Appendix A: California SLCP Emissions

California SLCP Emissions

ARB develops an annual statewide GHG emission inventory to track GHG emission trends and progress towards California's GHG emission reduction goals. The 2015 GHG emission inventory includes emissions from 2000 to 2013 for carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride.[1]

California's GHG inventory includes two short-lived climate pollutants: methane and F-gases. Because not all F-gases in the GHG emission inventory are short-lived, the SLCP inventory used for this Proposed Strategy includes only those hydrofluorocarbons (HFC) with lifetimes of a few decades[2] which represent about 97 percent of total F-gas emissions in California. Methane and short-lived F-gas emissions in this Appendix are presented using 20-year global warming potential (GWP) values from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4).

Unlike methane and F-gases, black carbon is not routinely inventoried by ARB. Per SB 605 and to support this Proposed Strategy, ARB has developed a black carbon emission inventory for key years. Black carbon emission data in this discussion are presented using the 20-year GWP value from the IPCC Fifth Assessment Report (AR5), the first report to define a GWP for black carbon. The black carbon inventory does not include emissions of brown carbon, or account for potential warming effects of brown carbon.

This Appendix provides a brief overview of current and projected SLCP emissions and inventory methods. Additional data tables and detailed methodology is available on the SLCP inventory webpage.[3]

A. Black Carbon

1. Emission Sources

Black carbon is emitted from combustion processes, primarily from diesel engines and biomass burning. Black carbon sources can be separated into two categories, anthropogenic non-forestry sources and forest-related sources.

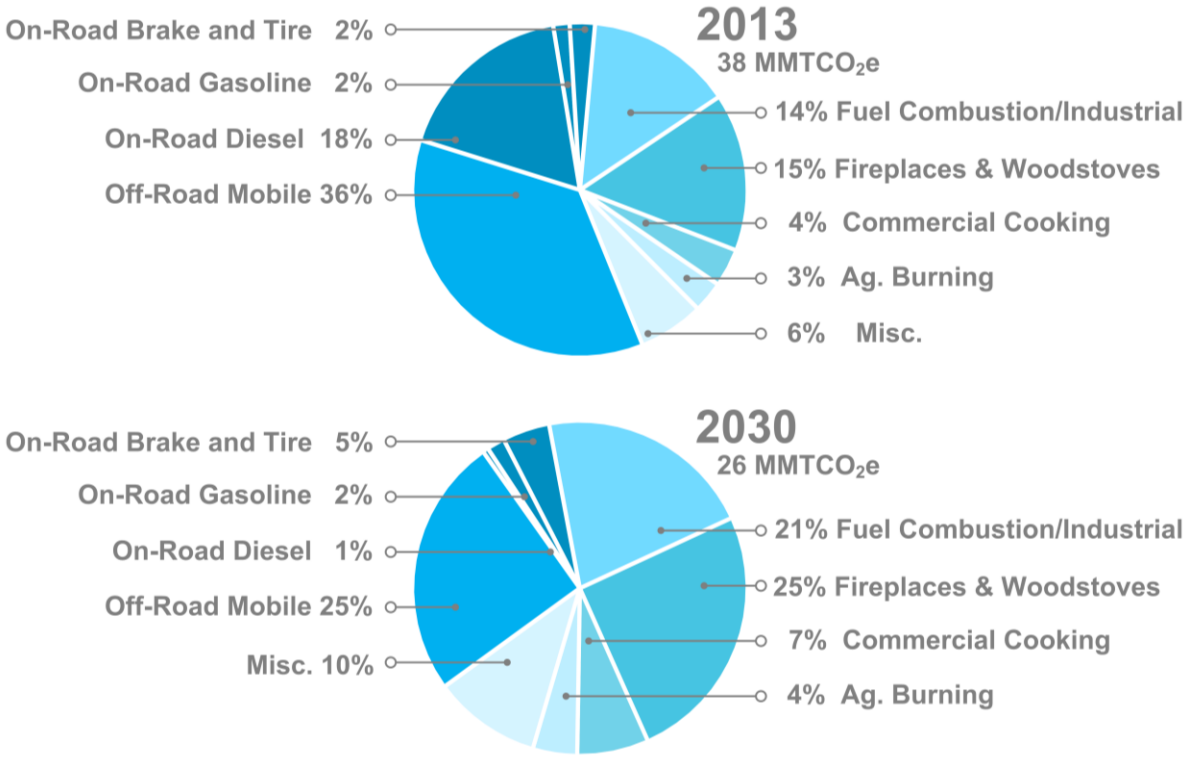
Anthropogenic Sources

The major anthropogenic, non-forestry sources of black carbon in 2013 include diesel-fueled mobile sources, fuel combustion and industrial processes, and residential

