Chapter Three

Air Quality Impacts from Well Stimulation

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3.1. Abstract

Well stimulation has the potential to emit greenhouse gases (GHGs), volatile organic compounds (VOCs), nitrous oxides (NO_x), toxic air contaminants (TACs), and particulate matter (PM). These pollutants can have impacts across various temporal and spatial scales ranging from long-term, global impacts (e.g., from GHGs) to local, short-term impacts (e.g., from TACs). Because oil and gas development in general can have these impacts, the purpose of this chapter is to evaluate what is known about the contribution of well stimulation to general impacts from oil and gas development. This chapter performs analysis at the statewide scale (GHGs) and at regional air district levels (criteria pollutants and air toxics). For an analysis of air impacts at small spatial scales, see Volume II, Chapter 6, which covers public health aspects of oil and gas development.

Detailed air pollution inventories are performed by the California Air Resources Board (CARB) for all major industrial sectors, including oil and gas production. Current inventory methods provide estimates of the air quality impacts related to oil and gas activities (see discussion of inventory data gaps below).

Statewide, oil and gas operations are small contributors to GHG emissions (4%), and most of these GHG emissions are associated with heavy oil production in oilfields developed without well stimulation.

In the San Joaquin Valley air district, oil and gas sources are responsible for significant contributions to sulfur oxides (SO_x) emissions (31%) and smaller contributions to reactive organic gases (ROGs) and NO_x (8% and 4%, respectively). Oil and gas activities in the San Joaquin Valley are estimated to contribute to non-negligible (>1%) fractions of some TAC species (benzene, formaldehyde, hexane, zylene) and the majority (70%) of hydrogen sulfide emissions. The fractional importance of upstream oil and gas sources to air quality concerns is higher in some sub-regions within air districts, such as western Kern County. In the South Coast air district, the oil and gas sector is a small source (<1%) of all studied pollutants.

Well stimulation is estimated to facilitate about 20% of California production, and direct well stimulation emissions represent only one source among many in the oil and gas production process. Applying these weighting factors, well stimulation emissions (direct and indirect) can be estimated at approximately one-fifth of emissions reported above.

Experimental studies of air quality in California suggest that current inventory methods underestimate methane and VOC emissions from California oil and gas sources. This suggests that the above inventory results should be considered lower-bound estimates, and the degree of inventory underestimation varies by study type and location.

Oil and gas activities occur in California air basins that already face severe air quality challenges. The two largest oil and gas-producing regions in California are in the San Joaquin and South Coast air basins, which are non-compliant with federal air quality (ozone and PM) regulations. In some cases, this non-compliance is rated as “severe” or “extreme.”

While well stimulation emissions are a small portion of overall emissions sources in California, they can still be improved. A significant reduction in emissions related to well stimulation is possible using currently available technology. Some mitigation technologies are currently mandated by federal or state regulatory requirements, such as “green completions” technologies that capture gas produced during the flowback process (which would otherwise be flared or vented). Current regulatory requirements do not cover or require application of all available control technologies, and the regulatory environment is in flux federally and in California. For example, the California Air Resources Board is currently examining oil and gas sector emissions in order to develop standards to supplement recent federal regulations.

Significant data gaps exist with respect to air emissions from well stimulation. It is not clear how completely the current inventory methods cover air quality impacts from well stimulation, although it appears that at least some well stimulation air impacts will be covered by current inventory methods. Current inventory methods are not designed to separately analyze well stimulation emissions. As noted above, inventories are only infrequently verified experimentally. A small number of studies have directly measured emissions from well stimulation or in regions where well stimulation occurs. A larger body of studies exists on indirect (remote) estimates of oil and gas-related emissions in oil and gas-producing regions. There is no current consensus on where well-stimulation-related emissions specifically are largest, and significant uncertainty exists regarding emissions sources from oil and gas activities in general, although as noted above the experimental estimates of emissions have generally been found higher than inventory levels of emissions from oil and gas sources.

Preliminary quantitative assessment of the impacts due to well stimulation is made in the Volume III case studies for the San Joaquin Valley and South Coast regions.

3.2. Introduction

Well stimulation can impact air quality via emission of a large variety of chemical species. These species can have local, regional, or global impacts, mediated by the regional atmospheric transport mechanisms and the natural removal mechanisms relevant for that species. For clarity, this report groups species into four categories of interest, each with unique potential impacts.

1. Greenhouse gases (GHGs).

2. Volatile organic compounds (VOCs), and nitrogen oxides (NO_x) that cause photochemical smog generation.

3. Toxic air contaminants (TACs), a California-specific designation similar to federal designation of hazardous air pollutants (HAPs).

4. Particulate matter (PM), including dust.

GHGs have global impacts over long time scales through their effects on the radiation balance of the atmosphere. GHGs can also have significant local ecosystem effects, such as ocean acidification from rising atmospheric carbon dioxide (CO_2) concentrations. VOCs have regional impacts over the short- to medium-term through their effects on formation of photochemical smog and exacerbation of chronic health problems. In portions of this report dealing with California inventories of criteria pollutants, the term *reactive organic gases* (ROGs) will be used instead of VOC. ROGs are a defined class of species in California regulation, and have similar membership as other designations such as volatile organic compounds, nonmethane volatile organic compounds or speciated nonmethane organic compounds (ROGs, NMVOCs or SNMOCs). TACs and PM have local and regional health impacts mediated by transport and inhalation processes.

Some chemical species have impacts across multiple categories. For example, in addition to smog-formation potential, VOCs often also function over short and long time scales as GHGs through their eventual decomposition into CO_2. In these cases, species will be discussed primarily in terms of their most notable impact pathway. For example, though the degradation products of benzene can act as GHGs, benzene will be discussed as a TAC due to its larger importance in that domain. Similarly, PM has health as well as climate and aesthetic (visibility) impacts.

3.2.1. Chapter Structure

This introductory section first describes methods of classifying well-stimulation-related air impacts, and the major sources and types of emissions from oil and gas activities (remainder of Section 3.2). This is followed by an outline of current treatment of well-stimulation-related emissions in current California emissions inventories (Section 3.3).

Then, the report discusses the California regions likely to be affected by the use of well stimulation technology (Section 3.3.17) and the hazards associated with possible air impacts (Section 3.4). Next, the report outlines current best practices for managing air quality impacts of well stimulation (Section 3.5). This is followed by a discussion of gaps in data and scientific understanding surrounding well-stimulation-related air impacts (Section 3.6). Finally, a summary of findings and conclusions is presented (Sections 3.7 and 3.8).

3.2.2. Classification of Sources of Well Stimulation Air Hazards

Emissions from well stimulation can be classified as direct or indirect emissions. Direct impacts are uniquely associated with well stimulation and do not occur when oil and gas are produced without the aid of well stimulation. Examples of direct impacts of well stimulation include greenhouse gas emissions from equipment used to stimulate the well, and off-gassing of VOCs from stimulation fluids held in retention ponds and tanks. Indirect impacts stem from the other aspects of the oil and gas production process apart from well stimulation. Examples of indirect impacts include emissions from equipment used for well-pad construction, well drilling, and production of oil and gas; and off-gassing from produced water. This chapter will focus primarily on direct impacts, although important indirect impacts will also be discussed. This is because indirect impacts play an important role in air quality impacts in regions of significant well stimulation activities, and may be important determinants of long-run air quality impacts of well stimulation.

3.2.3. Greenhouse Gas Emissions Related to Well Stimulation

GHG and climate-forcing emissions to the atmosphere associated with well stimulation include the following: carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), VOCs, and black carbon (BC) (IPCC, 2013, pp. 738-740). For the purposes of GHG accounting, IPCC practice recommends binning all VOC species by mass of carbon (IPCC, 2013, pp. 738-740). Well stimulation practice can also result in the emission of species with negative climate forcing (i.e., cooling impacts) such as NO_x and organic carbon (OC) (IPCC, 2013). Nevertheless, the net effect of emissions from well stimulation is expected to be primarily warming. The climate impacts, listed using current 20-year and 100-year global warming potentials (GWPs) for well-stimulation-relevant gases, are listed in Table 3.2-1.

Table 3.2-1. Global warming potential of well-stimulation-relevant air emissions. (IPCC, 2013)

Gas species	GWP 20-yr	GWP 100-yr	Notes
Carbon dioxide (CO_2)	1	1	a
Methane, fossil (CH_4)	85	30	a
Nitrous oxide (N_2O)	264	265	a
Carbon monoxide (CO)	5.6 (+/-1.8)	1.8 (+/- 0.6)	b
Volatile organic compound (VOC)	16.2 (+/- 9.2)	5.0 (+/- 3.0)	c
Black carbon (BC)	1200 (+/- 720)	345 (+/- 207)	d
Organic carbon (OC)	-160 (+/- 68)	-46 (+/- 20)	d
Nitrogen oxides (NO_x)	-2.4 (+/ 30.3)	-8.2 (+/- 10.3)	e

a – From (IPCC, 2013) Table 8.A.1
b – From (IPCC, 2013) Table 8.A.4, for CO emissions in North America. CO GWP varies by the region of emissions due to regional differences in atmospheric processes.
c – From (IPCC, 2013) Table 8.A.5. Measured on per-kg of carbon basis. Estimate for North America VOC GWP varies by the region of emissions due to regional differences in atmospheric processes.
d – From (IPCC, 2013) Table 8.A.6. BC and OC GWPs taken from "four regions" study result, which encompasses East Asia, European Union (EU) + North Africa, North America, and South Asia.
e – From (IPCC, 2013) Table 8.A.3. Values for NO_x from North America.

3.2.4. Volatile Organic Compounds and Nitrous Oxides Emissions Related to Well Stimulation

VOCs are a large class of organic compounds that are variously defined. Thousands of chemical species are included in VOC definitions, with many of them present in hydrocarbon gases and liquids. VOCs include benign compounds as well compounds that are directly hazardous to humans. Hazardous VOCs will be discussed in the TACs section below. In certain conditions, VOCs react in the atmosphere to increase ozone formation. Some VOCs are transformed by atmospheric processes to particulate matter (PM).

Definitions of VOCs vary between regulatory regimes. U.S. Environmental Protection Agency (U.S. EPA) definitions list VOCs as organic species with vapor pressure greater than 10^{-1} Torr at 25°C and 760 mmHg (U.S. EPA, 1999). This regulatory definition exempts non-photochemically active species such as CH_4 and ethane (C_2H_6). This definition is designed to include organic species that are likely to exist in gaseous phase at ambient conditions. VOC emissions associated with well stimulation are numerous, with oil-and-gas-focused air studies measuring concentrations of many dozens of species (U.S. EPA, 1999; ERG/SAGE, 2011).

NO_x emissions associated with well stimulation activities derive primarily from use of engines powered by diesel or natural gas, which are used directly in well stimulation applications. Examples include drilling and workover rigs, fracturing trucks with large pumps for generating high fluid injection pressure, and other trucks of various kinds (e.g., proppant delivery trucks). Flaring can be another source of NO_x from oil and gas operations.

3.2.5. Toxic Air Contaminant Emissions Related to Well Stimulation

There are numerous TACs associated with well stimulation, which most commonly fall into the category of toxic organic compounds (TOCs) (U.S. EPA, 1999). These well-stimulation-associated TACs include many of the species defined as VOCs in the Clean Air Act (CAA) Amendments of 1990. TACs can be an acute or chronic concern for workers in the oil and gas industry, due to possibly frequent exposure to elevated concentrations of TACs, as well as long-term work in environments with TACs. TACs may also present a health concern for more remote persons that are less heavily exposed, such as those who live near oil and gas operations.

3.2.6. Particulate Matter Emissions Related to Well Stimulation

PM emissions in oil and gas development occur most commonly due to stationary combustion sources (CARB, 2013b). Other PM sources include heavy equipment in on-road and off-road operations, and land disturbance. Common sources of PM include diesel-powered equipment such as trucks, drilling rigs, generators, and other off-road equipment (e.g., preparatory land-moving equipment) (CARB, 2013b). PM may also be emitted through combustion (flaring) of wet gas (i.e., gas containing high molecular weight hydrocarbons). PM emissions are associated with respiratory health impacts and increased rates of mortality (see Chapter 6 on health impacts).

3.3. Potentially Impacted Resource—Air

3.3.1. California Air Quality Concerns

California has faced air quality concerns for many decades. Historical attention has focused primarily on smog-forming pollutants (e.g., VOCs and NO_x) and toxic air contaminants (TACs). A number of factors result in California air quality being among the most impacted in the nation. First, a large population of 40 million residents results in significant air emissions. Second, some California regions have unfavorable topography for air quality management, including large urban areas surrounded by mountains that prevent mixing and transport of emitted species. Third, the generally warm and sunny conditions in the state promote photochemical reactions and formation of smog. In some regions (noted below), agricultural activities can result in fine particulate pollution of concern.

More recently, regulatory efforts at the California Air Resources Board (CARB) have focused on GHG emissions. This has resulted in the development of broad industry-spanning GHG cap and trade regulations (CARB, 2014a), as well as oil and gas-specific regulatory efforts and ancillary transport-fuel regulations that affect oil and gas operators (CARB, 2014b).

CARB defines 35 Air Pollution Control Districts (APCDs) and Air Quality Management Districts (AQMDs), which are collectively called "air districts" (CARB, 2014c). These air districts are shown in Figure 3.3-1.

The two largest California oil and gas-producing regions are contained within the San Joaquin Valley Unified air district (henceforth SJV) and South Coast air district (henceforth SC). Significant oil production also occurs in the Santa Barbara and Ventura air districts. Non-associated (dry) natural gas production occurs in a number of Northern SJV air districts.

Large quantities of GHGs, VOCs, TACs, and PM are emitted by non-oil and gas sources in California, including primary industry, homes and businesses, and the transport sector.

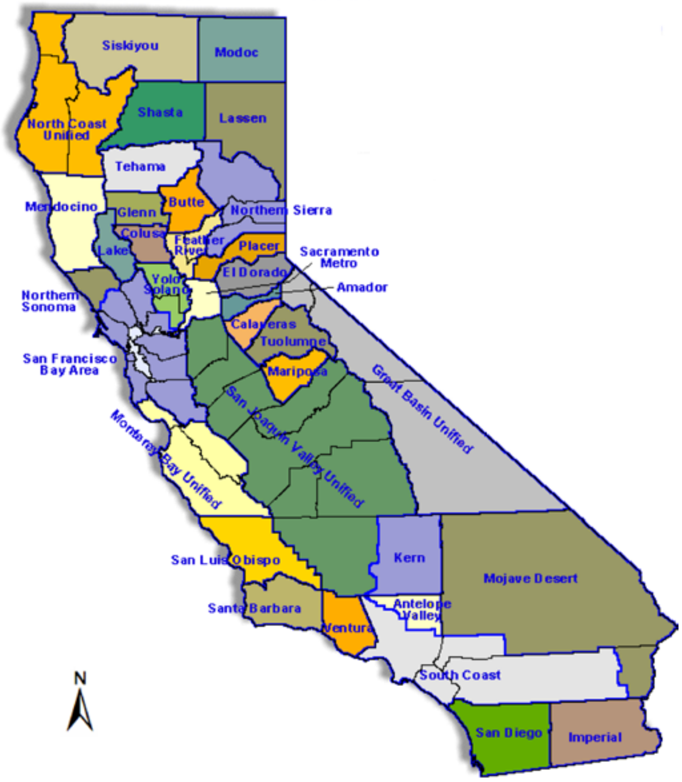


Figure 3.3-1. California Air Pollution Control Districts (APCDs) and Air Quality Management Districts (AQMDs), collectively called "air districts." Image reproduced from CARB (2014c).

3.3.2. Estimating Current Impacts of Oil and Gas Operations on California Air Quality

Estimates of emissions for species of interest in California are tabulated, estimated, or inventoried for a variety of sources in the oil and gas sector. These estimates include:

1. Field-level estimates of GHG emissions produced for transport GHG intensity regulations (i.e., Low Carbon Fuel Standard).
2. State-level inventories of GHGs, ROGs, TACs, and PM compiled by the California Air Resources Board (CARB)
3. State-level surveys of emissions from oil and gas operators
4. Federal databases of GHG emissions and toxics releases (U.S. Environmental Protection Agency)
5. Detailed (spatially and temporally) inventories of air emissions for photochemical grid-based modeling of ozone formation.

This chapter covers the first four of these sources of information, with a strong focus on California-specific methods (first three sources in above list). These methods are described in order below, starting with field-level GHG intensity estimates. Each section describes the estimation methods and estimates derived for each species of interest, in the order of GHGs, VOCs, TACs, and PM. Table 3.3-1 shows a summary of where data were obtained for each type of assessment.

Table 3.3-1. Coverage of different assessment methods and key sources for each method.

Estimate type	**Resulting data**	**Data source**	**Source**
Field-level GHG estimates	t CO_2eq[1]. GHGs per year	DOGGR[2] production data	(DOGGR, 2014)
		CARB and OPGEE[3] model results of GHG intensities	(Duffy, 2013) (El-Houjeiri et al., 2013, 2014)
State-level emissions inventory	t CO_2eq. GHGs per year	CARB yearly GHG inventory	(CARB, 2014d,e) (CARB, 2013a)
	t ROG per year	CARB criteria pollutants inventory, incl. stationary and mobile sources	(CARB, 2013b)
	kg TACs per year	CARB overall toxics inventory (California Toxics Inventory)	(CARB, 2013c)
	kg TACs per year	CARB facility-level toxics reporting	(CARB, 2014j)
	t PM per year	CARB criteria pollutants inventory, incl. stationary and mobile sources	(CARB, 2013b)
Surveys of oil and gas operators	t CO_2eq. GHGs per year	CARB special survey of oil and gas operators	(Detweiler, 2013)
Federal GHG and toxics databases	Various	Not studied extensively in this report	(U.S. EPA, 2012)

[1] *CO_2-equivalent*

[2] *Department of Oil, Gas, and Geothermal Resources*

[3] *Oil Production Greenhouse Gas Emissions Estimator*

The scale at which emissions are assessed, and how emissions and their impacts are quantified, can influence study results. With regard to spatial scale, this chapter covers emissions at the statewide scale (in the case of GHG emissions) and at regional air district scales (in the case of criteria pollutants and air toxics). GHG emissions are assessed for the state as a whole, because GHGs are a global problem largely independent of location of emissions. In contrast, regional air districts are assessed for other pollutants, because these regions are designated by CARB as regions where atmospheric mixing and transport require the pollutants in a given region to be co-regulated. With regard to how emissions are quantified in this chapter, we examine mass-emissions rates and the fractional responsibility of oil and gas industry sources to the air quality problems studied.

Other spatial scales can matter for some pollutants. For example, emissions responsibility for oil and gas operations over smaller spatial scales can be higher than for an air district-wide measure. For example, when emissions are assessed for Kern County alone, there is larger responsibility of oil and gas sources than those found in this chapter for the San Joaquin Valley air district. At an even finer spatial scale, the specific location of an air toxics source can be very important. These smaller-scale assessments can be found in the following locations:

- County-scale assessment of impacts: Volume III, San Joaquin Basin Case Study; Volume III, Los Angeles Basin Case Study.
- Local-scale assessment of emissions near sensitive populations: Volume II, Chapter 6 and Volume III, Los Angeles Basin Case Study and San Joaquin Basin Case Study.

Also, there are other ways to measure the importance of emissions than mass-emissions rates and the fraction of responsibility for a given industry. For example, in public health studies generally, the concentration of pollutant and the mass of pollutant being inhaled by the studied population is of concern, not necessarily the overall mass emissions rate in an air basin. Some health-damaging pollutants may therefore be of great concern at a local scale, even with small mass-emissions rates (e.g., oil and gas associated TACs such as benzene or toluene). See Volume II, Chapter 6, and Volume III, Los Angeles Basin Case Study for more information.

3.3.2.1. California Air Resources Board Field-Level Estimates of Greenhouse Gas Emissions from Oil Production

CARB produces an estimate of the greenhouse gas intensity of different producing oilfields in California, as part of the Low Carbon Fuel Standard (LCFS) effort (Duffy, 2013). The LCFS seeks to incentivize the production and consumption of transportation fuels with lower life cycle greenhouse gas intensity compared to conventional oil resources. Because the structure of the regulation assesses alternative fuels in comparison to oil-derived fuels, an accurate baseline emissions intensity for oil consumed in California is required.

As part of this effort, 154 California oil fields are assessed using the Oil Production Greenhouse Gas Emissions Estimator (OPGEE), an open-source tool produced by researchers at Stanford University (El-Houjeiri et al., 2014, El-Houjeiri et al., 2013). OPGEE takes the properties of an oilfield and uses them to estimate the greenhouse gas emissions associated with producing, processing, and transporting the crude oil to the refinery inlet gate. While OPGEE cannot be used to assess emissions individually from pools that are facilitated or enabled with well stimulation technologies, it can be used to assess the emissions from oilfields within which well-stimulation-enabled pools exist.

Using information from Volume I, Appendix N, a total of 45 pools across California were determined to be facilitated by or enabled by well stimulation technologies. These pools are located in 28 California oilfields. While the pools themselves were found to account for ~20% of California oil production, the fields within which these pools exist were responsible for nearly 40% of California's oil production in 2012. The fields in which these pools exist, in general, contain lighter crude oil and result in lower greenhouse gas intensity than the average California oilfield (see Figure 3.3-2). The production-weightedaverage GHG intensity for well-stimulation-enabled pools is approximately 74% that of non-stimulated pools and 64% of California fields in general.

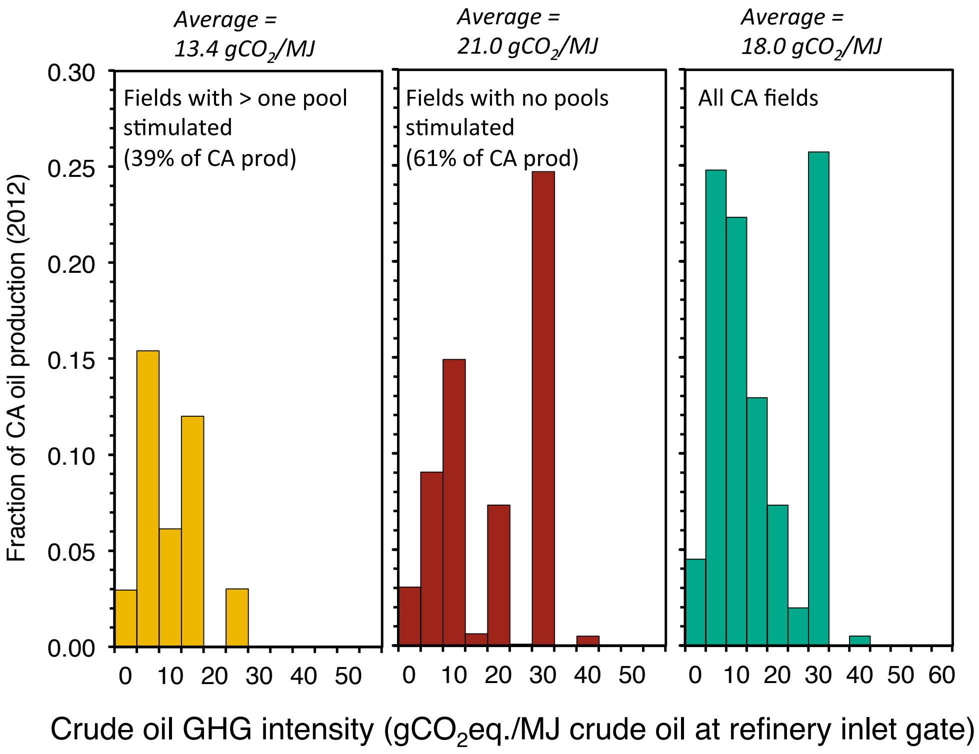


Figure 3.3-2. Distribution of crude oil greenhouse gas intensity for fields containing well-stimulation-enabled pools (left), those that are not stimulated (middle) and all California oilfields (right).

