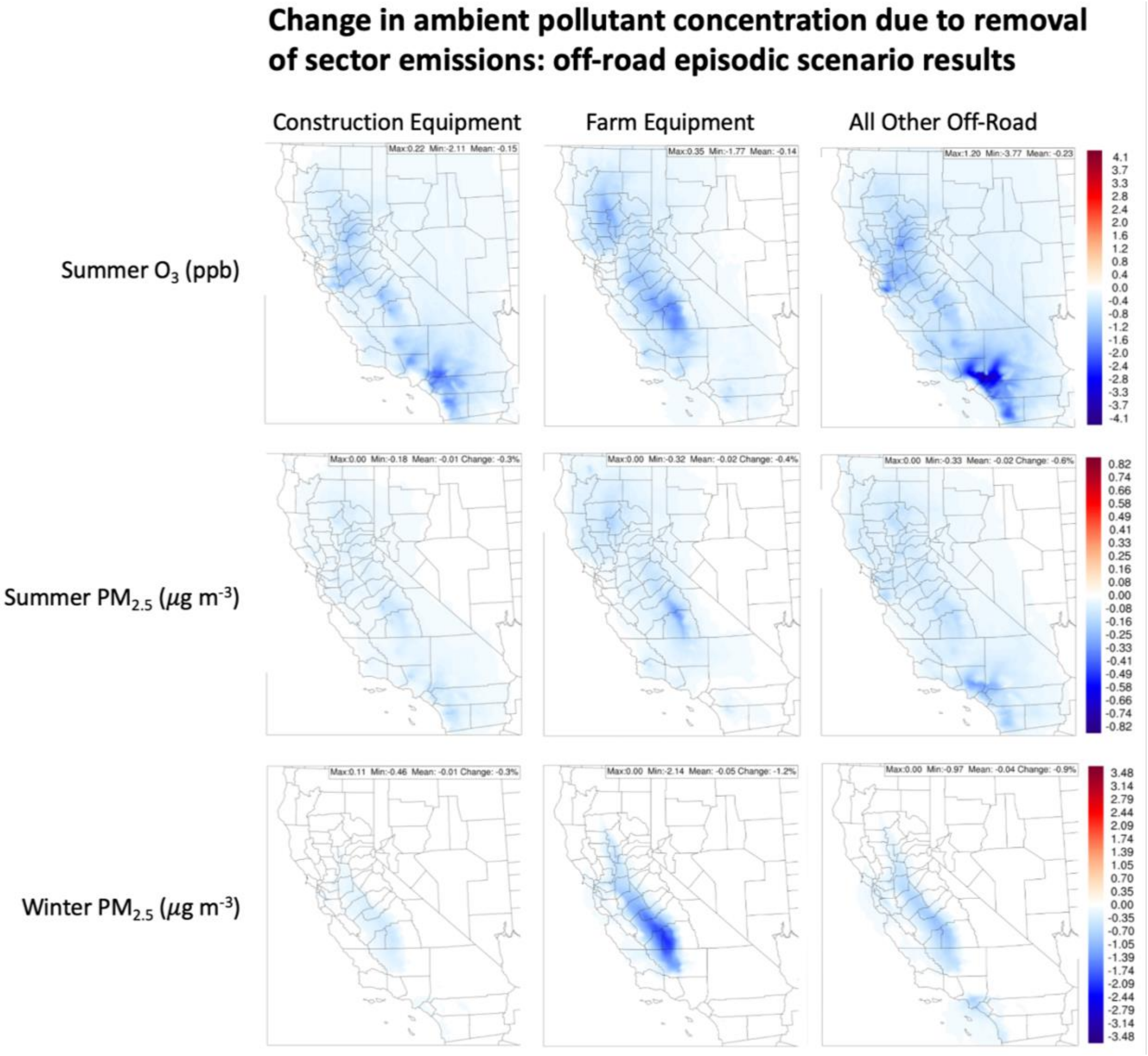

Figure 8. Change in ambient pollutant concentration in 2035 due to removal of sector emissions: off-road episodic scenario results.

3.3 Health impact assessment

The following section presents the results for the health impact assessment conducted using BenMAP to quantify the health savings that result from the air quality improvements presented in Section 3.2. There are two sections: Section 3.3.1 reports the health savings for the annual CMAQ simulations that were conducted for the NG generation, NG buildings, On-Road, and Off-Road scenarios, and Section 3.3.2

reports the health savings for the episodic CMAQ simulations used to provide more insight into the subsectors of vehicles and equipment modeled within the on-road and off-road sectors.

3.3.1 Annual health savings

Results for the health metrics that were assessed using BenMAP are shown in Table 5 for the annual simulations, including the avoided incidence of premature mortality from reduced exposure to $PM_{2.5}$ and ozone. The monetized versions of these values are shown in Table 6. The results follow the trends exhibited by the air quality impacts results in that the on- and off-road sector scenarios are responsible for the most avoided health incidence by far, NG buildings have a moderate impact, and NG generation has a comparatively minor impact. Another point to note is the importance of $PM_{2.5}$ exposure to the overall health impact assessment, as it results in significantly higher monetized health impacts than exposure to ozone, a trend that is consistent across all scenarios. However, differences in the scenarios are evident. For example, avoided mortality and morbidity from ozone are highest for the off-road scenario, while the on-road scenario has the largest avoided mortality overall due to the dominant impacts from $PM_{2.5}$. This means that removing emissions from the off-road sector reduces ozone exposure in total more so than removing emissions from on-road (although only slightly), despite the on-road sector achieving a greater peak reduction in ozone (the largest reduction in one grid cell). This further demonstrates the importance of the health impact assessment to help put the air quality results in context, as it accounts for the spatial distribution of populations concurrent with the magnitude and occurrence of pollutant changes.