[1] ARB (2015). California's Greenhouse Gas Emission Inventory – 2015 Edition. http://www.arb.ca.gov/cc/inventory/data/data.htm
[2] Short-lived F-gases include the nine short-lived hydrofluorocarbons: HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-245fa, HFC-32, HFC-365mfc, and HFC-43-10mee.
[3] Inventory methodology and detailed inventory tables available at: http://www.arb.ca.gov/cc/inventory/slcp/slcp.htm

fireplaces and woodstoves. Off-road mobile emissions account for over a third of statewide black carbon emissions. On-road mobile sources account for nearly a quarter of emissions, primarily from on-road diesel combustion. Fuel combustion and industrial processes are also an important source of black carbon. This emission category consists of a large number of engines and industrial processes, with a wide variety of applications including electricity production, manufacturing, concrete, asphalt, pulp and paper, and service and commercial sectors. Residential fireplaces and woodstoves account for approximately 15 percent of black carbon emissions in 2013. On-road gasoline and brake and tire wear emissions are small. Miscellaneous sources include dust, waste disposal, residential natural gas combustion, and unplanned structure and car fires. Figure 1 presents 2013 and projected 2030 black carbon emissions and sources.

Figure 1. 2013 Black Carbon Emissions and Projected 2030 Emissions* with Existing Measures[4]



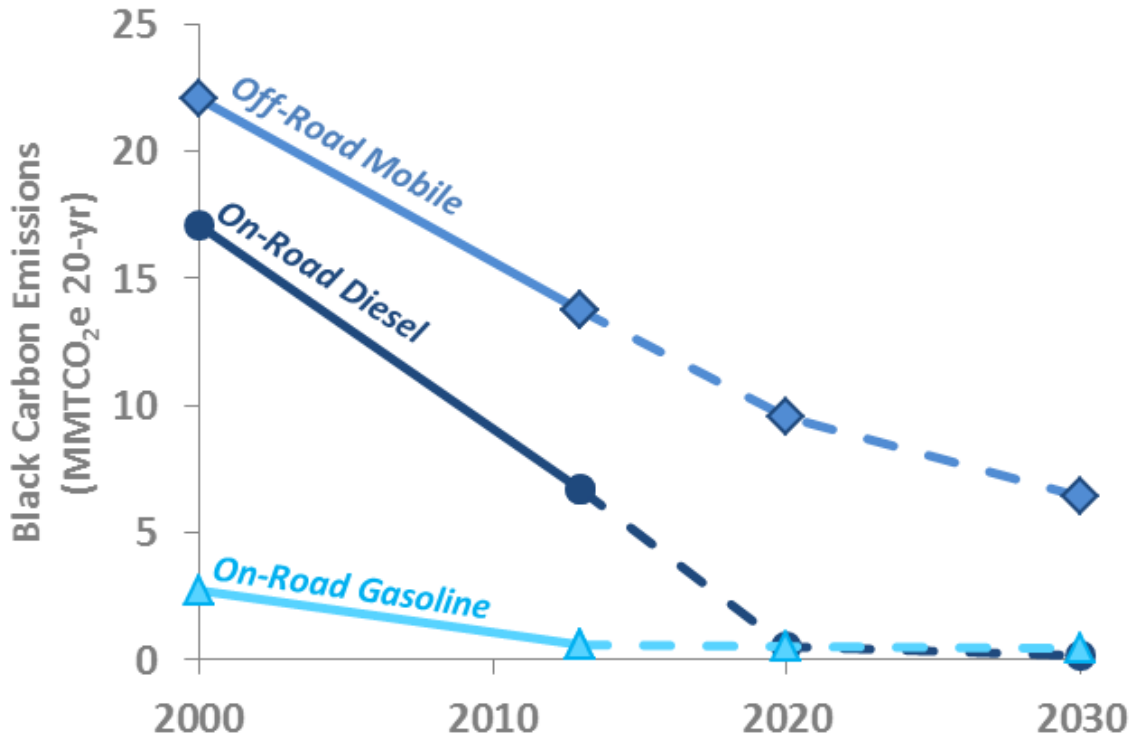
***Using 20-yr GWPs**

As illustrated in Figure 2, on-road mobile source emissions are projected to decline significantly by 2030 due to ARB's regulatory actions to reduce diesel emissions. On-road black carbon emissions have decreased by 62 percent since 2000 and are projected to decrease another 92 percent by 2030. Emissions from off-road vehicles are projected to decline by over 70 percent between 2000 and 2030 but remain an important source of black carbon, accounting for approximately one quarter of emissions in 2030. Non-mobile source categories will become a larger share of

[4] Excludes wildfire and prescribed fire emissions.

statewide emissions as mobile sources decline in the future. In 2030, fuel combustion and industrial processes will account for one quarter of emissions as will residential wood combustion.

Figure 2. Black Carbon Emissions from On-Road and Off-Road Mobile Sources with Existing Measures



Wildfire and Prescribed Fire

Wildfire is the largest source of black carbon emissions in California, accounting for over one half of total emissions in a typical year. Wildfires are difficult to prevent, and there is high uncertainty in the emission estimation. Prescribed fires are also a source of black carbon, but in practice can reduce overall black carbon emissions by preventing severe catastrophic wildfires. Wildfires may result in as much as 87 $MMTCO_2e$ (20-yr GWP) of black carbon emissions in a typical year. In recognition of the unique challenges associated with managing forests and other lands, wildfire and prescribed fire emissions are discussed separately in the Forest-Related Sources of Black Carbon Emissions (Chapter IV).