An important question regarding GHG emissions from stimulated wells is: "What would happen to GHG impacts if well stimulation were not practiced in the state?" If well stimulation were disallowed and consumption of oil and gas in California did not drop in response, the required oil would come from some other oilfields. That is, more oil and gas would be required from non-stimulated California fields or regions outside of California. This substitution would be the result of oil market shifts that would occur in response to the shift in California production.

Depending on the source of substituted oil and gas, overall greenhouse gas emissions due to oil production could increase if well stimulation were stopped. Computing the net GHG change associated with well stimulation therefore requires understanding of both in-state and out-of-state production, as well as the likely sources of "new oil." Thus, estimating the scale of impact requires a market-informed life cycle analysis (LCA). (This type of analysis is sometimes called "consequential" LCA.)

3.3.2.2. State-Level Emissions Inventories Produced by California Air Resources Board (CARB)

The California Air Resources Board (CARB) produces annual inventories of emissions of GHGs, VOCs, TACs and PM. These inventory methods and results are described in order below. In all cases, numerical results for 2012 will be presented, due to incomplete reporting for the year 2013 at the time of analysis.

The methods used to generate emissions inventories vary by the gas of interest. In general, emissions inventories collect data at the district level, and aggregate results to generate broader statewide estimates (CARB, 2014d). Direct measurements do not generally underlie emissions estimates included in inventories. For example, stationary source emissions are generally estimated using established emissions factors that are applied to the number of facilities of a given type in an analyzed region for a particular year. Similarly, rather than directly measuring vehicle emissions, databases of vehicle activities are used along with mobile source emissions factors (CARB 2014d). A full description of inventory methods is beyond the scope of this report, but where possible, methods and their impacts on emissions estimates are discussed.

3.3.2.2.1. CARB GHG Inventory for Oil and Gas Operations

CARB GHG inventories are produced on a yearly basis for the “six Kyoto gases”: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs) as well as nitrogen triflouride (NF_3) (CARB, 2014d). CARB GHG inventories report mass emissions of each gas, as well as CO_2-equivalent (CO_2eq.) emissions using IPCC Assessment Report (AR4) GWP factors.

Results from CARB GHG inventories can be queried by economic sector, as well as subsectors of various levels (CARB, 2014e). Direct well stimulation (WS) GHG emissions would be included in the subsector “Industrial > Oil & gas extraction.” Additional indirect well-stimulation-related emissions, such as those resulting from induced hydrocarbon production, may occur more broadly (e.g., oil refining, refined product transport).

CARB GHG inventory methods

For each CARB-defined subsector, an “Activity” is defined. Activities with relevance for WS and for oil and gas activities include “Fuel Combustion” and “Fugitive Emissions.” Within the “Fuel Combustion” activity, activity subsets exist to record the type of fuel consumed (e.g., natural gas, associated gas, distillate fuel). Each activity subset can result in emission of numerous GHGs. Combustion processes typically result in CO_2, CH_4, and N_2O, while fugitive emissions are a large concern due to their CH_4 content. The classification scheme under which direct well stimulation emissions would be classified in CARB GHG inventories is shown in Table 3.3-2. Many indirect emissions induced by WS activities would also be inventoried in these categories.

Table 3.3-2. CARB GHG inventory emissions of interest for WS (CARB, 2014e).

Main sector	Sub-sector Level 1	Sub-sector Level 2	Sub-sector Level 3	Main activity	Activity subset	GHG emitted
Industrial	Oil & gas extraction	Not specified	None	Fuel combustion	Associated gas	CH_4, CO_2, N_2O
		Not specified	None	Fuel combustion	Distillate	CH_4, CO_2, N_2O
		Not specified	None	Fuel combustion	Natural gas	CH_4, CO_2, N_2O
		Not specified	None	Fuel combustion	Residual fuel oil	CH_4, CO_2, N_2O
		Petroleum gas seeps	Fugitives	Fugitive emissions	NA	CH_4
		Process losses	Fugitives	Fugitive emissions	NA	CH_4, CO_2, N_2O
		Storage tanks	Fugitives	Fugitive emissions	NA	CH_4
		Wastewater treatment	Fugitives	Fugitive emissions	NA	CH_4

The CARB oil and gas GHG emissions inventory methodology is based on two key data sources and methodologies. First, CARB uses IPCC Guidelines with state and federal data sources (IPCC, 2006). More recently, CARB has augmented IPCC-based methods with more detailed reporting under the Mandatory Reporting Regulation (MRR), a state-level regulation requiring detailed reporting of GHG emissions by large emitters.

The IPCC methodology primarily tracks energy use. Briefly, energy use is gathered for a given sector, and this use is multiplied by a fuel-specific emissions factor for each fuel type (CARB, 2014f, pp. 56-58). To complete its oil and gas GHG inventory, CARB obtains fuel use data for oil and gas activities from the following state and U.S. federal sources: U.S. Energy Information Administration (EIA), California Energy Commission, and the California Department of Oil, Gas, and Geothermal Resources (DOGGR) (CARB, 2014f, p. 58). Fugitive emissions are estimated in this methodology using information generated from the California Emission Inventory Development and Reporting System (CEIDARS) database (CARB, 2014f, p. 59), which is developed for tracking criteria pollutants such as VOCs. See significant additional discussion of CEIDARS below.

More recently, the California GHG inventory leverages California MRR datasets relevant to well stimulation and oil and gas activities. MRR data are gathered from the category of processes entitled “Petroleum and Natural Gas Systems” (CARB, 2014g, sect. 95101). MRR data reporting is required from all oil and gas operators whose stationary and process emissions of CO_2, CH_4 and N_2O exceed 10,000 tonnes (t) of CO_2eq. per year, or whose stationary combustion, process, fugitive, and vented emissions of the above gases equal or exceed 25,000 tCO_2eq. per year (CARB, 2014g, sect. 95101). Detailed methods are given for estimation of emissions from various oilfield operations (CARB, 2014g, sect. 95150), with different oil and gas subsegments required to report information using a separate set of individual methodologies (CARB, 2014h). These methods rely on emissions-factor-like approaches for some categories, as well as engineering-based equations for other categories.

Coverage of well stimulation activities in GHG inventory

The CARB GHG inventory covers oil and gas emissions using a variety of mechanisms. With regard to combustion emissions analyzed under IPCC methods, the most important quantities are fuel consumption during well stimulation activities (e.g., diesel fuel to operate hydraulic fracturing operations). Distillate fuel consumption in California for the CARB GHG inventory is taken from U.S. EIA dataset "Adjusted Sales of Distillate Fuel Oil by End Use" (CARB, 2014f, p. 58). This dataset reports distillate fuel consumption partitioned by sector at the state level (U.S. EIA, 2014a). The end use sector of interest is the U.S. EIA-defined "Oil Company" sector, which is defined as per U.S. EIA definitions:

> *"An energy-consuming sector that consists of drilling companies, pipelines or other related oil companies not engaged in the selling of petroleum products. Includes fuel oil that was purchased or produced and used by company facilities for operation of drilling equipment, other field or refinery operations, and space heating at petroleum refineries, pipeline companies, and oil-drilling companies. Sales to other oil companies for field use are included, but sales for use as refinery charging stocks are excluded." (U.S. EIA, 2014b)*

This U.S. EIA definition is sufficiently general such that it should include diesel fuel use for WS activities. Because of the aggregated nature of the U.S. EIA diesel fuel consumption dataset, strictly maintained to provide operator confidentially, no greater specificity can be provided about how accurately this portion of the CARB GHG inventory accounts for combustion GHG emissions directly related to WS. If some California WS-related operators did not report fuel use to the U.S. EIA under these requirements, their use would not be counted.

Non-combustion emissions estimates that are not modeled using mandatory reporting regulation (MRR) methods are derived from the CEIDARS database of criteria air pollutants (CARB, 2014f, p. 59). Fugitive emissions of CH_4, CO_2 and other gases (VOCs) that arise during oil and gas operations are estimated using CEIDARS data. The CEIDARS total organic gases (TOG) emissions inventory (CARB, 2014f) is used for this purpose. This inventory is discussed further below, because this TOG inventory includes VOCs as well as methane emissions. A speciation model (CARB, 2000) is used to estimate emissions of GHGs from TOG emissions sources (CARB, 2014f, p. 59). As discussed below, the coverage of well-stimulation-related activities in the criteria pollutants inventories is uncertain.

Starting a few years ago, the above methods are being supplemented by data reported directly by operators through CARB's MRR program (CARB, 2014f, p. 59). MRR reporting requires reporting of fuel consumed by operators above a size threshold. MRR sources are also required to estimate "fugitive emissions from pipes, storage tanks, and process losses in the oil & gas extraction…sectors" (CARB, 2014f, p. 59), using a series of methods that have been harmonized with federal emissions reporting requirements. It is unknown what fraction of wells drilled in California are drilled by companies reporting to MRR databases, although most data from inventories are still derived from non-MRR sources.

Most relevant to well stimulation activities, flowback emissions from natural-gas well completion, post-well-stimulation activities are to be computed and reported in methods equivalent to U.S. EPA federal reporting requirements using the U.S. EPA GHGRP (GHG reporting program) (GHGRP Subpart W, see below). These methods are a mix of empirical and engineering-based methods for estimating emissions given technology characteristics and operating conditions (e.g., operating pressure).

Given the above level of detail required as part of MRR reporting, it is likely that many well-stimulation-related emissions sources will be included in MRR data. Some well-stimulation-related emissions may not be covered if subcontractor emissions occurring during well stimulation do not meet reporting thresholds related to operator size. It is not possible to discern the exact coverage (or lack thereof) of well stimulation activities within the MRR dataset, due to the aggregated nature of public data reporting.

Results of CARB GHG inventory

Statewide GHG emissions in California totaled 466 Mt CO_2eq. in 2012. The “Industrial > Oil & gas extraction” sector was responsible for ~17 MtCO_2eq., or somewhat less than 4% of statewide emissions (CARB, 2014d).

The dominant contributor to the oil and gas GHG inventory was CO_2 emissions resulting from fuel use. Fuel use in oil and gas development in California is heavily influenced by combustion of fuels for thermal enhanced oil recovery. Fugitive emissions from oil and gas totaled <1.5 Mt CO_2eq., or 0.3% of statewide emissions (CARB, 2014d). As shown in Figure 3.3-3, the overall trend in California oil and gas GHG emissions is downward over time, likely due to decreasing California oil and gas production.

If more recent IPCC AR5 GWPs (see Table 3.2-1) are used instead of CARB-applied IPCC AR4 GWPs, CO_2-equivalent GHG emissions from the California oil and gas industry increase by only a small amount between 2000 to 2012—specifically, the yearly increase ranges from 0.5% to 1.2%. Note that emissions sources classified as “combustion” sources can result in CH_4 emissions due to incomplete combustion or direct loss from combustion equipment.

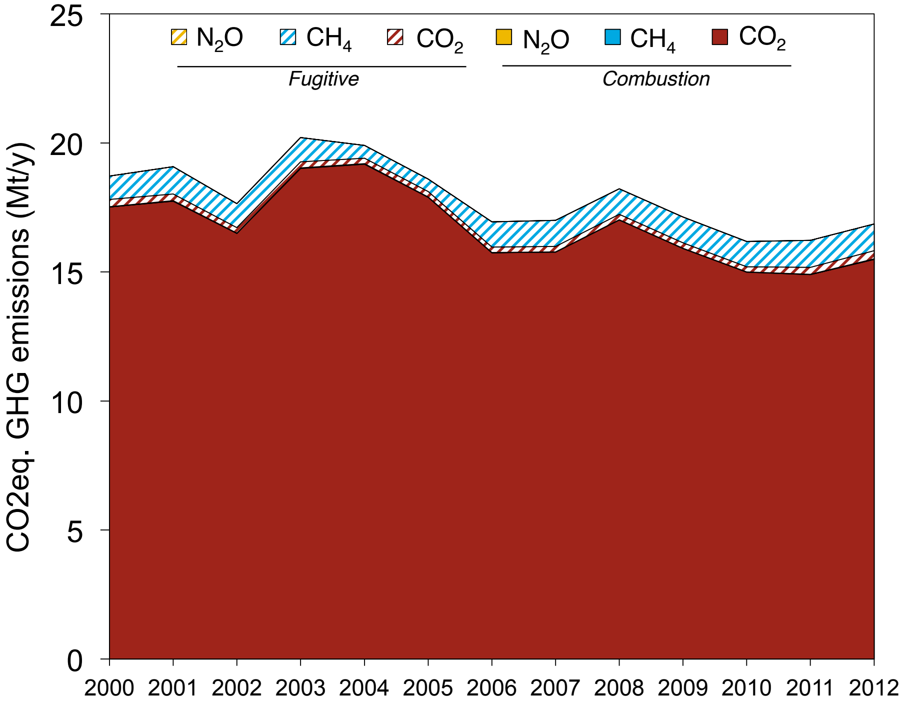


Figure 3.3-3. Emissions from “Oil and Gas Extraction” sources as reported in California GHG inventory. Source: plotted from (CARB, 2014d). Emissions in million metric tonnes per year (109 kg per year). Oil and gas extraction activities account for <4% of total statewide GHG emissions.”

Summary of CARB GHG inventory coverage

The CARB GHG inventory is likely to include emissions from many well stimulation activities. To summarize the discussion above:

- Baseline data for the GHG inventory data appear to derive from a combustion emissions inventory that uses (among other sources) federally reported fuel consumption data for a broadly defined oil and gas sector.

Oil and gas emissions are also subject to (for large producers) MRR requirements, which specify detailed reporting methodologies and broad coverage of combustion and noncombustion sources. Even given this broad reporting requirement and comprehensive coverage, it is not clear that GHG emissions from all well stimulation activities are reported as part of the CARB GHG inventory. For example:

- Smaller producers are exempt from MRR requirements. Given that the criteria pollutants inventory does not definitively include well stimulation activities, these operators could be a source of missing well-stimulation-related GHG emissions.

- MRR data reporting has some known coverage gaps. For example, MRR data reporting includes flowback emissions during completion of well stimulation applied to natural gas wells. However, MRR does not appear to require reporting of flowback emissions from well stimulation applied to oil wells.

3.3.2.2.2. CARB Inventories for VOC and NOx (Smog-Forming) Emissions

CARB inventories of criteria air pollutant emissions are performed on a yearly basis for each air district. Detailed estimates of emissions by sectors, sources, and subsources are presented for a variety of species, including total organic gases (TOG), reactive organic gases (ROG), NO_x, SO_x, CO, and PM. CARB documentation suggests that CARB ROG emissions are very similar to (though not exactly equal to) U.S. EPA-defined VOC emissions (CARB, 2000). TOG emissions include ROGs/VOCs, as well as non-photochemically active organic gases such as CH_4 and C_2H_6 (CARB, 2000). For the remainder of this section, we will use the CARB terminology of ROG.

CARB criteria pollutant inventory methods

The CARB criteria air pollutant inventory is divided broadly into three categories: stationary sources, area-wide sources, and mobile sources. These categories are then broken down into sectors, subsectors, and sources. Inventory methods vary for each broad source category, as well as within each source category. The most relevant categories for smog-forming emissions from well stimulation and oil and gas operations are given in Table 3.3-3. It does not appear that area-wide sources are relevant for well stimulation or oil and gas operations. Detailed lists of contributing equipment or technologies for each subsector are presented below.

Table 3.3-3. CARB criteria pollutant inventory sector/subsector pairings of interest for oil and gas and well stimulation emissions.

Broad category	Sector	Subsector
Stationary sources	Fuel combustion	Oil and gas production (Combustion)
	Petroleum production and marketing	Oil and gas production
Mobile sources	On-road motor vehicles	Various
	Other mobile sources	Off-road equipment

Compared to the GHG inventory described above, the criteria pollutants inventory reports emissions sources in considerable detail. For example, in the stationary source criteria pollutants inventory, emissions are tracked for multiple types of combustion technologies (i.e., reciprocating engines, boilers, turbines, steam generators) rather than a broad “combustion emissions” category. Also, more fuels are represented, with fuel subspecification available for types of distillate fuel or types of gaseous fuel. Lastly, different emissions mechanisms within a given equipment category are represented. For example, ROG emissions from tanks are classified into breathing and working losses for both fixed and floating roof tanks.

To determine the coverage of stationary-source oil and gas emissions, all sources classified in the “Stationary sources > Fuel combustion > Oil and gas production (Combustion)” and “Stationary sources > Petroleum production and marketing > Oil and gas production” subsectors are summed for the SJV and SC regions. The resulting sources and materials (e.g., fuel, working fluid, or chemical) responsible for emissions in these subsectors are listed in Table 3.3-4. While other possible sources might exist in other air basins, these two air basins are indicative of California oil and gas operations and are responsible for the majority of state oil production. The list of sources in Table 3.3-4 is therefore likely to be representative of statewide oil and gas sources (CARB, 2013b).

Table 3.3-4. CARB ROG/CO stationary source inventory emissions sources and material drivers of emissions within the broad categories “Oil and Gas Production” and “Oil and Gas Production (Combustion). Sources and materials taken from SJV and SC air district data.

Sources	**Materials**
Reciprocating engines	Diesel/Distillate oil (unspecified) Gasoline (unspecified) Natural gas Gaseous fuel (unspecified) Propane
Turbine engines	Natural gas Diesel/Distillate oil (unspecified)
Boilers	Natural gas Propane Process gas Residual oil #6 (Bunker C)
Process heaters	Natural gas Residual oil (unspecified)
Steam generators	Natural gas Process gas
Fugitives – Oil/water separator	Crude oil (unspecified)
Fugitives – Wet gas stripping/field separator	Gaseous fuel (unspecified)
Fugitives – Pumps	Crude oil (unspecified)
Fugitives – Compressors	Crude oil (unspecified)
Fugitives – Well heads	Crude oil (unspecified)
Fugitives – Well cellars	Crude oil (unspecified)
Fugitives – Valves	Natural gas Crude oil (unspecified)
Fugitives – Fittings	Crude oil (unspecified)
Fugitives – Sumps and pits	Crude oil (unspecified)
Fugitives – Miscellaneous	Crude oil (unspecified)
Floating roof tanks – Working	Organic chemicals (unspecified)

Fixed roof tanks - Working	Diesel #2 Crude oil – RVP 5 Ethylene Glycol Aromatics (unspecified) Acid (unspecified) Jet Naphtha (JP-4) Glycols (unspecified)
Floating roof tanks - Breathing	Organic chemicals (unspecified)
Fixed roof tanks - Breathing	Diesel #2 Crude oil – RVP 5 Organic chemicals (unspecified) Benzene Methanol Jet Naphtha (JP-4)
Tank cars and trucks - Working	Diesel/Distillate oil (unspecified) Gasoline (unspecified) Crude oil (unspecified)
Natural gas prod.	Natural gas
Steam drive wells	Crude oil (unspecified)
Cyclic steam wells	Crude oil (unspecified)
Oil production - Heavy oil test	Crude oil (unspecified)
Vapor recovery/flares	Process gas Liquefied Petroleum Gas (LPG)
Other	Material not specified Crude oil (unspecified) Mineral and metal products (unspecified) Natural gas

Mobile sources of criteria pollutants are estimated by air district for a variety of on-road and “other” mobile sources.

On-road vehicles are classified by duty class (CARB, 2013b), e.g., light duty trucks, medium-duty trucks, or heavy duty trucks. It is probable that transport of light equipment and personnel for well stimulation activities would take place using light duty trucks, while proppant, steel well casing, bulk materials, or chemicals would be hauled in heavy duty trucks. On-road truck emissions are subspecified at various levels of detail. For example, the “Heavy Heavy Duty Diesel Trucks” category has a variety of subcategories, including agriculture, construction, and port use. In contrast, “Light Heavy Duty Diesel Trucks” are not subspecified in results by the industry which employs them.

No on-road categories reported petroleum-related subcategories, so use of on-road trucks for oilfield activities such as well stimulation are not able to be determined from inventory results. At least some of the reported on-road criteria pollutant emissions are likely due to well stimulation or oil and gas activities, but inventory results are not specific enough to differentiate these uses. With access to the underlying models, examining truck use by industry sector may be possible.

The category of “Other mobile sources,” however, does present oil and gas-relevant categorization under the heading of off-road equipment. The relevant category is “Other mobile sources > Off-road equipment > Oil drilling and workover.” The types of equipment in this category are listed in Table 3.3-5. A variety of oilfield equipment (e.g., pumps, lifts, rigs) are modeled for a variety of equipment sizes. Mobile source emissions are modeled using a methodology that tracks populations of vehicles, vehicle usage and load factors, and vehicle distribution within the state air districts, etc. (CARB, 2010).

The vehicle database DOORS (Diesel Off-road On-line Reporting System) tracks the numbers of off-road vehicles in the state, as well as their rated horsepower for categorization (CARB, 2010). In the model base year (2010), documentation states that oilfield equipment in DOORS included 184 drilling rigs and 638 workover rigs (adjusted from reported values based on CARB estimated non-compliance rates). The load factor (fraction of maximum engine output) assumed is 50% for oilfield equipment (CARB, 2010, p. D-10). Oilfield rigs are assumed to operate for ~1,000 hours per year (CARB, 2010, p. D-14). Oil drilling equipment is allocated to the following air basins: SJV, 61.1%; Sacramento Valley, 14.5%; SC, 13%; and South Central Coast, 8.5% (CARB, 2010, p. D-33). Consulting the underlying DOORS database confirms that only these drilling rigs and workover rigs are included in the newest (2011) version of the DOORS database.

Table 3.3-5. CARB mobile source inventory emissions sources within the category “Off road, oil drilling and workover, diesel (unspecified)” taken from SJV and SC air district data.

Sources	**Sizes**
Compressor (workover)	D25, D120, D175, D250, D500, D750, D1000
Drill rig	D120, D175, D250, D500, D750, D1000
Drill rig (mobile)	D50, D120, D175, D250, D500, D750, D1000
Workover rig (mobile)	D50, D120, D175, D250, D500, D750, D1000
Generator (drilling)	D50, D120, D175, D250, D500, D750
Generator (workover)	D120, D175, D250, D500, D750, D9999
Lift (drilling)	D120, D175, D250, D500, D750
Other workover equipment	D120, D175, D250, D500, D750, D1000
Pressure washers	D250
Pump (drilling)	D120, D175, D250, D500, D750, D9999
Pump (workover)	D120, D175, D250, D500, D750, D9999
Snubbing	D120
Swivel	D120, D175, D250, D500

Coverage of WS activities in ROG inventory

From the stationary-source specification provided in Table 3.3-4, it appears likely that at least some well-stimulation-related activities are represented in the stationary source criteria pollutant inventory. For example, flowback emissions might be included in the category “Fugitives—Well heads” or “Fugitives—Oil/Water Separator.” The fundamental data underlying these categories are summed from facility-level data. CARB methodologies do not describe exactly what is or is not included in each source category, nor how emissions estimates might have been updated in light of development of new technologies such as well stimulation. Users are recommended to contact a particular air district for more information on how a particular source was estimated.

Regarding on-road mobile sources, no information is available about how well-stimulation-related on-road emissions might be counted in the inventory.

Regarding off-road and oilfield equipment, the information presented in Table 3.3-5 suggests that at least partial coverage of well-stimulation-related equipment is provided in the mobile source inventory (e.g., rigs, pumps, generators). The exact coverage of well stimulation equipment in these databases cannot be determined.

CARB ROG inventory results are presented in mass of ROG per year. Calculations of impacts based on species-specific reactivities have been used in California regulation for assessing the actual ozone-formation potential for different species (CARB, 2011). For this report, we use the reported mass emissions of ROGs.