Table 6 shows that the monetized value of the health savings from removing all emissions in each sector is \$0.96 billion for gas generation, \$7.35 billion for natural gas combustion in buildings, \$20.38 billion for on-road transportation, and \$15.79 billion for off-road transportation. The total health savings that would be achieved by removing emissions across all sectors modeled is \$44.49 billion. For all cases, the bulk of the value (~98%) is associated with reduced incidences of premature mortality resulting from reductions in $PM_{2.5}$. These values, along with a breakout into the benefits occurring in SoCAB, are also summarized in Figure 9.

Table 5. Avoided incidence of public health events estimated in BenMAP for the annual simulations.

HEALTH ENDPOINT	POLLUTANT	NG GENERATION	NG BUILDINGS	ON-ROAD	OFF-ROAD	ALL SECTORS MODELED
MORTALITY, ALL CAUSES	$PM_{2.5}$	105	813	2,106	1,658	4,682
MORTALITY, ALL CAUSES	Ozone	2	5	159	102	268
HOSPITAL ADMISSIONS, ASTHMA	Ozone	1	3	49	31	83

HOSPITAL ADMISSIONS, ALL RESPIRATORY	**Ozone**	2	3	177	117	300
SCHOOL LOSS DAYS, ALL CAUSE	**Ozone**	2,604	9,996	177,421	111,596	301,617
EMERGENCY ROOM VISITS, ASTHMA	**Ozone**	43	168	2912	1,827	4,951

Table 6. Valuation of avoided incidence of public health events estimated in BenMAP for the annual simulations (all values 2020$/yr in 2035). Note totals may not add due to rounding.

HEALTH ENDPOINT	**POLLUTANT**	**NG GENERATION**	**NG BUILDINGS**	**ON-ROAD**	**OFF-ROAD**	**ALL SECTORS MODELED**
MORTALITY, ALL CAUSES	**$PM_{2.5}$**	$0.94 billion	$7.3 billion	$18.9 billion	$14.8 billion	$42.0 billion
MORTALITY, ALL CAUSES	**Ozone**	$19.1 million	$43.7 million	$1.4 billion	$918 million	$2.4 billion
HOSPITAL ADMISSIONS, ASTHMA	**Ozone**	$4,831	$19,383	$350,973	$216,998	$592,187
HOSPITAL ADMISSIONS, ALL RESPIRATORY	**Ozone**	$39,412	$46,904	$2.8 million	$1.9 million	$4.9 million
SCHOOL LOSS DAYS, ALL CAUSE	**Ozone**	$405,045	$1.5 million	$27.6 million	$17.3 million	$46.9 million
EMERGENCY ROOM VISITS, ASTHMA	**Ozone**	$16,146	$62,299	$1.0 million	$679,779	$1.8 million
ALL HEALTH ENDPOINTS	**All**	$0.96 billion	$7.35 billion	$20.38 billion	$15.79 billion	$44.49 billion

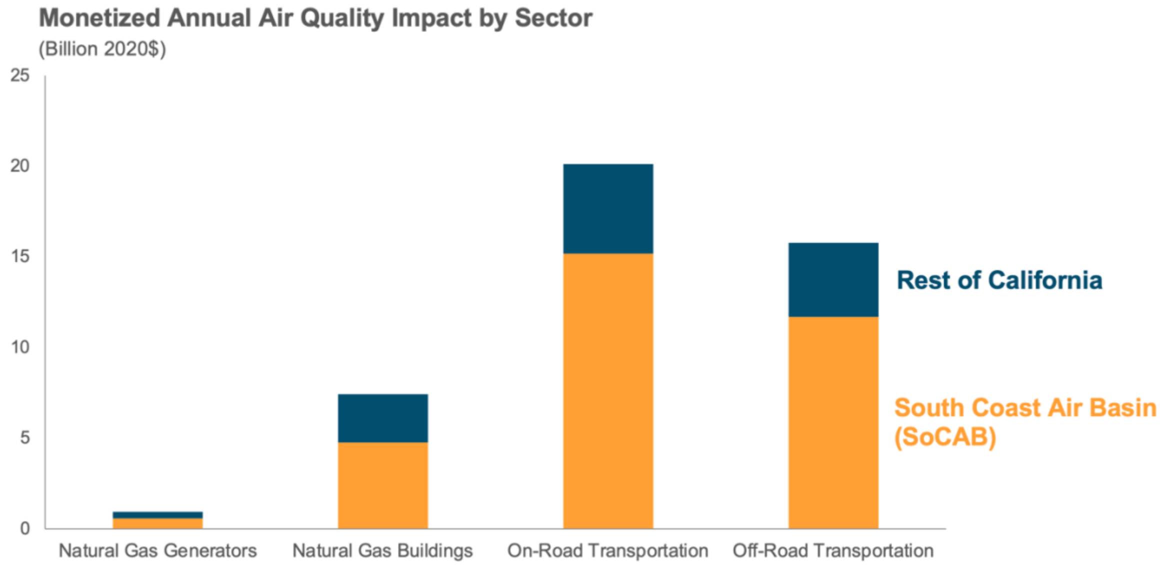

Figure 9. Annual value of the health savings in 2035 for the removal of emissions from the sectors of interest resulting from improvements in air quality. The values represent the mean value estimated in BenMAP for each case, for both statewide and SoCAB totals.