2. Inventory Methods

California's black carbon emission inventory was developed using existing particulate matter (PM2.5) emission estimates, combined with speciation profiles that define the fraction of PM2.5 that is elemental carbon. Elemental carbon is the "best available

indicator"[5] of black carbon, but is not a perfect proxy for warming effects, which depend on the physical and chemical properties of the particles. Elemental Carbon is not a proxy for brown carbon, thus brown carbon is not included in the inventory. The PM2.5 inventory was assembled using a wide variety of techniques including models, data reported by local air districts, and ARB inventory calculation methodologies.

Speciation profiles were developed by ARB as part of photochemical modeling efforts. Black carbon emissions depend on a variety of factors including fuel, engine operating conditions, age, maintenance, emission control technology, load, and drive cycle. Variability in these factors and their impact on speciation profiles remains a large source of uncertainty in black carbon inventory development.

The PM2.5 inventory, excluding wildfire, was projected using a 2012 base year, and includes both growth assumptions and existing control measures. Growth and control assumptions are defined for each source and air basin, in collaboration with applicable air districts.

Wildfire PM2.5 emissions are large, and can vary significantly from year to year. California's black carbon inventory uses the ten-year average wildfire PM2.5 emissions from 2001 to 2011 to avoid large year-to-year variations in the inventory. Annual PM2.5 emissions are calculated using geospatial fire activity and vegetation fuels data in the First Order Fire Effects Model (FOFEM).[6] FOFEM accounts for vegetation fuel size class distributions, configuration, moisture content, fuel consumption and emissions associated with flaming and smoldering phases. The geodatabase classifies wildfires according to management objective: suppression or non-suppression (wildfire use for resource benefit).

As with other sources, speciation profiles are applied to the ten year average PM2.5 emissions to estimate black carbon. Black carbon emissions from biomass burning vary dramatically depending on fire conditions, such as the fuel type, moisture content, oxygen availability, and local meteorology. This variation leads to high uncertainty in speciation assumptions, and adequate speciation profiles to account for various fire conditions are not available. For these reasons, the wildfire emission estimate contains very high uncertainty, and should be understood to be an order-of-magnitude estimate of emissions for a typical year.

3. Inventory Improvement

California's black carbon inventory relies on particulate matter inventories coupled with speciation profiles that define the fraction of particulate matter that is black carbon. The sources that emit black carbon are well understood from a control prospective, and

[5] USEPA (2012). United States Environmental Protection Agency, Department of the Interior, Environment and Related Agencies. "Report to Congress on Black Carbon". http://www.epa.gov/blackcarbon/

[6] Lutes, D. (2013) FOFEM User Guide. Missoula Fire Laboratory, Rocky Mountain Research Station, USDA Forest Service. Missoula, MT. Available at https://www.frames.gov/rcs/15000/15530.html

major sources are regulated in California. However, it is a challenge to estimate statewide black carbon emissions, and to define speciation profiles for all sources because of: 1) the diversity and large number of sources, 2) the wide variety of engines, after treatment, operating conditions, and fuels, and 3) the difficulty in measuring black carbon and its co-pollutants.

Additional representative source measurements are needed to better characterize black carbon speciation profiles by emissions source, fuel type, and combustion conditions. Better characterization of emissions from wildfire, open biomass burning, commercial charbroiling, and residential wood combustion can help improve inventory estimates. The scientific literature reports large variability in black carbon speciation profiles from biomass burning due to the many variables that affect emissions. Future research is needed to provide a scientific consensus on speciation profile choice and best practices to produce biomass burning emission inventories. In general, California's mobile source emissions are among the best characterized, but improved information is still needed for some sectors, such as off-road mobile sources.

Quantifying emissions from wildfires is an active area of research in the earth science and air quality community, but is technically challenging due to the inherent variability in vegetation fuel loads, fire behavior, and consumption. Ongoing efforts to improve the scientific understanding of the ecological role and air quality effects of wildland fire are occurring as part of the federal Joint Fire Science Program[7] and special projects such as the NOAA Fire Influence on Regional and Global Environments Experiment (FIREX)[8]. Research areas include development and evaluation of emission models and underlying model parameters, smoke in context of health and air quality standards, fire in a changing climate, and ecosystem health in relation to fire.

ARB is also in the process of comparing the black carbon emission inventory to field observations at the Mount Wilson monitoring station located above the Los Angeles basin. Air masses from Los Angeles exhibit consistent agreement between black carbon and carbon monoxide, indicating a well-mixed air mass and similar sources. This monitoring data will be used to derive a 'top down' observation for comparison to the 'bottom up' black carbon inventory.