Results of CARB criteria-pollutant inventory: ROG and NO_x

Criteria pollutant inventory results show that oil and gas operations are generally responsible for a minority of stationary ROG and NO_x emissions. In 2012 in the SJV Unified air district, upstream oil and gas emissions totaled 25.1 t ROG/d, representing ~7.7% of ROG emissions from anthropogenic sources and 2.3% of ROG emissions from all sources (natural and anthropogenic). In the SC air district, the equivalent values were 0.23% and 0.16%, respectively (CARB, 2013b). A breakdown of ROG emissions from oil and gas operations in these two air districts is shown in Figure 3.3-4 (SC) and Figure 3.3-5 (SJV) at two levels of specificity. The left-hand side of each figure groups sources listed in Table 3.3-4 into broader categories. Major stationary sources in the SJV air district are mixed evenly between fugitive emissions and production wells. Major stationary sources in the SC air district include fugitive sources, tanks, and engines.

Note that these stationary emissions only include upstream oil and gas production and surface processing emissions; they do not include petroleum refining emissions nor consumption of the refined fuels that are produced from oil (e.g., fugitive VOC emissions from automobile fueling).

Speciation of stationary source fugitive TOG emissions is determined based on emissions source using established standard speciation profiles (CARB, 2014i, see Figure 3.3-6). These speciation profiles have lower CH_4 concentrations than other observations (see below), perhaps due to the dominance of oil and heavy oil production over dry gas production in California.

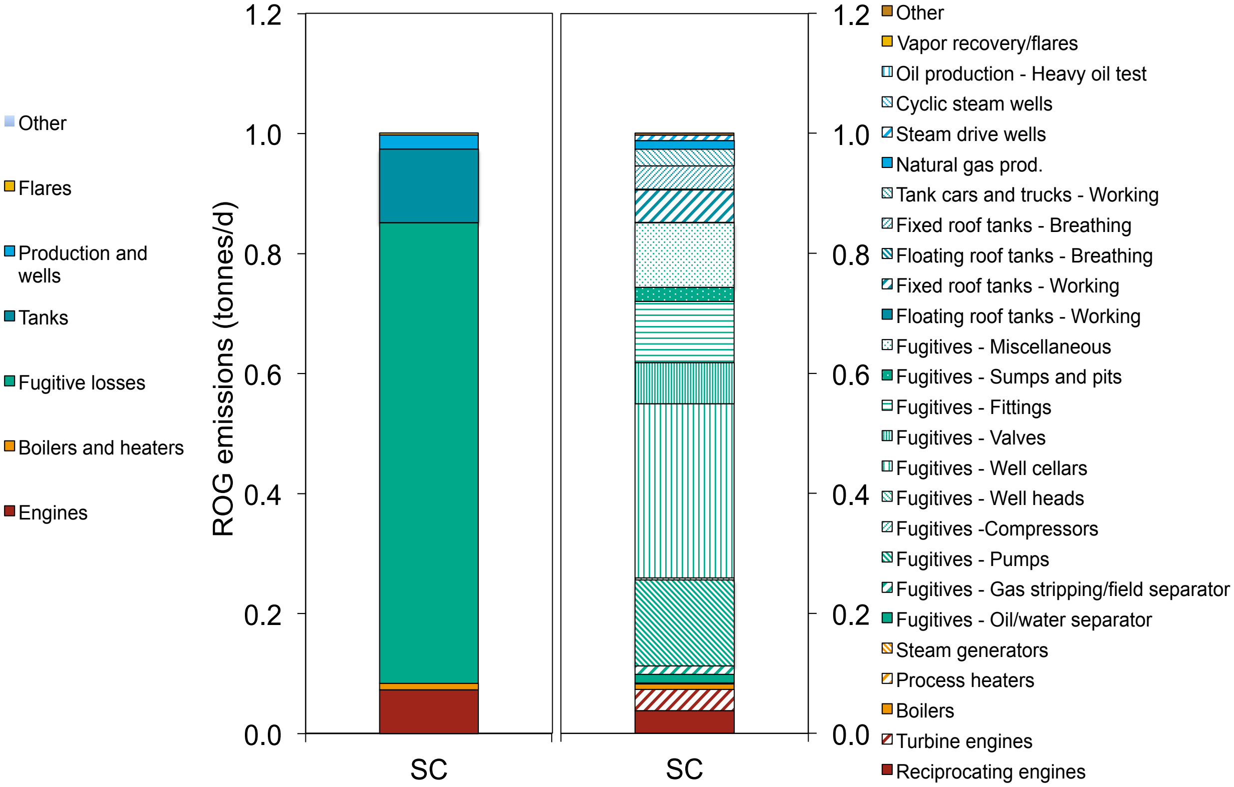


Figure 3.3-4. Stationary source 2012 emissions of reactive organic gas (ROG) from all stationary oil and gas production sources in the South Coast air district. Emissions in tonnes per day (1,000 kg/d).

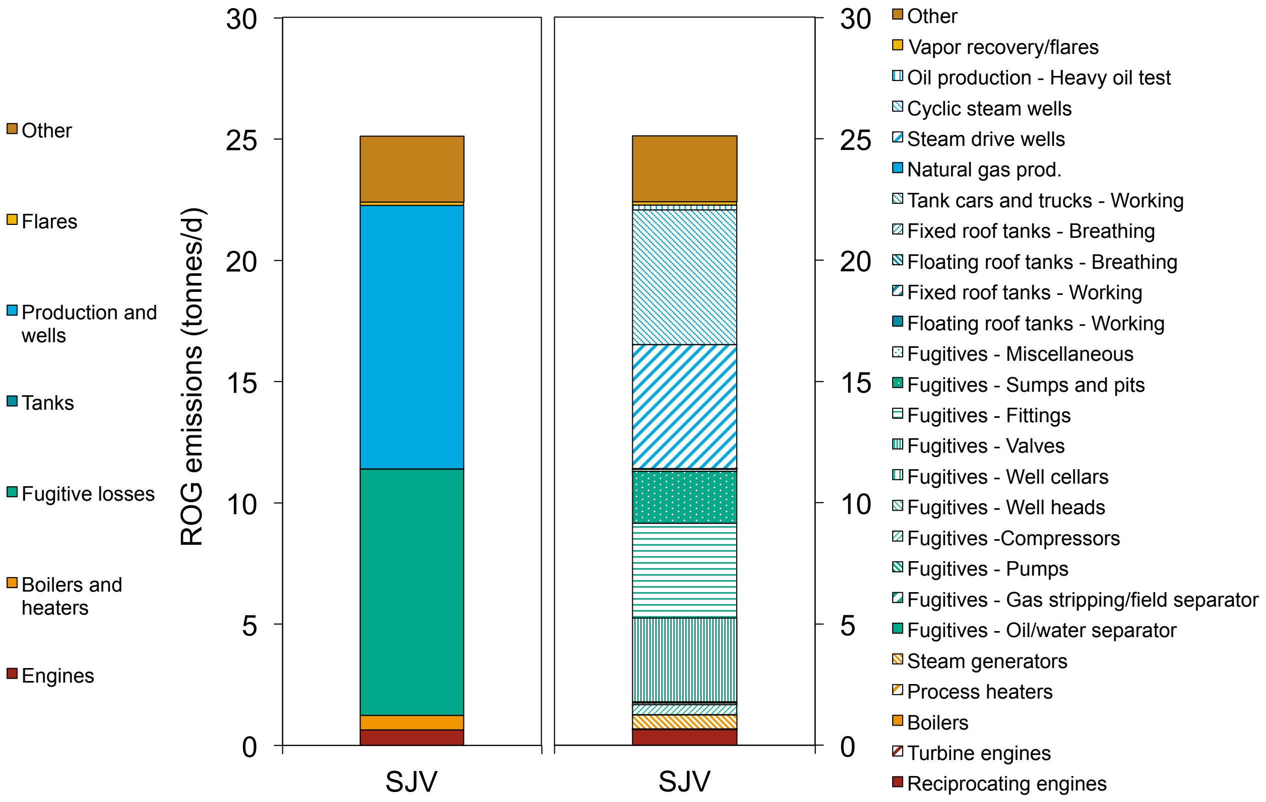


Figure 3.3-5. Stationary source 2012 emissions of reactive organic gas (ROG) from all stationary oil and gas production sources in the San Joaquin Valley Unified air district. Emissions in tonnes per day (1,000 kg/d).

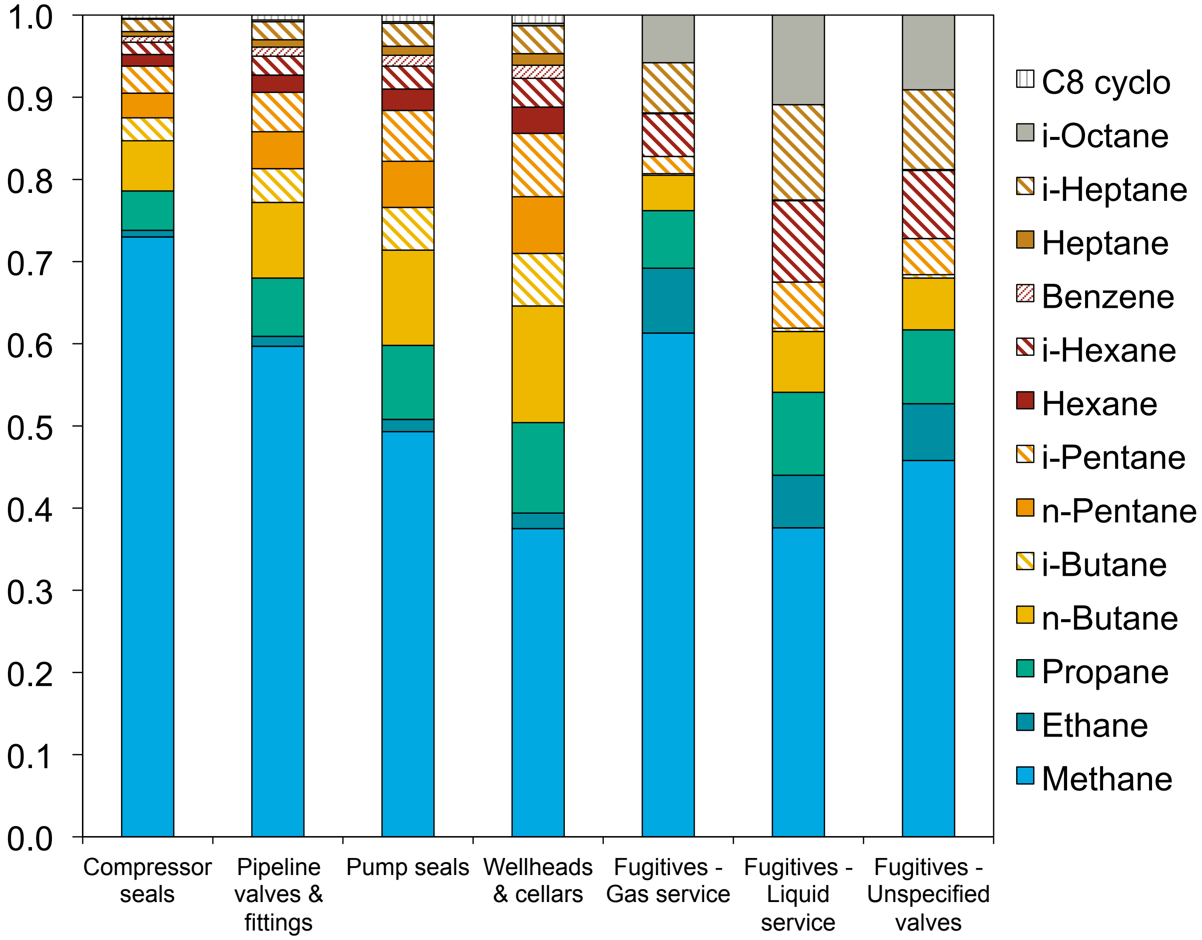


Figure 3.3-6. Stationary source speciation of TOG fugitive oil and gas production sources. Source: (CARB, 2014i)

Stationary source NO_x emissions from oil and gas sources can be computed similarly to the stationary source ROG/VOC emissions methods. Using the above methods, stationary source emissions in the “Oil and Gas Production” and “Oil and Gas Production (Combustion)” categories make up 1.1% and 0.3% of the stationary source NO_x emissions in the SJV and SC regions, respectively (CARB, 2013b).

Emissions from on-road vehicles associated with well stimulation or with the oil and gas industry cannot be partitioned from the inventory, but do represent some fraction of on-road ROG/VOC emissions.

ROG emissions from off-road oil and gas sources for the SJV and SC regions are shown in Figure 3.3-7. Off-road oil and gas ROG emissions in SJV region are 0.59 t per day. In the SJV air district, this is equivalent to 0.75% of mobile source ROG emissions and 0.18% of ROG/VOC emissions from all sources. In the SC region, ROG emissions from off-road oil and gas sources are 0.08 t per day: 0.04% of mobile-source ROG/VOC emissions, and 0.02% of total ROG emissions from all sources.

Using a reasonable assumption of the share of in-state on-road trucks used by the oil and gas industry, these sources will make up a small fraction of mobile source ROGs in California. This conclusion is not surprising, due to the relatively small size of the oil and gas sector in California compared to the many other industries supporting 40 million California residents.

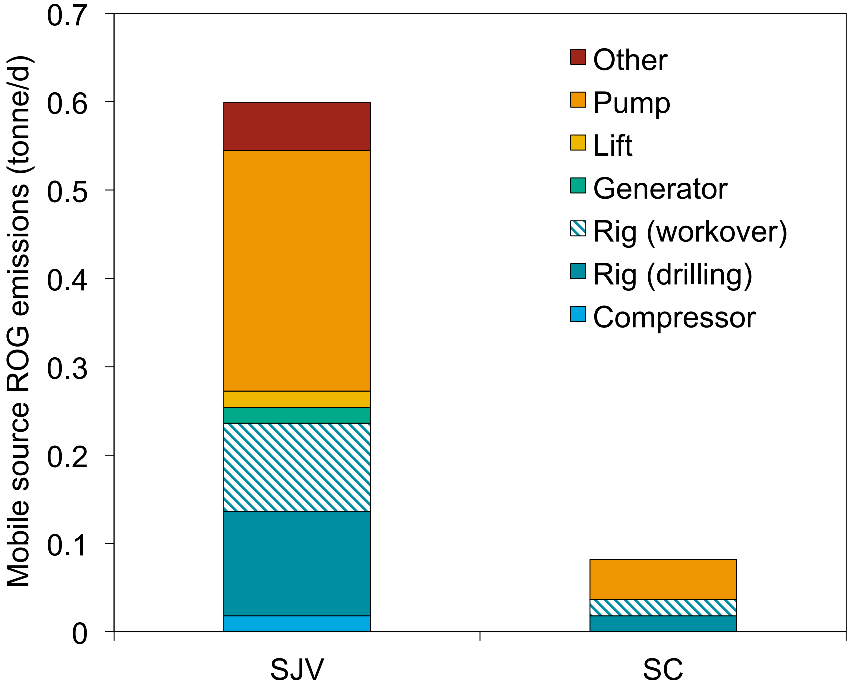


Figure 3.3-7. Mobile source 2012 emissions of reactive organic gas (ROG) from all sources within the categorization "Off road, oil drilling and workover, diesel (unspecified)" Emissions in tonnes per day (1,000 kg/d). Source: CARB (2013b).

The oil and gas industry represents a larger fraction of mobile source NO_x emissions and total NO_x emissions than ROG/VOC emissions. Using similar methods to those used above, NO_x emissions from off-road oil and gas equipment are 7.3 and 1.6 t per day in the SJV and SC regions, respectively. In the SJV region, this represents 2.9% of mobile source NO_x, and 2.5% of total NO_x emissions. In the SC region, oil and gas NO_x emissions of 1.6 per day represent 0.3% of total mobile sources and 0.3% of all NO_x sources (CARB, 2013b).

Summary of CARB criteria pollutant inventory coverage

A summary of all criteria pollutant emissions from oil and gas operations (stationary and mobile) is shown in Table 3.3-6.

Table 3.3-6. CARB criteria pollutant overview in emissions of criteria pollutants in t per day (1,000 kg/d). Includes all anthropogenic as well as all sources, natural and anthropogenic.

		ROG	**NO_x**	**SO_x**	**PM**	**PM10**	**PM2_5**
SJV	Oil and gas - Stationary	25.1	3.2	2.9	1.9	1.8	1.8
SJV	Oil and gas - Mobile	0.6	7.3	0.0	0.2	0.2	0.2
SJV	Total anthropogenic	324.9	295.2	9.4	479.8	255.7	68.7
SJV	Total anthropogenic + natural	1112.8	306.2	12.8	517.5	291.9	99.4
SJV	Percentage of anthropogenic	7.9%	3.6%	31.2%	0.4%	0.8%	3.0%
SJV	Percentage of total	2.3%	3.4%	23.0%	0.4%	0.7%	2.0%
		ROG	NO_x	SO_x	PM	PM10	PM2_5
SC	Oil and gas - Stationary	1.0	1.7	0.0	0.1	0.1	0.1
SC	Oil and gas - Mobile	0.1	1.6	0.0	0.0	0.0	0.0
SC	Total anthropogenic	438.2	517.7	17.7	228.3	157.6	66.7
SC	Total anthropogenic + natural	613.8	521.8	19.8	257.1	185.3	90.1
SC	Percentage of anthropogenic	0.2%	0.6%	0.1%	0.1%	0.1%	0.2%
SC	Percentage of total	0.2%	0.6%	0.1%	0.0%	0.1%	0.1%

The CARB criteria pollutant inventory is likely to include some emissions from well stimulation activities, but the level of coverage is uncertain. To summarize the above:

- Oil and gas criteria pollutant emissions are estimated using detailed categorization in stationary source and off-road mobile source databases. Criteria pollutant emissions from on-road oil and gas sources cannot be determined because the on-road emissions databases do not partition emissions by sector.

- Given the detailed categorization of stationary source emissions (e.g., “Fugitives—Well head”) and off-road mobile source emissions (e.g., “Rigs—Workover”) , it is possible that well-stimulation-related sources are being tracked. The level of well-stimulation-related coverage cannot be determined from reported data.

3.3.2.2.3. CARB Inventories for TACs

A variety of TACs can be released from well stimulation activities. Key TACs include VOC or fugitive hydrocarbon emissions, particulate matter (discussed separately below), and emission of substances used in hydraulic fracturing fluids.

Because of the large scope and complexity of TACs emissions (both in number of species and number of emissions processes), all results in this section are computed for 10 indicator TACs that can be emitted from oil and gas sources. These indicator TACs include the largest 5 sources from a recent EPA risk assessment for oil and natural gas production (U.S. EPA, 2011). This source lists oil and gas production associated TACs ordered by rate of emissions across 990 facilities in an EPA dataset (U.S. EPA, 2011, Table 4.1.-1). Next, ethyl benzene is included as in indicator TAC due to its importance in the suite of BTEX (benzene, toluene, ethylbenzene, and xylenes) hydrocarbon emissions (ethyl benzene was also ranked 6th in the EPA list by emissions rate). Hydrogen sulfide is included as an important hydrocarbon-related compound with potential health effects. We note that hydrogen sulfide is not technically classified as a TAC (U.S. EPA, 2014), but serious human health impacts are associated with breathing small amounts of hydrogen sulfide, resulting in stringent safety requirements and controls around hydrogen sulfide (H2S) releases. Lastly, four indicator species are added that were found upon inspection of CARB databases to be significantly driven by oil and gas sector sources.

The resulting 10 indicator TACs species are: 1,3-butadiene, acetaldehyde, benzene, carbonyl sulfide, ethyl benzene, formaldehyde, hexane, hydrogen sulfide, toluene, and xylenes (mixed). This list is not meant to be exhaustive of all possible species of interest, but indicative of the possible contributions of oil and gas sources.

CARB TAC inventory methods

TACs emissions by species for a broad variety of sources are reported in the CARB California Toxics Inventory (CTI). The CTI is not computed frequently: data were reported most recently for year 2010 (CARB, 2013c). Unlike the facility-scale “hot spot” dataset (see below), the CTI includes a variety of nonstationary sources, such as area-wide sources and mobile sources (gasoline, diesel, off-road equipment, etc.).

The CTI reports emissions by air district for ~340 toxic species (CARB, 2013c). These data are compiled from facility-level data noted above, as well as mobile sources and dispersed stationary sources such as homes and nonreporting businesses. TACs from mobile sources, which are not otherwise subject to air toxics reporting requirements, are estimated by applying speciation factors to criteria pollutant inventories noted above (CARB, 2013d). For example, ROG emissions from off-road combustion are obtained from the criteria pollutant inventory described above, and speciation factors are applied to these ROG emissions estimates to estimate emissions of a given TAC chemical species (CARB, 2000).

TACs from regulated stationary sources are recorded in CARB datasets at the facility level (CARB, 2014j). Emissions data are reported to CARB from stationary facilities as part of the Air Toxics “Hot Spots” program (AB 2588, enacted 1987). Various criteria are used to determine whether a facility must report data to the CARB (CARB, 2013e; 2014j; 2014l), but a chief criterion is the manufacture, formulation, use, or release of any of 600 substances subject to the regulation. Reporting requirements differ by chemical species or substance. Some species/substances require reporting only with regard to air emissions, while other species/substances are required to be reported if used or manufactured, regardless of estimated air emissions rate.

Facility-level TACs data are searchable by Standard Industrial Classification (SIC) code, air district, county, facility code, and chemical species. These facility-level data are further compiled by air districts, which publish annual reports summarizing emissions of TACs within each district from all sources (e.g., CARB, 2014k).

More recently, the South Coast Air Quality Management District (SCAQMD, or SC air district as above) passed legislation—Rule 1148.2—which requires reporting of use of potential TACs in oil and gas well stimulation (SCAQMD, 2013; PSR et al., 2014). This rule goes beyond existing TACs reporting requirements by specifically requiring reporting of the volume or mass of use of certain chemicals which are TACs, rather than reporting the estimated emissions rate.

In 2010, in the SJV air district, TACs of importance included (in order of mass rate of emissions): acetaldehyde, diesel PM, formaldehyde, and benzene (SJVAPCD, 2014). Mobile sources are responsible for over half of SJV TACs, while stationary sources were responsible for ~15% of emissions (SJVAPCD, 2014). Three of these four species are in the set of 10 indicator TACs species, and diesel PM is discussed further below.

Coverage of WS activities in CARB TAC inventory

Direct well-stimulation-related TAC emissions will occur in the upstream portion of the oil and gas industry. Key possible TACs impacts from well stimulation activities include:

- Release of hydrocarbons during the well completion (“flowback”) process;
- Release or volatilization of components of the fracturing fluid, which could represent toxic hazards;
- Release of combustion byproducts or hydrocarbon (HC) fugitives from consumption of fuels during WS activities (e.g., by pumps, generators, compressors, or other on-site engines);

The above activities could result in TAC emissions from a mixture of point-source and mobile source emissions. To the extent that stationary sources associated with oil and gas report TAC emissions as part of AB 2588, these emissions will be included in the TAC inventory. Given the detailed source categories treated in the off-road mobile source inventory (noted above), it is likely that at least some mobile source TACs from well stimulation activities are counted in the current inventory.

It is not clear how emissions unique to well stimulation (e.g., emissions during fracturing fluid preparation, injection or flowback) are treated in current TAC inventory methods. No data exist in either the "hot spots" dataset or in the CTI to clearly differentiate well stimulation from non-well-stimulation oil and gas emissions.

Results of CARB TAC inventory

Results of the CTI for the most recent year (2010) are presented in Figure 3.3-8 and Figure 3.3-9 for the SJV and SC regions respectively. Tabular data are presented in Table 3.3-7 and Table 3.3-8 for the SJV and SC regions respectively.