For all scenarios, the health savings in SoCAB represent the dominant fraction of statewide totals as a result of the dense populations and currently degraded air quality in the region. This is particularly true for on- and off-road vehicles, for which approximately 75% of the benefits are in SoCAB. In contrast, SoCAB benefits in the NG generation scenario are around 60% of the total due to the relative absence of power plants in the basin. The results show the importance of targeting electrification within SoCAB.

Figure 10 shows the monetized health impacts in each scenario allocated to census tracts. For the NG Buildings, On-Road, and Off-Road scenarios, the majority of impacts are located in the Central Valley and LA Basin (SoCAB). For the NG Generation scenario, impacts are minimal statewide, in relation to the other scenarios. The importance of the On- and Off-Road sectors are further emphasized when the benefits are considered in the framework of disadvantaged communities (DAC), including both the total health savings and the ratio of benefits in those communities. For example, the On-Road sector achieves benefits of $7.8 billion in census tracts designated as DACs, or approximately 38% of the total benefits for the scenario, and the Off-road sector achieves $6.1 billion or 39%. The ratio should be interpreted based off the structure of CalEnviroScreen, which ranks the worst scoring 25% of census tracts as DACs. Therefore, if the health benefits were weighted equally among all California census tracts the benefits in DAC would be approximately 25%. The higher DAC ratios for all the scenarios in this work indicate that electrification in those sectors will disproportionately *benefit* these communities.

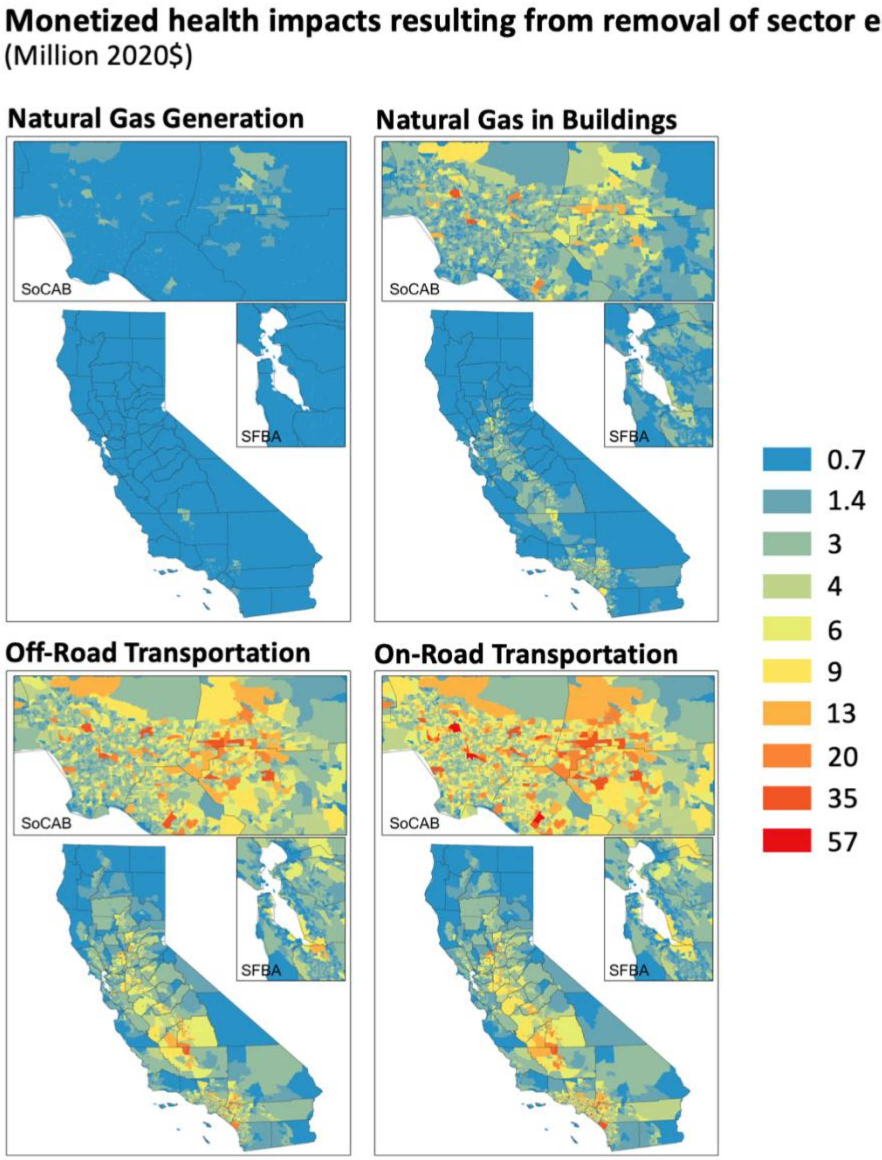

Figure 10. Map of monetized health impacts in 2035 resulting from removal of emissions for each scenario by census tract. Sub-plots for the South Coast Air Basin and the San Francisco Bay Area are also included.