B. Methane

1. Emission Sources

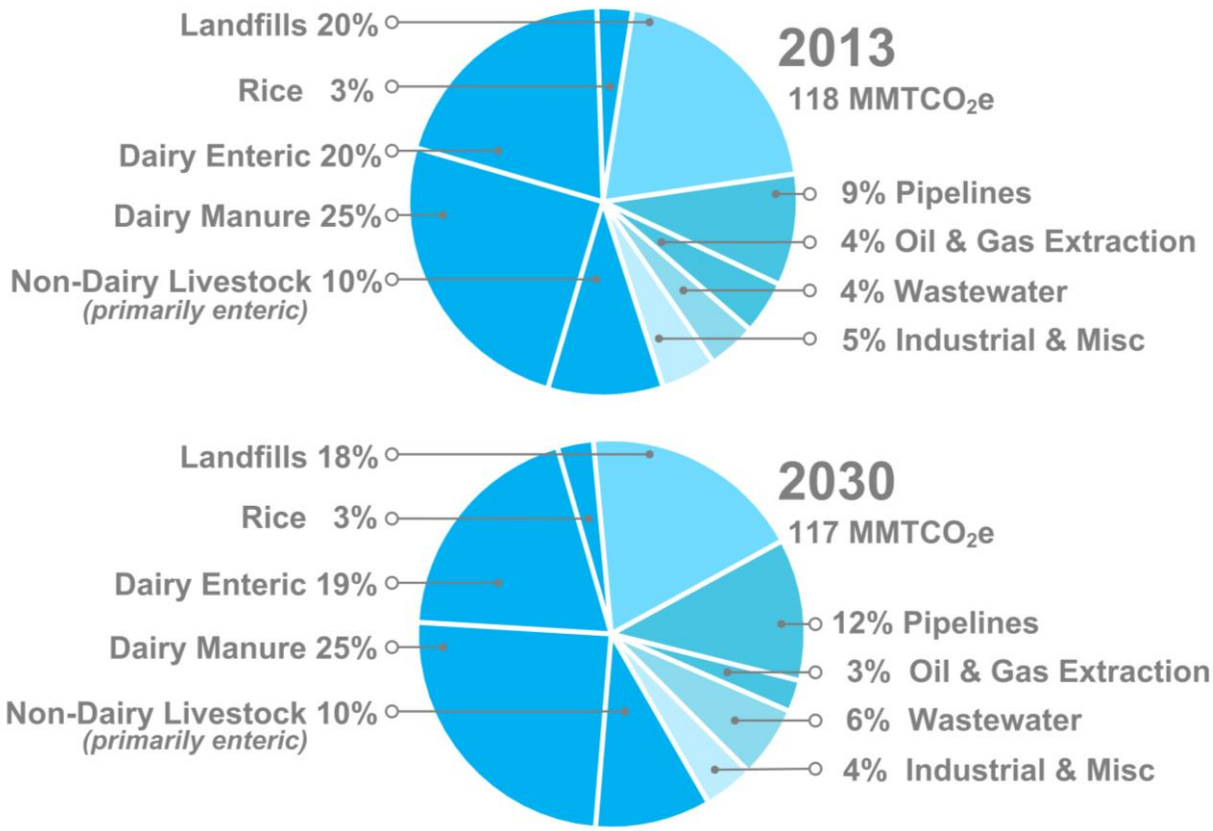
Methane is emitted from a wide range of fugitive sources and biological processes. In 2013, agriculture represented the largest methane source, accounting for nearly 60 percent of emissions. Enteric fermentation and manure management from dairy operations produced almost 80 percent of these agricultural emissions. Enteric fermentation and manure management from non-dairy livestock and rice emissions are smaller agricultural sources. 90 percent of non-dairy livestock emissions are from

[7] http://www.firescience.gov/
[8] http://www.esrl.noaa.gov/csd/projects/firex/

enteric fermentation, and the remaining emissions are from manure management. Landfills are the next largest source of methane, accounting for one fifth of statewide methane emissions. Natural gas pipeline leaks, oil and gas extraction, wastewater, and other industrial and miscellaneous sources make up the remainder of emissions. Miscellaneous sources include industrial fugitive emissions, methane produced as a byproduct of fuel combustion, composting, and petroleum seeps. Figure 3 presents 2013 and projected 2030 methane emissions and sources.

Compared to current emissions, projected 2030 methane emission sources and levels are not expected to change significantly without additional reduction measures. Natural gas pipeline leaks are projected to increase slightly due to aging infrastructure and expansion of the pipeline system.

Figure 3. 2013 Methane Emissions and Projected 2030 Emissions with Existing Measures*



*** Using 20-yr GWPs**

2. Inventory Methods

Statewide methane emission estimates rely on state, regional, or federal data sources using calculation methodologies consistent with the 2006 Intergovernmental Panel on

Climate Change guidelines.[9] Landfill emissions are calculated using a First-Order Decay Model with California-specific waste characterization. This model is supplemented with emission data for individual landfills provided by ARB surveys, CalRecycle, and U.S. EPA mandatory reporting. California's livestock methane inventory is based on U.S. EPA modeling of enteric fermentation and manure management. The model estimates methane emissions using detailed parameters by animal type such as age, size, volatile solids excretion, feed, and manure management pathways. Emissions from oil and gas extraction and pipeline leaks are estimated based on survey data conducted by ARB and other federal data sources. A complete description of the methodologies is available online.[10]

Methane emissions are projected for 2030 by applying sector-specific growth factors to base-year emissions. Base-year emissions use the average emissions from 2009 to 2011 to dampen the effects of year-to-year variability in factors that influence emissions. The sector-specific growth factors come from projection analysis prepared by other state and federal agencies. A complete description of forecast methodology is available online.[11]

3. Inventory Improvement

While improving inventory quality is not a prerequisite for many actions to reduce SLCP emissions, it is nonetheless important to inform ongoing efforts. ARB staff continually assesses ways to improve the methane inventory using the latest scientific understanding of methane sources and the best available activity data. The improvements made to the 2015 edition of the statewide methane inventory include incorporation of ARB oil and gas survey data for fugitive methane emission estimates, use of the new EMFAC 2014 on-road mobile emissions model, and updates to the emissions of non-citrus fruit wastewater methane emissions.