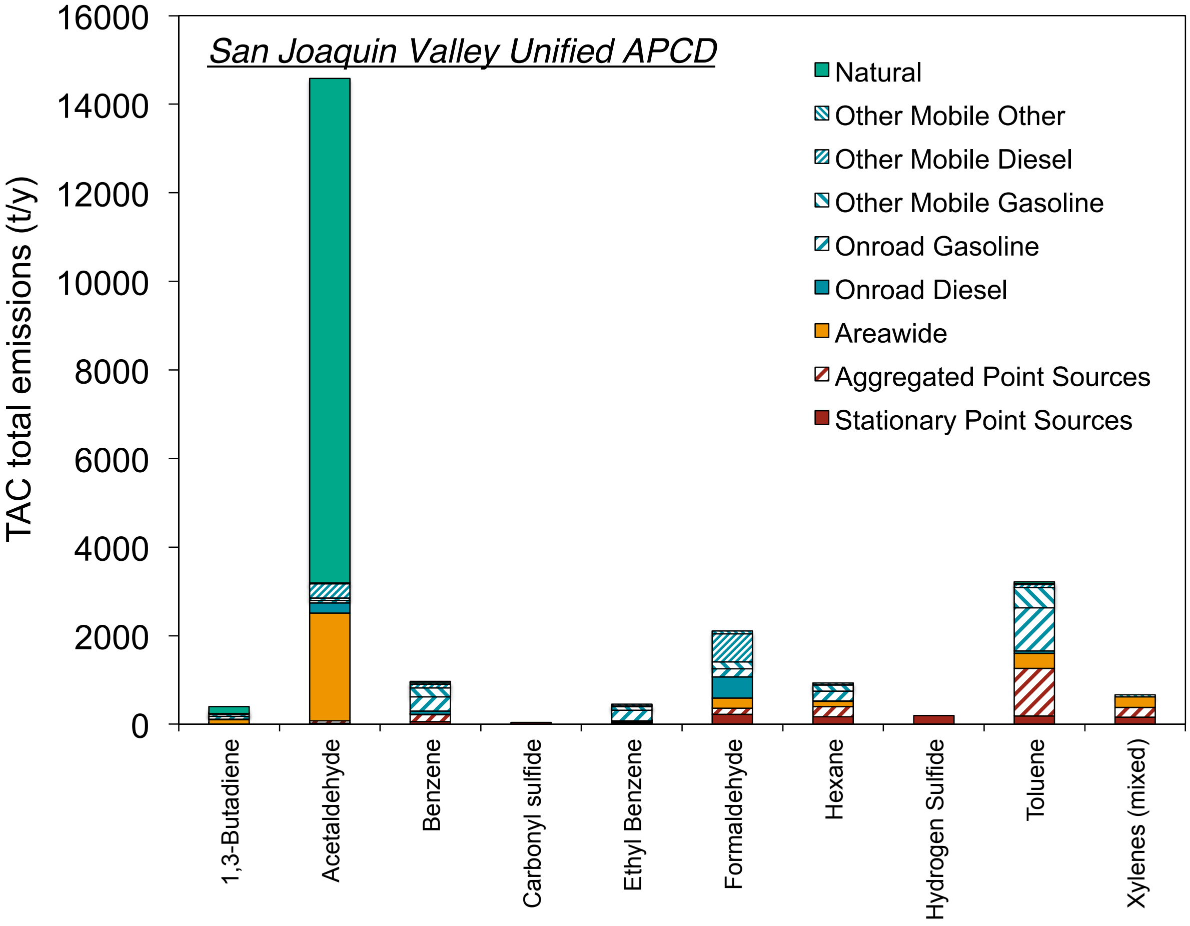


Figure 3.3-8. Total TACs releases for 10 indicator species in SJV region. Results for calendar year 2010, most recent available (CARB, 2013c). Emissions are in tonnes per year (1,000kg/y).

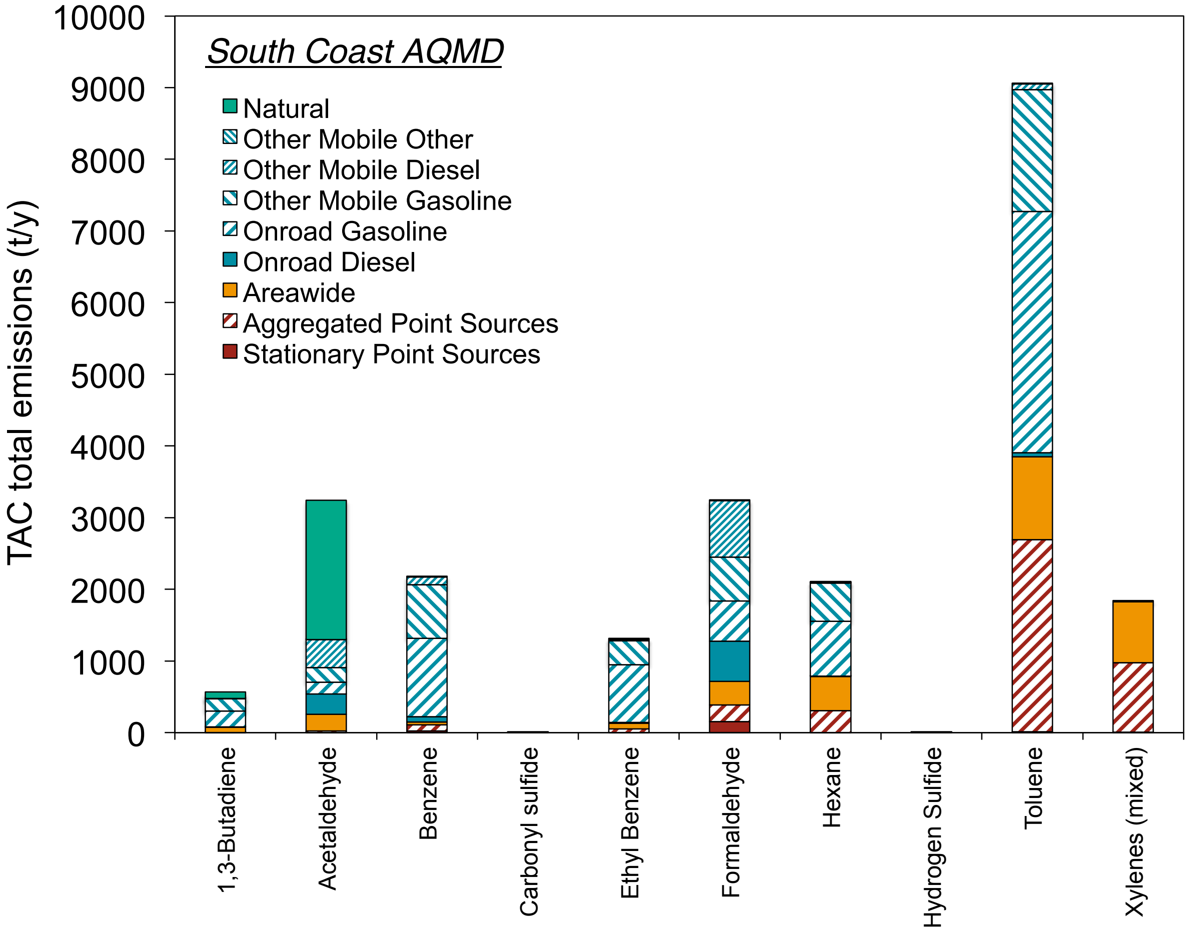


Figure 3.3-9. Total TACs releases for 10 indicator species in SC region. Results for calendar year 2010, most recent available (CARB, 2013c). Emissions are in tonnes per year (1,000kg/y).

Table 3.3-7. Overall toxics inventory results for indicator species in SJV region. Emissions are in tonnes per year (1,000kg/y). Results from 2010 calendar year (CARB, 2013c).

	Stationary Point Sources	**Aggregated Point Sources**	**Area-wide**	**Onroad Diesel**	**Onroad Gasoline**	**Other Mobile Gasoline**	**Other Mobile Diesel**	**Other Mobile Other**	**Natural**	**Total**	**Fraction stationary point sources**
1,3-Butadiene	0.4	1.4	105.9	6.1	67.3	44.5	8.2	10.3	150.9	395.0	0.1%
Acetaldehyde	20.4	53.3	2432.3	237.7	53.9	52.5	317.0	21.4	11395.1	14583.6	0.1%
Benzene	62.2	155.2	10.7	64.7	328.4	197.8	86.3	21.3	0.7	927.2	6.7%
Carbonyl sulfide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0%
Ethyl benzene	19.9	24.3	26.3	10.0	232.4	88.1	13.4	6.1	0.0	420.5	4.7%
Formaldehyde	222.5	141.8	231.1	475.7	178.8	160.8	634.4	59.7	0.0	2104.7	10.6%
Hexane	168.5	229.1	120.3	5.2	221.9	143.1	6.9	3.3	0.0	898.3	18.8%
Hydrogen sulfide	193.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	193.8	100.0%
Toluene	189.9	1074.7	340.3	47.5	980.7	451.7	63.4	29.7	0.7	3178.6	6.0%
Xylenes (mixed)	161.7	216.0	244.8	0.0	0.0	0.0	0.0	0.0	0.0	622.5	26.0%

Table 3.3-8. Overall toxics inventory results for indicator species in SC region. Emissions are in tonnes per year (1,000kg/y). Results from 2010 calendar year (CARB, 2013c).

	Stationary Point Sources	Aggregated Point Sources	Area-wide	Onroad Diesel	Onroad Gasoline	Other Mobile Gasoline	Other Mobile Diesel	Other Mobile Other	Natural	Total	Fraction stationary
1,3-Butadiene	2.9	0.1	72.6	7.2	217.8	168.7	10.2	0.0	86.5	566.1	0.5%
Acetaldehyde	2.8	21.4	232.8	280.3	168.9	199.2	393.5	0.2	1944.2	3243.4	0.1%
Benzene	23.2	83.2	39.9	76.3	1092.7	747.8	107.1	1.4	0.0	2171.5	1.1%
Carbonyl sulfide	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	100.0%
Ethyl Benzene	3.6	46.3	81.8	11.8	806.0	333.3	16.6	0.1	0.0	1299.5	0.3%
Formaldehyde	152.4	231.6	328.7	561.0	563.3	609.9	787.6	5.5	0.0	3240.0	4.7%
Hexane	1.9	304.1	478.2	6.1	763.2	531.8	8.6	0.6	0.0	2094.6	0.1%
Hydrogen Sulfide	9.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.3	100.0%
Toluene	10.0	2680.9	1160.0	56.1	3363.4	1701.3	78.7	1.0	0.0	9051.4	0.1%
Xylenes (mixed)	8.5	966.0	852.7	0.0	0.0	0.0	0.0	0.2	0.0	1827.5	0.5%

As can be seen from Table 3.3-7 and Table 3.3-8, key sources of the indicator TACs species in both SJV and SC region include vehicular sources (gasoline in particular) and aggregated (i.e., not individually reported) point sources. Some species (carbonyl sulfide and hydrogen sulfide) are emitted primarily or completely by stationary facilities. Facilities that report TACs emissions as part of the point-source reporting program are discussed in more detail below.

To the extent that oil and gas development contributes to overall diesel consumption (both on-road and off-road), some contribution of TACs from oil and gas activities in these categories is to be expected. Note that Figure 3.3-7 and the associated discussion suggest that the importance of ROGs from oil and gas related mobile sources is likely to be small. It is therefore likely that TACs from mobile source oil and gas activities are also small. However, no sector- or activity-level breakdown is available in the CTI TACs database as was available in the ROG database.

In contrast to the overall CTI results which cover all sources (stationary, areawide, mobile, natural), a much more detailed facility-level inventory is generated using reported data for facilities under the “Hot Spots” program, AB 2588. Using this data, it is possible to estimate TACs impacts of oil and gas activities from stationary source reporting facilities. In order to do this, the facility-level TACs databases were searched using Standard Industrial Classification (SIC) codes representing upstream oil and gas activities. Using OSHA (Occupational Safety and Health Administration) databases of SIC codes, 12 codes were determined to be related to oil and gas activities. Five of these codes are included in this report’s estimates of upstream oil and gas activities (see Table 3.3-9).

It is not possible to separate these facility-level stationary-source TACs emissions by oilfield or pools. The reporting facilities to the TACs database do not line up with pools or fields as reported in DOGGR databases. Also TACs emissions source facilities in the database are sometimes very generally defined (e.g., “AERA Energy LLC, heavy oil production”)

Table 3.3-9. SIC codes used in analysis of facility-level TAC emissions. Source: OSHA SIC database search for "petroleum" and "oil" (OSHA, 2014).

SIC code	**Description**	**Included as upstream O&G?**
1311	Crude petroleum and natural gas	Y
1321	Natural gas liquids	Y
1381	Drilling oil and gas wells	Y
1382	Oil and gas field exploration services	Y
1389	Oil and gas field services, not elsewhere classified	Y
2911	Petroleum refining	N
2922	Lubricants and greases	N
3533	Oil and gas machinery	N
4613	Refined petroleum pipelines	N
5172	Petroleum product wholesalers	N
5541	Gasoline stations	N
5983	Fuel oil dealers	N

Unlike the stationary source criteria pollutant inventory, no data source was found that separates TACs emissions by subsource (CARB, 2013c).

The distribution of facility-reported emissions for the 10 indicator species is shown in Figure 3.3-10 and Figure 3.3-11 for the SJV and SC regions, respectively. Tabular results are shown in Table 3.3-10 and Table 3.3-11 for SJV and SC regions. These values differentiate between emissions from the five SIC codes noted in the above table ("Y") and aggregate emissions from all other SIC codes. The five upstream oil and gas SIC codes noted in Table 3.3-9 are responsible for between 0% and 70% of the emissions of these species from stationary sources in the SJV air district. In the SC air district, these upstream stationary oil and gas sources were responsible for 0% to 10% of the emissions of these species from all stationary sources.

Because treatment of mobile source TACs in the CTI is derived from speciation of the criteria pollutant inventory, coverage of TACs from mobile sources associated with well stimulation or oil and gas activities will be subject to the same issues noted above. To recapitulate, a variety of mobile sources relevant to oil and gas (and presumably to well stimulation) activities are tracked, especially for off-road diesel equipment. However, it is not clear how to apportion these activities between conventional HC production and well stimulation activities without detailed study.

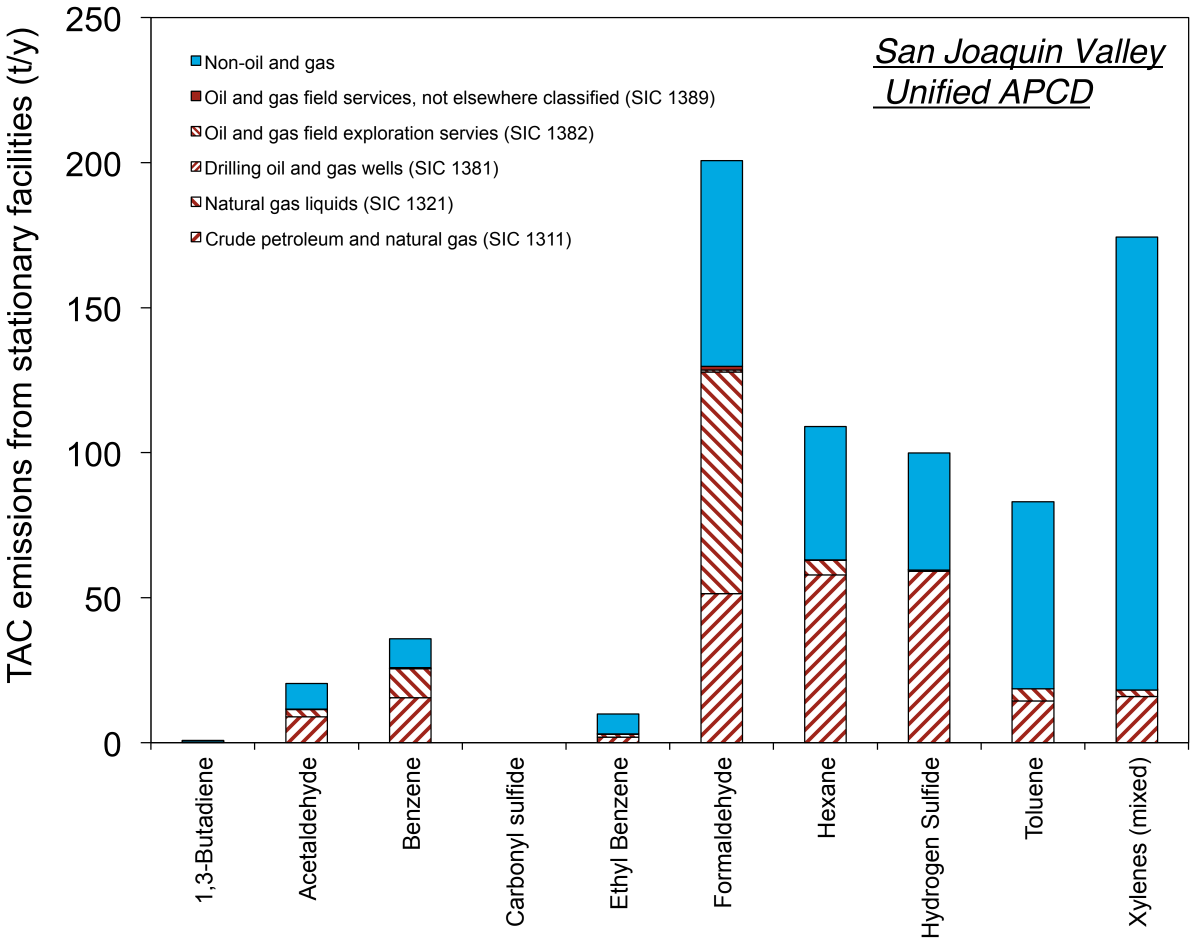


Figure 3.3-10. Summed facility-level TAC emissions in San Joaquin Valley (SJV) air district CARB, 2014j). Emissions plotted for indicator species for SIC codes 1311, 1321, 1381, 1382, and 1389. Facility-level emissions derived from CARB facility emissions tool. Total emissions are emissions from all SIC codes in the air district, including gasoline fueling stations.

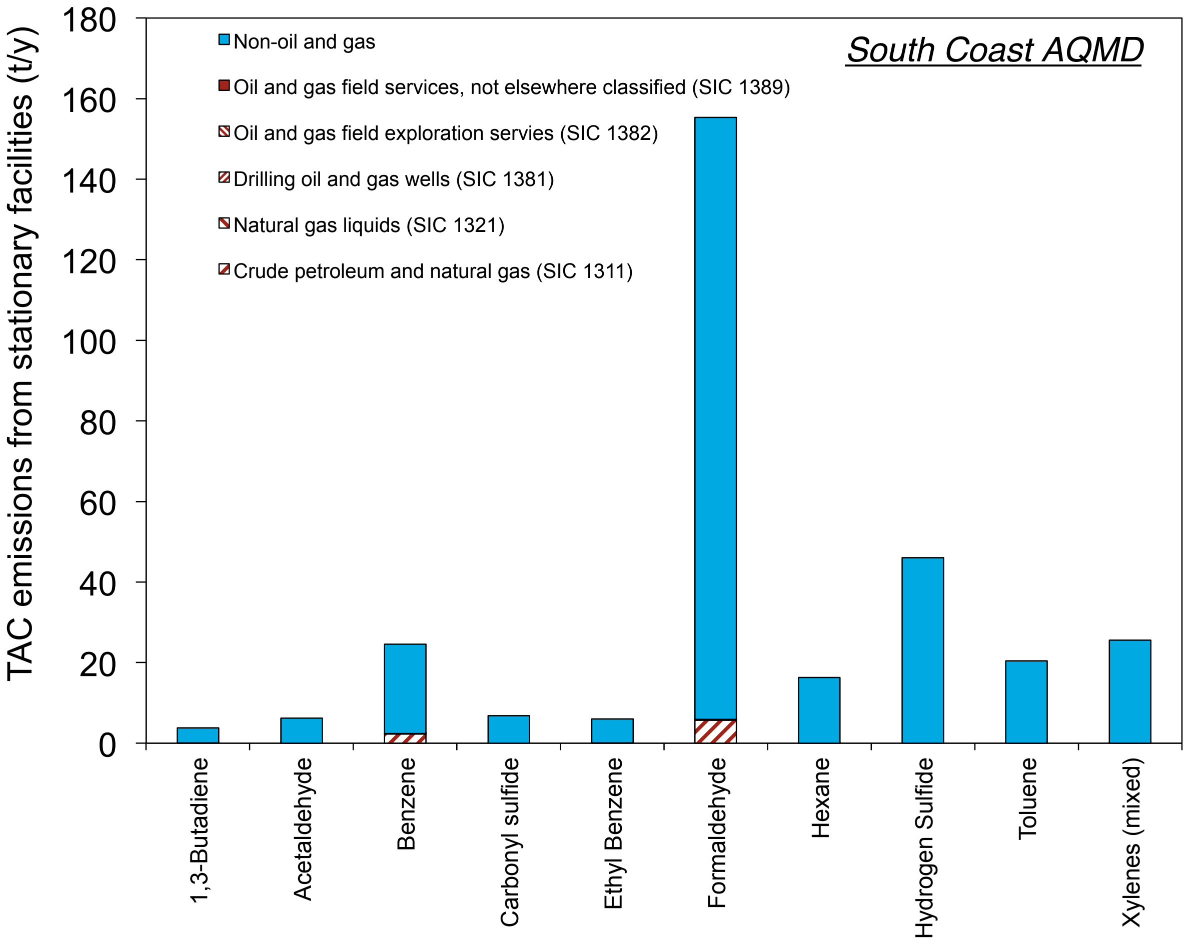


Figure 3.3-11. Summed facility-level TAC emissions in South Coast (SC) air district CARB, 2014j). Emissions plotted for indicator species for SIC codes 1311, 1321, 1381, 1382, and 1389. Facility-level emissions derived from CARB facility emissions tool. Total emissions are emissions from all SIC codes in the air district, including gasoline fueling stations.

Table 3.3-10. Emissions rates from stationary facilities in SJV region, as reported to facility-level reported TACs database (CARB, 2014j). Data from calendar year 2012. All emissions in tonnes per year (1,000kg/y).

	Crude petroleum and natural gas (SIC 1311)	**Natural gas liquids (SIC 1321)**	**Drilling oil and gas wells (SIC 1381)**	**Oil and gas field exploration services (SIC 1382)**	**Oil and gas field services, not elsewhere classified (SIC 1389)**	**Total oil and gas (SIC 1311-1389)**	**Non-oil and gas**	**Percentage oil and gas**
1,3-Butadiene	0.2	0.0	0.0	0.0	0.0	0.3	0.5	35.2%
Acetaldehyde	8.9	2.5	0.0	0.0	0.2	11.6	8.8	57.0%
Benzene	15.6	9.8	0.0	0.1	0.5	25.9	9.9	72.4%
Carbonyl sulfide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0%
Ethyl Benzene	1.9	1.0	0.0	0.0	0.2	3.1	6.8	31.2%
Formaldehyde	51.4	76.5	0.0	0.6	1.3	129.8	70.9	64.7%
Hexane	57.9	5.0	0.0	0.0	0.1	63.0	46.0	57.8%
Hydrogen Sulfide	59.2	0.3	0.0	0.0	0.1	59.5	40.3	59.6%
Toluene	14.4	4.2	0.0	0.0	0.1	18.6	64.4	22.4%
Xylenes (mixed)	15.9	2.3	0.0	0.0	0.0	18.2	156.1	10.4%

Table 3.3-11. Emissions rates from stationary facilities in SC region, as reported to facility-level reported TACs database (CARB, 2014j). Data from calendar year 2012. All emissions in tonnes per year (1,000kg/y).