3.3.2 Episodic health savings

This section presents the BenMAP results for the episodic simulations that were used to evaluate the health benefits of the On- and Off-Road subsectors. Only the health impacts for $PM_{2.5}$ are considered for the episodic simulations due to 1) the dominant contribution of $PM_{2.5}$ to the annual health benefits and 2) inverse relationship between ozone and precursor emissions noted in the technical appendix to this report. For clarity, it is again important to note that the benefits estimated for episodic simulations are generally an order of magnitude lower than those for annual air quality simulations because 1) the health savings accumulate over a much smaller time period (i.e., ~two weeks vs. 1 year) and 2) different C-R functions are used as appropriate. Therefore, the results should not be directly compared to the annual results in Section 3.3.1.

The monetized health impact results for the episodic simulations are shown in Figure 11. Among the on-road subsectors, HDV achieves the largest health savings statewide in both summer and winter, and also has the largest health savings in SoCAB in the summer. However, LDV has the largest health benefits for the winter episode in SoCAB. The tradeoff in seasonal impacts between HDV and LDV in SoCAB is driven by differences in $PM_{2.5}$ reductions which occur from 1) different relative rates per vehicle in terms of NO_x, ROG, and direct PM and 2) the higher number of LDV compared to MDV and HDV. These differences result in the HDV scenario achieving a larger reduction in NO_x and the LDV scenario having larger reductions in PM and ROG. The atmospheric chemistry associated with secondary $PM_{2.5}$ formation is complex and varies seasonally in response to meteorology, leading to different reductions in response to emission reductions. These results indicate that within the atmospheric chemical regime experienced by SoCAB, NO_x reductions from HDV are more efficient at reducing $PM_{2.5}$ in summer and ROG reductions and potentially direct $PM_{2.5}$ from LDV are more important in reducing $PM_{2.5}$ in winter. MDV are associated with the lowest health savings amongst the on-road sub-sectors for both seasons and both regional distinctions, but the magnitude of these health savings is still significant.

The health savings estimated for the off-road subsectors are more variable according to season and region as a result of the differences in the location and activity of the equipment. This is particularly true for agricultural equipment and vehicles, which are concentrated in the Central Valley. Additionally, the Central Valley experiences particularly high levels of $PM_{2.5}$ air pollution in winter as a result of meteorological conditions (although $PM_{2.5}$ is also a problem in summer months). Overall, the “other off-road” category has the highest health savings, which is to be expected given the scenario includes many different sub-sectors in aggregate. In summer, construction/mining equipment has the next highest benefits in both California and SoCAB. However, in winter emissions from farm equipment have a much higher impact statewide than do those used in construction/mining, although the bulk of those impacts are in the Central Valley.

Figure 12 shows the estimated annual impact of each subsector modeled in the episodic runs, with the total annual values included for comparison. The annual values are estimated by taking each subsector’s relative contribution to the total impact observed in the episodic runs, and applying this ratio to the annual impact. The error bars represent the uncertainty in this disaggregation, based on the difference in relative contribution to the total in the summer vs winter episodes.