ARB is further improving the methane emission inventory with ongoing coordinated research with other agencies. ARB and the California Energy Commission (CEC) have several ongoing partnerships for measurement and evaluation of methane emission sources in the energy sector. ARB operates a statewide methane monitoring network that provides a record of real time methane concentrations in California, supported by CEC and other sister agencies. Data from this network were used in several research contracts, and formed the basis of a comprehensive statewide inverse receptor-oriented modeling and various trends assessment analyses to verify and inform the statewide GHG inventory.

ARB is also actively participating in the Megacities Carbon Project in the South Coast Air Basin which is developing and testing methods for monitoring various GHG emissions to link measured concentrations to emission activity. In addition, researchers

[9] IPCC (2006). IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/
[10] ARB 2015 Edition GHG Inventory. http://www.arb.ca.gov/cc/inventory/data/data.htm
[11] http://www.arb.ca.gov/cc/inventory/slcp/slcp.htm

at ARB and NASA's Jet Propulsion Laboratory are collaborating to identify large "hot spot" methane sources through a systematic survey of high methane emitters using aerial and ground measurement to survey various sources in the agriculture, waste, and oil and gas sectors. The researchers have completed pilot studies in the San Joaquin valley, and plan to expand the study throughout California with research funding contributions from NASA and CEC. Collectively, these efforts are expected to improve our understanding of the various methane emission sectors and aid in developing effective mitigation programs to reduce GHG emissions in California.

In addition, CalRecycle is currently working with ARB to better quantify fugitive methane emissions from landfills by measuring methane fluxes at a representative sample of landfills across California. This study will provide information on landfill gas collection system efficiencies, and improve the State's ability to estimate the benefits associated with the diversion of organics from landfills.

ARB has funded a study to gather updated emission factors for natural gas pipeline leaks and is also developing a contract to study methane leakage from inactive oil and gas wells. This contract will provide data on the spatial distribution, type of well, and the volume of methane gas emitted. The CEC is sponsoring several research contracts to identify the main sources of emissions from the natural gas distribution system. Research activities also include methane surveys of residential housing, which may be an important and unrecognized source of methane.

Future research will be necessary to continue refining the methane inventory, and provide California-specific activity data. Emissions from enteric fermentation and manure management are currently modeled using international or national default parameters due to a lack of California-specific data. The ARB has committed to fund research on California-specific feed data, and its effect on methane emissions. This research will better reflect on-farm realities and inform the inventory. Additional research will fully characterize the diverse dairy manure management system in California, and help understand the effect of management practices on methane emissions.

Organic waste in landfills will remain a source of methane for years to come. More research is needed to help understand how methane emissions change as landfills age, and to verify the efficiency of methane capture systems over time.

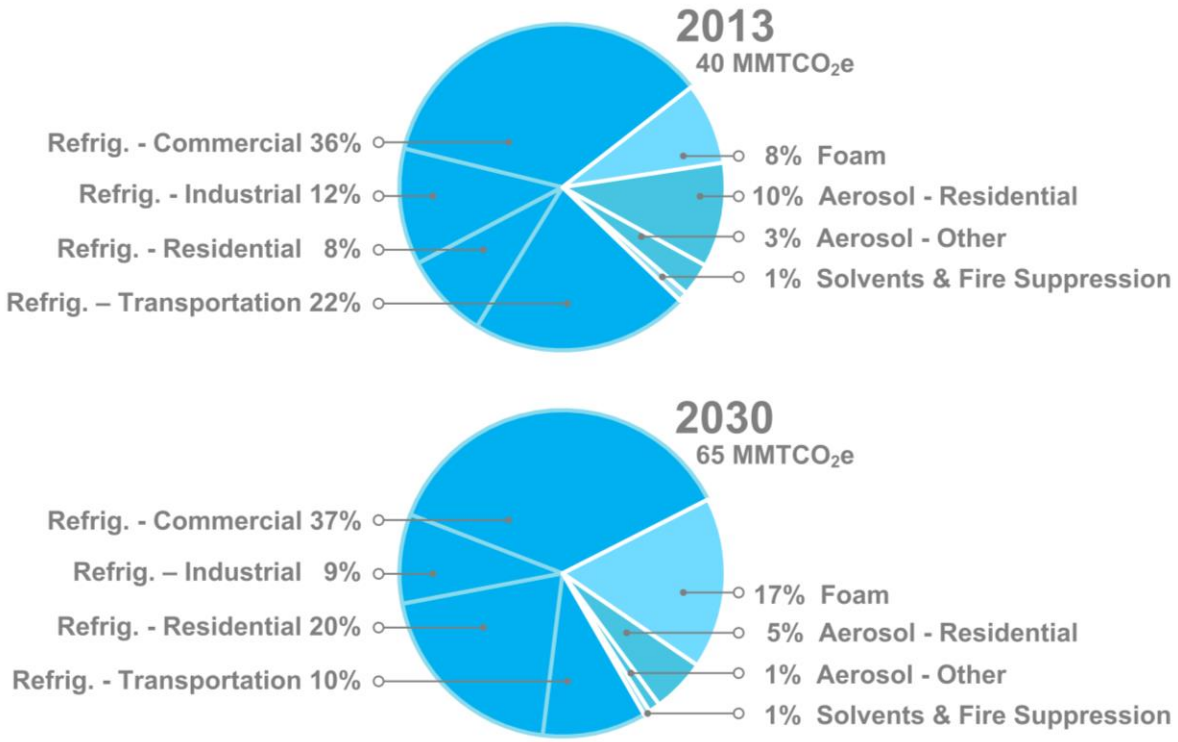
Research to better quantify fugitive methane emissions from the natural gas and oil systems, as well as from anaerobic digesters, are necessary to inform the emission inventory. Methane emissions from anaerobic digesters in domestic wastewater treatment facilities, and pulp and paper mill wastewater are currently estimated using activity data from U.S. EPA. Future research is needed to update these estimates with California-specific data to improve inventory estimates. Research into fugitive emissions from new infrastructure and technologies, including dairy anaerobic digesters, is also necessary to understand the impact of these new technologies on methane emissions.