	Crude petroleum and natural gas (SIC 1311)	**Natural gas liquids (SIC 1321)**	**Drilling oil and gas wells (SIC 1381)**	**Oil and gas field exploration services (SIC 1382)**	**Oil and gas field services, not elsewhere classified (SIC 1389)**	**Total oil and gas (SIC 1311-1389)**	**Non-oil and gas**	**Percentage oil and gas**
1,3-Butadiene	0.1	0.0	0.0	0.0	0.0	0.1	3.7	1.5%
Acetaldehyde	0.0	0.0	0.0	0.0	0.0	0.0	6.3	0.0%
Benzene	2.2	0.0	0.1	0.0	0.0	2.4	22.2	9.6%
Carbonyl sulfide	0.0	0.0	0.0	0.0	0.0	0.0	6.9	0.0%
Ethyl Benzene	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.5%
Formaldehyde	5.7	0.0	0.0	0.0	0.1	5.9	149.5	3.8%
Hexane	0.0	0.0	0.0	0.0	0.0	0.0	16.3	0.0%
Hydrogen Sulfide	0.0	0.0	0.0	0.0	0.0	0.0	46.0	0.0%
Toluene	0.0	0.0	0.0	0.0	0.0	0.0	20.4	0.0%
Xylenes (mixed)	0.0	0.0	0.0	0.0	0.0	0.0	25.6	0.0%

It does not appear possible to directly compare these two datasets. While the CTI (produced less frequently) reports emissions from "stationary point sources" that are in theory derived from the facility-level reporting explored above by SIC code, examination of the data for the 2010 year from both datasets shows discrepancies for all ten indicator species. For example, benzene emissions estimated by CTI datasets for the SJV region (defined as the San Joaquin Valley Unified APCD) in 2010 were 62.1 t/y for the category "stationary point sources." In contrast, querying the facility-level toxics database for 2010 for the same region, and summing resulting benzene emissions from all reporting facilities, results in total emissions of 38.6 t/y.

Given the above caveat, an approximate estimate of the relative importance of oil and gas stationary sources can be generated by comparing the upstream oil and gas facility level emissions (summed by SIC code as above) to the total CTI results for the same year. These results are shown in Table 3.3-12 and Table 3.3-13 below.

In summary, in the SJV region, upstream oil and gas point-source facilities are responsible for the great majority of H2S emissions (>70%) and are small contributors to emissions of benzene, formaldehyde, hexane and xylenes (1-10%). In the SC region, oil and gas sources are negligible contributors to emissions of our ten indicator TACs.

Note again that there will also be oil and gas mobile source TACs that are not accounted for in Table 3.3-12 and Table 3.3-13. Because oil and gas mobile sources are small contributors to both ROG and PM emissions (see Table 3.3-6), this is unlikely to affect the general results of this comparison.

Table 3.3-12. San Joaquin Valley oil and gas facility-reported emissions of ten indicator TACs compared to California Toxics Inventory estimates for all sources, both for year 2010. Emissions in tonnes (1,000 kg) per year.

SJVUAPCD	Total oil and gas (t/y, facility-level 2010)	Total all sources (t/y, CTI 2010)	Fraction
1,3-Butadiene	0.1	435.1	0.0%
Acetaldehyde	10.8	16061.2	0.1%
Benzene	24.2	1021.2	2.4%
Carbonyl sulfide	0.0	0.0	0.0%
Ethyl Benzene	2.3	463.1	0.5%
Formaldehyde	126.9	2318.0	5.5%
Hexane	47.2	989.3	4.8%
Hydrogen Sulfide	151.2	213.4	70.8%
Toluene	17.6	3500.7	0.5%
Xylenes (mixed)	17.6	685.6	2.6%

Table 3.3-13. South Coast oil and gas facility-reported emissions of ten indicator TACs compared to California Toxics Inventory estimates for all sources, both for year 2010. Emissions in tonnes (1,000 kg) per year.

SCAQMD	**Total oil and gas (t/y, facility-level 2010)**	**Total all sources (t/y, CTI 2010)**	**Fraction**
1,3-Butadiene	0.3	623.4	0.0%
Acetaldehyde	0.0	3572.1	0.0%
Benzene	2.3	2391.5	0.1%
Carbonyl sulfide	0.0	0.1	0.0%
Ethyl Benzene	0.0	1431.1	0.0%
Formaldehyde	8.5	3568.3	0.2%
Hexane	0.1	2306.8	0.0%
Hydrogen Sulfide	0.0	10.2	0.0%
Toluene	0.1	9968.5	0.0%
Xylenes (mixed)	0.1	2012.7	0.0%

3.3.2.2.4. SCAQMD Reporting of Hazardous Materials

The South Coast Air Quality Management District (SCAQMD, or SC region as above) recently approved regulation (Rule 1148.2), which requires the reporting of use of potentially hazardous materials in well stimulation, drilling, or workover activities. The chemicals which were reported in this regulation, as well as the average quantities injected or used, are tabulated in Table 3.3-14 and Table 3.3-15.

The SCAQMD database does not directly report masses of chemicals injected. For all operations reported in the SCAQMD database, the mass flow of each injected material (e.g., proppant) was reported, as well as the "maximum concentration" of a number of individual chemical constituents (e.g., proppant might be made of crystalline silica (max 95%) and phenol-formaldehyde resin (max 5%). These data are combined to determine a maximum injection rate for individual chemicals.

Table 3.3-14. TAC species associated with fracturing fluids extracted from SCAQMD dataset.

Toxic air contaminant	**Average maximum kg injected per well**
Crystalline Silica Quartz (SiO2)	67060
Phenol-Formaldehyde Resin	16369
Methanol	1619
Hydrogen Chloride	622
Ethylene Glycol	443
Hydrofluoric Acid	45
2-Butoxy Ethanol	37
Hexamethylene Tetramine	33
Sodium Hydroxide	31
Silica Fumed	2
Cristobalite (SiO2)	1

Table 3.3-15. TAC species associated in matrix acidizing extracted from SCAQMD dataset.

Toxic air contaminant	**Average max. mass injected (kg)**
Crystalline Silica (Quartz)	3546
Hydrocholoric Acid	1058
Phosphonic Acid	406
Aminotriacetic Acid	309
Xylene	207
Hydrofluoric Acid	179
2-Butoxy Ethanol	213
Ethylbenzene	63
Methanol	34
Thiourea Polymer	15
Isopropanol	13
Sulfuric Acid Ammonium Salt (1:2)	7
Acrylic Polymer	7
Toluene	4
1,2,4 Trimethylbenzene	2
Diethylene Glycol	1
Ethylene Glycol	1
Naphthalene	1
Cumene	<1

These reported chemicals are not universally present in Clean Air Act lists of TACs, but their usage is required to be reported by SCAQMD. Also, the list of chemicals reported to SCAQMD may differ from other lists of potential toxics noted elsewhere in this report.

Additives and components of fracturing fluids could potentially be released to the air during mixing and preparation, injection, or flowback of fracturing fluids. The volatility of each of the additives can vary. For example, the largest mass additive is crystalline silica quartz (proppant). This proppant is not generally volatile, and only the proppant fines are of a concern from an air quality perspective.

3.3.2.2.5. Naturally Occurring Radioactive Materials

One possible concern about hydraulic fracturing is the release of naturally occurring radioactive materials (NORM). NORM can result in contamination of water with radioactive species, as well as result in air impacts through liberation of species that can enter gaseous phase (e.g. radon).

Though NORM is a serious concern for some shale formations (in particular the Marcellus formation of Pennsylvania, where it poses serious water quality issues), it is seen as less concerning in California (U.S. EPA, 2015).

California does contain deposits of radioactive elements in Kern County (USGS, 1954; USGS, 1960). However, these deposits are found to the south and east of the Kern County oilfields (USGS,1954; USGS, 1960). EPA studies suggest that well fluids and oilfield equipment in California are not significantly affected by radioactive species (U.S. EPA, 2015).

3.3.2.2.6. CARB Inventories for PM emissions

As with the above-described ROG and NO_x inventories, CARB criteria pollutant inventories track PM emissions of various classifications from both stationary and mobile sources.

CARB PM inventory methods

The CARB criteria pollutant inventory also estimates emissions of total particulate matter (PM) as well as PM10 and PM2.5.

The stationary source PM inventory is performed using the same classification and categorization scheme noted above for the stationary source ROG and NO_x inventories. See discussion above for details of stationary source inventory construction and categorization.

The mobile source PM inventory is performed using the same classification and categorization scheme noted above for the mobile source ROG and NO_x inventories.
As noted above, on-road mobile source emissions are not clearly differentiated into oil

and gas-associated emissions sources. Off-road mobile source emissions have a detailed classification for oilfield equipment (see above).

Total PM emissions estimated for a given source are partitioned into PM size bins using a set of standard PM speciation factors for ~500 stationary sources, mobile sources, or industrial/agricultural activities (CARB, 2014m). Oil and gas-specific PM size data are not available, but data are available for multiple categories of off-road diesel vehicles, which will comprise the majority of well-stimulation-site emissions of PM. These emissions are differentiated by type of vehicle and vehicle age (CARB, 2014m). Given that oil and gas- or well-stimulation-specific PM will often be emitted from processes similar to those used across industries (e.g., heavy diesel equipment), the use of non-oil and gas-specific PM speciation factors is a reasonable approach.

Coverage of WS activities in CARB PM inventory

Coverage and scope of well-stimulation-associated PM emissions in the CARB PM inventory should be identical to coverage and scope noted above for the ROG and NO_x inventories, because the inventory structure is similar.

Results of CARB PM inventory

Oil and gas stationary sources in the SJV region are responsible for 1.9 t per day of total PM and a nearly identical amount of PM2.5 (see Figure 3.3-12). This amounts to 0.4% of stationary anthropogenic emissions of total PM and 2.7% of stationary anthropogenic emissions of PM2.5. In the SC region, total stationary oil and gas-related sources of PM and PM2.5 equal 0.04% of stationary anthropogenic emissions of total PM and 0.13% of stationary anthropogenic emissions of PM2.5 in the SC region.

In the SJV region, oil and gas off-road sources are responsible for 0.2 and 0.18 t per day of total PM and PM2.5, respectively (see Figure 3.3-13). These equal 1.4% and 1.6% of the mobile-source PM in the SJV. However, due to large area-wide sources of PM in the SJV, off-road oil and gas sources are only responsible for 0.04% of total PM and 0.26% of PM2.5. In the SC region, off-road oil and gas sources emit some 0.03 t per day of PM and PM2.5 (see Figure 3.3-13). This represents ~0.3% of total mobile-source PM and 0.01% of total PM from all sources.

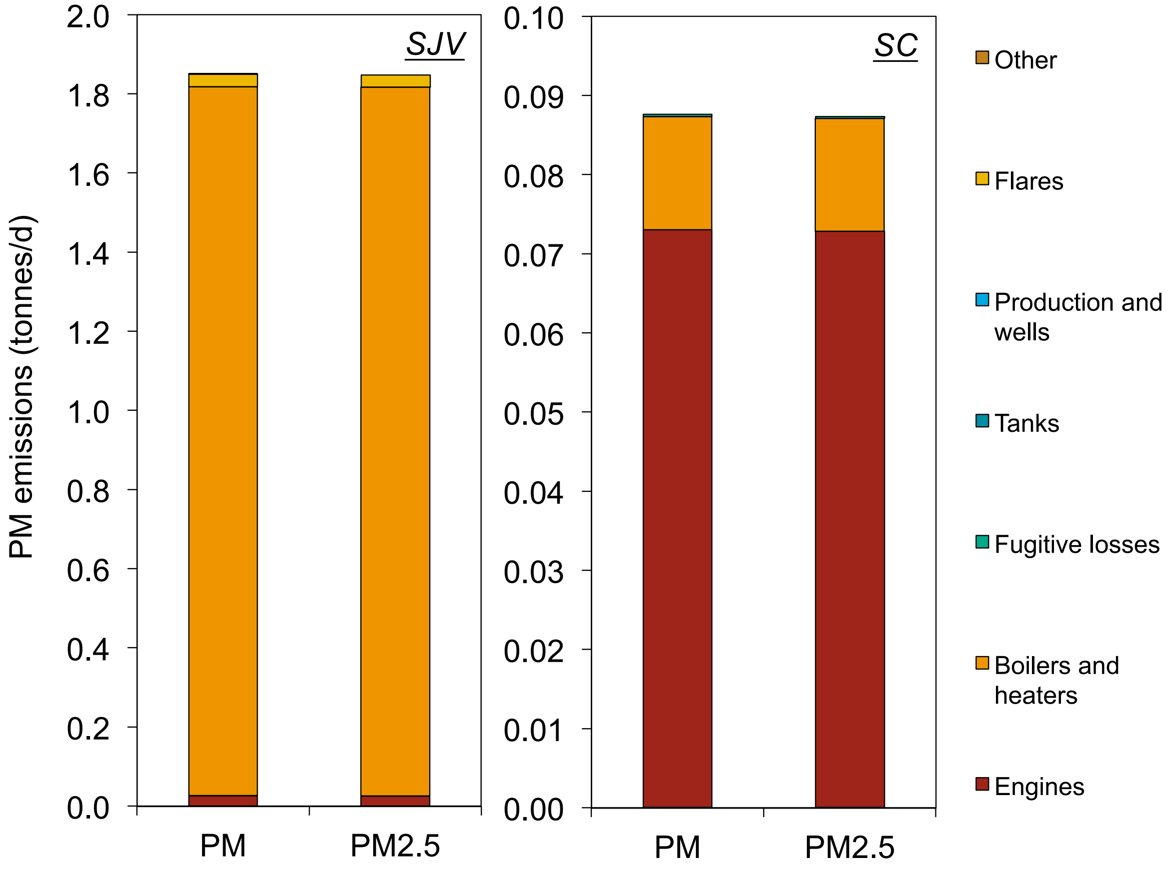


Figure 3.3-12. 2012 stationary source emissions of total particulate matter (PM) and particulate matter of less than 2.5 micrometer (PM2.5) from all oil and gas production sources in San Joaquin Valley and South Coast air districts. Source: CARB (2013b).

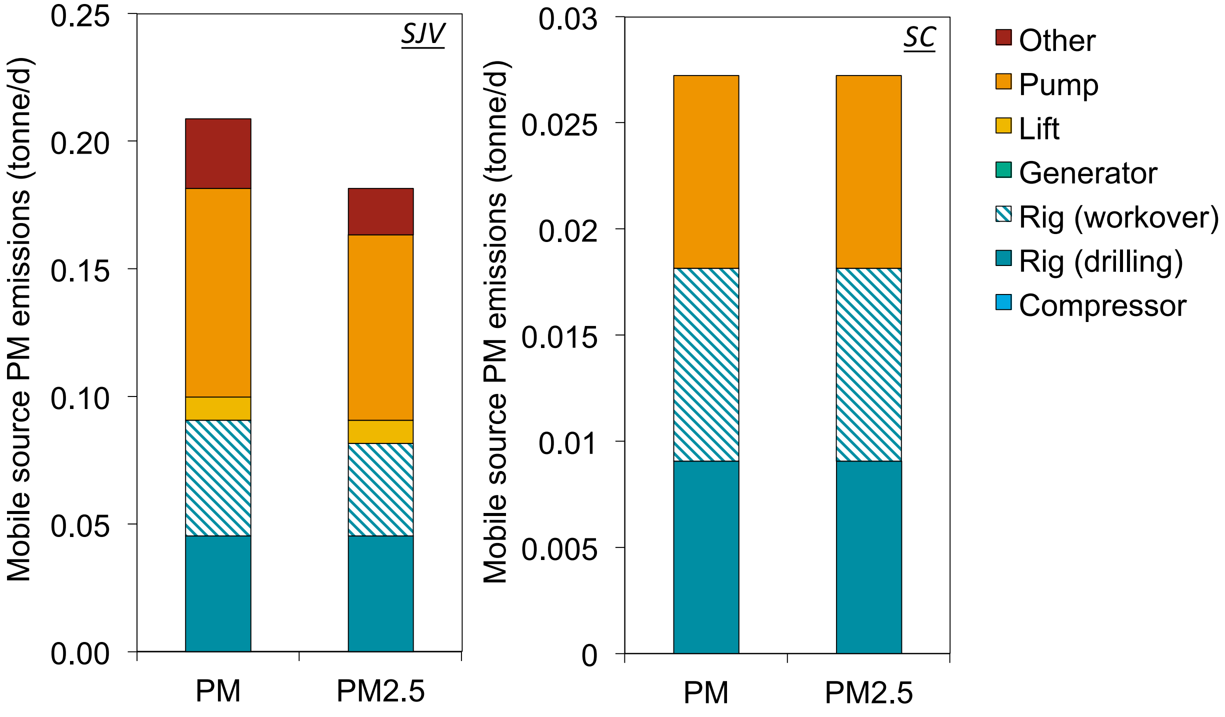


Figure 3.3-13. 2012 off-road mobile source emissions of total particulate matter (PM) and particulate matter of less than 2.5 micrometer (PM2.5) from all oil and gas production sources in San Joaquin Valley and South Coast air districts. Source: CARB (2013b).

3.3.2.2.7. CARB Inventories of Dust Emissions in Rural Regions

A major concern for air quality in rural California is the presence of dust from agricultural activities and other industrial activities occurring on non-paved surfaces. Dust is of particular concern in the SJV, where it contributes to the high levels of PM found in SJV air. If well stimulation technologies significantly affected regional dust levels, this could be an important air quality impact.

CARB creates inventories of dust emissions as part of their criteria pollutant inventory, adding dust emissions from all sources to PM, PM10, and PM2.5 totals. The breakdown of PM from dust sources, as compared to all sources of PM in the SJV region is shown in Table 3.3-16. All dust sources contribute a total of 86% of total PM and 41% of PM2.5 in the SJV (CARB, 2013b). Natural background dust sources are not included in the inventory (CARB, 2013b) and are likely difficult to determine, given the large extent of landscape modification undertaken in the SJV.

Most of the dust sources in the SJV region are farming related. Oil and gas operations could contribute to a variety of categories, including: "Construction and demolition - Building and construction dust: Industrial", "Construction and demolition – Road construction dust", "Fugitive windblown dust - Dust from unpaved roads and associated areas", "Unpaved road travel dust – city and county roads" and "Unpaved traffic area - Private". These sources contribute a total of 24% of total PM and 24% of PM2.5. It is unclear in general how important oil and gas sources are in these inventory categories.

The San Joaquin Valley Unified Air Pollution Control District (SJVUAPCD) has developed methods for assessing dust emissions in more detail than other air districts. For unpaved, non-farm roads, a simple methodology is used that computes emissions based on an assumed number of trips per day on each mile of unpaved county and other non-farm road (CARB, 2004a). No specification is made about how the oil and gas industry might contribute to these trip loads (CARB, 2004a). For unpaved private roads, a simple scaling of the above results is performed (CARB, 2004b), assuming one-tenth the travel seen on county and other public unpaved roads. For the "Unpaved traffic area – Private" source category, a method was developed by SJVUAPCD to include sources such as farms, mines, landfills, and oil and gas operations (CARB, 2003). The emphasis in this dataset is on parking lots, working areas, and other cleared land that is driven on. The results of these methods are shown in Table 3.3-17 for the year in which the methodology was developed. As can be seen, the oil and gas industry contributes to a small fraction (0.6%) of the unpaved road dust emissions in the SJV region, with farms dominating emissions again.

While exact quantification is not possible, these results suggest that farming is the major source of anthropogenic dust in the San Joaquin Valley, and that oil and gas is a minor contributor.

Table 3.3-16. Dust emissions contribution to overall PM emissions in the SJV region (CARB, 2013b). Emissions in tonnes per day (1,000kg/d).

	PM	**PM10**	**PM2_5**
Farming operations	155.6	70.7	10.6
Fugitive windblown dust	87.5	40.3	6.9
Paved road dust	68.6	31.4	4.7
Unpaved road dust	57.2	37.6	3.8
Other dust	17.5	8.6	0.9
Total dust	386.4	188.5	26.8
All PM sources	479.8	255.7	68.7

Table 3.3-17. PM10 from dust emissions from unpaved traffic areas (non-road), tonnes per year (1,000kg/y). (CARB, 2003).

	PM 10	**%**
Farms	2073.0	86.1%
Cotton processing	31.8	1.3%
Landfills	217.9	9.1%
Mining	37.2	1.5%
Oil drilling	14.3	0.6%
Construction	32.7	1.4%

3.3.2.2.8. Natural Sources of Hydrocarbon-Related Air Emissions (Geologic Seeps)

Hydrocarbon species can be emitted to the air from natural sources by surface expressions of hydrocarbon materials (e.g., tar pits) or geologic conduits, fractures, or fissures connecting hydrocarbon-containing reservoirs or sediments to the surface. This possible source is particularly important in the SJV and SC regions, where large oil and gas deposits exist. Because of the co-location of hydrocarbon seeps and oil and gas activities, this has been noted as a potential confounding factor in attributing atmospheric observations to oil and gas activities (e.g., see Wennberg et al., 2012 or Peischl et al., 2013).

The CARB criteria pollutant inventory indicates that petroleum seeps were responsible for 20.0 t per day of ROG out of a total of 6354 t per day across California from all sources (natural and anthropogenic). This can also be compared to 1579 tons per day of ROG from anthropogenic sources. CARB estimates that the vast majority of these ROG emissions are emitted in the South Central Coast Air Basin from offshore seeps in the Santa Barbara region (CARB, 1993).

3.3.2.2.9. Summary of CARB Inventories Treatment of WS Activities

A number of general conclusions can be drawn from the above discussion:

1. Oil and gas activities are responsible for small (generally <5%) fractions of GHG, VOC and PM emissions to California air basins where oil and gas activities are concentrated.

2. Oil and gas activities are responsible for small fractions of NO_x emissions in regions of significant oil and gas activities (<10%)

3. Oil and gas activities are responsible for significant fractions of SO_x emissions in the SJV region (~30%)

4. Oil and gas activities are responsible for significant fractions (30%-70%+) of some stationary source TAC emissions in the SJV (see Figure 3.3-10). Because of large mobile sources and dispersed sources of our indicator TACs, fractions of overall TACs contributions are smaller (see Table 3.3-12).

5. Oil and gas activities appear responsible for large fractions of total hydrogen sulfide and hexane emissions in the SJV region.

6. While dust is a major air quality concern in the SJV region, all evidence points to oil and gas sources being a minor contributor to overall anthropogenic dust emissions and PM from dust.

7. Current inventory methods do not generally allow for clear differentiation of well stimulation from non-well-stimulation oil and gas activities. Better understanding of sources for emissions (e.g., produced hydrocarbon release, processing, other ancillary processes) would allow for further differentiation between stimulation and non-stimulation sources.

8. In some categories (e.g., off-road mobile source), evidence points to some coverage of well-stimulation-related emissions sources, although the exact coverage of well-stimulation-related emissions cannot be determined from the inventory.

9. For some category/pollutant combinations (e.g., crystalline silica dust), coverage of the well-stimulation-associated emissions is unclear or uncertain.

10. Given the relatively small contributions of overall oil and gas activities to most pollutant inventories, treatment of well stimulation emissions is not likely to result in significant changes to larger-scale inventories (e.g., regional or state level).

11. Given the major contribution of overall oil and gas activities to emissions of some stationary TACs in the SJV, application of well stimulation technologies could significantly affect emissions of these TACs, either directly during well stimulation activities or indirectly due to increased production.

3.3.2.3. State-Level Industry Surveys Produced by the California Air Resources Board (CARB)

In 2009, CARB began a detailed survey of oil and gas producer emissions. This survey covers the year 2007, and was released in 2011. As the survey results were further analyzed, corrections were performed and the current version of the results is presented in the revised version of October 2013 (Detwiler, 2013).

3.3.2.3.1. Survey Methods

In early 2009, a survey was mailed to 325 companies representing 1,600 oil and gas facilities. These facilities represented ~97% of the 2007 oil and gas production in California (Detwiler, 2013). The results of the survey were used to compute emissions of CO_2eq. GHGs.

The survey coverage was designed to include all upstream, transport, and refining processes in California. Production and processing activities included all activities required to lift oil and gas to the surface, process it (e.g., acid gas removal), and prepare it for transport to refineries. Oil and gas extraction facilities were included in the survey (Detwiler, 2013, p. 1-3) as were drilling and workover companies (Detwiler, 2013, p. 1-4). In addition, companies that perform ancillary services such as produced water disposal were also included (Detwiler, 2013, p. 1-4). It is not clear if specialized oilfield services involved in well stimulation (e.g., companies that only perform hydraulic fracturing services as subcontractors) were included in the survey coverage.