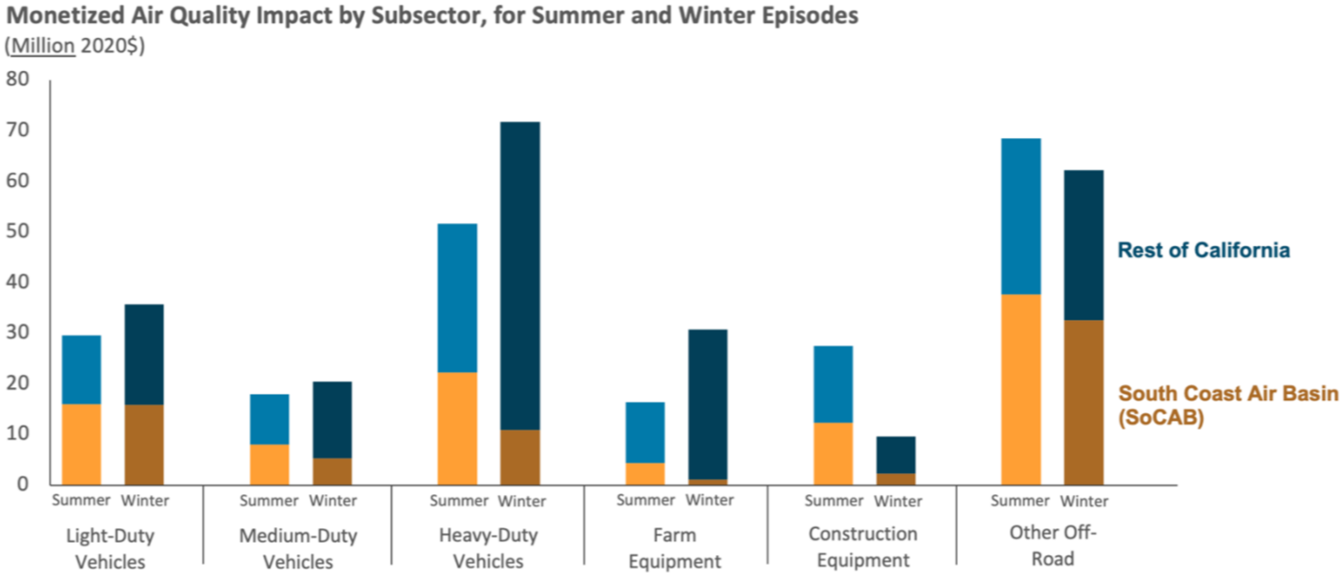

Figure 11. Value of the health savings in 2035 for the removal of emissions from the sectors of interest resulting from improvements in air quality, for summer and winter episodes. The values represent the mean value estimated in BenMAP for each case, for both statewide and SoCAB totals.

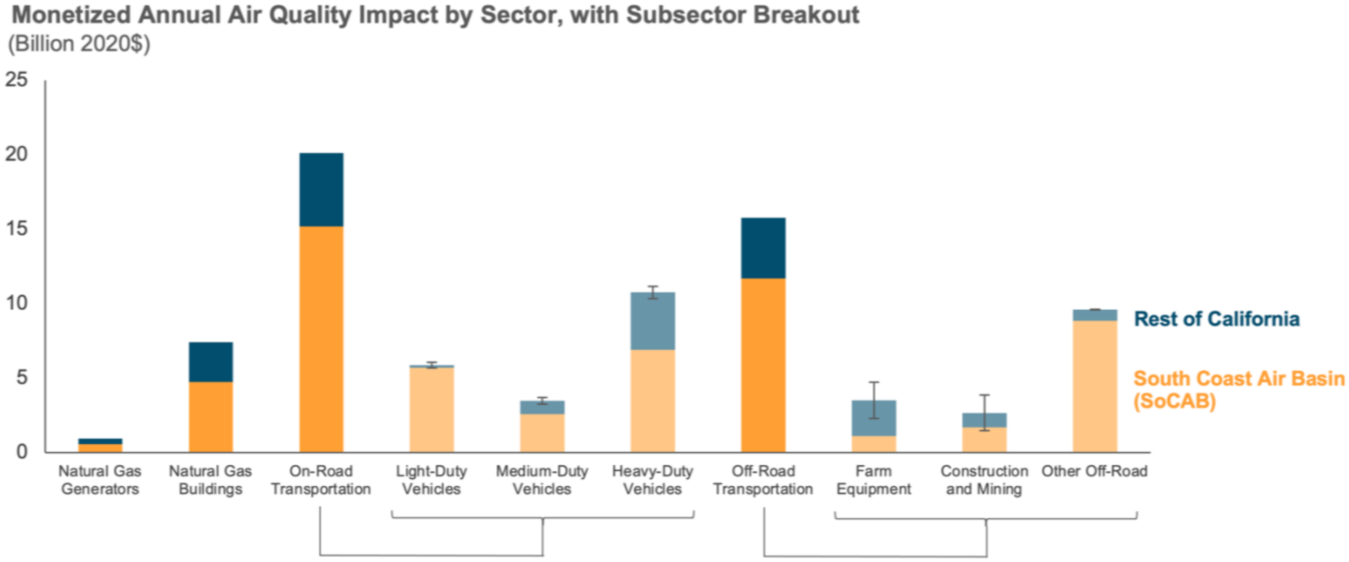

Figure 12. Annual value of the health savings in 2035 for the removal of emissions from the sectors of interest resulting from improvements in air quality, showing a disaggregation of the sector-wide results into subsectors using episodic run values. The values represent the

mean value estimated in BenMAP for each case, for both statewide and SoCAB totals. Error bars represent uncertainty based on ratio of total impacts in summer vs winter episodes.

3.3.3 Quantification of "per-unit" air quality impacts

A more useful quantification of the air quality impacts of the sectors modeled, in the context of quantifying the benefits of specific programs, is the $ benefits per unit energy metric, e.g., $/MWh for NG generation and $/gallon gasoline equivalent (gge) for vehicles. These metrics are useful because they can be compared to other costs and benefits associated with each end use. These per-unit metrics are quantified for each annual scenario and shown in Table 7. It is important to note that these per-unit values are not strictly "marginal costs," as they do not technically represent the marginal impact, but rather the average impact for each sector (i.e., the total air quality impact of a sector divided by the total energy used by that sector). The marginal air quality impact is likely to be higher than the average air quality impact for the sectors examined in this study, due to the nonlinear nature of air quality impacts.

Additionally, to provide an approximation of the potential annual health savings that could result for the on- and off-road sub-sectors, a range for LDV, MDV, HDV, and Construction, Farm, and all other vehicles and equipment is presented in Table 7 based upon the ratio of episodic $PM_{2.5}$ health savings for the summer and winter episodes. **It is important to note that using episodic modeling to estimate annual health impacts is not an ideal method as it does not capture the variable meteorological conditions, seasonal variations in energy demand, etc. that the annual simulations do. However, it provides a reasonable approximation of the relative breakout of each sub-sector within the annual runs.** It would be beneficial for future work to evaluate these sub-sectors using annual simulations as was done for the four main scenarios in this report.