C. F-Gases

1. Emission Sources

F-gases are used in refrigeration and air conditioning, insulating foams, solvents, aerosol products, and fire protection. Nearly 80 percent of F-gas emissions in California are from refrigeration and air conditioning equipment. Commercial refrigeration is the single largest source of short-lived F-gases, followed by commercial and residential air conditioning. Figure 4 presents the 2013 and projected 2030 F-gas emissions and sources. The F-gas inventory includes nine short-lived HFCs: (HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-245fa, HFC-32, HFC-365mfc, and HFC-43-10mee), but excludes two long-lived HFCs with negligible emissions.

Figure 4. 2013 F-Gas Emissions and Projected 2030 Emissions* with Existing Measures[12]



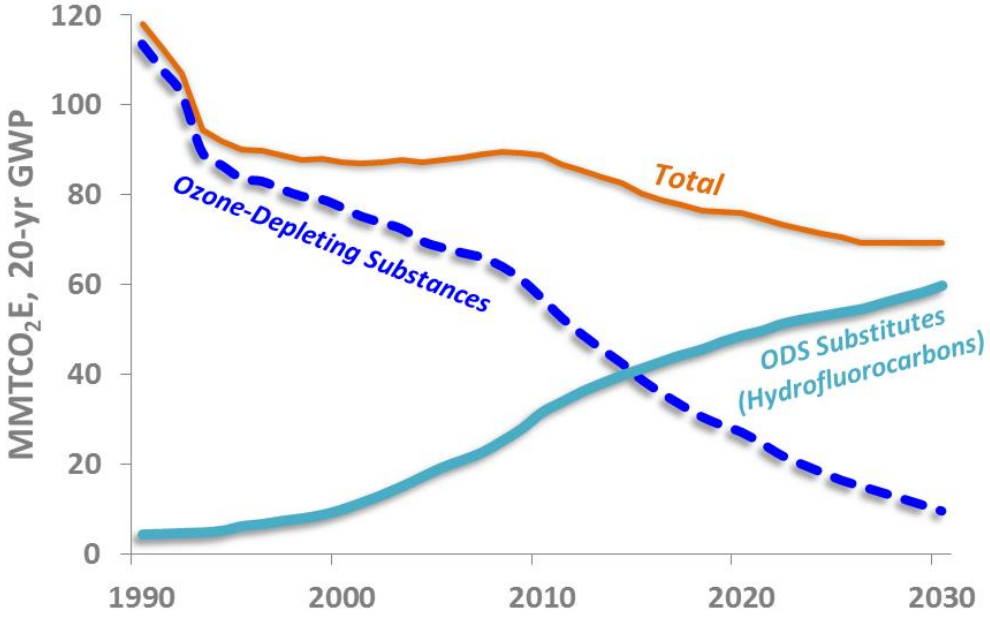
***Using 20-yr GWPs**

Annual F-gas emissions are expected to increase 60 percent by 2030, even with current ARB and U.S. EPA regulations in place. This is primarily because HFCs continue to replace ODS that have been phased-down or phased-out of new production by the 1987 Montreal Protocol. ODS are not included in the California GHG emission inventory since they are not listed in AB 32. However, ODS emissions are declining rapidly as HFC emissions increase (Figure 5). The net warming impact is declining

[12] "Refrig." includes both refrigeration and air conditioning.

overall, but emissions of high GWP compounds must be reduced to meet California's climate goals.

Figure 5. Emissions of ODS and ODS substitutes (hydrofluorocarbons) using 20-year GWPs.