Related to well stimulation activities, companies were required to report number of active wells, well cellars, and well-maintenance activities (Detwiler, 2013, p. 4-1). By CARB definitions, hydraulic fracturing is considered a well-maintenance activity (Detwiler, 2013, p. 4-1), so results from fracturing should be included in survey results. No discussion of acid fracturing or matrix acidization is explicitly included in the survey, although companies may have reported such activities under "well maintenance" or "well workover."

Of particular importance is the fact that this survey is significantly more detailed in coverage, scope, and specificity than the above-described inventory methods. The survey consists of 16 tables, with very specific required reporting (e.g., presence of access hatch or pressure relief valve on tank) (Detwiler, 2013, p. A-20). Other examples include nearly 30 types of pumps listed in survey appendices (Detwiler, 2013, p. D-4) and dozens of types of separators included in survey definitions (Detwiler, 2013, p. E-3). The calculation methods for determining emissions rates from reported data are included in a detailed methodological appendix.

3.3.2.3.2. Survey Results

The survey found CO_2eq. GHG emissions from the oil and gas industry to be 17.7 Mt CO_2eq. in 2007. This figure does not include refinery emissions, so results should be equivalent to the above GHG inventory result. The emissions are partitioned by type and gas, as shown below in Table 3.3-18. The emissions are partitioned by industry segment as shown in Table 3.3-19. Emissions by air district are reproduced below in Table 3.3-20.

The survey also reports emissions broken down by type of equipment. The most important emissions sources in the inventory were found to be as follows (all sources greater than

10% of total emissions presented): steam generators (41%), combined heat and power systems (22%) and turbines (17%) (Table 3-6 of Detwiler, 2013). Vented emissions came primarily from automated control devices (31%), compressor blowdowns (17%), natural gas gathering lines (14%), gas sweetening and acid gas removal (13%), well workovers (11%) and gas dehydrators (11%). Fugitive emissions came primarily from compressor seals (42%) and storage tanks (27%).

Table 3.3-18. Results from CARB 2007 oil and gas industry survey. Reproduced from Detwiler (2013), Table 3-1.

Type of source	Gas	Emission (kt/y)	Emission of CO_2 eq.
Combustion	CO_2	16073.4	16398.3
	CH_4	10.8	
	NO_x	0.3	
Venting	CO_2	56.0	392.6
	CH_4	16.0	
	NO_x	0.0	
Fugitive	CO_2	107.3	895.5
	CH_4	37.5	
	NO_x	0.0	

Table 3.3-19. Results from CARB 2007 oil and gas industry survey, presented by business type. Reproduced from Detwiler (2013), Table 3-2.

Type of source	Gas	Emission (kt/y)
Onshore crude production	CO_2eq.	10343.1
Natural gas processing	CO_2eq.	1043.4
Onshore natural gas production	CO_2eq.	547.6
Crude processing and storage	CO_2eq.	407.2
Natural gas storage	CO_2eq.	334.8
Offshore crude production	CO_2eq.	140.1
Crude pipelines	CO_2eq.	89.8
Other	CO_2eq.	4764.7

Table 3.3-20. Results from CARB 2007 oil and gas industry survey, presented by air district. Reproduced from Detwiler (2013), Table 3-4.

Air district	**Gas**	**Emission (kt/y)**
San Joaquin Valley	CO_2eq.	14,006
South Coast	CO_2eq.	1,205
Santa Barbara County	CO_2eq.	1,049
Monterey Bay Unified	CO_2eq.	498
Ventura County	CO_2eq.	265
Other	CO_2eq.	636
Total	CO_2eq.	17,659

3.3.2.3.3. Survey Alignment with other California Inventories

The above reported total emissions figure of 17.7 Mt CO_2eq. is slightly higher than the reported inventory value of 17.0 Mt CO_2eq. reported in the 2014 inventory for the year 2007 (CARB, 2014d). A disparity of <5% between these two estimates is consistent with differences that would occur due to methodological differences between the two fundamentally different studies (survey vs. inventory).

In the 2014 GHG inventory, estimated fuel combustion emissions of CO_2, CH_4, and N_2O totaled 15.767 Mt CO_2eq, or 92.7% of the total inventory. In the CARB survey, combustion emissions are responsible for 93% of the total inventory emissions (Detwiler, 2013, p. 3-1). In terms of emissions per gas, the GHG inventory reports 94% of total emissions (combustion + fugitive/venting) as CO_2, with the remainder from CH_4 and N_2O. In contrast, the survey estimates 91.8% of statewide oil and gas emissions as CO_2. Alignment in these sub-results between two different methodologies (e.g., industry survey vs. inventory) increases the confidence in these results.

The yearly GHG inventory is created at the state level, which does not allow for comparison of the emissions by air district reported in Table 3.3-20. Because the GHG inventory does not report emissions by source technology (e.g., steam generator), no comparison between the survey and the inventory at the technology level can be performed. In summary, there is generally very good agreement between the CARB GHG inventory (2014 version) and the CARB oil and gas emissions survey. Such alignment increases the confidence that GHG emissions from the oil and gas industry in California are well understood.

3.3.2.4. Federal Emissions Inventories

While the chief focus of this report is on California information sources, some U.S. federal data are also available on California oil and gas operations.

The U.S. EPA GHG reporting program (U.S. EPA GHGRP) is an annual facility-level-reported inventory for GHG emissions. The requirement for reporting emissions is currently set at 25,000 tonnes per year CO_2eq., and the facilities are separated by industry and state starting in 2008 (U.S. EPA, 2010). This is unlike the national GHG emissions inventory, which is an inventory of GHG emissions from oil and gas production aggregated by activity. The GHG inventory is constructed using standard emissions factors combined with activity counts across the national oil industry. This is compared to the GHGRP, where producers report emissions directly to U.S. EPA.

Within the U.S. EPA GHGRP, the specific section relating to the oil and gas sector is Subpart W, which covers all emissions from the well to the refinery gate. Each operator reports emissions for a facility, which is defined by Subpart W as all emissions associated with wells owned by a single operator, in a producing basin. Reported emissions are computed through a combination of direct measurement, mass balance, and emission factors. Most venting and fugitive emissions are based upon “engineering estimations,” which primarily utilize default emissions factors as a function of activity (U.S. EPA, 2010).

The emissions reported the GHGRP are aggregated over twenty categories (see Table 3.3-21). Emissions are reported by species (typically CO_2, N_2O, or CH_4). The data also report specific information about the equipment utilized on site (e.g., whether a vapor recovery system is used for atmospheric storage tanks). For most operators, emissions are reported for only a few of these categories. There is a designation for emissions that occur during well completions from hydraulic fracturing of gas wells. However, since well stimulation in California is utilized primarily for oil production, no well-stimulation-related emissions are reported in the GHGRP for California producing basins.

Table 3.3-21. Emissions reporting categories for GHGRP subpart W, reproduced from the FLIGHT tool (U.S. EPA, 2015b).

Natural gas pneumatic devices	**Associated gas venting and flaring**
Natural gas driven pneumatic pumps	Flare stacks
Acid gas removal units	Centrifugal compressors
Dehydrators	Reciprocating compressors
Well venting for liquids unloading	Other emissions from equipment leaks estimated using emission factors
Gas well completions and workovers	Local distribution companies
Blowdown vent stacks	Enhanced oil recovery injection pump blowdown
Gas from produced oil sent to Atmospheric tanks	Enhanced oil recovery hydrocarbon liquids dissolved CO_2
Transmission tanks	Onshore petroleum and natural gas production and distribution combustion emissions
Well testing venting and flaring	Offshore sources

Due to the 25,000 tonnes per year requirement, emissions from small oil and gas production will likely be undercounted. This is demonstrated in Table 3.3-22, which shows reported GHG emissions for California oil operations separated by basin and source of emissions. Note that these emissions are significantly below those reported by operators in the California oil and gas survey discussed above. For example, compare the results for the San Joaquin production basin from which GHGRP emissions are reported as ~2,050 kt/y CO_2eq., while California survey emissions are reported as ~14,000 kt/y CO_2eq (see Table 3.3-20).

Table 3.3-22. Results from GHGRP subpart W, presented by production basin for California. Reproduced from FLIGHT tool (U.S. EPA, 2015b).

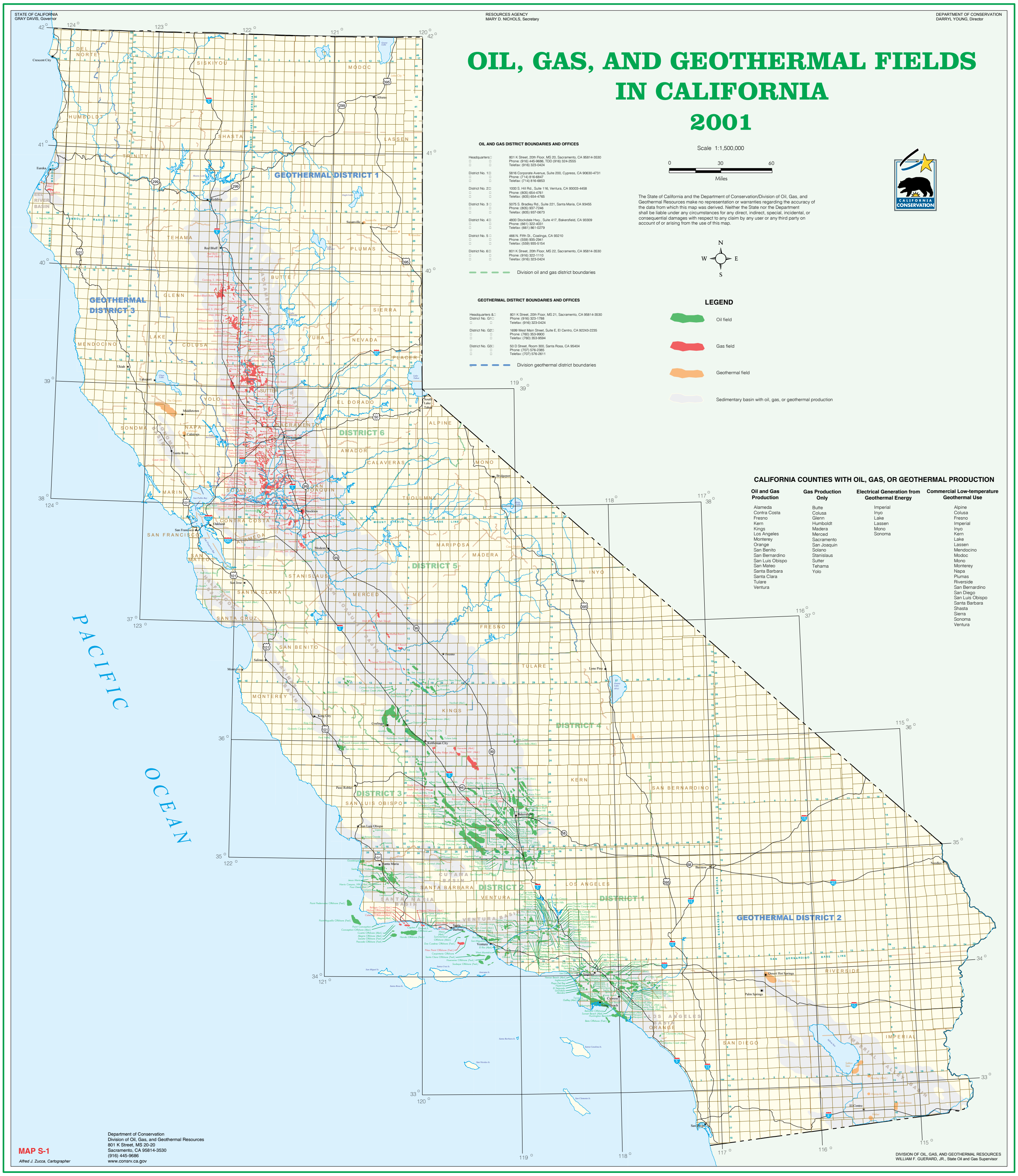
	Reported GHG emissions (kt CO_2eq/y)						
Basin	**Combustion**	**Pneumatics**	**Venting & Flaring**	**Tanks**	**Compressors**	**Other**	**Total**
San Joaquin	1924	18	56	13	18	19	2048
Los Angeles	220	0	2	2	0	0	224
Offshore	235	0	4	0	0	35	274
Other	125	79	5	24	4	40	277

3.3.2.5. Emissions From Silica Mining

One example of an offsite impact of concern is crystalline silica dust emissions during mining and processing of proppant. Crystalline silica dust is a TAC, and can affect human health. Silica dust can be created during the proppant mining, production, and usage phases. Silica is a topic of concern as a WST occupational hazard; for example, see work by Esswein et al. (2013) for exposure assessment in locations outside of California. No oil-and-gas-associated SIC codes in the SJV or SC air districts reported emissions of silica dust. In the SJV air district in total, facility-level total emissions of crystalline silica (CARB species ID 1175) equaled ~749,000 lbs, with a total of 85 facilities reporting from a variety of SIC codes. Similar values are reported for total crystalline silica emissions in the CTI database for 2010 in the SJV region. However, none of the five upstream (or 12 total) SIC codes associated with oil and gas report emission of crystalline silica. In the SJV air district, key SIC codes reporting silica emissions are as follows: construction sand and aggregate (SIC 1442); nonmetallic minerals (SIC 1499); asphalt paving mixtures (SIC 2951); and minerals, ground or treated (SIC 3295). It is not clear from public documents if any of the above facilities are supplying proppant materials for well stimulation activities, and therefore if they may be considered a well-stimulation-related emissions source.

3.3.3. Potentially Impacted California Air Basins

While GHGs have impacts on global climate, the other three well-stimulation-related emissions (VOC/NO_x, TACs and PM) are relatively short-lived and primarily influence the air basins where oil and gas extractions occur. According to the Department of Oil Gas and Geothermal Resources (Figure 3.3-14), the two largest California oil and gas producing regions are contained within the San Joaquin Valley (SJV) Unified air district and South Coast (SC) air district. Specifically, significant oil production occurs in the Kern, Santa Barbara, and Ventura air districts, while non-associated (dry) natural gas production occurs in a number of Northern SJV air districts.



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Division oil and gas district boundaries

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The State of California and the Department of Conservation/Division of Oil, Gas, and Geothermal Resources make no representation or warranties regarding the accuracy of the data from which this map was derived. Neither the State nor the Department shall be liable under any circumstances for any direct, indirect, special, incidental, or consequential damages with respect to any claim by any user or any third party on account of or arising from the use of this map.

CALIFORNIA COUNTIES WITH OIL, GAS, OR GEOTHERMAL PRODUCTION

Oil and Gas Production	Gas Production Only	Electrical Generation from Geothermal Energy	Commercial Low-temperature Geothermal Use
Alameda	Butte	Imperial	Alpine
Contra Costa	Colusa	Inyo	Colusa
Fresno	Glenn	Lake	Fresno
Kern	Humboldt	Lassen	Imperial
Kings	Madera	Mono	Inyo
Los Angeles	Merced	Sonoma	Kern
Monterey	Sacramento		Lake
Orange	San Joaquin		Lassen
San Benito	Solano		Mendocino
San Bernardino	Stanislaus		Modoc
San Luis Obispo	Sutter		Mono
San Mateo	Tehama		Monterey
Santa Barbara	Yolo		Napa
Santa Clara			Plumas
Tulare			Riverside
Ventura			San Bernardino
			San Diego
			San Luis Obispo
			Santa Barbara
			Shasta
			Sierra
			Sonoma
			Ventura

Department of Conservation
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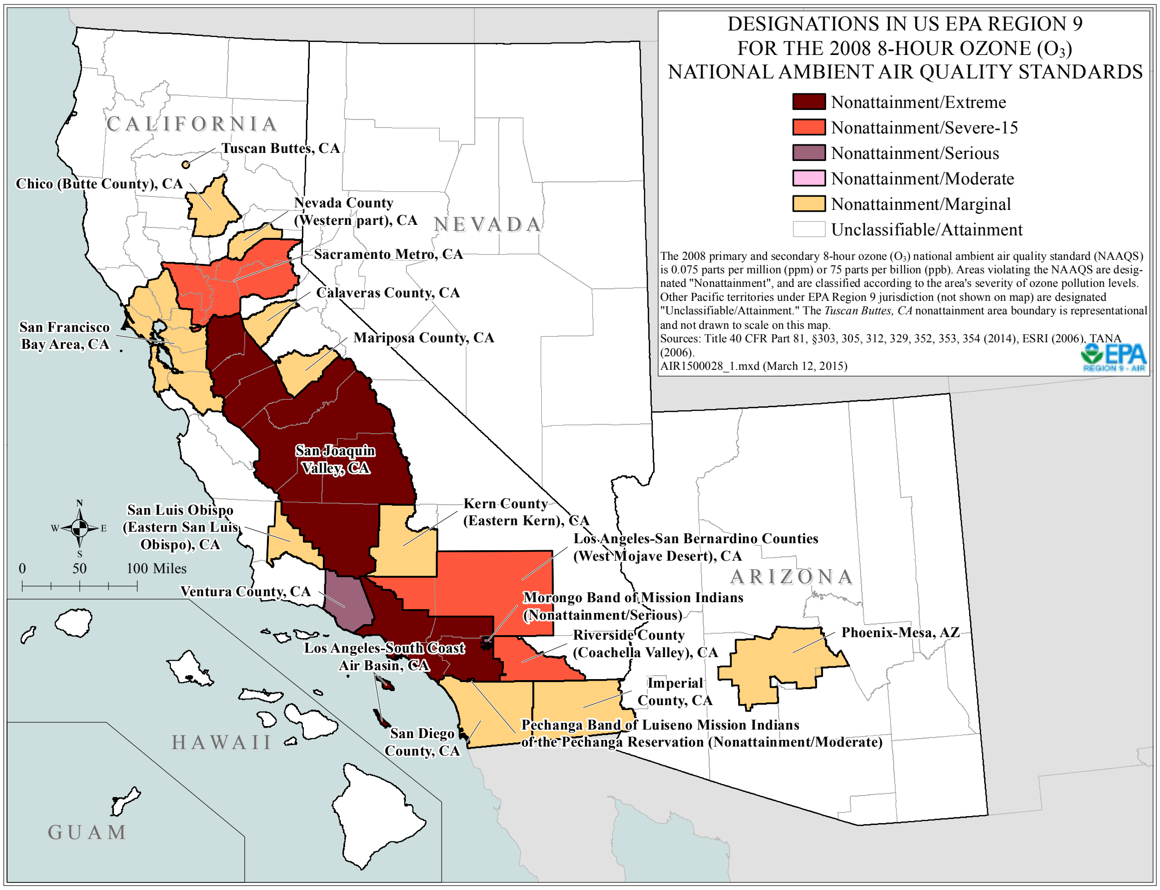
Figure 3.3-14. Map of oil (green) and gas (red) fields in California. Image courtesy of California Department of Oil, Gas and Geothermal Resources [DOGGR] http://www.conservation.ca.gov/dog/Pages/Index.aspx.

3.3.3.1. Status And Compliance in Regions of Concern

The two air basins (San Joaquin Valley and South Coast) most strongly impacted by oil and gas production also coincide with the worst air quality in California. Both air basins are currently out of compliance with both national ozone and PM2.5 standards.

Figure 3.3-15 shows the current designation of ozone attainment status of air districts in California. Ozone pollution level is characterized by a “design value,” a three-year rolling average of the fourth highest 8-hour ozone concentrations measured at the monitoring station. The designation of attainment status is determined by comparing the design value to the National Ambient Air Quality Standard. The nonattainment areas are further divided into six classes from “marginal” to “extreme” depending on the extent to which the design value exceeds the standard. Both San Joaquin Valley and South Coast are classified as an “extreme” nonattainment area, meaning their design values are greater than 175 ppb, which is more than double the current 8-hour ozone standard (75 ppb) and almost three times EPA’s proposed update to the standard (65 ppb). The Sacramento air district, located in the dry gas producing region, is also a “severe” nonattainment area for ozone (Figure 3.3-15).


DESIGNATIONS IN US EPA REGION 9
FOR THE 2008 8-HOUR OZONE (O_3)
NATIONAL AMBIENT AIR QUALITY STANDARDS

The 2008 primary and secondary 8-hour ozone (O_3) national ambient air quality standard (NAAQS) is 0.075 parts per million (ppm) or 75 parts per billion (ppb). Areas violating the NAAQS are designated "Nonattainment", and are classified according to the area's severity of ozone pollution levels. Other Pacific territories under EPA Region 9 jurisdiction (not shown on map) are designated "Unclassifiable/Attainment." The *Tuscan Buttes, CA* nonattainment area boundary is representational and not drawn to scale on this map.

Sources: Title 40 CFR Part 81, §303, 305, 312, 329, 352, 353, 354 (2014), ESRI (2006), TANA (2006).

AIR1500028_1.mxd (March 12, 2015)

Figure 3.3-15. Air basin designation of 2008 8-hour ozone standard. Source: U.S. EPA, 2012.

The majority of the counties within the SJV and SC air basins are out of compliance with the 24-hour PM2.5 standard (35 mg/m^3), and a few with the newly established annual PM2.5 standard (12 mg/m^3) (Table 3.3-23). Sacramento is a nonattainment area for the 24-hour PM2.5 standard, but not for the annual standard.

A number of factors result in the poor air quality in the SJV and SC regions. First, unfavorable topography creates local circulations trapping emissions in the air basins. Second, besides the oil and gas industry, both regions host diverse emission sources including industry, agriculture, residential homes, businesses, and the transport sector. The SJV is among the nation's largest agriculture areas, with emissions from dairy farms contributing to fine particle formation. Los Angeles County is the most populated county in the U.S. (U.S. Census, 2010) resulting in significant air emissions. Third, the generally warm and sunny conditions in the state promote photochemical reactions and formation of smog in the summer. Cool and humid conditions in winter promote fine particulate formation in the winter.

Table 3.3-23. Attainment status for PM2.5 in the main oil and gas producing regions. (Source: U.S. EPA, 2009 and CARB, 2013f)

Area name	**Counties exceeding 24-h PM2.5 standard (35 ug/m^3)**	**Counties exceeding annual PM2.5 standard (12 ug/m^3)**
Los Angeles-South Coast Air Basin	Los Angeles Orange Riverside San Bernardino	Mira Loma, Riverside County
San Joaquin Valley	Fresno Kern Kings Madera Merced San Joaquin Stanislaus Tulare	Clovis, Fresno County
Sacramento Air District	El Dorado Placer Sacramento Solano Yolo	

3.3.3.2. Likely Distribution of Impacts Across Air Basins

According to the emission inventory reviewed in previous sections, the well-stimulation-related emissions of VOC/NO$_x$ and PM are likely to be a small fraction of all the emissions occurring in California. More specifically, oil and gas activities are generally responsible for <5% of the emissions of VOC and PM and for <10% of NO$_x$ to the SJV and SC. Oil and gas activities, however, are responsible for significant fractions of some TAC emissions in the SJV with significant oil and gas activities (30–60%). This is particularly the case for VOC-related TACs.

As natural gas produced from a well with natural gas liquids and oil (wet gas) will be richer in VOCs than that from a well producing mostly natural gas (dry gas) (Jackson et al., 2014), the dry-gas producing regions, such as Sacramento Valley, are expected to have smaller contributions to VOCs and TACs.

As noted above, the contribution of oil and emissions in SC is generally much smaller than that in SJV. The population density in the Los Angeles region is also more than 10 times greater than the SJV region, and is largely collocated with oil and gas activities. As a result, the health hazard from oil and gas emissions can still present a significant problem in SC when source proximity and exposed population are taken into consideration (see Volume II, Chapter 6).