Fuel consumption for the on-road vehicle fleet was taken from EMFAC 2017 (California Air Resources Board (CARB) 2017) and converted to gasoline gallon equivalent (GGE), a unit of energy representing the energy content of one gallon of gasoline, for all emitting fuels including gasoline and diesel. GGE is used as a common unit because gasoline and diesel have different energy densities, so reporting in terms of GGE puts both fuels on a common playing field. Considering the allocation of benefits on a per GGE basis, we estimate the health savings from reducing emissions from on-road vehicles to be approximately $1.47/gge (2020$) averaged across the entire state and $2.88/gge (2020$) within SoCAB. While only an approximation due to the previously discussed limitations of episodic modeling, the value of benefits for LDV could range from $0.56-$0.60/gge in California to $1.29-$1.86/gge in SoCAB (2020$). The per-gallon values for HDV are particularly high as a result of dividing higher health impacts by a significantly lower total fuel consumption, estimated to be $4.20-$4.52/gge in California and $7.00-$9.94/gge in SoCAB (2020$). The results demonstrate the value of electrifying on-road vehicles, particularly HDV. The natural gas generation per-unit number was developed by dividing by the MWh of generation estimated from SERVM as described above in the methods section. The natural gas buildings per-unit number was developed by dividing by residential and commercial gas consumption in the IEPR Managed Forecast, which was used in the development of the CEPAM projections used in this work. Per-unit numbers were not developed for the off-road subsectors due to a lack of available data on fuel consumption feeding into the CEPAM projections.

Table 7. Per unit energy/vehicle public health savings by sector and subsector.

STUDY	CALIFORNIA HEALTH SAVINGS (2020$)	SOCAB HEALTH SAVINGS (2020$)	PER-UNIT SAVINGS CALIFORNIA	PER-UNIT SAVINGS SOCAB
NG GENERATION	$963M	$594M	$14/MWh	$35/MWh
NG GENERATION – CAISO**	$764-$856M	$461-516M	$14-$16/MWh	$41-$46/MWh
NG BUILDINGS	$7,353M	$4,703M	$1.23/therm	--
ON-ROAD VEHICLES	$20,389M	$15,374M	$1.47/gge	$2.88/gge
LDV**	$5,687-$6,069M	$5,300-$7,642M***	$0.56-$0.60/gge	$1.29-$1.86/gge
MDV**	$3,215-$3,648M	$2,509-$2,665M	$2.77-$3.14/gge	$5.45-$5.79/gge
HDV**	$10,477-$11,286M	$5,222-$7,407M	$4.20-$4.52/gge	$7.00-$9.94/gge
OFF-ROAD EQUIPMENT	$15,789M	$11,686M		
CONSTRUCTION & MINING**	$1,477-$3,862M	$745-$2,654M		
FARM EQUIPMENT**	$2,308-$4,739M	$348-$943M		
ALL OTHER OFFROAD**	$9,572-$9,619M	$8,088-$10,591M		

** represents ranges estimated using a ratio between episodic and annual impacts; see caveat in paragraph above.

*** note that the higher end of this range is higher than the statewide LDV range, due to the methodology for allocating impacts to subsectors, in which the CA and SOCAB impacts were allocated separately.

3.4 Benchmarking

3.4.1 Comparison with other studies

To benchmark the results of this study, the available scientific literature was surveyed for similar assessments. The most directly comparable is a study with reasonably similar methods that reported avoiding emissions from fossil fuel electricity was associated with health savings of \$5.5–\$14.3/MWh (2020\$) for 2015 in-state generation in California (Machol and Rizk 2013). There are several factors that explain the differences between the results of the Machol study and the current study. First and most importantly, to estimate the health impacts, Machol used a national average benefit per ton estimate derived from a 2009 national-scale assessment using a reduced form version of CMAQ at a significantly lower resolution (i.e., 36 km X 36 km). Health impacts vary substantially in urban areas because of local atmospheric conditions, population density, and baseline health, and other factors, and these national assessments do not capture these variations as well as the methods used in the current study. As a result, the authors of the study conclude that their results "tend to overestimate the impacts in rural areas and underestimate the impacts in urban areas". Additionally, the study uses older data inputs which are less precise than those we use, including the underlying emissions inventory, meteorology, and population projections. Another key difference is the use of population projections in our work, as opposed to current population, as increases in total population and differences in age distribution result in higher avoided health impacts, particularly in urban regions. Given the importance of accurately capturing impacts within the SoCAB due to the dominant contribution to the overall results, it is understandable that our estimate is higher.

It is important to mention the Interim Air Quality Adder estimate of \$6/MWh developed by the CPUC as another example of a comparable study. This estimate was produced using a US EPA tool called COBRA, which was developed as a user-friendly screening tool and is not intended to produce regulatory quality estimates. The Interim Air Quality Adder was developed with the intention of serving only as a temporary approximation, to be replaced with updated research once available. The current study represents this updated research. A further discussion of the differences between COBRA and the methods used in the current study can be found in the Methodology section.