Mobile air conditioning refrigerant emissions are one of the few HFC sources projected to decline by 2030 in response to State and federal programs to incentivize low-leak air conditioning systems and low GWP refrigerants for light-duty vehicles, and federal regulations prohibiting high GWP F-gases in new light-duty vehicles starting in model year 2021. The availability of low GWP refrigeration and air conditioning alternatives are increasing yearly, as industries anticipate a hydrofluorocarbon phase down in response to recent European Union F-gas regulations. Additionally, foam expansion agents, aerosol propellants, solvents, and fire suppressants are increasingly trending towards low GWP alternatives that are often less expensive.

2. Inventory Methods

ARB developed the F-gas emission inventory using California-specific data based on several research contracts funded by ARB. The inventory also leverages data from local and state regulations to inform emission estimates, including the South Coast Air Quality Management District Rule 1415 and ARB's Refrigeration Management Program.

Using these data, a California-specific F-gas emission model was developed by ARB, forming the basis for California's GHG emission inventory for F-gases. Equipment production, retirement, and F-gas usage and emissions are calculated annually for 37 F-gases. Historical F-gas emissions are backcast to 1990 from a 2008 base year using equipment inventories estimated by ARB research contracts. Future F-gas emissions are projected based on population growth, as F-gas emissions and

population are shown to be highly correlated in California. The emission estimates account for the rapid replacement of ODS with hydrofluorocarbons as well as reductions from existing regulations. Additional methodology details can be found in the GHG documentation[13] and in Gallagher, et al., 2014.[14]

3. Inventory Improvement

The F-gas inventory is updated annually as new regulations change the projected emissions, and new reported data become available. The assumptions for the aerosol propellant F-gas emission baseline (last updated 2006) will be updated using the final 2014-2015 ARB consumer products survey data. ARB also funds research and measurements contracts to collect F-gas measurements at a monitoring site at the Mt. Wilson Observatory. These data are being analyzed to verify and track the emissions of various F-gases from the Southern California basin. Emissions from medical dose inhaler propellants are the only remaining F-gas subsector that relies on scaled-down national estimates. This inventory could be improved if California-specific usage was available, but confidentiality becomes a factor for medical devices.

4. Sulfuryl Fluoride

Sulfuryl fluoride (SO_2F_2) is a fluorinated gas with a lifetime of several decades and a 20-year GWP of 6840. Sulfuryl fluoride is used as a pesticide fumigant and is one of the most common replacements for methyl bromide, an ozone-depleting substance whose use is being phased out. According to the California Department of Pesticide Regulation (DPR), 3 million pounds of sulfuryl fluoride were used in 2013 (most recent data available).[15] Its main use is as a structural pest control fumigant to kill drywood termites in homes and buildings, accounting for 82 percent of all usage in 2013. According to the University of California, Riverside, more than 100,000 structural fumigations with sulfuryl fluoride are conducted each year in California.[16] Sulfuryl fluoride is also a common fumigant for dried fruits, nuts, and other agricultural commodities that must be kept pest-free during storage prior to shipping (15 percent of all usage in 2013). The remaining three percent of sulfuryl fluoride application was for other fumigation uses. Sulfuryl fluoride is not registered for use as a field soil fumigant and is not used on agricultural fields.

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[13] ARB 2015 Edition GHG Inventory. http://www.arb.ca.gov/cc/inventory/data/data.htm

[14] Gallagher, G.; Zhan, T.; Hsu, Y-K.; Gupta, P.; Pederson, J.; Croes, B.; Blake, D. R.; Barletta, B.; Meinardi, S.; Ashford, P.; Vetter, A.; Saba, S.; Slim, R.; Palandre, L.; Clodic, D.; Mathis, P.; Wagner, M.; Forgie, J.; Dwyer, H.; Wolf, K. 2014. "High-global Warming Potential F-gas Emissions in California: Comparison of Ambient-based versus Inventory-based Emission Estimates, and Implications of Refined Estimates". Environ Sci. Technol., 2014, 48, 1084−1093. dx.doi.org/10.1021/es403447v

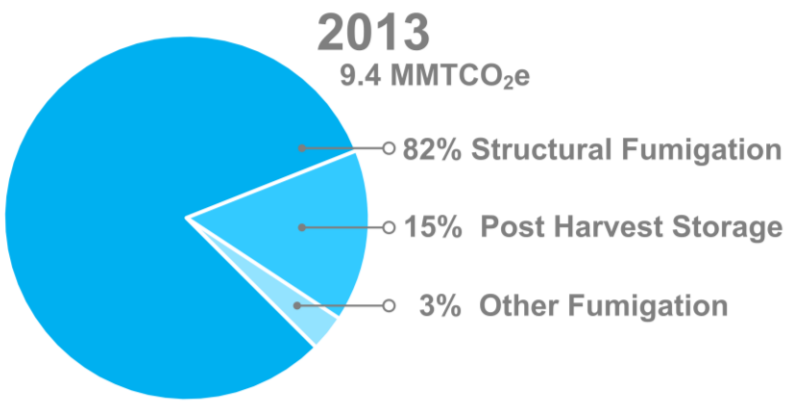
[15] Summary of Pesticide Use Report Data 2013 - Indexed by Commodity, California. California Department of Pesticide Regulation, May 2015. Available at: http://www.cdpr.ca.gov/docs/pur/pur13rep/13_pur.htm.