3.4. Hazards

3.4.1. Overview of Well-Stimulation-Related Air Hazards

In this chapter, various chemical species related to well stimulation have been grouped into the following four categories.

1. Greenhouse gases (GHGs);

2. Volatile organic compounds (VOCs) and nitrous oxides (NO_x) emissions leading to photochemical smog generation;

3. Toxic air contaminants (TACs);

4. Particulate matter (PM).

In general, GHGs impact global climate and the other three affect air quality.

GHGs: GHGs include carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), VOCs, and black carbon (BC) (IPCC, 2013, pp. 738-740). These species absorb and emit infrared radiation and thus affect the global radiative balance of the atmosphere. GHG emissions considered here generally produce an increase in the average temperature of the Earth.

VOCs and NO_x: VOC emissions are generated during venting of gases from the well and evaporation of chemicals from flow-back or produced liquids. NO_x emissions associated with WS activities will derive primarily from use of engines powered by diesel or natural gas, which are used directly in WS applications. Processing and compression facilities can also contribute to VOCs/NO_x emissions. VOCs/NO_x lead to environmental and health impacts through various pathways.

- NO_x and VOC can enhance formation of ozone, a key constituent of photochemical smog.
    - Ozone is designated as a criteria pollutant by the Federal Clean Air Act (U.S. EPA, 1994) due to its adverse effects on human health (Bell and Dominici, 2008) and on agriculture productivity (e.g., Morgan et al., 2003). Children, elderly, and people with lung diseases such as asthma are particularly sensitive to ozone concentrations.
    - Ozone and its photolysis also affect climate, because ozone is a greenhouse gas and its photolysis products strongly influence the oxidant content of the atmosphere, which, in turn, affects the lifetimes of other important greenhouse gases and TACs.
- The oxidation products of NO_x and VOC can condense into particle phase and lead to an increase in PM burden. PM formed during these processes is called secondary particulate matter, including particulate nitrate and organic carbon. Secondary particulate matter is associated with increased rates of premature mortality through their deep penetration into the lungs.
- In addition to smog-formation potential, VOCs often also function in the short and long-term as GHGs through their eventual decomposition into carbon dioxide (CO_2).
- Some VOCs are carcinogens or endocrine disruptors and are directly hazardous.

TACs: TACs included in a recent EPA risk assessment are listed in Table 3.4-1. These TACs are emitted in similar processes that contribute to VOCs. TACs can be a concern for workers in the oil and gas industry due to their frequent exposure to TACs. TACs may also present a health concern for those who live near oil and gas operations.

PMs: Diesel equipment used to pump the fluid into the well and the diesel trucks used to bring supplies to the well are the major sources of PM emissions directly related to WS activities. Incomplete combustion at flaring units can also produce PM (soot). PM has both environmental and health impacts. Note that PM considered in previous sections are direct emissions, also known as primary PM. Particles formed through complex reactions in the atmosphere (i.e., secondary PM), such as in NO_x and VOCs oxidation products, are not included in the estimation. Formation of secondary organic carbon is likely to be minor (Gentner et al., 2014), because the hydrocarbons emitted from well stimulation are mostly light alkanes whose oxidation products do not tend to condense into particle phase.

- PM is associated with respiratory health impacts and increased rates of premature mortality through its deep penetration into the lungs. Particulate matter with aerodynamic diameter less than 2.5 micron (PM2.5) and 10 micron (PM10) are both regulated by U.S. EPA as criteria pollutants, due to their adverse health effects.

- Fine particles (PM2.5) are the main cause of regional haze. Reduced visibility is a main concern in national parks and wilderness areas.

Table 3.4-1. TAC emissions ranked by mass emissions rate from oil and natural gas production source category, reproduced from U.S. EPA risk assessment. (U.S. EPA, 2011, Table 4.1-1)

TAC	**Emissions (tons per year)**	**Number of facilities reporting (out of 990 facilities)**	**Included as TACs indicator species in this report?**
Carbonyl sulfide	4,151	727	Y
Hexane	1,666	836	Y
Toluene	1,344	940	Y
Benzene	936	963	Y
Xylenes (mixed)	576	924	Y
Ethyl benzene	111	818	Y
Methanol	88	67	
2,2,4-Trimethylpentane	30	733	
Ethylene glycol	27	727	
Naphthalene	17	754	
Chlorobenzene	11	18	
m-Xylene	11	23	
1,1,1-Trichloroethane	9	4	
Glycol ethers			
- Glycol ethers	5	3	
- Ethylene glycol methyl ether	0.1	5	
- Triethylene glycol	0.02	2	
- Ethylene glycol ethyl ether	0.007	4	
p-Dichlorobenzene	4	13	
Formaldehyde	2	255	Y
Biphenyl	2	2	
Cumene	2	23	
Carbon disulfide	1	726	
Diethanolamine	1	4	
o-Xylene	0.8	7	
1,4-Dioxane	0.6	6	
o-Cresol	0.6	1	
Methylene chloride	0.5	1	
p-Xylene	0.3	7	

Phenol	0.2	16	
Acetaldehyde	0.02	245	Y
Polycyclic organic matter			
- PAH, total	0.02	29	
- Benzo[a]Pyrene	0.002	3	
- Chrysene	0.002	3	
- Anthracene	0.000006	1	
- Benz[a]Anthracene	0.000005	2	
- Benzo[b]Fluoranthene	0.000003	2	
- Benzo[k]Fluoranthene	0.000003	2	
- Dibenzo[a,h]Anthracene	0.000003	2	
- Indeno[1,2,3-c,d]Pyrene	0.000003	2	
Propylene oxide	0.009	4	
Cresols (mixed)	0.009	6	
Ethylene dichloride	0.007	9	
Chloroform	0.004	1	
Hydrochloric acid	0.004	4	
Acrolein	0.002	8	
Dibenzofuran	0.001	1	
Ethylene dibromide	0.0006	5	
Styrene	0.0003	4	
Vinylidene chloride	0.0003	1	
Ethylene oxide	0.00002	1	
Acrylamide	0.00002	1	
Methyl bromide	0.0000005	1	

3.4.2. Hazards due to Direct vs. Indirect Well Stimulation Impacts

Due to their different transport, transformation, and removal mechanisms, species emitted from well stimulation have atmospheric lifetimes ranging from hours (e.g., TACs) to more than 100 years (e.g., CO_2). Accordingly, their spatial impacts range from local, regional, to global scales. GHGs have global impacts over long time scales. As a result, for any given amount of GHG emissions, their impact is not tied to the source locations and emitted time. For the other three categories (NO_x/VOC, TACs, and PM), with generally shorter atmospheric lifetimes and local to regional dispersion, the impacts are closely related to their temporal and spatial allocation at different phases of the well stimulation life-cycle. Some TAC species, such as TAC metals species, can be persistent in the environment and may become more widely dispersed than the reactive organic TACs.

3.4.2.1. Direct Well Stimulation Impacts

On-site air hazards of NO_x/VOC, TACs, and PM affect the surroundings of the well site and downwind areas. Emissions from various phases of on-site activities generally affect the concurring time periods plus a few weeks after, as their atmospheric lifetimes are not longer than a few weeks. The phases of on-site activities and their occurring time frame are as follows:

- Well stimulation application and well completion last days to weeks for a single well and up to a couple of months for multiple wells. During these processes, NO_x and PM are emitted from the on-site diesel engines for trucking and pumping. Hydrocarbons, including smog-forming VOCs and TACs, are the major components from fugitive and vented emissions from well stimulation materials, pipe lines, and flowback water.

- On-site handling of proppant materials could pose a health risk to workers due to particulate matter emissions associated with silica proppant sands.

3.4.2.2. Indirect Well Stimulation Impacts

Some indirect WS hazards are described in this report:

- Well-stimulation-induced production impacts are impacts associated with hydrocarbon production that would not have been economically viable without application of well stimulation technology. The production of additional hydrocarbons on-site may last years after the well completion. Production and processing activities such as dehydration and separation can produce VOC and TAC emissions from equipment leaks, intentional venting from produced water storage tanks, and flaring. PM and NO_x can also be produced by incomplete combustion during flaring and use of diesel engines and compressor engines.

- Supply-chain impacts associated with well stimulation activity include air emissions generated during the course of numerous industrial activities associated with the preparation, distribution, and maintenance of well-stimulation-related materials.

In summary, the well-stimulation-induced hydrocarbon production produces continued air hazards affecting the well site and downwind areas. The supply chain impacts and macroeconomic impacts are more distributed in time and space.

3.4.3. Assessment of Air Hazard

3.4.3.1. Greenhouse Gas Hazard Assessment

GHGs affect global radiative balance. Due to their relatively long atmospheric lifetimes, emissions are well mixed globally once they enter atmospheric circulation. As a result, their impact can be well represented by the mass emitted. As described by the IPCC (2013), the hazard is usually assessed by global-warming potential (GWP), a relative measure of how much heat is trapped by a GHG relative to the amount of heat trapped by the same mass of carbon dioxide. The GHG impacts, listed using current 20-year and 100-year global warming potentials for well-stimulation-relevant gases, are presented in Table 3.2-1. When the GWP of a GHG is applied as a multiplier to its emissions, a CO_2 equivalency amount is derived. Essentially, CO_2 equivalency describes the amount of CO_2 that would have the same GWP as the given amount of emissions of another GHG over a specified time scale (e.g., 100 years). Using the GWP, emissions of a mixture of GHGs can be expressed by a single quantity of CO_2 equivalency to represent the time-integrated (100 years) value of radiative forcing of the mixture.

3.4.3.2. Air Quality Hazard Assessment

3.4.3.2.1. Overview of Air Quality Assessment Methods

NO_x/VOCs, TACs and PM emissions have shorter-term effects than GHGs, and the spatial impacts are not homogeneous due to their shorter atmospheric lifetimes. The air quality of a region is characterized by measurements of ambient concentrations of specific pollutants, including PM and ozone, from central monitors in that region. Before the pollutants emitted from well stimulation are measured by the monitoring devices, they are dispersed by wind and may undergo chemical transformation in the atmosphere. The manner in which the same emissions will affect air quality will differ, depending on the meteorological conditions and the other pollution already present in the atmosphere (the chemical transformations depend on total pollution levels). Although oil and gas activities have relatively low contributions to criteria air pollutant emissions (NO_x, VOCs, PM), as summarized in previous sections, they do in some cases produce relatively high contributions to TACs. Atmospheric dispersion of TACs needs to be tracked with models in order to determine their impacts on populations at varying distances downwind.

There are several methods one might employ to evaluate how well stimulation emissions impact air quality. One could try to determine the impact of emissions through analyzing air quality measurements, comparing air quality on days with high well stimulation activity to days with low well stimulation activity. However, the variability in meteorology and atmospheric chemistry between days would likely overwhelm any signal that might exist from well stimulation variability. Instead of depending only on measurements, air quality models are often used to describe how pollutants are dispersed through the atmosphere and chemically transformed. The models connect the pollutant emissions to their air quality impacts. Two different air quality models are discussed below; their suitability for application depends on the nature of the pollutant of interest.

Gaussian plume dispersion modeling is a simple yet powerful tool to calculate the evolution of air pollutant concentrations during the course of wind-driven transport and dispersion of non-reactive or first-order decaying pollutants, with decay rate linearly related to concentration. Gaussian plume models (see review by Holmes and Morawska, 2006) are based on analytical solutions to the advection-diffusion equation in simplified atmospheric conditions. Gaussian dispersion models can handle complex terrain and can be adapted to account for some atmospheric processes such as deposition. Gaussian plume models cannot account for interactions between plumes; they are not able to track nonlinear chemistry that leads to secondary pollutant formation in the atmosphere, such as ozone formation. They require relatively little data and computational resources.

A more useful method for calculating ambient pollution levels is to use chemical transport models (CTMs). CTMs solve the advection-diffusion equation numerically for a reactive flow on a gridded domain. CTMs implement chemical mechanisms containing hundreds of reactions. They can also include time-resolved representations of nonlinear chemistry and particle dynamics with various degrees of complexity. CTMs require very detailed meteorological forcing inputs, such as wind velocity, temperature, humidity, etc., at each grid cell of the domain, are computationally expensive, and require advanced training. The advantages of using CTMs to estimate exposure include the capacity to account for the effects of space- and time-resolved influential parameters (e.g., detailed wind and temperature fields) and the capacity to model nonlinear processes such as second-order chemistry and particle dynamics in a time-resolved manner. This approach is suited for simulating concentrations of secondary pollutants such as ozone and secondary organic carbon.

Air quality hazards discussed here include species of emissions associated with well stimulation (directly emitted species) and the pollutants formed through chemical transformation of these emissions in the atmosphere (chemically formed species). Suitability of air quality models for assessing these two types of pollutants is discussed further in the following sections.

3.4.3.2.2. Well-Stimulation-Induced Air-Quality Hazard Assessment: Directly Emitted Species

Directly emitted species can be tracked with Gaussian plume dispersion models, which link the amount of emissions from the source locations to changes in concentrations. These species include all the air hazards considered in previous emission inventories (e.g., NO_x/VOCs, TACs, and primary PM). These can be done for on-site emissions of selected case studies, where a clear emission boundary can be defined. Modeling and analysis protocol is briefly described below.

- Required inputs:
    - Meteorological data (obtained from national weather service): hourly or daily wind speed and direction, amount of atmospheric turbulence, ambient air temperature, inversion height, cloud cover and solar radiation
    - Emission parameters: source location and height, spatial characteristic of source as in point (i.e., smoke stack), line (i.e., highway), or area (i.e., oil field), and exit velocity and mass flow rate of the plume
    - Terrain elevations and surface characteristics: ground elevations at the source and at the locations where pollutant level are to be computed, surface roughness
- Model simulation: use the meteorological data and surface characteristics to drive the dispersion model for emitted pollutant of interest, accounting for depositional loss and first-order decay.
- Post-model analysis: enhancement in ambient concentrations of the pollutant of interest can be plotted as a function of time and space and summarized by season. The most impacted times and locations can be identified and used for subsequent exposure and health studies.

3.4.3.2.3. Well-Stimulation-Induced Air-Quality Hazard Assessment: Chemically Formed Species

Chemically formed species such as ozone and secondary PM are not directly emitted and thus cannot be tracked by dispersion models, as there is no discrete “source location.” Another challenge is that the formation chemistry of these pollutants is often nonlinear. In other words, the amount of pollutant formed cannot be linearly scaled from its precursor emission quantities, but rather depends on the pollution levels present in the air. For example, in a NO_x-rich environment such as a densely populated Los Angeles urban area, additional NO_x emissions from well-stimulation-related activities may actually decrease ambient ozone concentration locally, while affecting downwind regions (Rasmussen et al., 2013). In NO_x-poor areas, such as a remote well pad location in the San Joaquin Valley, the opposite is true, i.e., well-stimulation-related NO_x emissions contribute to an increase in ambient ozone levels (Rasmussen et al., 2013). Chemical transport models (CTMs) are required in this case to simulate the formation process of these species from their precursors. In the case of ozone, CTMs track the production and removal of ozone as its NO_x/VOC precursors disperse from the source location downwind accounting for the nonlinear chemistry. Conducting computer simulation with CTMs is beyond the scope of this study. Many past studies have investigated ozone and secondary PM responses to changes in emissions (Jin et al., 2008; 2013; Rasmussen et al., 2013; Chen et al., 2014) in California.

3.5. Alternative Practices to Mitigate Air Emissions

This section presents a review of alternative practices that reduce emissions of pollutant and GHG related to well stimulation with a focus on direct hazards.

3.5.1. Regulatory Efforts to Prescribe Best Practices

Many states outside of California where hydraulic fracturing takes place have begun to regulate the overall environmental impacts of the oil and gas industry, by requiring emission controls and best practices. As reviewed in Moore et al. (2014), Colorado, Wyoming, Montana, and New York have taken the most aggressive regulatory steps to reduce both pollutant and GHG emissions (Table 3.5-1). In the regulations passed from 2007 to 2009 in Colorado, operators are required to apply alternative practices and controls to reduce VOC emissions, including use of “green completion” or reduced emission completion technologies at oil and gas wells when technically feasible, and control evaporative emissions from condensate and oil storage tanks. In the northeastern Front Range O3 nonattainment area, further actions are required, such as use of no-bleed or low-bleed pneumatic devices.

In California, regulations are set at local air district levels. San Joaquin Valley Air Pollution Control District Rule 4402 regulates the emissions of VOCs from crude oil wastewater sumps. Under this rule, VOC emission control, such as a covering in place, is required for any produced water containing over 35 mg/L of VOCs. Small oil producers and “clean produced water” containing less than 35 mg/L are exempt from the rule. The South Coast Air Quality Management District (SCAQMD), have more stringent regulations for open pits. The SCAQMD (Rule 1176) for example, requires produced water in open pits contain less than 5 mg/L VOC’s, compared to the San Joaquin threshold of 35 mg/L.

At the national level, in 2012, the U.S. EPA released a set of new source performance standards (U.S. EPA, 2012) which were phased in starting in late 2012, with full effect in early 2015. The standard requires the use of green completion technologies and reduced VOC emissions from temporary storage tanks during well completion. Historically, the fluids and gases in flowback water are routed to an open-air pit or tank to allow evaporation. Green completion captures liquids and gases during well completion with temporary processing equipment for productive use.

Further VOC and TACs controls are required by the rule (U.S. EPA, 2012), including limiting emissions of VOCs from a new single oil or condensate tank to four tons per year, and limiting the hazardous air pollutants benzene, toluene, ethylbenzene, and xylenes (BTEX) from a single dehydrator to one ton per year. In addition to VOC reduction through vapor controls at temporary storage tanks, green completion also benefits the control of methane emissions by essentially requiring natural gas companies to capture the liquid and gas at the wellhead immediately after well completion instead of releasing it into the atmosphere or flaring it off.

The U.S. EPA also adopted multiple tiers of emissions standards for new diesel engines that may influence emissions incurred by the trucking and pumping processes related to well stimulation. Vehicle and engine pollutant emissions, including NO_x, non-methane hydrocarbons, CO, and PM can be largely controlled if new engines, vehicles, or equipment is used that meet the latest emission tier. However, the long useful life of diesel equipment and vehicles has prompted California to add additional emission requirements for in-use on-road diesel trucks and other diesel equipment. For example, California requires that almost all heavy-duty trucks and buses that currently operate in the state meet stringent particulate matter emission standards now, and meet stringent NO_x emission standards within the next decade.

3.5.2. Control Technologies and Reductions

Many emissions from the above three key processes can be addressed with best controls and alternative practices. U.S. EPA (2012) estimates implementation of green completion will result in a 95% reduction of VOC emissions and a 99.9% reduction in SO2 emissions. These green completions technologies are evolving over time due to relative novelty, and will likely improve with additional deployment (e.g., cost could be reduced). Allen et al. (2013) reported low leakage rates from well completions after some of the controls listed above were implemented compared to uncontrolled processes, and ICF International (2014) analyzed the costs and viability of methane reduction opportunities in the U.S. oil and natural gas industries. Harvey et al. (2012) reviewed 10 technologies with the capability estimated to reduce more than 80 percent of methane emissions in the oil and gas sector. In addition to methane emissions, many of the technologies have the co-benefit of reducing explosive vapors, hazardous air pollutants, and VOCs.

Large reductions in pollutants and GHGs through use of new technologies and compliance with regulations should be interpreted as best-case scenarios and should not be used to estimate real-operation efficacy. For example, current requirement in VOC reductions from tanks in Colorado are 90% in the summertime and 70% in other times of year of the actual annual average reduction in emissions. However, actual reductions were estimated to be 53% (State Review of Oil & Natural Gas Environmental Regulations, 2011). More importantly, in fast-developing areas, increasing numbers of new wells may counter the overall pollution-control benefits resulting from emission controls applied to individual wells. Despite tightening of emission standards for the oil and gas industry in Colorado, the oil and gas-related VOC measurements made in the non-attainment area in Erie showed a continued increase (Thompson et al., 2014). System-wide emission reduction needs careful planning and monitoring, accounting for both technology advances and industry development and expansion.

Table 3.5-1 summarizes the control technologies and alternative practices available in the literature according to their related processes, as reviewed in previous sections. The national- and state-level adoptions of the various practices are also noted. Depending on their attainment status, local air districts may have more stringent regulations of air emissions than the state level, such as permitting programs for new sources. For example, while emission data from the oil and gas industry are collected in Texas, regulation of emissions is limited to the Houston and Dallas—Fort Worth federal ozone standard non-attainment areas. These local regulations can be important, but are not included in the table.

Table 3.5-1. Best control or practices for controlling emissions from key processes.

Process	**Best Control or Practice**	**Description**	**Emissions addressed**	**Regulation adoption**
Trucking and pumping supplies/fluid to the well	U.S. EPA tier 4 diesel engines	Installed with control technologies to reduce emissions from diesel equipment by 90% compared to the one from 1990s.	NO_x, PM	
	Use of newest truck built since 2010	Included exhaust controls	NO_x, PM	
Venting and flaring	Green completion	Capture liquids and gases coming out of the well during completion.	CH_4, VOCs, and TACs	U.S. EPA, Colorado, Wyoming, Montana.
	Plunger lift system	Collect liquids inside the wellbore and capture methane.	CH_4, VOCs, and TACs	
	Dehydrator emission controls	Capture methane with emission control equipment placed on dehydrators	CH_4, VOCs, and TACs	Montana
	Methane capture during pipeline maintenance and repair	Re-route or burn methane, use of hot tap connections, de-pressuring the pipeline etc.	CH_4, VOCs, and TACs	
	Low-bleed or no-bleed pneumatic controllers	Reduce methane release to the atmosphere, or move away from gas-operated devices.	CH_4, VOCs, and TACs	Colorado
Fugitive and/or evaporation of gas and chemicals	Dry seal systems and improved compressor maintenance	Reduce emissions from centrifugal compressors and reciprocating compressors	CH_4, VOCs, and TACs	Montana
	Tank vapor recovery units	Capture gases released from flashing losses, working losses, and standing losses	CH_4, VOCs, TACs.	Colorado, Montana.
	Leak monitoring and repair	Monitoring potential leaks at equipment locations subject to high pressure.	CH_4, VOCs, TACs.	

3.6. Data Gaps

A number of data gaps exist in understanding emissions from well stimulation activities. The challenges that exist include:

- Few studies exist that directly measure emissions from oil and gas activities;

- Even fewer studies exist that directly examine well stimulation activities, none of which occurred in California; and

- It is unclear how applicable results from a given study conducted elsewhere might be to California well stimulation activities, due to significant differences in treatment and regulation of both air emissions and well stimulation between states.

These challenges noted, the available studies that were deemed most relevant to understanding air impacts of well stimulation are reviewed below. These studies can be broken down into studies that will directly measure or assess emissions at a facility or device level (henceforth "bottom-up" studies) and studies that perform indirect or remote measurement of gas concentrations and then estimate emissions from these measurements (henceforth "top-down").

3.6.1. Bottom-Up Studies and Detailed Inventories

A number of experimental studies or bottom-up inventories were performed in regions with significant well stimulation activities. These studies include:

- Study of direct emissions from well stimulation by Allen et al. (2013).

- Study of direct emissions from hydraulically fractured natural gas wells by ERG (Eastern Research Group) and Sage Environmental.

- Study of emissions in the Eagle Ford hydraulically fractured oil basin.

- The Barnett area special inventory.

3.6.1.1. Allen et al. (2013) Study of Hydraulic Fracturing Processes

3.6.1.1.2. Overview of Study and Goals

Aside from the Fort Worth study, the most significant scientific assessment examining the GHG impacts of well stimulation was conducted by Allen et al., funded by the Environmental Defense Fund and with the cooperation of operators (Allen et al., 2013).

3.6.1.1.2. Methodology

This study calculated methane emissions and emissions factors at 190 natural gas facilities across four regions of the country where well stimulation was utilized (Appalachian, Gulf Coast, Mid Continent, and Rocky Mountain). Of these natural gas facilities, they examined 150 production facilities with 489 wells, along with 27 well completion flowbacks, nine well unloadings, and four well workovers across nine different operators.