In addition, while not directly comparable, there are some recent studies that can provide insight into the relative scope and scale of the results. The first is an assessment of the air quality and human health impacts of a high electrification scenario in California conducted for the CEC that used very similar methods to the current study, including comparable air quality and human health impact assessments (Alexander et al. 2019). However, a major difference is that the CEC's electrification assumptions resulted in prominent emission reductions from many end-use sectors simultaneously, including on- and off-road equipment, industry, buildings, etc. within each scenario, whereas our study examined reductions from only one sector at a time. Thus, the results are not directly comparable in terms of total magnitude, but we include a comparison of \$ benefit per ton of NO_x reduced in Table 7 below (which should be more comparable than the total impact numbers) to benchmark the results.

An additional study that is not directly comparable but still serves as a useful benchmark is the South Coast Air Quality Management District's (SCAQMD's) socioeconomic modeling in support of the 2016 Air Quality Management Plan (AQMP), which estimated health benefits of the air quality management plan in 2031 of \$33.9 billion in 2020\$ (Shen, Oliver, and Dabirian 2017). As previously noted, the methods used in the current study were directly informed by those employed for that work. Similar to the CEC report, the AQMD's report involves quantification of emission reductions from many different end-use sectors including transportation, residential and commercial buildings, and industry. It should be noted that the emission reductions projected in the AQMP are not complete removal of those sectors as was done for the current study. Additionally, the results include only those occurring in SoCAB. Nonetheless, the order of magnitude of the \$ benefits per ton of NO_x reported in the SCAQMD study are consistent with the modeling results of the current study.

Table 8 below shows a comparison of NO_x benefit per ton in SoCAB between the current study and the SCAQMD and CEC studies mentioned above. SoCAB is used as the point of comparison because the majority of health impacts found in the current study are in SoCAB, and because the SCAQMD study is SoCAB only. Overall, the benefits per ton estimated in the current study are higher than those reported in the other studies, although the results for the On-Road and NG Buildings scenarios are comparable. While the results for NG generation and Off-Road equipment are higher per ton NO_x than both the CEC and SCAQMD studies, it should again be considered that there are differences across the studies which could contribute to this difference including methods of population projection, spatial differences in the sources of emission reductions, meteorological inputs, choices of health impact functions in BenMAP, etc.

In particular, population projections have a major influence on the results. The results for NG generation are presented with the 2018 population distribution instead of the 2035 population in the table below to illustrate this point; a similar reduction would be observed if the impacts of the other sectors under a 2018 population were included. In particular, the 65+ age group population, which has a 20x higher incidence rate of morbidity compared to the under-65 age group, is a key driver of results. The Department of Finance population projections used to develop population estimates for 2035 include an approximately 42% increase in the 65+ population in SoCAB, which explains the significantly higher benefits in 2035 compared to 2018. For natural gas generation it is also important to note that only a small amount of NO_x is removed relative to the other sectors. As the response to air pollutant concentrations is often nonlinear, the benefit per ton reported in the current study for natural gas generation could be higher compared to the other studies in part because of the nonlinear nature of air quality impacts (i.e., removing a small amount of NO_x could have a higher benefit per ton than removing a larger amount of NO_x).

Table 8. Comparison of NO_x Benefit per Ton in SoCAB Across Studies.

STUDY	HEALTH BENEFITS IN SOCAB (2020$)	NOX REDUCTION IN SOCAB (TONS PER DAY)	MILLION $ BENEFITS PER TONS PER DAY NOX (2020$)
THIS STUDY: NG GENERATION	$594M	0.7	**$849**
THIS STUDY: NG GENERATION WITH 2018 POPULATION	$487M	0.7	**$696**
THIS STUDY: NG BUILDINGS	$4,703M	12.2	**$385**
THIS STUDY: ON-ROAD	$15,374M	33	**$466**
THIS STUDY: OFF-ROAD	$11,686M	16	**$730**
CEC STUDY (HIGH ELECTRIFICATION SCENARIO)	$61,490M	205	**$300**
SCAQMD STUDY (IMPACT OF NEAR-TERM REGULATIONS)	$34,000M	128	**$266**

This discrepancy in results due to population estimates (which can be seen by comparing the first two rows of the table) illustrates the sensitivity of the results to this key metric. It also helps explain much of the difference in NO_x benefit per ton between the current study and the CEC and SCAQMD studies, as these studies may have used different methods for estimating population growth.

There are other differences across the studies which could also contribute to the differences noted, including spatial differences in the sources of emission reductions, meteorological inputs, choices of health impact functions in BenMAP, etc. Additionally, since the response to air pollutant concentrations is nonlinear, the benefit per ton reported in the current study could be higher compared to the other studies listed above in part because this study involved removing only a relatively small amount of pollutants (i.e., this study examined the “marginal” effect of removing NOx from specific sectors, whereas the other studies examined something closer to the “average” effect of removing NOx across multiple sectors at the same time). It is important to note, however, that some difference is to be expected between the results of the current study and the CEC and SCAQMD studies shown in the table above, even if the methodology were the exact same between the studies, as the studies are examining the impact of different sectors which each emit different pollutants in distinct locations.