[16] Sulfuryl Fluoride Structural Fumigation, Personal Chemical Exposure Program, Department of Entomology, University of California, Riverside. Available at: http://faculty.ucr.edu/~krieger/SF%20Web%20Presentation%20Krieger%207%2019.pdf.

Sulfuryl fluoride was not recognized as a high-GWP GHG until 2009. Because sulfuryl fluoride was not identified as a high-GWP gas by the time AB 32 was enacted, it was not initially included as a part of ARB's statewide GHG inventory. However, the annual usage of sulfuryl fluoride is inventoried by DPR as a highly-regulated pesticide and ARB uses this data to track emissions. In 2013, the 3 million pounds of SO_2F_2 usage was equivalent to 9.4 $MMTCO_2E$ emissions (using 20-year GWP values), or approximately 20 percent of all F-gas emissions.

Sulfuryl fluoride emissions and sources in California are presented in Figure 6.

Figure 6. 2013 Sulfuryl Fluoride Emissions*

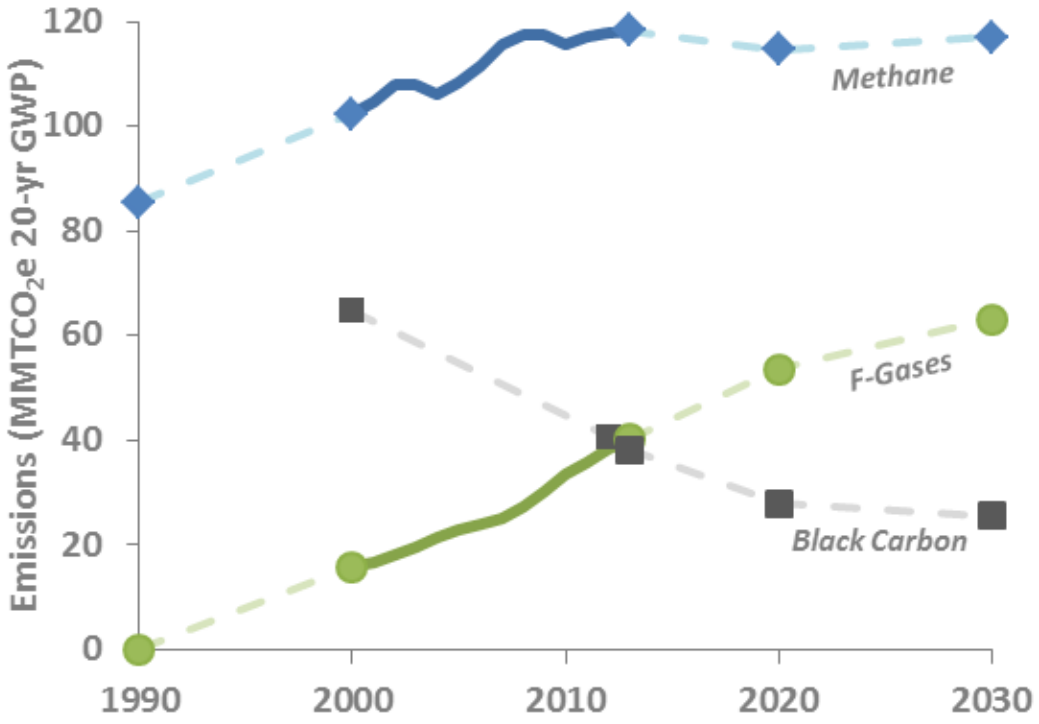


Using 20-yr GWPs

D. Emission Trends for SLCPs

Figure 7 shows the trends in emissions for methane, F-gases, and black carbon. Solid lines represent annual GHG emission inventory data available for 2000 to 2013. Symbols represent individual data years for 1990, 2013, 2020, and 2030. Dashed lines are meant to guide the eye, and do not represent emissions for intermediate years. 2020 and 2030 projections represent expected future emissions based on the current state of knowledge. The projections in the figure include existing control measures, but do not include measures under development or planned programs to reduce black carbon.

Figure 7. Trends in Methane, F-gases (HFCs), and Black Carbon Emissions with Existing Measures Using 20-year GWPs.[17]



Methane emissions have increased since 1990 but are expected to remain relatively constant going forward, as dairy cow populations are expected to stay flat. F-gas emissions increase between 1990 and 2030 as HFCs replace ozone depleting chlorofluorocarbons, which are also potent warming compounds. Black carbon emissions decline significantly from 2000 to 2020, primarily due to mobile source diesel regulations, but are projected to decrease only slightly between 2020 and 2030 as reductions from existing regulations are already realized.

[17] - F-gases include the nine short-lived F-gases: HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-245fa, HFC-32, HFC-365mfc, and HFC-43-10mee.
- Black carbon excludes prescribed fire and wildfire.
- Dashed lines are linearly interpolated between points to guide the eye but are not mean to represent emissions for intermediate years.