In order to capture emissions from flowback, completion, unloading, and workover operations, they bagged and diverted all hatches to temporary stacks, where the emissions were analyzed and fluxes calculated. For the production facilities, they utilized an IR camera and recorded leaks for equipment that were detected by the camera. If leaks were detected, they utilized a Hi Flow sampler to measure emissions rates. All of these leaks were reported under the category "Equipment Leaks." (Included in this category are valves, connectors, and well equipment.) In addition, Allen et al. reported detailed results for pneumatic devices, all of which were analyzed with a high-flow sampler.

3.6.1.1.3. Key Findings

The most significant finding was that, overall, methane emissions were found to be slightly lower than the 2011 U.S. EPA inventories. This was the result of measured methane emissions from completion flowbacks that were an order of magnitude lower than the U.S. EPA inventory, offset by higher emissions rates for chemical pumps, pneumatic controllers, and equipment. The overall emissions estimates report a methane leakage rate of 0.42% compared to the U.S. EPA value of 0.47%.

3.6.1.2. City of Fort Worth Air Quality Study

3.6.1.2.1. Overview of Study and Goals

A comprehensive study of direct measurements of emissions from natural gas production in a region of hydraulic fracturing is the "City of Fort Worth Natural Gas Air Quality Study." This was commissioned in 2010 by the city of Forth Worth, TX, and prepared by Eastern Research Group along with Sage Environmental Consulting, LP (ERG/SAGE 2011). The goals of the study were to quantify the environmental and public health and safety impacts of hydrocarbon production activities. They measured leaks from 388 sites, which included 375 well pads with 1,138 wells. The results of this study were published in a report as well as spreadsheets that detail component-level emissions for each site.

3.6.1.2.2. Study Methods

At each of the well locations, leaks were recorded with the following methodology. Initially a FLIR infrared camera was utilized to detect large leaks. The emissions flux for these large emitters was measured with a Hi Flow Sampler. In addition to recording these large leaks, 10% of all valves and connectors were recorded with a toxic vapor analyzer, and any leak greater than 500 ppmv was recorded and measured with a Hi Flow Sampler. Additionally, Summa Canisters were utilized to provide gas speciation.

Leaks were placed into three broad categories: "valves," "connectors," or "other." Leaks were also classified by study authors using detailed categorization with 94 designations. Neither of these categorization schemes align well with U.S. EPA or other established methodologies, making construction of emissions factors difficult from this dataset.

3.6.1.2.3. Study Findings

As is typical for analysis of gas leakage, emissions are driven by a small percentage of leaks. In this case, 6% of wells account for half of the total measured emissions in the study on a well basis, and the average emissions rate ($\sim 1 \times 10^4$ kg/year) aligns with the 75th percentile.

While this study represents a large group of measurements on a significant number of wells that were hydraulically fractured, it is not clear how applicable the observed emissions rates are to California. Also, since the Barnett shale studied in the report is a dry gas region, data would be most applicable to analogous types of environments, such as gas production in the northern SJV region.

3.6.1.3. Alamo Area Council of Governments Eagle Ford Emissions Inventory

3.6.1.3.1. Overview of Study

The Alamo Area Council of Governments (AACOG) conducted an oil and gas emissions inventory for criteria air pollutants. Though some work is still in progress, the bulk of the results were released as a technical report in 2013 (AACOG, 2014). The purpose of the report was to quantify criteria air pollutants (CO, NO_x, and VOCs in particular) from oil and gas drilling, completion, production, and processing (midstream) operations in the Eagle Ford shale formation. Due to regulatory constraints, they did not conduct any measurements of GHG emissions.

3.6.1.3.2. Methods

As part of the study, the authors developed detailed activity counts of drilling rigs, compressors, compressor stations, equipment at production facilities, as well as timelines for production activities (such as drilling and completions). Emissions were calculated from these activity counts with existing emissions factors from the literature or from the Texas Commission on Environmental Quality. Specific emissions factors were calculated for compressor stations as well as drilling rigs, while activity counts and emissions factors for production facilities were aggregated at the county level. They then utilized these aggregated data as inputs to an air-quality impact model, and also provided an uncertainty analysis discussing potential future scenarios of well stimulation air quality impacts in the Eagle Ford.

3.6.1.4. Barnett Shale Special Inventory

3.6.1.4.1. Overview of Study

In response to observing VOC leakage from surface equipment coinciding with the growth of gas production in the Barnett shale, the Texas Commission on Environmental Quality (TCEQ) conducted an emissions inventory of upstream and midstream sources in the twenty-three counties that overlie the Barnett shale. The study was conducted over two phases between 2009 and 2011 and presented county-aggregated emissions factors and activity counts covering the 2009 production year. The pollutants reported in the publicly available summary are NO_x, VOCs, and HAPs (though more detailed information can be requested and are included in the internal TCEQ database).

3.6.1.4.2. Methods

TCEQ collected these data through operator self-reporting. The first phase of the project, which covered activity counts, acquired data from 9,123 upstream and 519 midstream facilities. Results were generated for twenty-two different equipment categories. Produced water storage tanks and piping components are the largest sources of activity, with over 15,000 tanks and 12,500 piping component fugitive areas in the sample data (TCEQ, 2010). Part one of the special inventory included activity counts of higher emissions equipment (TCEQ, 2010).

The second phase of the project was conducted over 2010–2011 and accounted for emissions estimates for sites and equipment at 8,500 sites (TEQ, 2011). The emissions rates for NO_x, VOCs, and HAPs were computed either through taking site-specific samples or through the utilization of TCEQ emissions factors which were provided in the surveys. This allowed for emissions rates as categorized by equipment type across the Barnett region (tons per year). More detailed speciation and some site-level emissions rates can be obtained through contacting TCEQ, but this was determined to be beyond the scope of this work. Maps of results from the TCEQ Barnett inventory are available (TCEQ, 2014).

3.6.2. Top-Down Studies and Experimental Verification of California Air Emissions Inventories

Understanding the accuracy of emissions inventories is an important factor in understanding the impact of well stimulation on air quality in California. If experimental evidence suggests that inventories of the air pollutants of concern (GHGs, VOC/NO_x, TACs, PM) are inaccurate, then this could point to the need for improved understanding of poorly understood or novel contributors to air emissions, such as well stimulation.

Using observations to determine the accuracy of inventories is difficult, and such experimental studies tend to be expensive and performed in a sparse set of locations and time periods. Thankfully, California air quality is the topic of a significant number of experimental studies, over many decades. For this reason, observations that allow assessment accuracy of inventories are numerous in California compared to other regions. A prime example of such activities is the recent large CalNex effort, funded by CARB and NOAA (National Oceanic and Atmospheric Administration), to examine a number of scientific questions at the interface of climate and air quality. CalNex resulted in the publication or submission of approximately 100 peer reviewed scientific papers over a four-year period, with flights and samples occurring in 2010 (Ryerson et al., 2013). A key scientific goal of CalNex was the assessment of CARB inventory accuracy. For more information, the CalNex campaign is introduced in Ryerson et al. (2013) and summary results to scientific questions are presented in a synthesis report (Parrish, 2014).

Using observations to check the accuracy of CO_2 inventories is difficult (Ryerson et al., 2013). This is because CO_2 sources are ubiquitous, and natural diurnal variation in sources and sinks of CO_2 makes discerning a signal challenging. Noting these challenges, CO_2 observations from CalNex agree within experimental error with scaled inventory results (Parrish, 2014, Finding F1). Similar accuracy was found for the CARB CO inventory (Parrish, 2014, Finding F5). NO_x emissions were also found to be in general agreement with CARB inventories, with some caveats about spatial distributions of emissions (Parrish, 2014, Finding F6). No studies of PM or TACs with specific implications for oil and gas or well-stimulation-related emissions were found.

Notably, in CalNex, significant divergence or error was found in comparing CH_4 and VOC observations to inventories. Importantly, in each of these cases, oil and gas sources were examined as specific possible contributors to excess emissions.

Numerous studies, including some before CalNex, examine CH_4 concentrations in California. Some of these studies make explicit comparison to CH_4 inventories, with some specifically examining the role of oil and gas sources in California CH_4 emissions.

CH_4 relevant studies reviewed below are:

- Wunch et al. (2009): Emissions of greenhouse gases from a North American megacity
- Zhao et al. (2009): Atmospheric inverse estimate of methane emissions from Central California
- Hsu et al. (2010): Methane emissions inventory verification in Southern California
- Wennberg et al. (2012): On the sources of methane to the Los Angeles atmosphere
- Peischl et al. (2013): Quantifying sources of methane using light alkanes in the Los Angeles basin, California
- Jeong et al. (2013): A multitower measurement network estimate of California's methane emissions
- Jeong et al. (2014): Spatially explicit methane emissions from petroleum production and the natural gas system in California
- Johnson et al. (2014): Analyzing source apportioned methane in northern California during Discover-AQ-CA using airborne measurements and model simulations

VOC-relevant studies include:

- Gentner et al. (2014): Emissions of organic carbon and methane from petroleum and dairy operations in California's San Joaquin Valley

These studies are reviewed below including their methods and their key results as related to oil and gas CH_4 sources in California. Findings are summarized to determine if there is a consensus regarding the accuracy of California inventories, and whether well-stimulation-associated emissions could be responsible for inventory discrepancy.

Note that top-down atmospheric studies typically report emissions in Tg of CH_4. At typical upstream (production) compositions, 1 Tg of CH_4 (or 52.2 BCF of CH_4) is equal to about 60 BCF (billon cubic feet) of produced natural gas.

3.6.2.1. Wunch et al. (2009)

Wunch et al. (2009) analyzed air column concentrations of CH_4 and CO_2 in the atmosphere of the south coast air basin (SoCAB) in 2007–2008 (Wunch et al., 2009). Fourier transform spectroscopy of sunlight was performed for 131 days of observations. This study cannot reliably partition CH_4 emissions into oil and gas and non-oil and gas sources, due to lack of isotopic sampling and lack of observations of higher alkanes which may provide a chemical "fingerprint" of an oil-and-gas-associated source of CH_4.

Wunch et al. estimate CH_4 emissions in the SoCAB region of 0.6 (+/-0.1) or 0.4 (+/-0.1) Tg CH_4 per year, depending on whether the CARB CO_2 inventory or CARB CO inventory is used to provide temporal scaling of emissions to relate atmospheric concentrations to emissions rates. They compare this result to the CARB CH_4 inventory as follows: CH_4 from all "urban sources" (non-forestry, non-agriculture sources of CH_4) is scaled to the region using the fraction of California population in the SoCAB region. Thus, they argue that the CARB CH_4 inventory underpredicts CH_4 emissions.

3.6.2.2. Zhao et al. (2009)

Zhao et al. (2009) utilized data from a tall tower in the northern SJV, with measurements taken at ~90 m and ~480 m heights. Observations were performed from October to December 2007. A high precision (0.3 ppbv) cavity ring-down spectrometer was used to measure CH_4 concentrations at five-minute intervals. These observations were coupled to an atmospheric transport model. The model was used in an inverse approach to estimate, for a given gas concentration observation, where the gases observed are likely to have been emitted (parcels of air are modeled backward in time for five days). The coupling of tower observations of gas concentrations with simulation allowed an estimate of the likely emissions rates in a spatially resolved manner. They compared their emissions estimates to the Emissions Database for Global Atmospheric Research (EDGAR) spatially resolved emissions inventory (EDGAR v. 3.2).

Zhao et al. find that for the region (central California) and time period (October–December 2007) of analysis, actual emissions are estimated to be 37% +/- 21% higher than annually averaged inventory estimates from the EDGAR inventory. In particular, they believe that livestock emissions are underestimated by an even larger fraction. They do not compare their results to the CARB inventory, as at the time of their study, there existed no spatially resolved version of the CARB inventory (see below for more discussion).

3.6.2.3. Hsu et al. (2010)

Hsu et al. (2010) performed analysis of captured flasks of air from a remote location (Mt. Wilson observatory) to estimate the concentrations of gases in a well-mixed sampling of air from the Los Angeles region. Their study is the Los Angeles County portion of the SoCAB region. In order to estimate CH_4 flux from CH_4 concentrations, they used observed ratios of CH_4 to CO in the atmospheric observations, and coupled this ratio to the CARB CO inventory to estimate CH_4 emissions rate.

Hsu et al. estimated methane emissions of 4.2 +/- 0.12 Mt CO_2 eq. GHGs per year. They then compared this to the CARB inventory of the time, which estimated CH_4 emissions of ~3 Mt CO_2 eq./y from the study region. Thus, they argued that the CARB CH_4 inventory underpredicts CH_4 emissions from the study region.

3.6.2.4. Wennberg et al. (2012)

Wennberg et al. (2012) combined observations of a variety of types to estimate emissions of methane in the SoCAB region. They included air flasks from remote observation locations, aircraft observations from a set of flight campaigns, as well as ground-based Fourier transform spectroscopy to estimate air-column concentrations of CO_2, CO, and CH_4. This study can be seen as an extension and improvement of the work of Wunch et al. (2009) and Hsu et al. (2010). In a novel advance from those previous studies, Wennberg et al. used C_2H_6 concentrations to attempt to partition emissions into various sources.

Wennberg et al. estimated CH_4 emissions in the study region to be 0.44 +/- 0.15 Tg CH_4/y. They compared this to an inventory based largely on CARB sources, which has a scaled emissions estimate for the study region of 0.21 Tg CH_4/y. Thus, they argued that CH_4 emissions may be approximately two times larger than an inventory approach would produce in the region.

3.6.2.5. Peischl et al. (2013)

Peischl et al. (2013) use a variety of sampling methods with aircraft data to estimate CH_4 emissions in the SoCAB region. Similar to other studies noted above, they used CO concentrations and the CO inventory to estimate CH_4 fluxes from CH_4 concentrations.

Peischl et al. created estimates for all sources of CH_4 (0.41 +/- 0.04 Tg CH_4/y) and oil and gas sources (0.22 +/- 0.06 Tg CH_4/y). Their estimate of oil and gas sources was based on concentrations of seven alkanes observed in the air, apportioned to sources using assumed compositions of emissions from those sources in a least-squares-fitting approach. They compared this oil and gas result to a CARB-inventory-estimated quantity of 0.064 Tg CH_4/y. Thus, they estimated that in the SoCAB region, inventory methods underestimate CH_4 emissions by a factor of 3.5 (2.5 to 4.4).

3.6.2.6. Jeong et al. (2013)

Jeong et al. (2013) used observations from five locations in California's central valley (SJV), including one tall tower (samples at ~90 and 480 m) and four small towers (samples at ~10 m). They combined these observations with aircraft observations of the Pacific boundary (i.e., incoming CH_4 concentrations) and urban regions. They compared these observations to a spatially resolved version of the CARB inventory, in which the CARB 2008 inventory was scaled to a detailed spatial emissions model. They also used the EDGAR spatially resolved inventory as a source of comparison emissions estimates, but this report focuses on California Greenhouse Gas Emissions Measurement program (CALGEM) comparisons, as these are more consistent with CARB inventory methods.
In this study, atmospheric transport was modeled using an inverse approach with the WRF-STILT model (coupled weather research and forecasting–stochastic time-inverted lagrangian transport model). This approach traced "particles" of air backward through time in a time-inverted weather simulator, to estimate from where gases observed in particular locations were likely to have been emitted. This approach has been used in a number of national and regional atmospheric studies of GHGs.

The "prior" model in the Bayesian analysis of Jeong et al. (2013) is the spatially resolved CALGEM inventory, which predicts CO_2eq. CH_4 emissions of 28 TgCO_2eq./y. The emissions estimated incorporating the observations (the posterior estimate) is 48.3 Tg CO_2eq./y (+/- 6.5 at 1σ level). Thus, they argued that the CALGEM inventory is likely underpredicting California methane emissions.

3.6.2.7. Jeong et al. (2014)

Jeong et al. (2014) generated a much more detailed spatially resolved estimate of emissions from the California oil and gas industry than used in other studies. For example, well-level activity data (production of oil, gas, and water) were compiled from DOGGR data sources, while gas processing data were derived from federal U.S. EPA reporting. Also, pipeline fugitive emissions were modeled using detailed spatial representations of the California oil and gas distribution system. These activity factors were coupled to emissions factors (i.e., emissions per unit of activity) generally derived from U.S. EPA emissions factors. Lastly, they augmented this detailed "bottom-up" approach with data from the SoCAB region collected in atmospheric studies noted above (Wunch et al., 2009; Hsu et al., 2010; Wennberg et al., 2012; Peischl et al., 2013).

Jeong et al. (2014) found that using non-CARB emissions factors with detailed California activity data results in emissions estimates that are significantly larger than either the CARB GHG inventory or the CARB oil and gas survey. For example, the initial bottom-up result from their study was 330 Gg CH_4/y of emissions from all portions of the California oil and gas sector (uncertainty range 220-518 Gg CH_4/y). This compared to CARB GHG inventory and survey results of 210 and 204 Gg CH_4/y respectively. When they scaled their bottom-up approach to better match atmospheric observations, they found that their bottom-up estimate increases to 541 +/- 144 Gg CH_4/y. Thus, Jeong et al. (2014) found that the CARB inventory significantly under-predicts CH_4 emissions compared to what would be expected using existing U.S. EPA emissions factors or using atmospheric data.

3.6.2.8. Johnson et al. (2014)

Johnson et al. (2014) utilized aircraft observations in a series of flights taken in January and February of 2013 in the San Francisco Bay Area and northern San Joaquin Valley. They then coupled these observations to a 3-d atmospheric chemical transport model (GEOS-Chem) to derive flux estimates for CH_4 in the study region. They compared their results to the EDGAR spatially explicit emissions inventory.

They found that the EDGAR emissions inventory must be scaled by a factor of 1.3 to arrive at results that agree with atmospheric observations. They found that increasing oil and gas and waste (landfill) emissions by a factor of two results in a decrease in overall model bias, but degrades the model fit by overpredicting background CH_4 values. They found that increasing livestock emissions between a factor of two to seven would result in reduced overall model-observation bias and decrease overall RMSE (root mean square error). They argued that a correction factor of two for livestock emissions is not sufficient to correct overall underprediction, while a factor of seven is an upper limit. Therefore, Johnson et al. argued that in the SFBA and northern SJV region, it was likely that livestock CH_4 emissions were underestimated in existing spatial inventories. They did not directly compare their results to CARB inventories.

3.6.2.9. Gentner et al. (2014)

Gentner et al. (2014) used ground-based measurements with a meteorological transport model to examine the role of petroleum operations on emissions of hydrocarbon-derived VOCs. The meteorological model was used similarly to other studies above: back trajectories of parcels of air were traced over 6- and 12-hour periods to estimate sources of measured VOCs at the sampling location. These sources were then compared to spatial distributions of petroleum production operations (as well as dairy operations).

Gentner et al. found reasonable agreement between their sampling efforts in Bakersfield and the CARB inventory results. They found that 22% of VOC measured at their site could be attributed to petroleum operations, which was similar to their reported CARB partitioning for the SJV air district of 15%. Dairy sources were found to contribute 22%

(compared to 30% for CARB inventory) and motor vehicles 56% (compared to 55% for CARB inventory). In contrast, a smaller inventory comparison to just the Kern County portion of the SJV air district implies less petroleum emissions observed than expected in the inventory (as should be expected, given large petroleum operations in Kern County).

Gentner's explained fraction of ROG emissions in the SJV region, partitioned 15% to petroleum operations, is not in alignment with our computed value of 8% above. The causes for these differences were unable to be determined.

3.6.2.10. Summary Across Studies: How do Experimental Observations Align With California Inventory Efforts?

Taking the above experimental efforts in the aggregate, some general conclusions can be drawn about the California GHG inventory:

- Experimental evidence points to CARB inventories generally underpredicting CH_4 emissions in California. The degree of estimated underprediction varies by study, and no scientific consensus has yet emerged.

- Uncertainties are not reported for CARB inventories, and uncertainties for experimental studies are typically on the order of 15–30%.

- Studies point to livestock and oil and gas sources as drivers of these excess CH_4 emissions. There may be a regional effect observed here: livestock underprediction may be more important in studies focused on the northern SJV, while oil and gas under-prediction may be more important in studies focused on southern SJV and SC air districts.

- There is still considerable uncertainty in the observational literature about the precise level of CH_4 emissions from the California oil and gas industry.

- None of the experimental studies performed in California targeted well stimulation activities, so none of these studies provides evidence as to the accuracy of potential inventory treatment of well stimulation activities.

3.7. Findings

- Fields that are currently produced with well stimulation technologies in California have, on average, lower greenhouse gas emissions from oil production than a typical California oil field, and lower than fields produced without well stimulation.

- Because California produces a significant amount of high carbon intensity heavy crude oil in non-stimulated fields, reducing the use of well stimulation could result in an increasing reliance on more GHG-intensive sources of crude oil. More analysis involving market-based life cycle analysis is required to understand the potential impacts of removing hydraulic-fracturing-induced oil from California's oil supply.

- Current California air quality inventory methods likely include at least some well-stimulation-related emissions in their results. Inventory methods are not designed to estimate well stimulation emissions directly, and it is not possible to determine well stimulation emissions from current inventory methods.

- Using current inventory methods, the oil and gas sector is a minor contributor to GHG, emissions in California, contributing about 4% to state emissions.

- In the San Joaquin Valley, the oil and gas sector is a material contributor to TAC emissions, especially hydrogen sulfide, which is emitted mostly from oil and gas sources. In the San Joaquin Valley, the oil and gas sector contributes 30% of SO_x and 8% of ROG emissions.

- In the South Coast region, the oil and gas sector emits less than 1% of all studied species.

- Due to the fact that about 20% of California production is induced by well stimulation, direct and indirect impacts from well stimulation should be approximately 1/5 of above impacts.

- Local effects of air emissions can be more significant than the above analyses at the air basin scale. See Volume II, Chapter 6 for more discussion of local air impacts and impacts on populations that live near production sites.

- More research is required on overall leakage rates from oil and gas systems to better understand the breakdown of VOC and TAC emissions between sources (e.g., produced hydrocarbons, solvents, other process chemicals).

- Regulatory processes are currently in flux in a number of U.S. states, as well as federally. Current regulatory processes (e.g., federal EPA regulations) will greatly reduce some previously large emissions sources from well stimulation.

- Technologies exist to greatly reduce GHG and VOC emissions from well stimulation. Well stimulation direct emissions can be controlled through reduced emissions completions technologies.

- There are currently a number of significant gaps in the scientific literature with respect to the air emissions from well stimulation in particular, as well as in understanding air emissions from the oil and gas sector more generally.

3.8. Conclusions

Well stimulation is a potential source of air quality impacts in California. The oil and gas industry in general is a minor source of California's GHG emissions. In regions with large oil and gas sectors, such as the SJV region, the oil and gas industry is a major contributor to some TAC emissions and to SO_x emissions. The oil and gas industry materially contributes to ROG emissions as well. Because current inventory methodologies used in California were not designed to differentiate well stimulation emissions from other oil and gas emissions, it is not currently possible to estimate direct air emissions from well stimulation in California.

A number of regulatory and technical approaches to reducing emissions from well stimulation (and oil and gas production more generally) are available and currently used in at least some jurisdictions. The regulation of well stimulation emissions is still in flux at state and federal levels, and California is no exception.

The few studies that have examined well stimulation emissions directly have found that emissions are generally small, especially if control technologies are applied (as required by federal regulations for stimulated natural gas wells). These studies are few in number, so uncertainty still remains about the sources of air emissions from well stimulation. Given the importance of the California oil and gas sector for some emissions sources (e.g., TACs in the San Joaquin Valley), a significant induced increase of oil and gas production due to well stimulation could result in meaningful additional indirect air impacts. For other air quality concerns, or for smaller induced production volumes, it is unlikely that well stimulation will materially affect air quality.

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