4 Key Conclusions and Discussion

This study has several key conclusions:

- The electrification of on-road transportation, off-road transportation, and natural gas combustion in buildings would achieve monetized human health benefits of about $44 billion per year in total, reflecting the avoidance of 4,843 premature deaths per year as well as other health benefits such as reduced hospital visits. These impacts can also be expressed as per-unit-energy impacts, highlighting the particularly high air quality impact of heavy-duty vehicles (all values in 2020$):

• SECTOR	UNIT	$/UNIT	$/MMBTU
GAS GENERATION*	$/MWh	$ 14.00	$ 1.75
GAS COMBUSTION IN BUILDINGS	$/therm	$ 1.23	$ 12.30
ALL ON-ROAD VEHICLES	$/gge	$ 1.47	$ 10.97
LIGHT-DUTY VEHICLES	$/gge	$ 0.56-0.60	$ 4.18-4.48
MEDIUM-DUTY VEHICLES	$/gge	$ 2.77-3.14	$ 20.67-23.43
HEAVY-DUTY VEHICLES	$/gge	$ 4.20-4.52	$ 31.34-33.73

* for gas generation, the $/MMBtu is based on the quantity of natural gas consumed

- In comparison, the removal of emissions from all gas generators in the state would achieve air quality benefits of about $1 billion, reflecting the avoidance of 107 premature deaths per year, due to the significant emissions controls already required for gas generators, the cleaner profile of natural gas combustion relative to other fuels including petroleum fuels, and efforts to locate large gas generators outside of population centers.
- Due to these relative benefits, programs that reduce direct use of fossil fuels, such as electrification programs and natural gas energy efficiency, are likely to have an air quality benefit that is orders of magnitude greater than that of programs such as electric energy efficiency and rooftop solar that impact air quality solely by reducing emissions from gas generators. (Note that this result would not hold for other states with less stringent emissions controls for point sources, and/or with a bigger dependence on coal generation.
- Most of the potential air quality benefits achievable are in the South Coast Air Basin (LA Basin), highlighting the importance of targeting fossil fuel reducing programs in this region.
- Transportation electrification has the potential to achieve significant benefits for disadvantaged communities, since these communities are much more likely to be located near roadways. For example, we find that 39% of the air quality benefits from on-road transportation electrification

can be expected to occur in disadvantaged communities, which represent only 25% of the population.

The results of this study will allow the quantification of societal air quality co-benefits from any program that changes emissions from natural gas generators, on-road transportation, or buildings. These results have the potential to be applied in cost effectiveness modeling via a Societal Cost Test, which is not yet used in decision making, but could potentially be applied in the future using data from this study.

5 Technical Appendix: CMAQ Methodology Details

CMAQ is a comprehensive air quality modeling system developed by the USEPA and widely used for various air quality assessment needs, including regulatory compliance and atmospheric research associated with tropospheric ozone, PM, acid deposition, and visibility (K M Foley et al. 2010; Kristen M. Foley et al. 2014). To appropriately model atmospheric chemistry and transport, various inputs are required in addition to the emissions from energy systems, including meteorological conditions and emissions from natural sources. For this study, the SAPRC-07 chemical mechanism (Carter 2010) is selected for gas-phase chemistry, and AERO6 module (Pye et al. 2017) is used to calculate aerosol dynamics. The Advanced Research Weather Research and Forecasting Model (WRF-ARW, 3.7) is used to downscale meteorological conditions from the (Final) Operational Global Analysis data (Ncep 2000). The boundary conditions are obtained via the Model for Ozone and Related Chemical Tracers (Emmons et al. 2010). CMAQ model output has been compared with observational data and verified to satisfy the statistical requirements for acceptable performance established by both USEPA and the research community (S. Zhu et al. 2019). Although simulations are conducted with anthropogenic emissions that have been projected to 2035, the boundary and meteorological conditions are held constant to ensure the impacts that result are solely from the changes in emissions from the sectors of interest. Therefore, it should be noted that additional factors influencing future regional air quality are not considered, including the impacts of climate change and transported pollution from outside California.

The two pollutants used to assess air quality are $PM_{2.5}$ and tropospheric ozone, as many regions of California experience ambient levels in excess of State and Federal health-based standards (CARB 2017b), and both are associated with human health detriments supported by a broad body of scientific literature (Dockery et al. 1993; Samet et al. 2000; Pope III and Dockery 2006). For consistency with ambient air quality standards, ground-level concentrations are reported as maximum daily 8-h average ozone (MD8H) and 24-h average $PM_{2.5}$. For $PM_{2.5}$, to provide a marker of the general impact experienced throughout the entire year the average 24-h $PM_{2.5}$ experienced for each modeling grid cell is calculated. For ozone, the average MD8H difference is calculated and reported only from April to November as those months typically experience a higher prevalence of factors that drive ozone formation including ample sunlight, warm temperatures and potentially stagnant conditions (Parrish et al. 2017). Conversely, ozone concentrations do not typically exceed health based standards in winter months and often respond inversely to precursor emission reductions due to complex atmospheric phenomena associated with NO_x titration, i.e., reductions in NO_x yield increases in ozone (Jhun et al. 2015). This outcome is well known in California, particularly in the SoCAB, and would be concerning for the accuracy of the modeling if it was not present (S. Zhu et al. 2019).

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